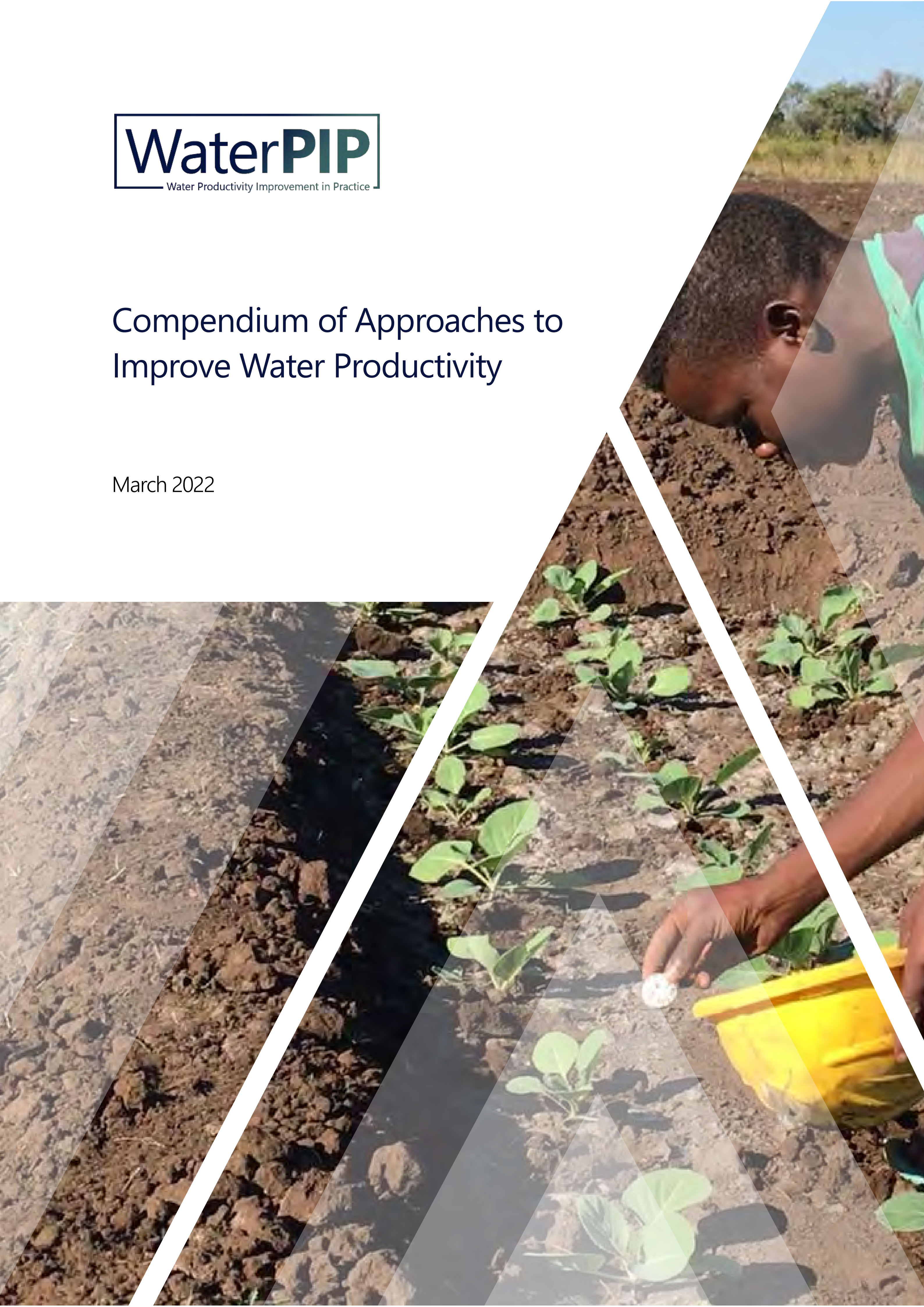
WaterPIP
Water Productivity Improvement in Practice

Compendium of Approaches to Improve Water Productivity

March 2022



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MetaMeta and IHE Delft

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Acronyms

A	Adequacy
CV	Coefficient of Variation
FAO	Food and Agriculture Organization of the United Nations
IWMI	International Water Management Institute
LP	Land productivity
MASSCOTE	Mapping System and Services For Canal Operation Techniques
SDG	Sustainable Development Goals
WaPOR	FAO portal to monitor Water Productivity through Open access of remotely sensed derived data
WaterPIP	Water Productivity Improvement in Practice
WFD	Wetting Front Detector
WP	Water Productivity
WUE	Water Use Efficiency

1 Introduction

1.1 Background

Globally, agriculture is the largest user of water, accounting for at least 70% of all water withdrawals (Scheierling and Tréguer, 2018). The demand for water in agriculture will in 2050 is expected to go up by 50% over 2013 figures (FAO, 2017). This is triggered by:

- The demand for food is expected to rise by 60% by 2050 (FAO, 2011). This is caused by rising population (40%) and by increasing per capita calorie intake (11%).
- This demand for food is matched by demand for non-food products. The demand for timber is to increase by 45% from 2005 to 2030; in the same period demand for roundwood will go up by 47% (FAO, 2009). Demand for cotton is to increase with 81% between 2010 and 2050.

While livelihoods of people and national food securities are dependent on effective crop production, water is often the limiting factor. Water resources are finite and there is competition with other water users and the environment. It therefore is important to improve the water use efficiency in agriculture to improve water and food security and farm returns. This is also explicitly reflected in the Sustainable Development Goals (SDG) 6.4, which reads: *By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity.*

Improving water productivity, defined as the amount of agricultural production per volume of water consumed, is thereby an important component. There are different definitions of water productivity, ranging from biophysical, economic to socio economic.

In spite of this urgency and all the attention given to improving water use efficiency in the last two decades, the overall trends in actual performance of the water systems in many countries has been negative rather than positive. A study implemented for the Islamic Development Bank evaluated the change in several agricultural indicators from 2009-2020[1]. It shows that more water is used in the existing irrigation systems and water productivity in many countries has gone down rather than up (MetaMeta, forthcoming). Similarly, in rainfed systems, water productivity has consistently gone down in a large number of countries. These analyses illustrate that there is a huge potential to reach food security through improving water management practices than on expanding irrigated areas. It is time to make better use of the limited resource we have rather than inefficiently exploiting more of it.

1.2 Improving water use in agriculture

Against these negative trends, some experts believe that improving water productivity in agriculture by 25%, in general, is feasible. The improvements in water productivity apply to both irrigated and rainfed areas, as briefly described in the following sections.

1.2.1 Irrigation systems

In many irrigation systems, there is a tremendous scope for improvement by improving water management 1) at irrigation scheme level by for example optimizing water allocation rules, using appropriate water control structures, controlling leakages, promoting conjunctive management of surface and groundwater and 2) at field level by introducing a wide array of precision techniques that enable better water management. While many of these interventions focus on increasing water use efficiency, further focus should be on increasing yields thereby improving the overall water productivity. This leads to similarly,

[1] See for the interactive platform: https://waterpiporg.users.earthengine.app/view/cia-annualtrends

important improvements on 3) the agricultural production side through improved crop agronomy, better selection of crops and varieties, adjusting crop calendars and better use of agri-inputs. The important argument in favour of such interventions is that they often yield immediate results. They do not have the long gestation period, financial onus and social disruption that comes with the development of new irrigation systems for instance. It may be much more attractive to invest in better water management and higher water productivity than in additional water resource capture (see box 1). However, a thorough understanding should be obtained of the reasons *why* such investments may not have been made yet and combined with local knowledge on what types of investments are beneficial for both water productivity and the farmers.

Box 1 Increasing water productivity in Koga (Ethiopia)

It has been said many times that there is very little irrigation development in Africa, that there is little water storage per head of population, and that this adds up to high vulnerability to droughts. Several medium- and large-scale irrigation systems have been developed over the last 15 years. However, what they have in common is that water productivity has been disappointing.

The Koga Irrigation Scheme in Amhara region in Ethiopia is one such example. It draws water from the reservoir created on Koga River, one of 50 tributary streams joining the Ethiopian Upper Blue Nile. The scheme was meant to irrigate 7,000 ha, but in reality, its service area is close to 5,000 ha. Also, it was meant to be used for water intensive crop cultivation but instead the main crop is wheat.

Figure 1-1 The Koga Dam in Amhara in Ethiopia

In a two-year field program under the project "Monitoring water productivity by Remote Sensing as a tool to assess possibilities to reduce water productivity gaps", implemented by the International Water Management Institute (IWMI), a large number of water users, water user group leaders and irrigation managers were introduced to technical innovations to enhance on-farm irrigation management decisions (FAO and IWMI, 2021). This was done by providing soil moisture measuring devices to allow them to assess whether the land should be irrigated or has been irrigated too much. In particular the Wetting Front Detector (WFD) and Chameleon Soil Water Sensor were used. These two sensors were rolled out to six out of twelve blocks in the scheme, targeting 54 water user groups (FAO and IWMI, 2021).

In the groups, farmers were taught how to use the devices, with some farmers actually operating the instruments on their farm. Special data collectors were deployed to help share the information between farmers. The results were spectacular. Within one or two seasons, farmers realized they applied too much water and this suppressed their wheat yield and reduced their field irrigation supplies. According to key farmers, they typically lengthened the irrigation cycle from the local storage reservoirs from 8 to 11 days, or 9 to 12-13 days – effectively a water use reduction of 35%, as everyone's irrigation turns became less frequent. Part of this high-water wastage earlier, related to the need to make ploughing easy. With reduced water applications the wheat crop yield went up: according to farmers' estimations with 10 to 20%. The gain in terms of water use efficiency or 'crop per drop of water supply' was an impressive 35-40%. Field research by Bahir Dar University confirmed this range of improvement. The farmers noted that improved water management resulted in a faster rotation among water users in the same group and resulted in a decline in water related conflicts. The saved water was used to extend the area under cultivation within the blocks, but also to reduce water deliveries from main scheme operations to the particular night storages. There was also a reduction in soil nutrient loss, as there was less leaching.

Figure 1-2 Farmers showing the Chameleon Sensor (handheld) and the Wetting Front Detector

1.2.2 Rainfed and flood dependent systems

There is also considerable scope to improve water use efficiency in rainfed and flood-dependent agricultural water systems. There is a broad repertoire of measures that can help 1) retain and store the more erratic rain dependent water resources, to 2) use them more efficiently and thereby to optimize the cropping systems. The focus is on lowering water loss through (non-beneficial) evaporation, and using the captured water in case of low rainfall amounts or dry spells and thus preventing crop failure. The potential gains in increasing productivity in rainfed and flood-based farming are high. Several predictions are that the larger part of the increase in global food production will have to come from such rainfed and flood-based systems (Molden, 2007; 2013). Moreover, in Sub Saharan Africa, smallholder farmers largely depend on subsistent rainfed agriculture (Rockström, 2000). Improved water productivity measures may lift them out of poverty and make them less vulnerable to rainfall variability and shifting rainfall patterns. With climate change expecting to increasing the variability and reduce the predictability of rainfall, coping mechanisms to improve water productivity will be even more needed.

1.3 Focus of compendium

In this Compendium we are mainly focussing on interventions improving the biophysical water productivity – or in popular terms the 'crop per drop' (Giordano et al., 2007; 2021). While the focus is on improving water productivity, we also included interventions that improve of land productivity (LP) and water use efficiency (WUE) as they go hand in hand. These concepts are explained in chapter 2.

This compendium also presents how analyses using the FAO portal to monitor Water Productivity through Open access of remotely sensed derived data (WaPOR) can be used to identify practical measures to increase crop production relative to the water consumed in specific agricultural systems. WaPOR data is open access and provides near real-time pixel-based information on actual evapotranspiration, biomass production and reference evaporation on a 10-day basis and biophysical water productivity at a seasonal or annual scale.

2 Compendium goal, concepts and definitions

This compendium aims to identify suitable areas of improvement in water and land productivity and water use efficiency based on systematic analyses of land and water systems with the WaPOR database and /or Aquacrop model (Figure 2-1). For details of the WaPOR analyses, the readers are referred to the Standardized protocol for land and water productivity analyses using WaPOR (Chukalla et al., 2020a[2]) and a protocol for diagnostic analyses is under preparation with the framework of the WaterPIP project[3]. The compendium describes the concepts and different definitions used and provides a comprehensive overview of different types of interventions which enhance water use in agriculture through improving land and water productivity and water use efficiency. It is meant to be a live document, expected to go through a series of updates and improvements, similar to the other protocols.

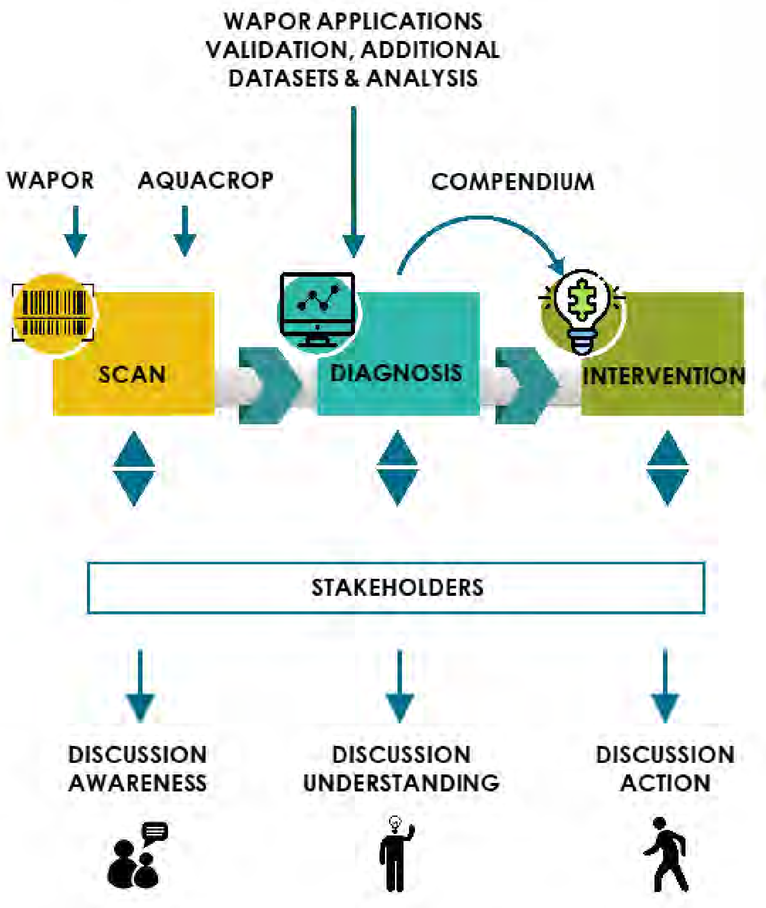


Figure 2-1 The Water Productivity Improvement Analysis Process

Parallel to the scan-diagnosis-interventions process, the engagement with the stakeholders throughout the process is very important. These stakeholders may be water managers, operational staff of irrigation systems, implementers of watershed campaigns and rainwater harvesting programmes, but also farmer organizations, cooperatives and main service providers. The process can also be used to design new Water Productivity programs with decision makers, investors and water users.

[2] https://github.com/wateraccounting/WAPORWP
[3] https://waterpip.un-ihe.org/

As Figure 2-1 highlights, the engagement of stakeholders is throughout the process – in defining the initial scope of questions, in helping to understand the overall context, in validating the analysis – both the scan and the following diagnosis – and in discussing possible solutions and improvements. This increases the chance of the analysis leading to actual action.

What is preferred is to have the analysis done by and with the experts from the water or agricultural organizations concerned, training and coaching them to undertake the analyses themselves, and supplement it with field insights and field feedback.

2.1 Water productivity concepts

Water productivity can be defined in different terms of biophysical, nutritional, economic and social water productivity (Figure 2-2). This distinction provides important insights and can therefore support water management decisions on the ground as well as inform policies. While this compendium will focus on the biophysical water productivity, decisions are often made considering the other definitions of water productivity. For example, economic water productivity, which measures the economic or financial value created with the volume of water consumed, or the number of jobs created per volume of water ('job per drop') is of much concern in countries with high unemployment, and there is an urge to create jobs. Social WP analyses who benefits from the additional value created with water use. Box 2 illustrates an example where these other water productivity concepts were more important factors in the final decision making. For now, we will focus on the biophysical water productivity, we anticipate the project to develop additional resource materials related to the other types of water productivity.

Box 2 Example of the importance of including social and economic WP

Using non-renewable groundwater for high value semi-mechanized export production of potatoes may create high returns in yield per hectare or the financial revenues. However, the benefits may accrue to a few large producers only, with very few jobs created, no contribution to national food security and hidden subsidies in production (for instance in pumping).

Figure 2-2 Water Productivity definitions. From left to right: Biophysical WP, Nutritional WP, Economic WP, and Social WP

2.2 Water use in agriculture

The concept of water productivity is gaining increasing global attention as a way to become more efficient and effective with water use in agriculture (Molden et al., 2010). However, it is important to note that solely focussing on improving water productivity will not address the concerns of farmers nor will it address the issue of dwindling water resources availability. The concept therefore has to be used in conjunction with other indicators, such as land productivity and water use efficiency. There is a frequent confusion between water productivity and water use efficiency. While Water Productivity considers the yield or biomass production per unit of water consumption, Water Use Efficiency is the ratio between the water that is applied and the water that is being consumed (Figure 2-3). The concept can be applied to a plot or field or to an irrigation scheme or irrigation unit, which can provide useful insights into efficiencies at plot/irrigation unit/ scheme level.

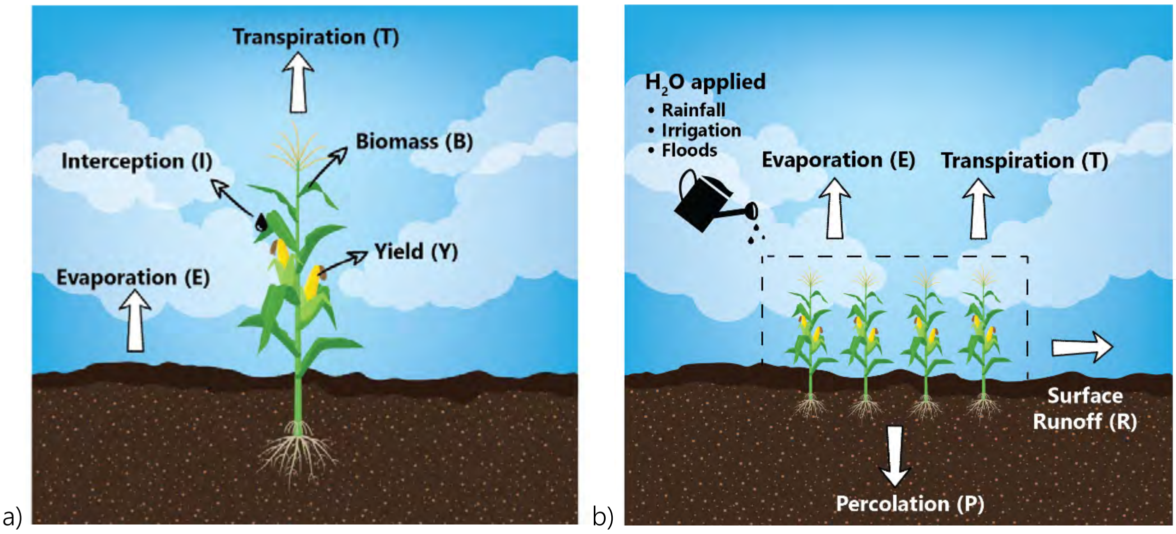


Figure 2-3: Schematisation of a) Water Productivity (B or Y over E&T) and b) Water Use Efficiency (WUE – E&T over H_2O applied) at field scale.

The following section provides the definitions of the most used concepts.

2.3 Definitions

Land productivity can be defined as the above-ground biomass production (*B*) or yield (*Y*). Yield is considered to include all or any part of the crop that is usable for consumption (both human and animal) or processing purposes (oils, cottons, fuels, etc.) and can be derived from the above-ground biomass production using the following equation:

$$Y = B * H_i$$

Equation 2-1

Harvest index (H_i) is the ratio of grain weight (*Y*) to total plant weight (*B*) (Sinclair, 1998). The harvest index is an important factor associated with increases in crop yields in the twentieth century. It is affected by stresses a crop may have endured during the growing season, and particular when the stresses occur during critical growing stages. If this ratio is below the attainable (i.e. the standard harvest index for that crop) it can be assumed that the crop has endured stresses during its growing season.

Transpiration (*T*) is considered the beneficial part of the evapotranspiration, which plants release during biomass formation. The transpiration is therefore directly linked to biomass production (Perry et al., 2009).

Beneficial fraction (*T/ET*) is an indicator which provides the fraction of water that is consumed beneficially (*T*) over total consumptive use (*ET*), which includes non-beneficially consumed water (E). The ratio provides an insight into the efficiency of on farm and agronomic practices on water use for crop growth.

Adequacy (A) is "the measure of the degree of agreement between available water and crop water requirements in an irrigation system" (Chukalla *et al.*, 2020b, p. 12). It is the ratio between the AETI and the crop water requirements.

$$A = \frac{ET_a}{ET_c}$$

Equation 2-2

Water productivity (*WP*) is defined as the biomass or yield per the amount of water consumed. For the gross *WP* the water consumed is considered the total evapotranspiration (excluding interception) (equation 2-3 and equation 2-4):

$$WP_{B(ET)} = \frac{B}{ET}$$

Equation 2-3

$$WP_{y(ET)} = \frac{Y}{ET}$$

Equation 2-4

The net *WP* then defines the consumed water as the beneficial fraction (*T*) (equation 2-5 and equation 2-6):

$$WP_{B(T)} = \frac{B}{T}$$

Equation 2-5

$$WP_{y(T)} = \frac{Y}{T}$$

Equation 2-6

As these indicators refer to crop production, the values are therefore aggregated for the cropping season.

Water Use Efficiency (WUE) is defined as the ratio between the consumed water (*ET*) and applied water for a specific domain (Figure 2-3). The water applied includes the amount of rainfall and irrigated water (*Q* including depth of flooding in spate irrigation systems).

$$WUE = \frac{ET}{P + Q}$$

Equation 2-7

In case of rainfed agriculture this efficiency may also be referred to as Precipitation use efficiency (WUE_p) in which the denominator is then only the amount of precipitation received during the cropping season. The *WUE* in irrigated areas can be calculated at farm or field level (WUE_f) or for the irrigation scheme or a sub-section of the scheme (WUE_s). Differentiating this is necessary as it requires different interventions for improvement.

3 Approaches to improving water productivity and water use efficiency

There are many reasons why there is sub-optimal water use in agriculture, affecting land and water productivity and water use efficiency in different ways. Understanding these causes and the response is therefore important as this will also influence the right kind of interventions to improve the system. This chapter will also clearly illustrate that certain interventions are beneficial for the different indicators. This is described in the next sections. Chapter 4 and the annexes provide more detailed information on the different interventions.

3.1 Improving water productivity

Improving water productivity should go hand in hand with improving land productivity (yield) as this is a key target for farmers. Improving water productivity can be done by influencing the two factors of the equation, through increasing yield and/or reducing ET through reducing non-beneficial E (Figure 3-1).

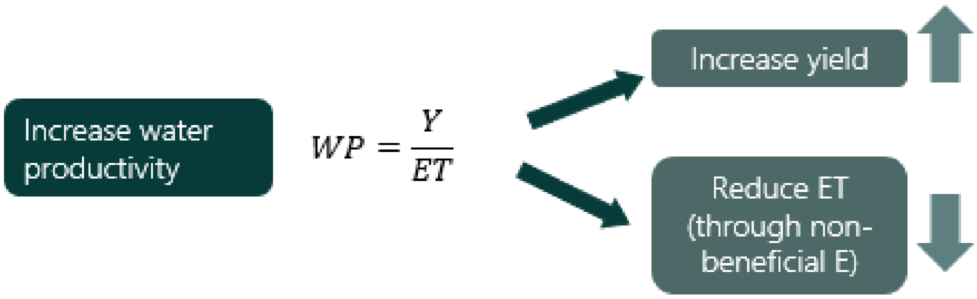


Figure 3-1 Water Productivity improvement

3.1.1 Improving yield

Land productivity (yield) is influenced by yield defining, limiting and yield reducing factors (van Ittersum et al., 2013). Yield defining factors can be grouped into climate, crop and cultivar features. Plants require water and nutrients to grow and sub-optimal availability limits the yield. Other factors such as weeds, pests and diseases and pollutants reduce yields (van Ittersum et al., 2013). Different intervention areas that target these factors to optimize yields are described in the sections below.

3.1.1.1 Increasing water availability

The relationship between biomass production and transpiration (water productivity) is known to be linear for a given crop in a specific climate, and with optimal or non-limiting nutrient conditions (Steduto et al., 2012). Under such conditions, increasing yield can be attained through increasing water resources availability for the crops, allowing for higher land productivity along the same water productivity slope (Figure 3-2).

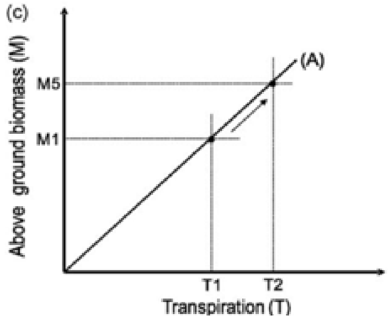


Figure 3-2 The linear relationship between T and biomass affected by water availability (Perry et al., 2009).

Besides making more water available through supplementary, spate or full-scale irrigation, in field management can also help retain more water in the soil and allow plants to access water in deeper layers. Typical field scale interventions focus on reducing runoff and increasing infiltration such as deep tillage to allow deeper root depth and for example increasing soil quality to increase soil water retention. Interventions which support water availability to the crop can be found in these five intervention areas:

- Water resources enhancement (intervention area 1)
- Irrigation scheme water management (intervention area 2)
- Irrigation field water management (intervention area 3)
- Water management in rainfed and flood dependent systems (intervention area 4)
- Soil moisture management (intervention area 5)

To assess if water is the limiting factor, remote sensing-based analyses can assist in identify areas where such interventions may be beneficial (Box 3). Further field investigations are required to identify the most suitable intervention.

Box 3 Adequacy Example

The adequacy (A) indicator is "the measure of the degree of agreement between available water and crop water requirements" (Chukalla et al., 2020b; Bastiaanssen and Bos, 1999; Clemmens and Molden, 2007). It can be calculated using Equation 3-1, illustrating that the adequacy represents the amount of water which is consumed compared to the amount of water which could have been consumed for the specific climate conditions under unlimited water conditions and for the crop. Identifying which adequacy value is considered 'good' and which 'poor' is crop and context specific. Karimi *et al.* (2019) based this determination on the adequacy which correlates to the *critical* yield which is required for a farmer to recover the investment costs. Based on this an adequacy value for sugarcane above 0.8 was considered to be 'good' performance, 0.68 <A ≤ 0.8 acceptable and ≤ 0.68 poor (Karimi et al., 2019)

$$A = \frac{ET_a}{ET_c}$$

Equation 3-1

The adequacy was estimated for the Xinavane sugar cane estate from 2014/2015 to 2018/2019 (Figure 3-3; Chukalla et al., 2020b). The seasonal relative evapotranspiration varies between 0.61 in 2015/2016 to 0.71 in 2016/2017. For the period 2014/2015 to 2018/2019, plots irrigated by centre pivot had the highest adequacy (0.74±0.05 [-], and plots irrigated by furrow had the lowest adequacy (0.65±0.07 [-]).

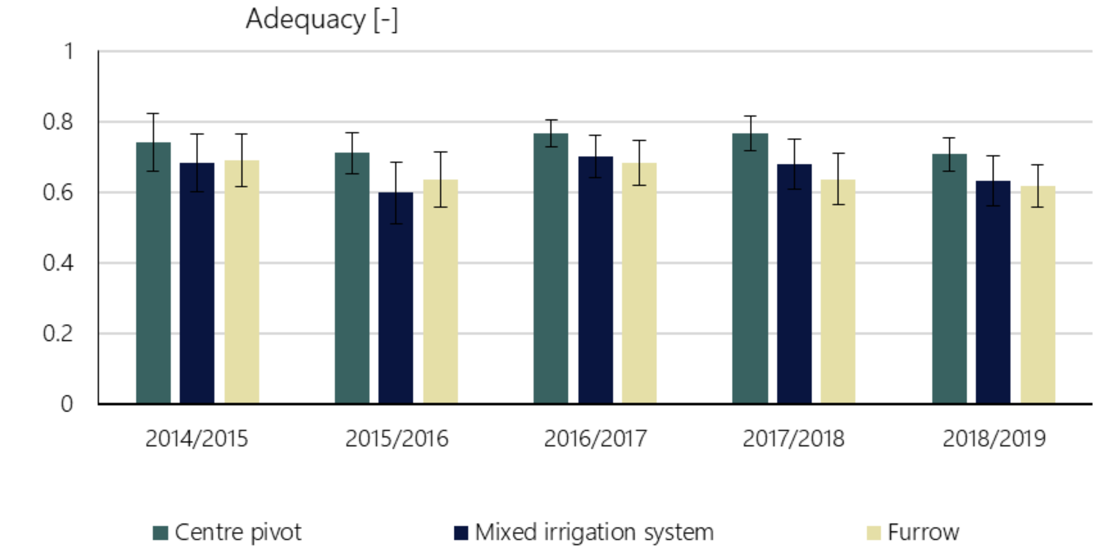


Figure 3-3 Seasonal adequacy at Xinavane sugarcane estate categorized by irrigation method.

The spatial distribution of the adequacy across the Xinavane irrigation scheme categorized into centre pivot, furrow and mixed irrigation system is shown for 2017/2018 in Figure 3-4. In 2017/2018, the average relative evapotranspiration of the plots irrigated by mixed irrigation system and centre pivot, and furrow are 0.77±0.05, 0.68±0.07, and 0.64±0.07, respectively.

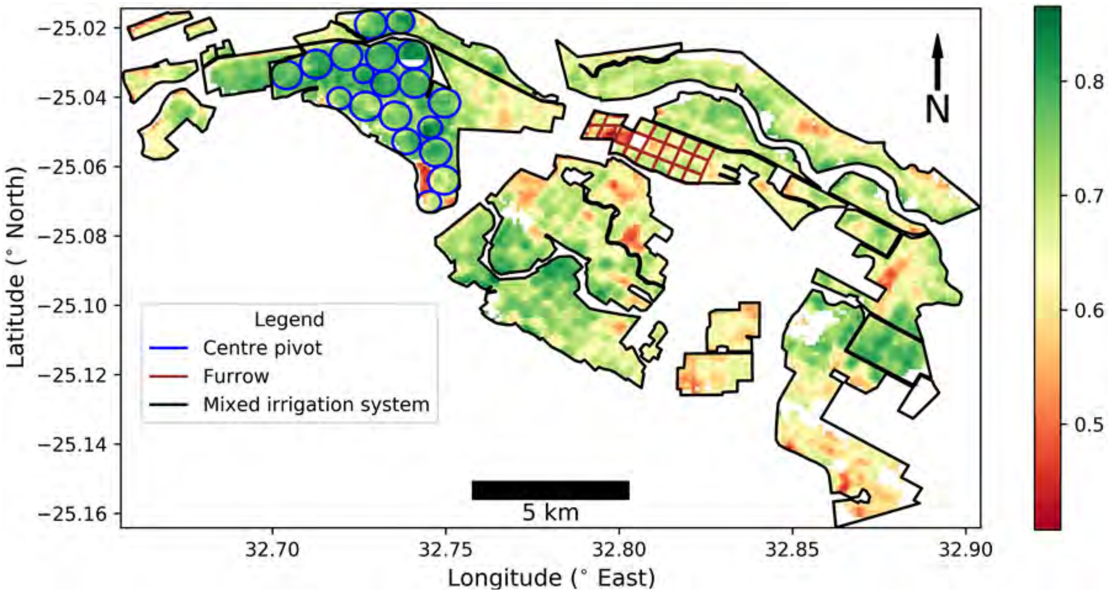


Figure 3-4: Spatial distribution of the adequacy at Xinavane sugarcane estate in 2017/2018.

3.1.1.2 Improving crop and field management

Next to increasing water availability there are many other ways to increase yields, as well as avoiding crop failure. Many of these interventions also influence the water productivity by being more efficient with the water used for crop production (Figure 3-5).

A' nutrient poor
B genetically modified crop (incl adapted to climate or season)

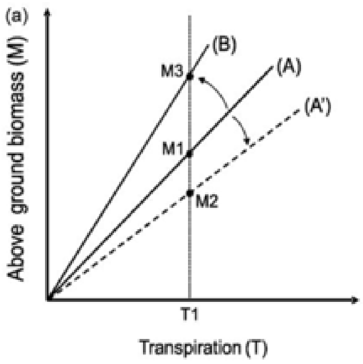


Figure 3-5 The linear relationships between T and biomass affected by fertility and crop variety (Perry et al., 2009).

The interventions include using improved crop selection, better nutrient management and controlling pests and diseases.

- Cropping system management (intervention area 6) including
    - Crop type selection
    - Crop rotation
    - Intercropping
- Crop input management (intervention area 7) including
    - Nutrients
- Control pest and diseases (intervention area 8) including
    - Use of herbicides and pesticides

Box 4 provides an example of water productivity analyses using the remote sensing derived WaPOR database for a sugar cane estate in Ethiopia, and how the analyses can inform improved management.[4]

Box 4 Example Water Productivity Wonji Sugar cane (Alemayehu et al., 2020)

The Wonji sugarcane plantation, located in the Rift Valley in Ethiopia, is a major producer of processed sugar and relies completely on the water supply from the Awash River (Figure 3-6). Following the drought of 2016 and the subsequent stress on the sugarcane crop, it became increasingly clear that the limited water resources available should be used more effectively. The system consists of a furrow irrigation system which has been in use since the 1960, further expansion areas were developed using sprinkler, centre pivot and hydroflume irrigation

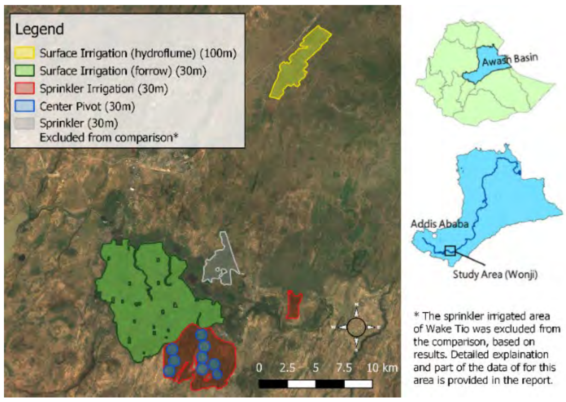
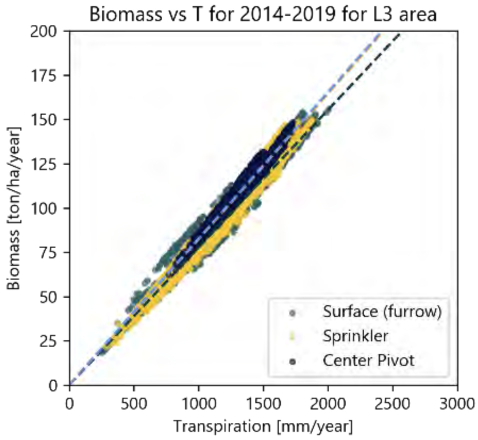


Figure 3-6: Wonji sugarcane plantation (EOX Sentinel-2 cloudless image)

Following field observations and stakeholder engagement a study was carried out by the WaterPIP team to provide insight into water and land productivity, and irrigation performance at the Wonji-Show Sugar Plantation using WaPOR data. The biomass – transpiration graph differentiated for the different areas is shown in Figure 3-7, with the key values provided in the table.

[4] For more information about the methodology, assumptions and additional results the reader is referred to Chukalla et al. (2020b) and Alemayehu et al. (2020).



Irrigation technology	WP (kg/m³)	R^2
Surface (furrow) n = 74,576	0.777	0.958
Centre Pivot n = 7,140	0.827	0.965
Sprinkler n = 23,547	0.824	0.971

Figure 3-7 Water productivity lines for three different irrigation systems in Wonji sugar case estate (analyses done using WaPOR data level 3) (Alemayehu et al., 2020).

The low productivity of the furrow irrigation, locate in the oldest part of the plantation, is both confirmed by field data and WaPOR data. As a detailed analysis of the water productivity, including the response to climatic evaporative demand (ET_{ref}) and the elimination of the non-productive evaporation component shows that variations in agronomic management practices or plant growing conditions can be statistically discerned within the (disaggregated) dataset from WaPOR. The outcome supports the local perception that soil fertility is the limiting factor and previous research that identified salinised groundwater at shallow levels in the furrow irrigated areas. This study however, argues that there is distinct room for increasing the yields in that furrow irrigated area without actually increasing overall water consumption (*ET*), although the exact extent of these plant stress levels within the Wonji plantation and therewith the 'room for improvement' of the Wonji main sub-scheme needs to be further determined.

3.1.2 Reducing ET (through non-beneficial E)

While the net biomass water productivity (B over T) is a fixed ratio under similar conditions, the gross biomass water productivity (B over ET) can vary substantially depending on the amount of non-beneficial ET (Figure 3-8).

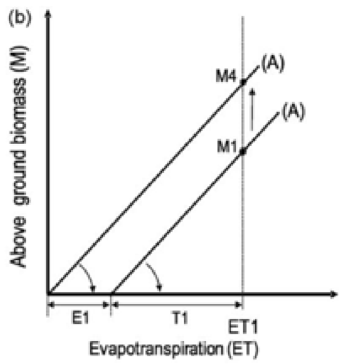


Figure 3-8 The linear relationships between ET and biomass affected by non-beneficial ET (Perry et al., 2009).

The difference can be attributed to, for example, high evaporation which does not contribute to biomass production (non-beneficial ET). Over the last decades many researchers and practitioners have worked on developing strategies to reducing this non-beneficial evapotranspiration through a so-called vapor shift (Rockström, 2003; Rockström and Barron, 2007). Various interventions that preserve the soil moisture and enhance infiltration can support this vapor shift (see also Figure 3-9).

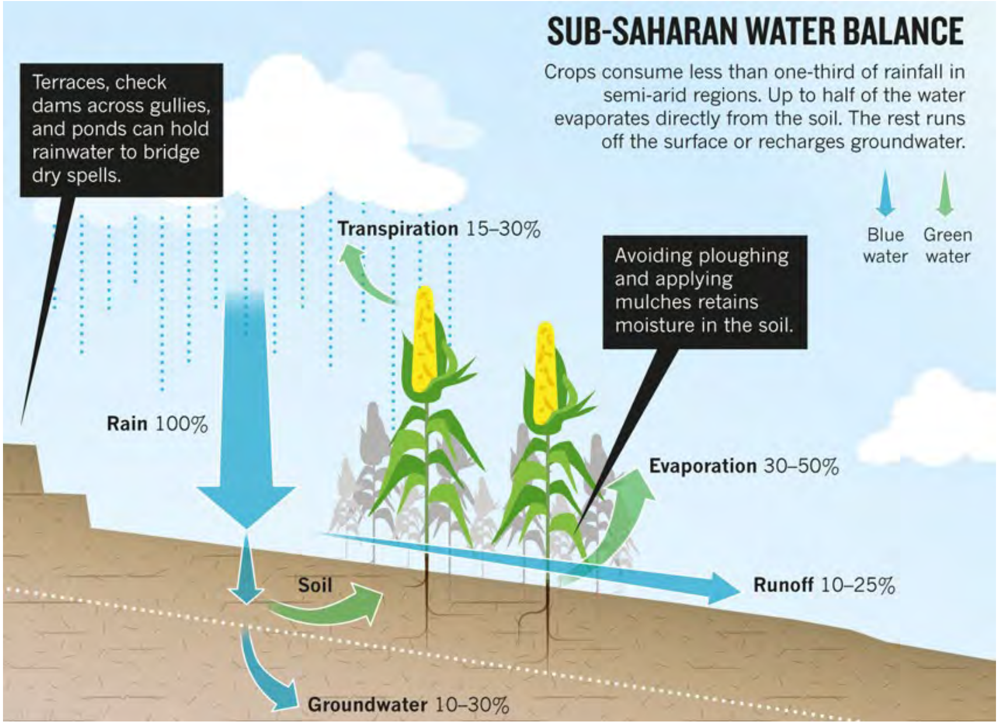


Figure 3-9 Water balance of an agricultural field in sub-Saharan Africa (after Rockström and Falkenmark, 2015; Molden, 2013)

Regulated deficit irrigation, which is practiced by applying water less than the full irrigation requirement at crop stages less sensitive to drought, increases water productivity by triggering physio-biochemical processes that makes plants less sensitive to water stress (Ali et al., 2007), and increase the harvesting index.

Examples of such interventions are the following:

- Soil moisture improvements (intervention area 5) which reduce non-beneficial ET
    - Using mulching to reduce soil evaporation
    - Tillage (conservation or zero tillage) moderate evaporation (Busari et al., 2015)
    - Different types of terracing, enhancing infiltration
    - Weed management (including removing invasive species)
    - Address water logging

These interventions can be applied in any agricultural system from rainfed to irrigated agriculture. Box 5 shows an example of the water lost through invasive species in a spate irrigation system in Yemen.

Box 5 Removing invasive species

Wadi Mawr is a spate irrigation system in Yemen (Figure 3-10). The system is affected by an invasive species (*prospis juliflora*) which has spread rapidly and is competing with crops for water resources. As the invasive species is a perennial shrub, we were able to obtain its extent by assessing the WaPOR NPP data outside of the cropping season (see Figure 3-10 for example of the seasonal NPP for the season 31 July 2019 - 10 February 2020). The invasive species were introduced to decrease erosion, rehabilitating degraded lands, however, at its current extent it is affecting canal structures and, in the end, decrease the amount of flood water reaching the fields.

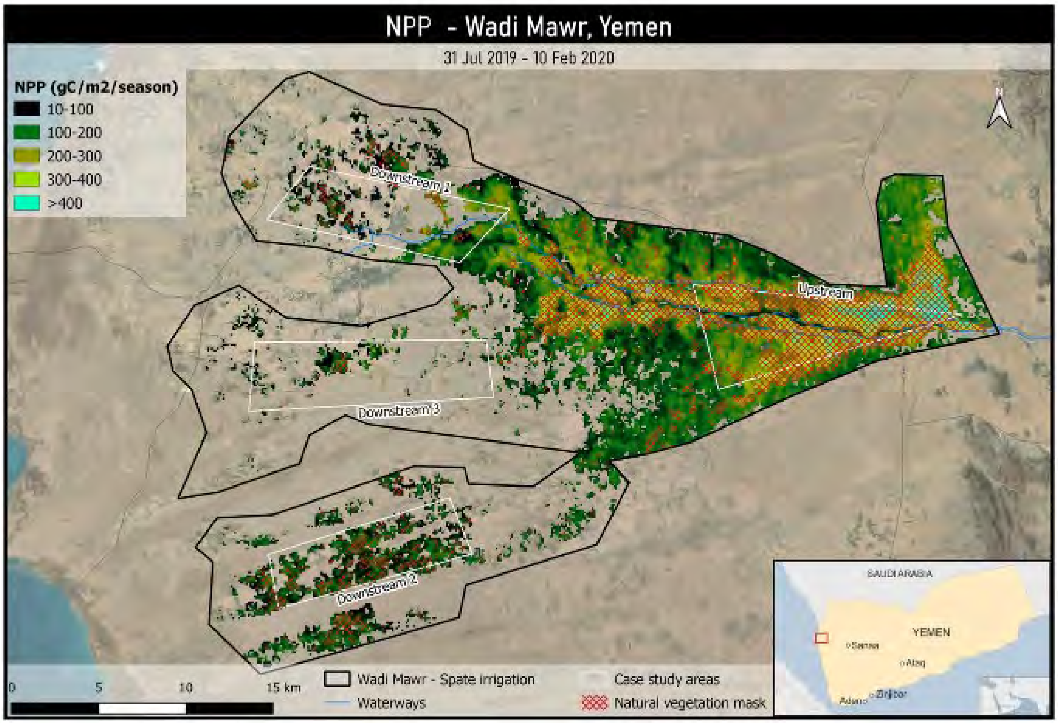


Figure 3-10: Season Net Primary Production (NPP) outside of the cropping season in Wadi Mawr, Yemen.

The WaPOR analyses show that the invasive species consume 1.5 to 2 times the amount of water compared to the natural vegetation. In addition, the problem seems to be more in the upstream parts of the spate irrigation system. It is therefore recommended to investigate replacing the upstream invasive vegetation areas with natural vegetation.

For irrigated areas, interventions such as alternating wetting and controlled soil drying in rice production can enhance the ratio of transpiration over evapotranspiration, also called the beneficial fraction (Yang & Zhang, 2010). This concept of the beneficial fraction can help identify areas with high non-beneficial ET, this can be identified using remote sensing information. As the products and algorithms are improving that they can distinguish between the different components of ET. The WaPOR database also provides separate datasets for Interception, Transpiration and Evaporation[5]. Box 6 shows an example of such analyses.

Box 6 Beneficial fraction example

The beneficial fraction (the ratio of seasonal transpiration over seasonal ET_a) across the Xinavane irrigation scheme categorized into centre pivot, furrow and mixed irrigation system is shown for 2017/2018 in Figure 3-11 (annual maps from 2014-2019 are provided in Chukalla et al., 2020b). The beneficial fraction across Xinavane in 2014/2015 to 2018/2019 is above 80%; the average beneficial fraction is 83±3% and it ranges from the minimum ~82.4±3.6% in 2014/2015 to the maximum ~84.2±3% in 2017/2018. The average beneficial fraction is the highest where pixels are irrigated by centre pivot and smallest where pixels are irrigated by furrow.

In the season of 2017/2018, the beneficial fraction is 85.3±1.3% on pixels irrigated by centre pivot, 84.2±2.4% on the pixels irrigated by the mixed irrigation system, and 82.9±3.4% on the pixels irrigated by furrow (Figure 3-11). Comparing the average beneficial fraction over the latest five seasons (2014/2015-2018/2019), pixels irrigated by centre pivot show higher seasonal average beneficial fraction (84.1±1.8%) compared to pixels irrigated by mixed irrigation system (82.8±3%) and furrow (82.5±3.4%).

[5] However, it must be noted that although the WaPOR AETI layer is well evaluated in several studies (e.g. Weerasinghe et al., 2020; Blatchford et al., 2020; FAO, 2020), there are still concerns about the quality of the WaPOR layers that split ET into E, T and I (FAO and IHE Delft, 2019; Chukalla et al., 2021).

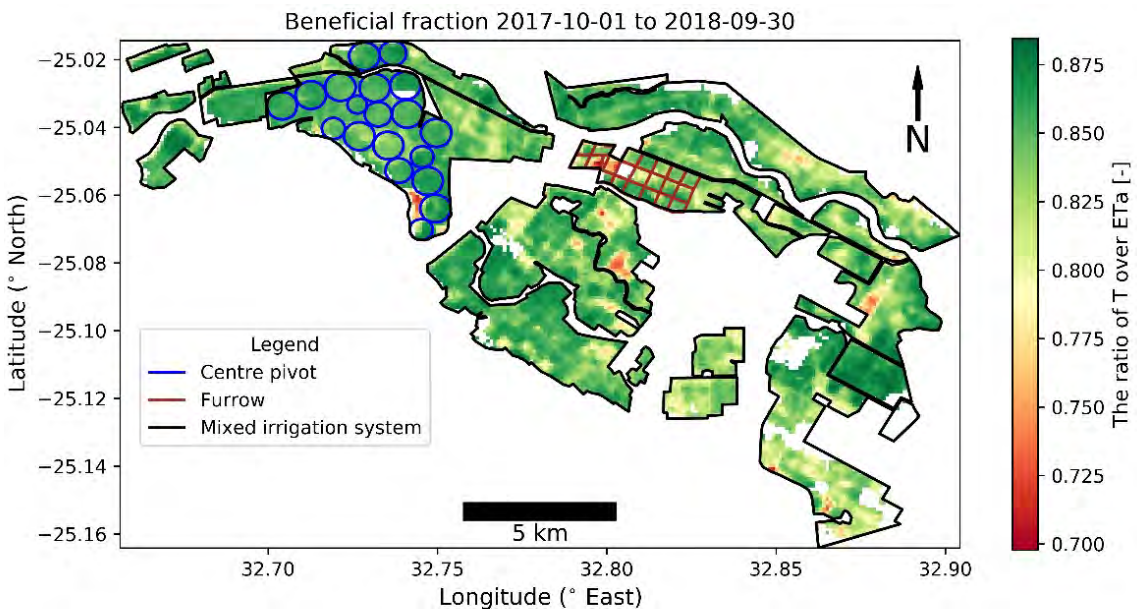


Figure 3-11. Spatial distribution of the beneficial fraction across Xinavane irrigation scheme categorized by irrigation methods in 2017/2018

3.2 Improving water use efficiency

Many improvements in agriculture, and particularly irrigation, in the past decades focussed on increasing water use efficiency. While improving water use efficiency is not the primary objective of this compendium, we decided to incorporate it as many of the interventions targeting water use efficiency can also benefit water productivity. Similar to the water productivity, water use efficiency can be improved by influencing the two factors of the equation, through increasing (beneficial) water consumption and/or reducing water applied (Figure 3-12).

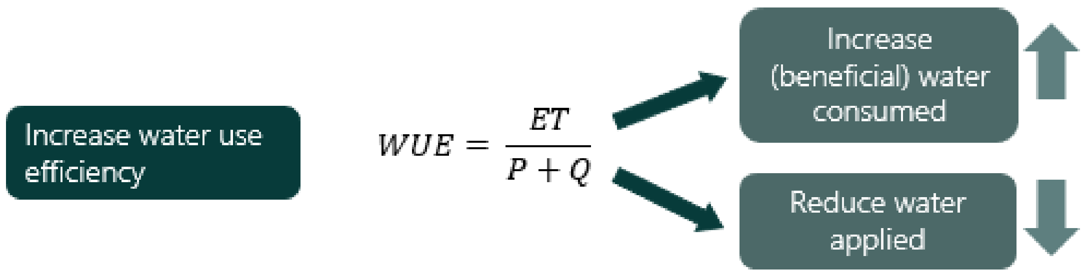


Figure 3-12 Water Use Efficiency improvement

While water productivity is a concept generally applied at farm or field scale level, the scale of analyses of water use efficiency can range from rainfed field to irrigation field to irrigation system level (Figure 3-13). In the interventions described below, reference will be made to these different scales.

Rainfed field | Irrigated field | Irrigation system

Figure 3-13 Scales considered for water use efficiency

3.2.1 Increase (beneficial) water consumed

Water use efficiency improvements focus on making more of the precipitation, water withdrawal or applied available for crop water consumption (ET). At the scale of an irrigation system the focus is on reducing conveyance losses (leakage, seepage and evaporation) in the canals and improved water allocation. Similarly, at the scale of an irrigated field, the focus is reducing percolation and runoff. An even application of irrigation water avoids over watering at the head (with high percolation as a result), and deficits at the tail end (lower *ET*). Typical interventions focus on improving allocation and distribution, the typical intervention areas are:

- Irrigation water system management (intervention area 2)
- Irrigation field water management (intervention area 3)

Water use efficiency of an irrigated field or irrigation system cannot be directly estimated using remote sensing as it requires information on the amount applied to the field. We therefore use a proxy (uniformity) estimated from remote sensing, which is a measure of irrigation uniformity (Bastiaanssen and Bos, 1999), it is calculated using the coefficient of variation (CV) of ET_a. For an irrigation scheme the value can be calculated at two levels—at field level and at irrigation scheme level (see Box 7).

Box 7 Example uniformity

The evenness of the water supply in the Wonji irrigation scheme (uniformity) can be assessed with the coefficient of variation (CV) of ET_a. Figure 3-14 shows the CV of ET_a for the different irrigation methods for the average annual ET_a for the period 2014-2019. The uniformity of the ET_a in the total L3 area (Wake Tio included) is 12%. For the areas under surface irrigation (furrow), centre pivot irrigation and sprinkler irrigation the CV of ET_a are respectively 9.8%, 10.3% and 15.9%. Wake Tio has, with CV of 17.3%, the lowest performance on uniformity, but still well within the range of fair uniformity. The uniformity for the L2 area is 12.4%. Overall, the Wonji has a fair uniformity, with good uniformity in the surface (furrow) irrigated area of Wonji Main.

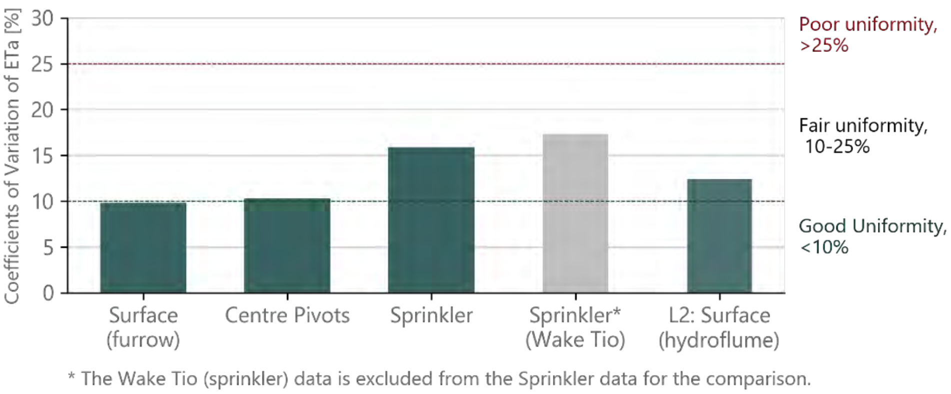


Figure 3-14: Coefficient of variation of the annual average ET_a at Wonji sugarcane estate categorized by irrigation method (Alemayehu et al., 2020).

To improve the water use efficiency in rainfed agriculture, it is important to direct more water to the evapotranspiration component and to reduce runoff and percolation (Figure 2-3). The interventions therefore are very similar to those identified to improve land productivity, where the focus is on directing more water to the beneficial component of ET (T):

- Water management in rainfed and flood dependent systems (intervention area 4)
- Soil moisture management (intervention area 5) which reducing runoff and enhance infiltration through:
    - Using mulching to reduce soil evaporation
    - Different types of terracing
    - Weed management (including removing invasive species)
    - Address water logging
    - Tillage
    - Field bunds reduce runoff

While it may sound counterintuitive that most of the above mentioned interventions are also mentioned under reducing ET (section 3.1.2) for the water productivity improvement. The finesse is in selecting the interventions that benefit both indicators.

3.2.2 Reduce water applied

Too much water supply to a system or field may lead not only to high amounts of percolation and surface runoff (return flows) and therefore low water use efficiencies, it may also affect the crop growth due to water logging and loss of soil and nutrients. Adequate water supply is therefore needed to improve the systems performance, particularly in schemes where water is applied beyond the irrigation water requirement (including the leaching requirement). The following interventions focus on adequate water supply and reduce water logging. In some cases, deficit irrigation may be beneficial and a reduction in yield may out way the benefits of improving efficiency and reducing water use.

- Irrigation system management (intervention area 2)
    - Deficit irrigation
    - Improving irrigation scheduling
    - Improve the quality of irrigation water
    - Improve drainage management
    - Manage water logging

4 Intervention areas

The interventions listed in this compendium are organized in the following categories:

- Water resources enhancement
- Irrigation-scheme system management
- Irrigation field water management
- Water management in rainfed and flood dependent systems
- Soil moisture management in rainfed and flood dependent systems
- Cropping system management
- Crop input management
- Pests control

The following sections provide an overview of each intervention area and the expected impact on water productivity, water use efficiency and yield for each intervention. In annex 1, a more detailed description of fifty plus of the most common interventions is provided. It does not comprise an exhaustive overview of all the possibilities (it is a living document), nor does it solely refrain to those that might only impact water productivity. Also it is important to consider that the expectations associated with water productivity are not only restricted crop performance (the bio-physical) but may also include economic, social, ecological and technical (as referred to in chapter 2.1). Water productivity measures also do not only take place at plant level, but also at field, scheme and policy level.

What is important to consider that the indicators suggest an impact, which implies a (significant or measurable) change over time for a specific place and for some indicators also for same crops. The following considerations are provided when browsing through the solutions list and write-up:

- most if not all solutions are not stand-alone solutions if intending to improve water productivity;
- besides introducing solutions, improving water productivity comes with: adequately being able to measure to do so (as this compendium suggests); performing the right comparison; having a clearly identified objective; and keeping the intended impact in mind;
- keep in mind the potential trade-offs a solution may have in a given context, with regards to water resources management (within a basin or hydrogeological unit); the environment; the societal and economic impact. These trade-offs are mentioned in the descriptions of the solutions.

Where the fields are left open, ie. no significant impact is expected.

Box 8 Illustration of the conjunctive use of different interventions

A three year field study (Arora et al., 2011) on the effects of irrigation, tillage and mulching on soybean yield and water productivity on sandy loam and loamy sand trials (Indian Punjab), show that: deep tillage (chiselling up to a depth of 0.35m) and use of straw mulch (6t/ha) enhanced water productivity from 1.39 to 1.97kg/ha/mm in a partial irrigation regime (withholding irrigations during pod-filling) and from 1.87 to 2.33kg/ha/mm in full irrigation regime. Yield and WP gains are ascribed to deeper and denser rooting due to moderation of soil temperature; and to water conservation with straw mulching and tillage-induced reduction in soil mechanical resistance. Comparable yield responses to deep tillage or mulching in the loamy sand soil suggest that either deep tillage or mulching, depending on cost and availability considerations, can be employed for improving soybean yield and water productivity.

4.1 Water resources enhancement

There are several techniques to ensure that a larger portion of the run-off is captured and stored and made available for (re)use. This will help the availability of water, effectively enhancing the water that can be used for crop production. Enhancing the availability of surface water – also called water harvesting – is common in rainfed and flood dependent systems, where the strategy is to capture a larger part of the run-off and the floods. It can also be applied in irrigated areas – creating more buffer capacity within the irrigated areas – through more storage, either in surface ponds or in the shallow groundwater.

1. Water resources enhancement	Impact			Application area		
	WP (ET)	WUE	Y	irrigated	rainfed	Spate irrigation
I 1-1: Surface water storage			+			
I 1-2: Shallow groundwater storage			+			
I 1-3: Water harvesting			+			
I 1 4: Water harvesting: using roads			+			
I 1-5: Water harvesting: using rock outcrops			+			
I 1-6: Conjunctive use of ground and surface water		+	+			

4.2 Irrigation scheme system management

Many irrigation schemes globally are under performing due to various reasons from degrading soils to a lack of proper operation and maintenance. Scheme managers and farmers may also be confronted with less water due to increasing competition between users or changing climate. Modern irrigation management is essentially concerned with responding to the needs of current users with the best use of the available resources and technologies as well as a sense of anticipating the future needs of the scheme (Renault et al., 2007).

This is, however easier said than done, as for most large-scale open-channel water conveyance and distribution systems, chaos often dominates, having a direct and negative impact on productivity. This low productivity of irrigation projects is seldom the result of poor performance by individuals at any level, but reflects systematic flaws in the overall management approach. A change in management philosophy is required, which includes both (re)iteration of administrative and physical controls as well as the adequate measurement and accounting of water at intermediate points within the distribution network (Clemmens, 2005).

Focussing on canal operation techniques the FAO published a methodology called MASSCOTE, which embeds a service-oriented approach (Renault et al., 2007). This approach focusses on the conveyance and delivery of irrigation water to users according to an agreed level of service that is well adapted to their requirements for water use and cropping systems. The irrigation scheme services, however can in many cases not be seen separate from other challenges within irrigated areas and often conjunctive measures are required to improve irrigated agriculture.

2. Irrigation system management	Impact			Application area		
	WP (ET)	WUE	Y	irrigated	rainfed	Spate irrigation
I 2-1: Canal and water course lining		+				

4.3 Irrigation field water management

In this chapter the interventions listed focus on improving soil and crop interaction in irrigated areas. The intention is not to circumvent the valid global discussion on irrigation efficiency improvement, water use and water consumption which as been nicely caught by Berbel et al (2018) for example. The interventions are meant to provide farmers and irrigation scheme managers ideas for the improvement (or intensification) of crop production by means of the sustainable continued use of fields and schemes. The interventions are also meant to show the trade-offs, e.g. overhead irrigation high investment might outweigh potential water saving; the possibility of salt injure, interception and spread of pathogens from overhead irrigation may favour surface irrigation methods; lack of labour might favour pressurised systems over non-pressurised non-pressurised; and so forth. Focus is on increasing the water that is consumed beneficially (T) versus the amount that is consumed non-beneficially (E) and not consumed at all (including the recoverable and non-recoverable fraction).

3. Irrigation field water management	Impact			Application area		
	WP (ET)	WUE	Y	irrigated	rainfed	Spate irrigation
I 3-1: Root zone irrigation (or sub-irrigation)	+		+			
I 3-2: Land levelling		+				
I 3-3: Surface irrigation (furrows and basins)		+	+			
I 3-4: Pressurized irrigation systems		+	+			
I 3-5: Rootzone drainage			+			
I 3-6: Deficit irrigation	+					
I 3-7: Alternate wetting and drying (AWD)	+	+				

4.4 Water management in rainfed and flood dependent condition

Field level preparations to retain and conserve water, ie. improving soil moisture, is crucial to maximize productivity in rainfed and spate irrigation systems. As floods arrive before the cropping season in spate irrigation areas, the moisture is stored to be available for use later in the season. Rutting and gullying of fields is to be avoided. There are several techniques to conserve moisture and improved field water management: deep ploughing, planking and mulching, controlled overflow structure, bund spill overs, gated field intakes and drop structures. All these can result in higher water productivity in spate irrigation areas. There are many overlaps in preparing rainfed and spate irrigated areas, such as creating (temporary) means to retaining water on fields and measures to retaining soil moisture after wet spells or floods. Rainfed agriculture however will not require (temporary) diversion structures and are commonly not benefitted by deep ploughing unless crusting takes place or hardpans are present (or have developed over time).

4. Water management in rainfed and flood dependent conditions	Impact			Application area		
	WP (ET)	WUE	Y	irrigated	rainfed	Spate irrigation
I 4-1: Supplemental irrigation			+			
I 4-2: Storm water drainage			+			
I 4-3: Ploughing and planking in spate irrigated areas	+	+				

4.5 Soil moisture management in rainfed and flood dependent conditions

Soil moisture is one of the essential components in crop production. The water reaches the plant through the soil, making sufficient soil moisture essential for crop production besides also influencing bio-chemical processes in the soil as microorganisms can avail nutrients to the plants. Soil moisture also has an indirect role in crop production since it is one of the strongest determinants for the microclimate in which plants need to thrive (Ismangil et al., 2016). The water content in any soil layer can decrease by soil evaporation, root absorption, or flow to an adjacent soil layer (Tsuji et al., 1998). Improving soil moisture management can contribute to achieving yields in areas where none were possible, increased yields in areas where crops did not reach their potential and reduce non-beneficial water consumption.

5. Soil moisture management in rainfed and flood dependent conditions	Impact			Application area		
	WP (ET)	WUE	Y	irrigated	rainfed	Spate irrigation
I 5-1: Mulching	+		+			
I 5-2: Planting pits		+	+			
I 5-3: Double dug beds		+	+			
I 5-4: Demi lunes/ half-moons		+	+			
I 5-5: Bench terracing		+	+			
I 5-6: Gully plugging		+	+			
I 5-7: Grass strips		+	+			
I 5-8: Tied ridge		+	+			
I 5-9: Bunds (contour, stone and trapezoidal)		+	+			
I 5-10: Conservation tillage and direct seeding	+		+			
I 5-11: Improving soil structure by using invertebrates		+	+			

4.6 Cropping system management

Knowing which crops and varieties to grow under specific environmental, socio-economical or even policy conditions and getting it right to provide food and income is a challenge continuously faced by farmers. As climates change and weather patterns become more erratic resilience needs to be built into farming practice by means of anticipation, forecasting, diversification and where feasible (collectively) investing. Managing cropping systems can mean salvaging crops and yields where bio-physical contexts are dire by means of adjusting crop sowing dates, rotations or crop varieties; or reducing risks by trying multiple cropping systems or applying agroforestry; or investing in cropping systems that can provide greater returns such as greenhouses, polytunnels and reel gardening.

6. Cropping system management	Impact			Application area		
	WP (ET)	WUE	Y	irrigated	rainfed	Spate irrigation
I 6-1: Adjusting crop sowing dates	+		+			
I 6-2: Crop rotation and multiple cropping	+		+			
I 6-3: Using improved crop varieties	+		+			
I 6-4: Inter cropping systems			+			
I 6-5: Agroforestry/shelter belts			+			
I 6-6: Greenhouses and polytunnels	+		+			
I 6-7: Reel gardening	+		+			
I 6-8: Farm mechanization			+			
I 6-9: Weed management	+		+			
I 6-10: Eradication of invasive species	+		+			

4.7 Crop input management

What a plant has readily at its disposable at the right moment in its crop stages determines how it grows and what yield it may produce. A good understanding of soil and soil biota (micro organisms), micro nutrients, water, oxygen and plant requirements is needed to know what external inputs are required. If plant stresses can be avoided, then plants can flourish and optimal water use is possible. Crop input management will not only increase yield but may also improve the beneficial fraction, ie. the ratio beneficially consumed water versus the non-beneficial consumed water.

7. Crop input management	Impact			Application area		
	WP (ET)	WUE	Y	irrigated	rainfed	Spate irrigation
I 7-1: Efficient fertilizer use	+		+			
I 7-2: Integrated nutrient management	+		+			
I 7-3: Smart fertilizers	+		+			
I 7-4: Bio-fertilizers	+		+			
I 7-5: Rock dust soil amendments	+		+			
I 7-6: Micro-nutrients	+		+			
I 7-7: Precision use of chemicals: fertigation	+		+			

4.8 Pest and disease control

FAO estimates that annually between 20 to 40 percent of global crop production are lost to pests. Each year, plant diseases cost the global economy around $220 billion, and invasive insects around US$70 billion[6]. Undisputedly pest control should therefore receive prime attention when considering water productivity improvements, be it from a bio-physical point of view or from socio-economic.

Measures that can reduce the incidence of disease and invasive insects are guided by the International Plant Protection Convention (IPPC) and its governing body the commission on phytosanitary measures. Following from a global inventory carried out by the IPPC (2016) the most urgent issue identified was the lack in phytosanitary capacity both in pest surveillance, inspection and pest reporting systems. And as pests are expected only to spread more, with global increase in agricultural trade and travels, warding of 'new' pests and diseases will only become more challenging[7]. Changing climates are further expected to complicate and make pest control more difficult, as the reproduction, spread and severity of many plant pathogens are affected (Gautam et al., 2013).

An array of mechanical, chemical and biological (pre-emptive) measures are available to stop the spread, incidence and impact of pests at local and global level (commodity pathways). However, as pests can never fully be eradicated or avoided, early and rapid detection will remain essential to protect standing crop, salvage harvests and supress spread.

8. Pest and disease control	Impact			Application area		
	WP (ET)	WUE	Y	irrigated	rainfed	Spate irrigation
I 8-1: Plant disease control	+		+			
I 8-2: Desert locust control	+		+			
I 8-3: Integrated Pest Management (IPM)	+		+			
I 8-4: Nanotech pesticides	+		+			
I 8-5: Ecologically based rodent management	+		+			
I 8-6: Precision use of chemicals: chemigation	+		+			

[6] FAO - News Article: New standards to curb the global spread of plant pests and diseases (accessed, 2021)
[7] Ibid

5 Glossary

Actual evapotranspiration and interception	This is the sum of the actual canopy transpiration, the actual soil evaporation, and the evaporation of rainfall intercepted by the leaves.
Beneficial water consumption	The amount of consumed water that is beneficial for the crop production, which is the transpiration.
Biophysical water productivity	Biophysical water productivity is the ration between the biomass, or yield, produced and the volume of water applied. This is also called 'crop per drop'.
Gross biomass water productivity	The gross biomass water productivity is the total biomass production of a season or year in relation to the total volume of water consumed in that period (actual evapotranspiration and interception).
Net Primary Production	The Net Primary Production expresses the conversion of carbon dioxide into biomass driven by photosynthesis.
Reference evapotranspiration	Reference evaporation is the estimation of the evapotranspiration from a hypothetical reference crop, derived from the Penman-Monteith equation; it simulates the behaviour of a well-watered grass surface
Water consumption	The water consumption in this document is defined as the total amount of water evaporated through direct soil evaporation, plant transpiration and evaporation from rainfall intercepted by leaves.
Water productivity	Water productivity is an indicator used in agriculture to measure production given a certain amount of water. Production commonly relates to the amount of crop that is produced, but can also relate to value of the crop, or the amount of jobs that are sustained in the production which is then called the economic or social water productivity.

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Annex 1: Interventions

1 Water resources enhancement

List of interventions
I 1-1: Surface water storage
I 1-2: Shallow groundwater storage
I 1-3: Water harvesting
I 1 4: Water harvesting: using roads
I 1-5: Water harvesting: using rock outcrops
I 1-6: Conjunctive use of ground and surface water

Intervention:	I 1-1: Surface water storage
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas
Contributes to:	• Improved crop production (B or Y)
Description:	There are a lot of ways in which water can be stored to provide for agricultural systems. In rainfed agriculture, the construction of ponds and mini dams can make water available during dry spells in the rainy season, and for a few months after the rains cease. In irrigated areas storage ponds can create a (irrigation system) buffer capacity and avoid night irrigation. Surface water storages come in many different shapes, materials, and dimensions. Water may be concentrated from the surrounding sloping surfaces, or conveyed from paved surfaces (roads, paths) and channels (cut-off drains). Circular and trapezoidal ponds are the most common design, though circular ponds such as charco-dams, are considered to have the best excavation to storage ratio. In many cases ponds can be built on pre-existing depressions or for instance they can consist of a converted borrow pit or even elephant pond. To avoid seepage, if unwanted, the pond should be lined or compressed. There is wide range of material for this – plastic liners, geotextile, clay/ termite soil or ferro-cement. Replenishing constructed ponds, natural depressions or even shallow aquifers; the water can be used to irrigate crops, provide water for livestock, and even for (certain) domestic uses. Considering the investment, in many circumstances it may be beneficial to consider multiple water needs and integrating productive with multiple domestic uses. Surface water storage bears the disadvantages of water being lost through evaporation, which may be reduced or overcome by planting a shelterbelt in the prevailing wind direction; or in very arid areas by constructing using a roof or cover. Ponds may also harbour mosquitoes, particularly where sides have a gentle slopes a comfortable habitat is created for the larvae. And where ponds are also used as domestic source, the storage time will determine whether the quality is still suitable, it may become insufficient for drinking purposes but also for bathing and watering animals.
Additional sources	Knoop, L., Sambalino, F., & van Steenbergen, F. (2012). Securing Water and Land in the Tana Basin: a resource book for water managers and practitioners. The Netherlands: 3R Water Secretariat. (https://metameta.nl/wp-content/uploads/2010/05/FINAL_tana_manual_digital_LQ.pdf) Renwick, et. al, 2007, "Multiple Use Water Services for the Poor: Assessing the State of Knowledge," Winrock International: Arlington, VA. (https://www.musgroup.net/sites/default/files/d852d750a8eafb2fb7ba1427b1c320bd.pdf) Web resources: Global Database on Sustainable Land Management (https://www.wocat.net/en/global-slm-database/)

Intervention:	I 1-2: Shallow groundwater storage
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas
Contributes to:	• Improved crop production (B or Y)
Description:	There are many techniques to intercept run-off and floods and to recharge shallow groundwater such as percolation ponds and contour trenches, tube recharge, subsurface dams, sand dams and sand dune water infiltration. The best storage is in shallow sandy or sandy loamy aquifers. In canal irrigated areas conjunctive management can contribute to improved shallow groundwater storage with excess canal flows recharging the tapped aquifers underneath the canal system and in some places creating freshwater lenses. A controlled shallow groundwater table can moreover contribute to crop production through the phenomena of sub-irrigation. Capillary rise from shallow groundwater may be considered as an important contribution to secure soil moisture and hence agricultural productivity (Beltrão et al., 1996). Under dry climate water table contribution to crop evapotranspiration may reduce or even completely eliminate irrigation requirements without compromising on crop yields (Prathapar & Qureshi, 1999); (Nosetto et al., 2009). On the other hand, when groundwater becomes too shallow, such as during flooding, it limits oxygen availability to roots and the resulting water logging harms crop productivity. Targeted management of shallow groundwater at the landscape scale and active tile drainage at the field scale could help close the "yield gap" - between maximum potential crop production and actual production - thus improving efficiency in agriculture.
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Additional sources	Liu, T. & Luo, Y. (2011). Effects of shallow water tables on the water use and yield of winter wheat (Triticum aestivum L.) under rain-fed condition. Australian Journal of Crop Science. 5. (http://www.cropj.com/luo_5_13_2011_1692_1697.pdf) Web resources: www.bebuffered.com

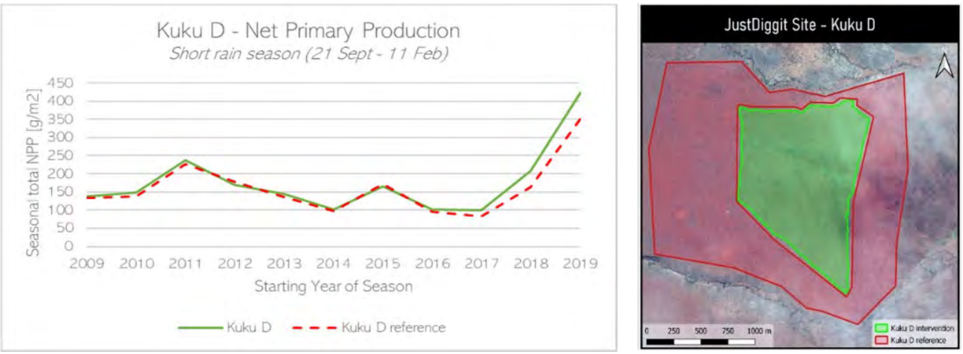
Intervention:	I 1-3: Water harvesting
Application	• Rainfed areas
Contributes to:	• Improved crop production (B or Y)
Description:	Water harvesting is the collection of runoff for productive purposes. Instead of runoff being left to cause erosion, it is harvested and utilized. Water harvesting (WH) can be considered as a rudimentary low-cost alternative form of irrigation. The difference is that with WH the farmer has no control over timing. Runoff can only be harvested when it rains. In regions where crops are entirely rainfed, a reduction of 50% in the seasonal rainfall, for example, may result in a total crop failure. If, however, the available rain can be concentrated on a smaller area, reasonable yields will still be received. Off course in a year of severe drought there may be no runoff to collect, but an efficient water harvesting system will improve plant growth in the majority of years (Critchley et al., 1991). In arid environments, where 90% of rainfall evaporates back into the atmosphere, water harvesting can increase the beneficial rainwater available for transpiration from 20% to 50% (Oweis et al., 1999). Water harvesting as such increases the soil moisture available for the

plants to grow, and hence contributes to water productivity improvement reducing E, raising T hence increasing biomass (or yields).

Water harvesting can take place in almost any given part of the world, from arid regions receiving less than 250 millimetres rainfall per year to harvesting water in the tropics. Techniques can be categorised into three basic categories: Microcatchments (sometimes referred to as "Within-Field Catchment System"); External catchment systems (Long Slope Catchment Technique); and Floodwater farming (floodwater harvesting, often referred to as "Water Spreading" and sometimes "Spate Irrigation") (Critchley et al., 1991).

An example of an 'external catchment system' would be the Jessour in the arid environment (<200mm rainfall) of Tunisia in which catchments are combined with the construction of terraces and dykes to capture and direct water for the production of fruit trees (e.g. olive, fig, almond, and date palm), legumes (e.g. pea, chickpeas, lentil, and faba bean), barley and wheat.

An example of micro-catchments is the semi-circular bunds which are typically used for rangeland rehabilitation or fodder production. In Kenya (Amboseli) semi-circular bunds were dug at scale (JustDiggit) to restore rangelands for pastoralist. By means of using WaPOR data and google earth engine (GEE) an assessment could be made to ascertain whether or not the intervention area is actually regreening. To assure observations in change are not due to climatic changes, the intervention site was compared to a buffer area around it (the reference site). As the graph shows the NPP (or net primary production, an indication of biomass) in the intervention area increased as compared to the reference are starting from 2016 when the semi-circular bunds were developed. The percentage difference (in NPP) in 2019 already amounted to more than 20%. To verify whether the regreened area is indeed pasture restoration and no other unpalatable vegetation, this WaPOR assessment can be combined with ground observations.



(a) (b)

A comparison of the Net Primary Production (NPP) between the Kuku Intervention site (Kenya) where semi-circular bunds where constructed, and the reference site. Figure (a) shows the timeseries of the NPP in which a positive difference between the intervention and reference site are visible from 2016 onward (when the bunds where constructed). The intervention site (green) and the reference site (red) are shown in figure (b).

References:

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Oweis, T., Hachum, A., & Kijne, J. (1999). Water harvesting and supplemental irrigation for improved water use efficiency in dry areas. In Rainfed Agriculture: Unlocking the Potential.

Intervention:	I 1-4: Water harvesting: using roads
Application	• Rainfed areas
Contributes to:	• Improved crop production (B or Y)
Description:	One of the most promising water harvesting techniques is the capture of run-off from roads. Rainwater runoff during rainy seasons is often considered undesirable for roads as it can damage

	the road and by creating gullies and water logging in the landscape. However, with simple measures this runoff can be harvested and utilized in agriculture. For example, during a 30 mm rain shower, a 1 km-long, 4 m-wide road catches 96,000 l of water. Harvesting runoff from roads enables farmers to use water that previously would cause flood damage, by intercepting the water and guiding it through channels or culverts to recharge areas, surface storage structures or distributing it over the farmland. There is a wide variety of available techniques to harvest water from roads depending on the geography, climatic conditions, and local needs of each examined area. Some examples include earth dams, tanks, underground cisterns, subsurface dams, water ponds, runoff farming, etc. The tools and materials needed depend on the chosen technique. The most common requirements include sand, cement, stones, bricks, PVC pipes, water, lime, barbed wire, chicken mesh, transport, and labour. In arid and semi-arid regions, where crop production is critically limited by soil moisture, the agricultural production can be significantly increased by the additional water supply from road runoff. This helps farmers to overcome rainfall variability and dry spells by increasing water availability for agriculture. Also, by harvesting water from roads and guiding it for productive uses, not only the road infrastructure is protected from water damage allowing the access of people to markets and services but also the landscape around the roads which in turn can be used for agricultural production. This intervention can be done at different levels community level, district level or national level. Besides roads can be used to control water levels in adjacent low-lying fields, control erosion and influence micro-climate and reduce wind erosion
Additional sources	Web resources: www.roadsforwater.org

Intervention:	I 1-5: Water harvesting: using rock outcrops
Application	• Rainfed areas
Contributes to:	• Improved crop production (B or Y)
Description:	Harvesting water from rock outcrops is widely used in the drylands of Kenya. A wide variety of techniques is currently in practice, ranging from harvesting from natural depressions such as rock pools and gorges to harvesting from complete rock catchments with dam walls. The largest rock catchment in Kenya can store up to 8 million litres of water (Nissen-Petersen, 2006). The amount of water generated by rock catchments is significant: a rock surface of 1 ha can harvest 1 million l of water from 100 mm rain (Nissen-Petersen, 2006). Harvesting water from rock outcrops increase water supply for people, livestock and drinking water. When water is used for irrigation purposes, the agricultural production is increased due to the increased water availability. Regarding the construction of such structures, after identifying a suitable rock outcrop (most rock surfaces in arid and semi-arid regions are suitable) and the development of a design, all loose parts need to be removed from the rock surface. Removed stones can be crushed to be used in constructing the dam wall. Rainwater is diverted through garlands or gutters towards the reservoir. Stone gutters must have a minimum gradient of 30% to avoid overflow.
References:	Knoop, L., Sambalino, F., & van Steenbergen, F. (2012). Securing Water and Land in the Tana Basin: a resource book for water managers and practitioners. The Netherlands: 3R Water Secretariat. https://metameta.nl/wp-content/uploads/2010/05/FINAL_tana_manual_digital_LQ.pdf Nissen-Petersen, E. (2006). Water from Rock Outcrops site investigations, designs, construction and maintenance rock catchment tanks and dams. https://www.samsamwater.com/library/Book1_Water_from_Rock_Outcrops.pdf
Additional sources	Video: Water from Rocks (https://thewaterchannel.tv/videos/water-from-rocks/)

Intervention:	I 1-6: Conjunctive use of ground and surface water
Application	• Irrigated areas • Spate irrigated areas
Contributes to:	• Improved water use efficiency (WUE) • Improved crop production (B or Y)

Description:

Conjunctive use of surface and groundwater consists of combining the use of both sources of water in order to minimize the undesirable physical, environmental and economic effects of utilisation of each source and to optimize the water demand/supply balance (FAO, 1995). In many the application of conjunctive uses systems is not planned beforehand, but in practice it is implemented as the result of water deliveries falling short in quantity and timing and where drainage is failing or not present. In these cases, farmers, complement the shortage with the exploitation of groundwater resources.

In Pakistan, less than 50% of water applied in various large-scale irrigation commands comes from the canal system, the rest coming from groundwater wells. Conjunctive use of groundwater irrigation has developed widely in numerous irrigation-canal commands, usually on a spontaneous basis but sometimes encouraged by government subsidy. In part these measures were taken to overcome drainage challenges but also considering the strained surface water deliveries and dilapidated systems based on the re-use of canal seepage.

The following benefits have been the driving force for spontaneous conjunctive use of shallow aquifers in irrigation-canal commands worldwide (Foster & van Steenbergen, 2011):

(1) much greater water-supply security—by taking advantage of natural aquifer storage,
(2) larger net water-supply yield than would generally be possible using one source alone,
(3) better timing of irrigation-water delivery—since groundwater can be rapidly deployed to compensate for any shortfall in canal-water availability at critical times for crop growth,
(4) reduced environmental impact—by reducing water-logging and salinisation of agricultural land, and restoring aquifers and river-flow (baseflow)

Important to consider is that the institutional dimension of conjunctive use management is significantly more complex than where surface water or groundwater alone is the predominant water-supply source. Therefore, it is important for surface water managers and groundwater managers (hydrogeologists) to consider facilitating these systems institutionally besides also supporting local initiatives that showcase the potential. This spontaneous conjunctive use usually arises in situations where canal-based irrigation commands are:

(1) tied to rigid canal-water delivery schedules and unable to respond to crop needs;
(2) over-stretched with respect to surface-water availability for dry season diversion
(3) inadequately maintained and unable to sustain design flows throughout the system, and
(4) poorly administered, allowing unauthorized or excessive off-takes

Whereas conjunctive water use in existing crop lands can distinctly improve crop performance and sustainability of cropping areas (water buffering and soils improvement); the systems may lead to cater expansion of agricultural land as farmers in the Rio Dulce irrigation system in Argentina did resort to. Due to rigid water delivery schedules and the underperformance of the canal systems farmers in reacted by developing a new source 'groundwater form a (tube)well', thereby gaining independence of the system to expand to high-value drip irrigated agriculture (Borghuis, 2017).

References:

Borghuis, G. (2017). Assessing drip irrigation implementation in the Rio Dulce irrigation system, Argentina. Wageningen University.

FAO (1995). Land and water integration and river basin management. Proceedings of an FAO Informal Workshop, Rome, Italy, 31 January - 2 February 1993. http://www.fao.org/3/v5400e/v5400e00.htm#Contents

	Foster, S., & van Steenbergen, F. (2011). Conjunctive groundwater use: a 'lost opportunity' for water management in the developing world? Hydrogeology Journal, 19(5), 959–962. https://doi.org/10.1007/s10040-011-0734-1
Additional sources	Video: Conjunctive win-win (https://thewaterchannel.tv/videos/conjunctive-win-win/)

2 Irrigation scheme system management

List of interventions
I 2-1: Lining

Intervention:	I 2- 1: Canal and water course lining
Application	• Irrigated areas
Contributes to:	• Improved water use efficiency (WUE)
Description:	When considering lining the objective and the interdependency with the management, operation and maintenance of the scheme is considered. Lining can be done in canals and watercourses. The objective of lining canals or water courses can be (a combination) the following: - to conserve both quantity and quality of water, water losses in unlined canals can be very high due to seepage and water consumed by weeds; as well as that any water lost as seepage will to a varying degree reduce in quality (particularly in populated areas or saline environments); - avoiding of seepage to adjacent land or roads, severe seepage of canals can cause very wet or waterlogged conditions, making adjacent land unsuitable for productive agriculture; - increasing the reliability of water deliveries; as flow velocity increases in lined canals, the timeliness and reach of irrigation water can be improved as well as reducing the siltation in canals. - reducing the maintenance as concrete, brick, or plastic, on the canal prevents the growth of plants and discourages hole-making by rats or termites, and so the maintenance of a lined canal can be easier and quicker than that of an unlined canal. The most common used types of lining include concrete, concrete blocks, bricks or stone masonry, sand cement, plastic, and compacted clay. The following needs to be considered: - Lining is not a substitute for robust scheme management (effective canal operational and maintenance) particularly if increasing irrigation reliability is the objective or equally when considering reducing delivery amounts (accommodating water productivity improvement in the field). - Maintenance of lined canals may become less cumbersome as appose to unlined canals, however research has shown that desilting of canals (annual practice in Pakistan by farmers), even for unlined canals, results in higher distribution reliability and reach than (only) lining (Murray-Rust & Vander Velde, 1994). - Except in cases where underlying groundwater is saline or very high seepage rates, the lining of canals would in most cases need to be considered as a subsidy. As lining comes at incredible costs, in most irrigation schemes this means that the positive rate of return (ie. the investment costs versus the increase in cropping intensity and hence increase in farmer irrigation duties) is difficult to achieve if not impossible. - Farmers may have become dependent on seepage losses from canals (by means of directly capturing seepage or pumping from shallow aquifers), this gives to question the objective of conserving water and for whom.
References:	Murray-Rust, D.H., & Vander Velde, E.J. (1994). Changes in hydraulic performance and comparative costs of lining and desilting of secondary canals in Punjab, Pakistan. Irrigation and Drainage Systems, 8(3), 137–158. https://doi.org/10.1007/BF00881015
Additional sources	FAO and ILRI (1992). Canals (Irrigation). Food and Agricultural organisation of the United Nations. http://www.fao.org/3/ai585e/ai585e.pdf

3 Irrigation field water management

List of interventions

I 3-1: Root zone irrigation (or sub-irrigation)
I 3-2: Land levelling
I 3-3: Surface irrigation
I 3-4: Pressurized irrigation systems
I 3-5: Rootzone drainage
I 3-6: Deficit irrigation
I 3-7: Alternate wetting and drying (AWD)

Intervention:	I 3- 1: Root zone irrigation (or sub-irrigation)
Application	• Irrigated areas
Contributes to:	• Improving water productivity (WP(ET)) • Improved crop production (B or Y)
Description:	Rootzone irrigation is an irrigation system buried below the soils surface. Systems can consist of (low-pressure) drip tubes, buried diffusers or clay pots (pitcher method). It can be installed for the purposes of growing tree crops and orchards as well as in permanent high-production (high-value) crop growing setups such as for horticulture or fruit crops. Rootzone or sub-irrigation considerably reduces the amount of evaporation from the soils and with that (particularly in arid climates or in open-soil greenhouses) also the accumulation of salts at the surface. It also reduces weed growth (as soil surfaces are not continuously wetted) and keeps infrastructure in the field out of the way and out of sight, which reduces the damages as a cause of field activities or theft. Comparing with surface irrigation systems and their common effects such as crusting, saturated conditions of ponding water, and potential surface runoff (including soil erosion) are eliminated when using subsurface irrigation (Reich et al., n.d.). This type of irrigation system does come with a high-labour and often high-capital investment to start off with, however there are also low-cost developments. One of these low-cost systems is the System of Water for Agriculture Rejuvenation (SWAR), whereby low-cost drip systems are combined with unglazed clay plots that have diffusers which provides for a combination of wetting and sweating at the rootzone of the crops. This has an advantage over conventional drip systems as water efficiency is even higher and by providing precision water to the tree roots water is reduce water application with 30-70%, and as literature suggests 'as much as 10 times' higher plant root efficiency 'than conventional surface irrigation' (Bainbridge, 2001). SWAR also encourages deeper root development which makes plants more resilient to drought events. (Gebru et al., 2018) describe how bar-shaped clay pots performed in comparison with furrow irrigation on tomato, pepper, and Swiss chard, with yields increasing up to 32, 30 and 51% respectively and water savings for all by 41%. Separately (Hsiao et al., 2007) describes subsurface trickle systems that eliminate most if not all of the E loss (direct or from the soils surface). Finally, studies have shown that up to 40% total water savings (compared to surface irrigation) without compromising yield capacity can be attained through subsurface drip irrigation. In addition, systems such as micro irrigation allow for optimal root zone management of water, fertilizer and pesticides, reducing the leaching and runoff and reducing the subsequent pollution from these substances.
References:	Bainbridge, D.A. (2001). Buried clay pot irrigation: A little known but very efficient traditional method of irrigation. Agricultural Water Management, 48(2), 79–88. https://doi.org/10.1016/S0378-3774(00)00119-0 Gebru, A.A., Araya, A., Habtu, S., Wolde-Georgis, T., Teka, D., & Martorano, L.G. (2018). Evaluating water productivity of tomato, pepper and Swiss chard under clay pot and furrow irrigation technologies in semi-arid areas of northern Ethiopia. International Journal of Water, 12(1), 54–65. https://doi.org/10.1504/IJW.2018.090188

	Hsiao, T.C., Steduto, P. & Fereres, E.A. (2007) systematic and quantitative approach to improve water use efficiency in agriculture. Irrig Sci 25, 209–231. https://doi.org/10.1007/s00271-007-0063-2. Reich, D., Godin, R., Chávez, J.L., Broner, I. (n.d.). Subsurface Drip Irrigation (SDI) (Crop Series, Issue Fact Sheet No. 4.716). https://extension.colostate.edu/docs/pubs/crops/04716.pdf
Additional sources	Video: SWAR: Irrigation at the Roots (https://thewaterchannel.tv/videos/swar-irrigation-at-the-roots/) Subsurface Drip Irrigation (https://extension.colostate.edu/docs/pubs/crops/04716.pdf)

Intervention:	I 3-2: Land levelling
Application	• Irrigated areas • Spate irrigated areas • Rainfed areas
Contributes to:	• Improving water use efficiency (WUE)
Description:	Levelling, smoothing and shaping the field surface is often forgotten as one of the first measure that can improve irrigation water distribution in the field, reduce non-beneficial evaporation and in the long run help in avoiding water logging and salinisation (to varying degree). It is a process for ensuring that the depths and water discharge variations over the field are relatively uniform and, as a result, that water distribution in the root zone is uniform facilitating equal access for all crops. Depending on irrigation method and the disruption following harvesting, land levelling needs to be considered after every season. The preparation of the field surface for conveyance and distribution of irrigation water is as important to efficient surface irrigation as any other single management practice the farmer employs. There are two main land levelling philosophies: (1) to provide a slope which fits a water supply; and (2) to level the field to its best condition with minimal earth movement and then vary the water supply for the field condition. The second philosophy is generally the most feasible. Because land levelling is expensive and large earth movements may leave significant areas of the field without fertile topsoil, this second philosophy is also generally the most economic approach. Although this approach may not always practically feasible when irrigating large plots of land or when mechanised land preparation takes place.

Intervention:	I 3-3: Surface irrigation (furrows and basins)
Application	• Irrigated areas
Contributes to:	• Improved water use efficiency (WUE) • Improved crop production (B or Y)
Description:	Surface (non-pressurised) irrigation application by far constitutes the largest portion in irrigated agriculture around the world, estimated in 2015 at 63% of total irrigated area (Jägermeyr et al. 2015). Most irrigation systems; their setup in terms of water distribution and allocation (frequencies and amounts) are designed, operated and maintained to accommodate surface irrigation. The two main methods of surface irrigation (field application) are explained below, aiming to underpin considerations and choices for both proper design of schemes and field application as well as potential (water application) improvements for both. This considering local conditions such as slope, soil type, type of crops but also access to technology, previous experience with irrigation and the required labour inputs. Surface irrigation, although always considered having a lower water use efficiency, may if comparing with other irrigation methods, crop combinations and local context make perfect sense. Basin irrigation Basin irrigation is the most common form of surface irrigation, particularly in regions with layouts of small fields. If a field is level in all directions, is encompassed by a dyke to prevent runoff, and provides an undirected flow of water onto the field, it is herein called a basin. A basin is typically

square in shape but exists in all sorts of irregular and rectangular configurations. It may be furrowed or corrugated, have raised beds for the benefit of certain crops, but as long as the inflow is undirected and uncontrolled into the field, it remains a basin. There are few crops and soils not amenable to basin irrigation, but it is generally favoured by moderate to slow intake soils (clay / clay loam), deep-rooted and closely spaced crops.

Key practices for optimal basin irrigation:

- Land levelling is particularly essential also for basin irrigation, this to avoid uneven supply within the basin; prolonged ponding in certain parts or shortage in others;
- Crops which are sensitive to flooding and soils which form a hard crust following an irrigation can be basin irrigated by adding furrowing or using raised bed planting
- Reclamation of salt-affected soils is easily accomplished with basin irrigation and provision for drainage of surface runoff is unnecessary. Of course, it is always possible to encounter a heavy rainfall or mistake the cut-off time thereby having too much water in the basin. Consequently, some means of emergency surface drainage is good design practice.
- Finally, comparing with furrow systems, basins can be served with less command area and field watercourses because their level nature allows water applications from anywhere along the basin perimeter.

Furrow irrigation

Furrow irrigation avoids flooding the entire field surface by channelling the flow along the primary direction of the field using 'furrows,' 'creases,' or 'corrugations'. Water infiltrates through the wetted perimeter and spreads vertically and horizontally to refill the soil reservoir. Furrows are often employed in basins and borders to reduce the effects of topographical variation and crusting. The distinctive feature of furrow irrigation is that the flow into each furrow is independently set and controlled as opposed to furrowed borders and basins where the flow is set and controlled on a border by border or basin by basin basis. Furrows provide better on-farm water management flexibility under many surface irrigation conditions. The discharge per unit width of the field is substantially less than basin irrigation and topographical variations can be more severe, ie. lesser necessity of levelling or grading. A smaller wetted area reduces evaporation losses. Furrows provide the irrigator more opportunity to manage irrigations toward higher efficiencies to adapt to field conditions that change for each irrigation throughout a season. Examples include applying 'alternative wetting and drying' (AWD) also coined as alternate furrow irrigation which for many crops has proven to reduce water consumption (be it in certain cases also a reduction in biomass). With long standing or broad-leafed crops that cover most of the bare soil (maize, sugarcane) furrow irrigation may allow higher water productivity as compared to overhead sprinkler systems as interception and evaporation of water by leaves (as foliage extends) does not take place in furrow irrigated plots.

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Intervention:	I 3- 4: Pressurized irrigation system
Application	• Irrigated areas
Contributes to:	• Improved water use efficiency (WUE) • Improved crop production (B or Y)
Description:	Using pressurised irrigation systems that reduce evaporation while increasing productive transpiration can improve crop production and water use efficiency at the field level as compared to surface irrigation methods. Evaporation varies with agricultural practices (Burt et al., 2005) and ranges from 4% to 25% in sprinkler irrigation systems (Burt et al., 2001), drip irrigation 10% and less, and up to 40% and more in rainfed systems (Rockström et al., 2010). Surface irrigation application methods often have low water application efficiencies; usually around 40% because of high evaporative losses particularly at the start of a cropping season. Hence in switching to pressurised systems field application efficiencies can take a jump, besides that also system

conveyance losses (ie. conveyance efficiency) are minimal. Pressurized systems have minimal runoff and evaporation losses and hence can have better field application efficiencies.

There are several pressurized systems in use and a service industry has developed that produces and installs the systems. In some cases, packages are offered whereby for instance drip systems are combined with soil moisture sensors and advise whether to irrigate or not is generated.

Pressurized systems include:

(1) Drip (or trickle) irrigation systems
(2) Sprinkler systems
(3) Centre-pivot systems
(4) Bubbler systems

The benefits of precision irrigation are not only limited to water savings. Studies have shown that 10-54% increase in yield is possible, especially in the horticulture field if more precise water applications could be implemented. Benefits such as reduced incidence of fungi in fruit and vegetable farms are also related benefits. However, care should be taken in the use of precision irrigation as drip irrigation can lead to accumulation of salt in the root zone of plants and hamper development of crops in salt affected areas or in areas where saline water is used for irrigation. The major trade-off between surface and pressurized methods lies in the relative costs of land levelling for effective gravity distribution and energy for pressurization (Walker, 1989). In tree crops, for example, the E reductions by localized irrigation can be substantial (Bonachela et al., 2001), especially when the canopy cover is sparse. Although this 'gain' must be off-set against the investments costs for such systems.

There is considerable difference as to the ease of use and longevity of the systems. In drip irrigation the emitters for instance are often weak link, as they make clog easily and are difficult to clean. There is also a low-cost version suitable for small farmers. Mini sprinklers for instance are widely available at low costs in Kenya for instance. There is also the mini-pivot system (developed by Practica) and several versions of simple tubes being used as low cost drip systems.

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Intervention: I 3-5: Rootzone drainage

Application

- Irrigated areas

Contributes to:

- Improved crop production (B or Y)

Description:

Applying more water than necessary is common in many large irrigation systems. It is often the results from inappropriate irrigation duties, i.e. allowing too much water into a command area. It is not unusual for such irrigation duties to be defined at one point in time but never to be updated and adjusted to real requirements.

Root zone drainage will remove excess water from the soil in canal command areas. This can be done by subsurface drains or by open drains. These drains will be placed in the command areas – the distance and depth depending on the drainage co-efficient, i.e. the volume of water to be removed. A special drain version are interceptor drains – located alongside the main source of seepage, i.e. the irrigation canals. Drainage can also be done by direct pumping, however the energy costs make this an expensive option. A particular version of the drainage tube well is the scavenger well, that removes the thin layers of fresh water on top of the saline groundwater for reuse and for controlling water tables.

In developing rootzone drainage, the general principles are:

- to create enough storage space in the upper soil layers to ensure adequate soil aeration for crop growth. In addition, this root zone aeration would help to avoid rainfall flooding
- controlling irrigation amounts; as overirrigation often takes place this should first be controlled and investment in drainage should be refrained from.
- Stimulating the pumping of groundwater in fresh groundwater zones by the curtailing and rationalization of surface supplies; pumping will lower local groundwater tables and act as points of drainage, the water can then be used for irrigation (ideally redistributed through existing channels). Groundwater pumping may in certain areas also create enough space (drained subsoils) to accommodate excess rainfall or floods.
- ideally, where root zone drainage is envisioned there should be the possibility of flexibility in adapting irrigation water amounts within the scheme rather than continued uniform distribution

Intervention: I 3-6: Deficit irrigation

Application

- Irrigated areas

Contributes to:

- Improving water productivity (WP(ET))

Description:

Deficit irrigation is an optimization strategy whereby net returns are maximized by reducing the amount of irrigation water; crops are deliberately allowed to sustain some degree of water deficit and yield reduction. Deficit irrigation takes place where farmers have less access to water than their consumptive needs (maximum ET), particularly in arid and semi-arid areas. The timing (during the plant stages) and the volumes and frequency then applied are important for farmers to be aware of. Deficit irrigation requires '*an intimate knowledge of crop behaviour, as crop response to water stress varies considerably*' (FAO, 2000). Example of plant stages during which deficit irrigation could take place are provided below:

Crop	Plant stages during which deficit irrigation could take place
Crop	Appropriate growth stages
Cotton	Flowering, boll formation
Sunflower	Vegetative, yielding
Sugar beet	Vegetative, yielding
Soybean	Vegetative growth
Wheat	Flowering, grain filling
Groundnut	Early season (once crop is established), 20-25 days
Chickpea	Progressive (terminal)

Considering the application of irrigation needs to be below the total crop water use (ET), following specific benefits of deficit irrigation are summarised:

- reducing percolation to the groundwater.
- yield biomass ratio (or harvest index) may be enhanced as full irrigation may lead to excessive vegetative growth
- as soil moisture content is lower than under normal practice, infiltration of irrigation water is commonly higher in deficit practices, reducing the amount of direct soil moisture evaporation.

Before recommending deficit irrigation it is important to consider the trade-off between reduced yield and higher water productivity which would need to be quantified in (socio) economic terms.

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Intervention:	I 3-7: Alternate wetting and drying (AWD)
Application	• Irrigated areas
Contributes to:	• Improved water use efficiency (WUE) • Improving water productivity (WP(ET))
Description:	Alternate wetting and drying (AWD) is a water-saving technology that lowland (paddy) rice farmers can apply to reduce their water use in irrigated fields. In AWD, irrigation water is applied to flood the field a certain number of days after the disappearance of ponded water. Hence, the field is alternately flooded and non-flooded. The number of days of non-flooded soil in AWD between irrigations can vary from 1 day to more than 10 days depending on the soil type. AWD has also been used for other crops, such as sugarcane. Water savings may be up to 15 to 25 percent with no yield penalty. AWD promotes root development, thus reducing plant lodging. In pump irrigation systems, it reduces pumping costs and fuel consumption and an increased income of USD 67 to 97 per hectare (IRRI, 2013). It reduces 30 to 70 percent of methane emissions depending on the combination of water usage and management of rice stubble. It also promotes higher zinc availability in soil and grains by enabling periodic aeration of the soil, which releases zinc from insoluble forms and makes it available for plant uptake. AWD is a water saving technology for lowland (paddy) rice production under irrigation. A special form of AWD is the System of Rice Intensification (SRI), whereby rice is broadcast – so that a large root system develops, and the rice is not all the time inundated. The challenge with the AWD and SRI methods is that more weeds develop because the land is not all the time covered with water.
References:	IRRI, 2013. Rice farming: saving water through Alternate Wetting Drying (AWD) method, Indonesia (http://www.fao.org/3/ca4023en/ca4023en.pdf)
Additional sources:	Video: Alternate wetting and drying (AWD)--using less water to grow rice (https://www.youtube.com/watch?v=tfKWKfagfFs)

4 Water management in rainfed and flood dependent systems

List of interventions
I 4-1: Supplemental irrigation
I 4-2: Storm water drainage
I 4-3: Ploughing and planking in spate irrigated areas

Intervention:	I 4-1: Supplemental irrigation
Application	• Rainfed areas
Contributes to:	• Improved crop production (B or Y)
Description:	Supplemental Irrigation (SI) is a key strategy, still underused, for unlocking rainfed yield potential and water productivity (Rockström et al., 2010. SI is the addition of limited amounts of water to essentially rainfed crops to improve and stabilize yields when rainfall fails to provide sufficient moisture for normal plant growth. SI can take place in areas with unreliable rainfall or with periods of extreme heat. The timing of SI is again irrigation scheme and weather dependant. Either before planting (or 'onset rainfall'), allowing farmers to plant their crop early or optimally scheduling it during the critical stages of crop growth (flowering and grain filling). SI is an effective response to alleviating the adverse effects of soil moisture stress on the yield of rainfed crops during dry spells. This in particular during critical crop growth stages, can improve crop yield and water productivity.
Additional sources	Rockström, J., Hatibu, N., Oweis, T., Wani, S., Barron, J., Bruggeman, A., Qiang, Z., Farahani, J., & Karlberg, L. (2010). Managing Water in Rainfed Agriculture —The need for a paradigm shift. Agricultural Water Management. Volume 97, Issue 4, Pages 543-550.

Intervention:	I 4-2: Storm water drainage
Application	• Irrigated areas
Contributes to:	• Improved crop production (B or Y)
Description:	The timely removal of excess water following heavy rainfall or local floods is important to avoid crop damage and build-up of water logging. The inability to remove excess rainfall runoff can be problematic in low lying areas or areas with a particular flat gradient. In storm water drainage, before constructing dedicated storm water drainage systems a number of aspects should be considered: • Priority should be given to unblocking natural drains closed by roads and residential areas and make adequate cross drainage on new and old infrastructure compulsory. • Retaining runoff at source or diverting excess water where the gradient allows to recharge areas will have a double benefit: the runoff will be used beneficially and no downstream flooding problems will occur. • Besides capturing storm water, local dugouts in some cases may (in drier periods) also serve to lower groundwater tables and provide local freshwater storage.

Intervention:	I 4-3: Ploughing and planking in spate irrigated areas
Application	• Spate irrigated areas
Contributes to:	• Improved water use efficiency (WUE) • Improved water productivity (WP(ET))
Description:	In spate irrigated areas (Pakistan, Eritrea and Yemen) the combination of ploughing prior to and after irrigation are important soil moisture conservation measures. Breaking the topsoil through

	ploughing land prior to irrigation greatly increases infiltration rates with initial infiltration rates for Wadi Rima in Yemen increasing from 40 to 60 mm/hour (van Steenbergen et al., 2010). Pre-irrigation ploughing also makes cultivation much easier and quicker to carry out once the floodwaters arrive, which is important, as a great deal of labour is required to cultivate the land after irrigation (Williams, 1979). Having captured as much water during the spates farmers then need to make sure that the water does not evaporate or is lost to deep groundwater. The common recommendation then is not to delay ploughing for more than two to three weeks, to avoid water loss through evaporation or deep percolation. Research in Yemen suggests that, if land is not ploughed within two weeks after irrigation, up to 30–40 percent of the moisture may be lost. Following the ploughing seeding can take place which in certain spate irrigated areas is followed by planking. Which by means of bullock or tractor drawn planks (weighed down by people) ensures modest compaction of the top soil (<10cm) and further reduces evaporation; essential for ensuring soil moisture retention during the first planting stage.
References	van Steenbergen, F., Lawrence, P., Mehari, A., Salman, M., & Faurès, J.-M. (2010). Guidelines on spate irrigation (Irrigation). FAO. http://www.fao.org/3/i1680e/i1680e.pdf. Williams, J.B. (1979). Yemen Arab Republic. Montane Plains and Wadi Rima Project: a land and water resources survey. Physical aspects of water use under traditional and modern irrigation/farming systems in Wadi Rima Tihama.
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5 Soil moisture improvements

List of interventions

I 5-1: Mulching
I 5-2: Planting pits
I 5-3: Double dug beds
I 5-4: Demi lunes/ half-moons
I 5-5: Bench terracing
I 5-6: Gully plugging
I 5-7: Grass strips
I 5-8: Tied ridge
I 5-9: Bunds (contour, stone and trapezoidal)
I 5-10: Conservation tillage and direct seeding
I 5-11: Making use of invertebrates

Intervention:	I 5-1: Mulching
Application	• Rainfed areas • Irrigated areas
Contributes to:	• Improving water productivity (WP(ET)) • Improved crop production (B or Y)
Description:	Mulches form a barrier to the heat and vapour flow from the soil and thereby inhibit heat and moisture exchanges with the atmosphere (Rosenberg et al., 1983; Wilken, 1972). Mulching decreases the evaporation rate, enhances infiltration, and thus increases moisture conservation. Hopkins (1954) showed that the moisture infiltration over two hours was 183% greater for mulched sites than for un-mulched areas. Dhaliwal et al. (2019) also showed that soil moisture was 4.2 per cent higher in mulched sites than in un-mulched sites. Kader et al. (2017) state that mulching buffered extreme soil moisture and temperature fluctuations. Fang et al. (2009) researched the effects of straw mulching on the microclimate, and the results showed that straw mulching had a dramatic impact on surface temperature and soil temperature. Straw mulch increased surface sensible heat flux but decreased latent heat flux and soil heat flux, so water evaporation from the soil was restricted, and moisture accumulation was increased accordingly. Mulching avoids the fluctuations in temperature in the first 20 to 30 centimetres depth of the soil. This favours root development, and the soil temperature in the planting bed is raised, promoting faster crop development (Moreno & Moreno, 2008). Mulching materials, should where as much as possible be composed of locally available materials (crop residues or other organic matter) that do not compete as source for animal fodder, home consumptive or sellable produce. Extending the examples provided above are tree leaves such as banana for nutrient input (Lekasi et al., 2001) and mango (Das and Dutta, 2018), husk of rice or other grains. Black polythene (or low-density polyethylene (LDPE)) has for many crops and in many different agro-climatic zones proven to be highly affective and application is (still) very widespread. However, the associated environmental impact should be considered, as common practice is that these are not reused (or reusable) and simply become non-degradable waste problem.
References	Das, K., Dutta, P. (2018). Effects of Mulching on Soil Properties and Post Harvest Quality of Mango Cv. Himsagar Grown in New Alluvial Zone of West Bengal. International Journal of Agriculture, Environment and Biotechnology, 11(2), 259–264. https://doi.org/10.30954/0974-1712.04.2018.6 Dhaliwal, L.K., Buttar, G.S., Kingra, P.K., Singh, S., & Kaur, S. (2019). Effect of mulching, row direction and spacing on microclimate and wheat yield at Ludhiana. Journal of Agrometeorology, 21(1), 42-45. Hopkins, H.H. (1954). Effects of Mulch Upon Certain Factors of the Grassland Rangeland Ecology & Management/Journal of Range Management Archives, 7(6), 255-258. Fang, W.S., Zhu, Z.X., Liu, R.H., Ma, Z.H., & Shi, L. (2009). Study on microclimate characters and yield-increasing mechanism in straw mulching field. Agricultural Research in the Arid Areas, 6.

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Intervention:	I 5- 2: Planting pits
Application	• Rainfed areas
Contributes to:	• Improved water use efficiency (WUE) • Increase crop production (B or Y)

Description:

Planting pits collect rainfall and concentrate soil moisture for food and fodder production. Plants are grown inside pits, benefitting from the higher moisture content. Often manure and/or compost is added. This adds nutrients and attracts termites that loosen up the soil around the planting pits, thus increasing the capacity of the soil to absorb runoff water. Planting pits contribute to a significant increase in yields. Thy are used to grow trees but recently they have started to be used also for crop production (Mati, 2006).

Planting pits vary in dimensions, shape, and husbandry system (see table below). The best-known system is the western African "zai". Zai pits are circular holes dug by hand on gently sloping land in order to catch and retain runoff water. They are scattered on the surface and approximately follow the contour lines. The pit size and depth vary but a general rule is not to make the pits too small (Reij et al. 2009). If pits are under-sized, the amount of water trapped will not satisfy the plants requirements. Zai pits require a considerable amount of mainly manual labour. To make the process easier, it is suggested to perform the excavation in the dry season - right after the rain period - when the soil is easier to work with (Desta et al., 2005). Thereafter, they are filled with organic materials such as manure, compost or dry biomass. This leads to increased microbial activities which in return increases the rate of water infiltration during the rainy season. This creates a micro-environment that increases drought resistance and improves crop yields. After the first rains, sorghum or millet can be sown. Following the harvest, the plant stalks should be left in the pits to increase the organic matter content for the next season. In the second year, new zais planting pits can be dug in between the first year's lines (progressively adding more in the landscape) and sown with Sorghum or Millet. Also, legumes can be planted in the one-year-old pits. To decrease the runoff speed, stone lines are laid along the contours with a spacing of 20-30 cropping lines in between.

Name	Crop	Shape	Depth (cm)	Width (cm)	Inter-row dist. (cm)	In-row dist. (cm)	Country
Zai	Sorghum	Circular	15 - 50	30 - 50	60 - 75	30 - 50	Burkina Faso
Katumani	Fodder	Demi-lune	15 - 20	#NA	#NA	Conti-nuous	Kenya
Chololo pits	Millet	Circular	20 - 25	20 - 25	100	0.5	Tanzania
Banana pits	Banana	Square	60	60	300	300	Kenya, Tana
Sugar cane	Sugar cane	Square	60 - 75	100	60	60	Kenya, Mwingi
Five by nine pits	Maize	Square	60	60	#NA	#NA	Kenya

Tumbukiza	Napier	Various	Various	Various	Various	Various	Western Kenya

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Intervention: I 5-3: Double dug beds

Application
- Rainfed areas

Contributes to:
- Improved crop production (B or Y)
- Increase water user efficiency (WUE).

Description:

With the double dug bed technique, it is possible to create small productive vegetable gardens. This is done by double-digging the soil and incorporating adequate amounts of manure. This alternative digging process allows the farmer to work the soil deeper and to spread compost evenly along the whole excavation profile. The hard pan that is often formed on tropical soils is broken by the process. This allows aeration and improved nutrient adsorption in the soil. The deep incorporation of compost favours the breakdown of humic components, and reduced loss of nutrients via runoff and decomposing gaseous emissions. The deep cultivation creates a soft medium that allows roots to grow longer and stronger, retains more water and it is likely to increase yields.

Double dug gardens are created in an elongated shape with a width of around 1.5 m. The length can vary, but 7 m is often suggested as ideal (Nandwa et al., 2000). The double dug bed should be narrow enough to be conveniently farmed in every section by standing on its edges. Its establishment entails the cultivation of the designated garden in a stepwise manner by applying one layer of compost or manure and then digging small, adjacent trenches until the whole area is double dug. In the end, the double dug bed will look elevated due to the increased volume of the air voids and the incorporated organic matter. The same procedure must be followed in the following years. After some time the soil will be softer, darker and easier to work (Stein, 2000).

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Intervention: I 5-4: Demi lunes / half moons

Application
- Rainfed areas

Contributes to:
- Increased crop production (B or Y)
- Improved water use efficiency (WUE)

Description:

Demi lunes - also known as semi-circular bunds or ‘eyebrows’ - require the creation of small bunds in the shape of a half-moon with their tips on the contour. The ponding area inside the demi lune retains water flowing down the slope from above the bund. Demi lunes capture runoff and are used to improve rangeland and increase grass, tree, and crop production. Demi lunes

	are more efficient than trapezoidal bunds in terms of the ratio between the bund volume and the ponded area. The design varies according to topography, climatic conditions, and plant requirements. In dry conditions, the bunds are bigger and equipped with spillways. In wetter conditions, more bunds of smaller radius are constructed per hectare. They are rarely used on slopes steeper than 5%. When used for rangeland improvement, local grasses can be grown, but the introduction of more productive trees and shrubs is recommended. When used to grow crops, drought resistant species such as sorghum, pearl millet and certain pulses must be chosen. To satisfy the plant's water requirements, farmers tend to reduce the catchment area of the semi-circular bunds to increase the cultivated land.
References:	Knoop, L., Sambalino, F., & van Steenbergen, F. (2012). Securing Water and Land in the Tana Basin: a resource book for water managers and practitioners. The Netherlands: 3R Water Secretariat.

Intervention:	I 5-5: Bench terracing
Application	• Rainfed areas
Contributes to:	• Improved water use efficiency (WUE) • Improved crop production (B or Y)
Description:	Alternating series of 'shelves' and 'risers' characterize bench terraces. They are usually developed on relatively steep slopes (15-55%) with deep soils that allow this type of landscaping. Bench terraces help to store water and by reducing runoff and by capturing sediment they also prevent soil erosion. Therefore, by using this technique more water can be made available for the plants which, in turn, increases the agricultural production. In bench terraces the riser (steeper ascending slope) is often reinforced with stones and/or vegetation cover. When the bench is made slightly inward sloping, water storage increases, and soil protection is improved. In arid areas, conservation bench terraces are preferred. In such cases, the distance between terraces is increased and a portion of the sloping land is left to act as catchment area. The runoff generated by the catchment area will nourish the plants placed immediately above the riser wall. The construction of bench terraces is labour or equipment intensive. The bench terraces must be laid carefully on the contours – so that the hydraulic pressure is evenly spread. The design starts with a careful survey and pegging of the contour lines. This process can be carried out with an A-frame level or a water tube level. Consequently, the cut and fill areas are defined, and the excavation is performed. Care is taken to preserve the upper layer of the soil that holds most of the nutrients. The construction must start from the lower level of the field and then proceed upwards. Thereafter the newly created riser can be reinforced with locally available stones. When required, ditches and drains must be dug to dispose excess water. Conservation bench terraces should be considered as water harvesting techniques, as they allow the generation of additional runoff. They should be planned according to plant requirements and climatic features of the area.
References:	Knoop, L., Sambalino, F., & van Steenbergen, F. (2012). Securing Water and Land in the Tana Basin: a resource book for water managers and practitioners. The Netherlands: 3R Water Secretariat.

Intervention:	I 5- 6: Gully plugging
Application	• Rainfed areas • Spate irrigated areas
Contributes to:	• Improved water use efficiency (WUE) • Improved crop production (B or Y)
Description:	Temporary and permanent gully plugs are used to rehabilitate gullies and retain sediments that would be otherwise washed away. Gully plugs are structural barriers that obstruct the

	concentrated runoff inside gullies and ravines. They are often temporary structures built to favour the establishment of a permanent soil cover to effectively conserve soil and water. In some cases, they are used to create new farmland using the harvested and intercepted sediments. They are often built-in series to progressively decrease the runoff speed and trap sediments through the whole length of the gully. Gully plugs can have an enormous beneficial effect on the soil moisture in adjacent lands as well as shallow groundwater tables which leads to improved agricultural production. Gully plugging is essential in both arid and humid areas. In non-humid regions earth plugs can be used to restore gullied areas. The gully should preferably not be steeper than 10% or deeper than 2 m. In more humid areas diversion channels may be added to decrease the burden on the gully plug structure (Geyik, 1986). When stones are readily available stone check dams can be constructed to restore small gullies. The trapped sediments can be used as arable land, which can provide additional income to the farmers (Desta et al., 2005). Preferably flat stones are used as they add more strength. Brushwood check dams are constructed across gullies with width less than 3 m and slope length less than 100 m. Plant materials are stacked behind a series of wooden posts that are driven deep into the soil. Brushwood from species that propagate vegetatively from cuttings is ideal to use as the roots encourage consolidation of the structure and the soil (Desta et al., 2005). After few years the established stems-plants can be pruned providing fodder and fuel (Liniger & Critchley, 2007). Once the check dam structure is in place, gully reshaping is required to ease plant establishment. In case of big gullies, a sediment storage and overflow dam can be used. The overflow dam is a stone-faced earthen dam that traps sediments and creates new farming land. It also acts as a rainwater collector, improving water availability for crops. It can potentially create new land and restore eroded landscapes (Desta et al., 2005).
References:	Knoop, L., Sambalino, F., & van Steenbergen, F. (2012). Securing Water and Land in the Tana Basin: a resource book for water managers and practitioners. The Netherlands: 3R Water Secretariat. Geyik, M. (1986). FAO watershed management field manual. Gully control. FAO Conservation Guide (FAO). Liniger, H., & Critchley, W. (2007). Where the land is greener: Case-studies and analysis of soil and water conservation initiatives worldwide. CTA/CDE/FAO/UNEP/WOCAT. Desta, L., Volli C., Asrat W-A., and Yitayew A., 2005. "Community-based participatory watershed development. a guideline. annex."

Intervention:	I 5-7: Grass strips
Application	• Rainfed areas • Spate irrigated areas
Contributes to:	• Improved water use efficiency (WUE) • Improved crop production (B or Y)
Description:	Grass strips are widely used as vegetative barriers to reduce soil loss and to increase infiltration and soil moisture. Due to increased soil moisture, there is more water available for the crops which leads to increased agricultural production. Grass is grown in alternating strips following contour lines. Depending on the grass used, the strips may provide fodder for livestock as well. Compared to other interventions grass strips can be easily crossed by oxen and ploughs. Grass strips can filter sediment, evacuate excess runoff, and can also withstand inundation. They may ultimately form into bench terraces. Grass strips work best in areas with a good amount of rainfall. The technique can be applied on gentle slopes as well as on steep slopes. Preparing grass strips involves relatively modest-labour inputs and basic equipment (e.g. hoes, wires and tree branches.) The grass type chosen should not be too aggressive: it should not expand into adjacent crop land. The width of grass strips ranges from 0.5 to 1.5 m (Desta et al, 2005). Permanent vegetation strips (used on steep slopes) range from 2 to 4 m. The interval between the strips depends on the slope: 33 m is common over 3% slopes while a 7 m distance is used over 15% slopes. Since grass strips are usually laid along the contours, the distance between them is dictated by the slope of the land.

	Preferably, perennial grasses are planted on the strips. Grass types should be persistent and be able to withstand drought and flood. Suitable species include Napier grass (*Pennisetum purpureum*), Guatemala grass (*Tripsacum laxum*), Makarikari grass (*Panicum coloratum*), Canary grass (*Phalaris canariensis*), Oat grass (*Hyparrhenia spp.*), Wheat grass (*Agropyron spp.*), and Lyme grass (*Elymus spp.*). Seedbed preparation is necessary in the case of direct sowing. A depth of 0.5 to 1.5 cm is optimum for most species. The grass seeds should be covered with a thin layer of soil (Desta et al., 2005). If grass splittings are used to establish the strips, they should be planted in a staggered way using double or triple rows.
References:	Desta, L., Volli C., Asrat W-A., and Yitayew A., 2005 "Community-based participatory watershed development. a guideline. annex.".
Additional sources	Knoop, L., Sambalino, F., & van Steenbergen, F. (2012). Securing Water and Land in the Tana Basin: a resource book for water managers and practitioners. The Netherlands: 3R Water Secretariat.

Intervention:	I 5- 8: Tied ridge
Application	• Rainfed areas • Spate irrigated areas
Contributes to:	• Improved water use efficiency (WUE) • Improved crop production (B or Y)
Description:	Small earthen tied contour ridges break the slope, slow down erosive runoff, and store water in the soil. They enable water to infiltrate the soil more efficiently and add soil moisture storage which contributes to increased crop production. They usually have a height of 15 to 20 cm and have an up-slope furrow. These upslope furrows accommodate runoff from an uncultivated catchment strip. The catchment strips between the ridges can be used for small-scale production. Tied ridges can be used in arid and semi-arid areas with annual average precipitations between 200-750 mm per year. The soil should be at least 1.5 m deep to ensure adequate tree root development and to store sufficient water. The topography must be even without too many gullies and slopes can be up to 5% (Critchley et al., 1991).
References:	Critchley, W., Siegert, K. and Chapman, C. (1991). Water Harvesting. A Manual for the Design and Construction of Water Harvesting Schemes for Plant Production. Food and agricultural organisation of the UN - Rome, 1991
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Intervention:	I 5-9: Bunds (contour, stone and trapezoidal)
Application	• Rainfed areas • Spate irrigated area
Contributes to:	• Improved water use efficiency (WUE) • Improved crop production (B or Y)
Description:	Contour bunds are small barriers to capture runoff coming from external catchments and possibly to a field where crops are to be grown. Bunds slow down water flow on the ground surface, reduce erosion, encourage infiltration and soil moisture and increase yields. Contour bunds exist in many different designs and have been globally used as a means of water buffering and soil conservation. Stone bunds is one example of how the basic principles of contour bunds can be applied. On gentle slopes, stone bunds are also used for harvesting water for the crops in between the lines and increase crop production (Gurtner et al., 2011; Liniger and Critchley, 2007). Stone bunds are suitable for arid and semi-arid areas, but when the soils are well drained, they can also be applied in wetter zones. Stone bunds are used on sandy, sandy/loamy crusty soils and on slopes less

	than 5%. Small stone ties can be constructed every 5 m along the upslope face of the bund for an even distribution of the impounding water (Desta et al., 2005). The width and, consequently, the height of the bund vary considerably with slope and availability of construction material. Sometimes the structure can be just one stone high. When enough sediments have been trapped behind the structure, the stone bunds can be upgraded to stone-walled level terraces by carefully raising their height (Desta et al., 2005). Trapezoidal bunds are a type of non-enclosed bunds which upstream side is left open to collect water from the slopes and its downstream side is enclosed on three sides by a trapezoidal shaped bund with 45° angles (Critchley & Reij 1992). They enclose large areas (up to 1 ha) and they are usually made out of soil. The wings of the side bunds are preferably reinforced with stones. Trapezoidal bunds are not suitable for steep slopes because the construction would involve prohibitive amounts of earthwork and they should not be built on cracking clay soils that will not be able to hold the water. The most common uses of trapezoidal bunds is cereal cultivation within the enclosed area and livestock watering. The spacing of the trapezoidal bunds can vary depending on the ration between catchment and cultivated area and the climate (for example in arid areas there is less water to go around and the spacing may be larger).
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Intervention:	I 5- 1: Conservation tillage and direct seeding
Application	• Rainfed areas • Irrigated areas
Contributes to:	• Improving water productivity (WP(ET)) • Improved crop production (B or Y)
Description:	Tillage is the agricultural preparation of soil by handheld, or ox or tractor drawn agitation. This agitation can be described as shovelling, hoeing, and raking or as ploughing, disking and cultivating. Conservation (or zero) tillage systems aim to reduce the amount and frequency of soil agitation taking place with the purpose of managing and maintaining soil nutrients and moisture (reducing exposure to the air causing soil evaporation). Zero tillage is the central element in what is now widely termed Conservation Agriculture (Landers, 2001) and refers to cultivation with little or no soil surface disturbance, the only disturbance being during planting (Busari et al., 2015). Zero tillage can not be seen as a standalone practice but goes hand in hand with direct seeding, besides many other practices such as leaving crop residues and crop rotation. Zero tillage and direct seeding have distinct advantages such as less soil compaction, more fertile and resilient soils, less soil moisture loss and ability to plant early (before the onset of rains). These advantages may improve crop yields (particularly in the long run) and reduce non-beneficial water loss from field. Zero tillage requires (ripping, sowing tools) these can come at high costs when aiming for large scale application, tractor drawn implements such as no till drill or no till planters. Various hand, oxen or bullock or 2-wheel tractor drawn implements have also been produced globally, examples are the Magoye Ripper (Zambia), Jab-planter or the original BARI/CIMMYT tined zero till seed drill. These specialised rippers and planters cut through the desiccated cover and residues accumulated on the soil surface, slotting seed (and fertilizer) into the soil with minimal disturbance. Major constraint to zero tillage practices are soil wetness problems (permeability, drainage and water logging) and imbalance in soil particles, i.e. poor soil aggregation. Also a shortage of mechanized options suitable for small holder farmers is creating an impediment to the adoption (Johansen et al., 2013) as markets are not well developed (sales, repair, spare parts). Finally, even

	though zero-tillage is commonly combined with leaving crop residues and crop rotation, weeds can still play up. Integrated weed management strategies are needed that can be combined with small-scale planters (Johansen et al., 2013). Separately for crops such as rice, separate propagation was common practice rather than directly seeding the crop. Whereas, zero tillage does not necessarily come into play, directly seeded (broadcast, drilling or dibbling), such as for rice requires less labour and the crop tends to mature faster than transplanted crops (Singh et al., 2008). Besides the fact that when dry seeding methane emissions - that account for 15-20% of human-induced emissions when growing paddy rice - can be avoided.
References:	Busari, M.A., Kukal, S.S., Kaur, A., Bhatt, R., & Dulazi, A.A. (2015). Conservation tillage impacts on soil, crop and the environment. International Soil and Water Conservation Research, 3(2), 119–129. https://doi.org/https://doi.org/10.1016/j.iswcr.2015.05.002 Johansen, C., Haque, M.E., Bell, R.W., Thierfelder, C., & Esdaile, R.J. (2012). Conservation agriculture for small holder rainfed farming: Opportunities and constraints of new mechanized seeding systems. Field Crops Research, 132, 18–32. https://doi.org/10.1016/j.fcr.2011.11.026 Landers, J. 2001. Zero tillage development in tropical Brazil. FAO, Rome. Zero tillage development in tropical Brazil (fao.org) Singh, Y., Singh, V.P., Chauhan, B., Orr, A., Mortimer, A.M., Johnson, D.E., H., & B (Eds.). (2008). Direct Seeding of Rice and Weed Management in the Irrigated RiceWheat Cropping System of the Indo-Gangetic Plains. International Rice Research Institute, and Pantnagar (India): Directorate of Experiment Station, G.B. Pant University of Agriculture and Technology. http://books.irri.org/9789712202360_content.pdf
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Intervention:	I 5-11: Improving soil structure by using invertebrates
Application	• Rainfed areas • Spate irrigated areas
Contributes to:	• Improved water use efficiency (WUE) • Improved crop production (B or Y)
Description:	Many useful invertebrate species live under our feet and pass unnoticed until the soil is exposed and they are brought to the surface. Termites, earthworms and sowbugs are some of the best-known examples. What is less known is the positive effect that they have on the soil (aggregate stability) and the capacity to store moisture. Invertebrates do so as they loosen up and mix the soil, reinvigorating the structure (more aggregation: mix of micro-, meso-, and macropores) creating more aeration and stimulating plant root development. Many invertebrates, also through their constant burrowing activities, improve and maintain the infiltration capacity of the soil and ensure that runoff continues to be absorbed, soil is not 'clogged' and crop production is increased. To ensure vertebrates can play their part in soils (particularly in dry-humid and humid environments) it is important to consider the tillage tools and methods. Heavy machinery and severe soil disturbance by means of (deep)ploughing will induce compaction and dehydration respectively; with both conditions least preferred by invertebrates. Minimal and zero tillage practices are some of the means to reduce soil disturbance and maintain better soil conditions for invertebrates. Sowbugs In floodwater spreading systems, ie. spate-irrigated areas, sowbugs (naturally present) can increase aggregate stability constituting an environmentally sound and a financially viable

	method of lengthening the economic life of soils and the artificial recharge of groundwater systems (Rahbar et al., 2015). <u>Termites:</u> Termites build mound-shaped nests that are a common sight in arid and semi-arid regions of East Africa. There are many kinds of termites, and although only a few of them are plant pests, farmers often consider all of them to be a plague. Nevertheless, the termite's activity is a positive influence on soil's physical properties, with their tunnelling enhancing porosity and lowering soil bulk density. This leads to improved water infiltration. Additionally, mound nests are constructed with fine soil particles brought to the surface by termite activity. These fine particles often have a high nutrient concentration thanks to termites' feeding habits. The mounds can be used as soil amendment. They are destroyed and the resulting material ploughed into the soil (Okwakol & Sekamatte, 2007). The main constraint to the utility of termites is the slow growth of the nest and the large amount of termite soil needed to fertilize land. A sustainable way of managing this involves using only a portion of the termite nest to allow for its regeneration (Miyagawa et al., 2011). <u>Earthworms:</u> Earthworms ingest organic matter and transform it into nutrient-rich material. Their activity (be it in more moist environments) can increase soil structure stability and the storage of soil C and N (Ketterings et al., 1997). Earthworms present in the soil should be fostered, by means of minimal soil disturbance. Separately earthworm populations can be used in vermi-composting. This is the practice of using earthworms to produce high quality compost in controlled conditions. By constructing a simple worm-box it is possible to transform 1000 tons of wet organic material in 300 kg of good compost (Butterworth et al., 2003). Compost can be harvested from a typical box every 3 to 4 months (Liniger & Critchley, 2007). This vermi-compost greatly improves soil water retention capacity – besides improving soil fertility.
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6 Cropping system management

List of interventions
I 6-1: Adjusting crop sowing dates
I 6-2: Crop rotation and multiple cropping
I 6-3: Crop varieties selection
I 6-4: Inter cropping systems
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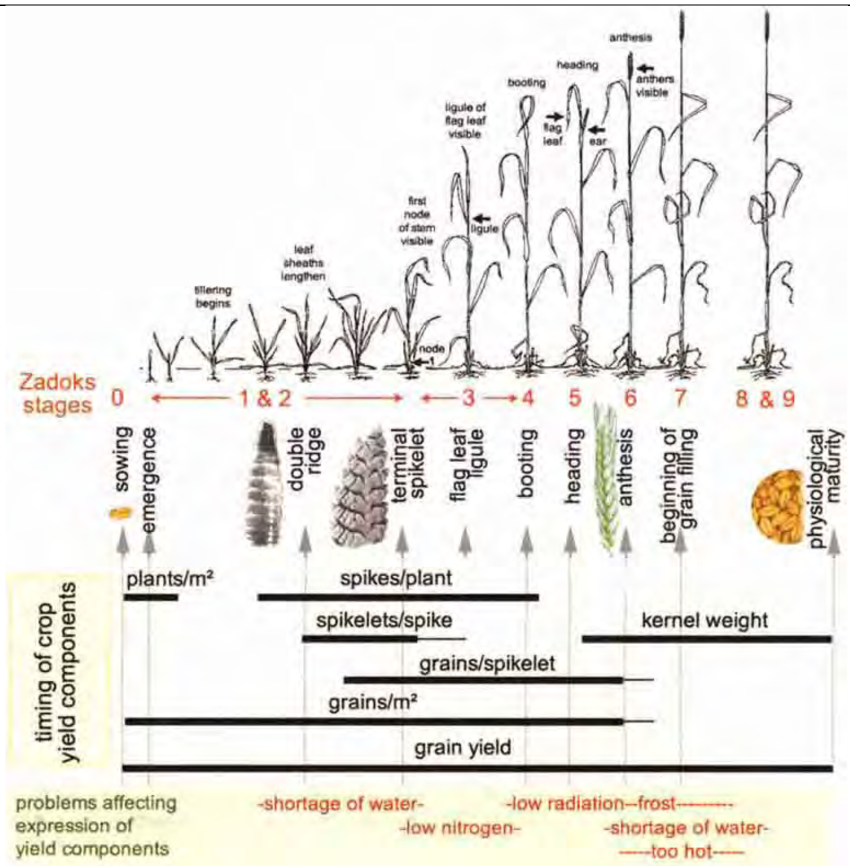
I 6-6: Greenhouses and polytunnels
I 6-7: Reel gardening
I 6-8: Farm mechanization
I 6-9: Weed management
I 6-10: Eradication of invasive species

Intervention:	I 6-1:Adjusting crop sowing dates
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas
Contributes to:	• Improving water productivity (WP(ET)) • Improved crop production (B or Y)
Description:	The sowing date of a crop defines the environmental conditions to which the crop will be exposed in key moments of its developmental cycle (e.g., critical periods for yield and quality components). Farmers are often well aware of the required environmental conditions, ie. the amount of water (rainfall / irrigation) required during different cropping stages and the ideal temperatures. However, if environmental conditions change, for example if droughts and rains become more intense or erratic, farmers will need to adjust sowing, possibly consider supplemental irrigation and or drainage where flooding and water logging (threatens to) occurs. Various researchers have already concluded that for staple crops such as maize, wheat, rice the adaptation of sowing dates is the first most reasonable measure to consider where climate changes is felt (Krishnan et al., 2007; Hai-dong et al., 2016; Lv et al., 2020). Empirical analysis of rainfall data can help in forecasting dry spell frequency and length (Sivakumar, 1992), which in turn can help ascertain if planting dates for seasons to come should change and or if other measures such as alternative varieties, cropping patterns, fertiliser quantities and composition or supplementary irrigation is needed. Considerations in changing sowing dates do not only relate to the first sowing date for the season because it is dependent on first rains or other season break factors, there are choices after that time. Researchers and farmers over decades have examined the effects on yield of changing planting dates. (shifts in) Climatic conditions throughout the cropping season should be considered, when looking at potential problems affecting expression of yield. These are set out against the various plant stages in the figure below. Particularly the anthesis and grain filling stages should be set out against rainfall forecasting and or (supplementary) irrigation (FAO, 2003).



Zadoks growth scale (FAO, 2003)

Shifts in crop sowing dates should not be seen a standalone solution to attainable yields, consider it an adaptation measure to changing environmental contexts. Complementary adaptation which farmers considered in different agro-ecological zones in Pakistan include: the use of improved varieties (agro-ecological zone specific), higher seeding rates and additional fertilizer application (Shah et al., 2021).

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Intervention	I 6-2: Crop rotation and multiple cropping
Application	• Irrigated areas

	• Rainfed areas • Spate irrigated areas
Contributes to:	• Improving water productivity (WP(ET)) • Improved crop production (B or Y)
Description	Crop rotation is the practise of consecutively changing crops on a field. A cycle may include a different number of years, from 3 up to 7+ planting various crops in turns and/or leaving the land fallow to recover. In this case, areas may be either unused or used as green leys for livestock. These practices can be helpful since there are certain crops contribute to nutrient depletion and retention. At the same time there are other crops that release nutrients which can support the development of other crops. Therefore, selecting specific crop rotations reduce the negative effects of certain crops on the soil and can foster benefits. There is no standard crop rotation chart though, however there are certain combination recommendations to achieve certain objectives. There are multiple benefits of implementing the crop rotations approach such as (a) fixing nitrogen (b) optimization of expenses saving on chemicals, (c) increase biodiversity, (d) increase water retention, (e) reduced usage of pesticides, (f) protection from erosion, (g) increased yields. Multiple cropping, is a distinct crop rotation effort as farmers harvest a crop more than once a year. Together with crop rotation it is a widespread land management strategy. In tropical and subtropical agriculture cropping often happens consecutively, whereas in many other systems a second crop may be planted during the running cropping season (this commonly referred to as intercropping). Multiple cropping is a way of intensifying agricultural production and diversifying the crop mix for economic and environmental benefits (Waha et al., 2020). Besides increasing the number of harvests (risk spreading and diversification) multiple cropping also increases sustainability in crop production, pest reduction, resistance to climate events and reduction in fertiliser use when combined with (nitrogen fixing) legumes (Peoples et al., 2009). An approximated 135 million hectares worldwide are found to have multiple cropping systems (Waha et al., 2020). Those systems that have proven improve sustainable crop production (sustained yield) include: cereal – legumes and cereal – groundnut (cereals in Africa commonly being maize, millet, sorghum, wheat); or combinations of winter (rabi) and summer (kharif) crops in South-Asia typically consisting of rice-/maize-potato/cereals combinations.
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Intervention:	I 6-3: Using improved crop varieties
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas
Contributes to:	• Improved crop production (B or Y) • Improved water productivity (WP(ET))
Description:	Crop varieties can be classified into two broad categories by the way in which their characteristic properties were developed: traditional varieties and improved varieties. *Traditional varieties* (also known as landraces, local varieties or farmers' varieties) were selected by farmers over many generations for their special characteristics, and normally are well adapted to the natural and cultural environment in which they are grown (drought, pest, disease tolerance). *Improved or modern varieties* are those obtained after a systematic and scientific process of selection and

	breeding (Fajardo Vizcayno et al., 2014). Plant breeders change the traits of plants in order to produce desired characteristics and increase their value. Increased crop yield is the primary aim of most plant breeding programmes. However, varieties were also developed to be more resilient to non-optimal conditions, be it as a cause of biotic stresses (pests and diseases) or abiotic stresses (nutrients, water, temperature, salinity) (Borgia et al., 2014). This kind of 'smart breeding' would allow crops to grow in new agricultural areas, be adapted to altered agricultural calendars (production outside traditional cropping periods or cropping lengths), as well as make them more resilient in places where climates are changing. Global seed markets can offer a great diversity improved or modern varieties, small-scale farmers in many developing countries however have very limited access to those varieties and to the knowledge and required inputs associated with them. Selecting the most appropriate variety therefore is a consideration of natural conditions but particularly also farming contexts. Besides being low-cost and reusable traditional varieties may also offer the best bargain considering seed reusability and limited inputs required. If the local markets and or farmers have appropriate means (dry and cool) for storing seed, local varieties should be preferred. For crops such as maize or vegetables, for which in most parts of the world traditional (or local) varieties are not available, the general rule for selecting the right variety is to choose the 'open-pollinated varieties' (OPVs), because rather than hybrids, OPVs maintain the properties of the variety for several seasons (hence seed reusability) (Fajardo Vizcayno et al., 2014). When considering improved or modern varieties particularly the access to implements and inputs -the right tools, plant nutrition and associated skills and knowledge - needs to be taken into account. Because what shows is that in many areas of the world the potential yields of these varieties are often not achieved. In areas where this actual yield is 50% below the varieties potential, there is still sufficient scope to improve its yield and at the same time improve water productivity. Note: when yields are above 40–50% of their potential, however, yield gains come at a near proportionate increase in the amount of ET, thus incremental gains in water productivity become smaller as yields become higher.
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Intervention:	I 6-4: Inter cropping systems
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas
Contributes to:	• Improved crop production (B or Y)
Description:	Intercropping is the practice of growing two or more crops in proximity. The most common goal of intercropping is to produce a greater combined yield on a given piece of land by ways of: mutualism; and making use of resources that would otherwise not be utilized by a single crop. The traditional mixed farming system, Baranaja, across the rainfed Garhwali agricultural regions in Uttarakhand (India), is a system where twelve, or sometimes more, crops such as cereals, lentils, vegetables, creepers and root vegetables are grown. The creepers of legumes use the stems of grains/plants as a natural support, while the grain roots grip the soil firmly, preventing soil erosion. Due to their nitrogen fixing abilities, legume crops return to the soil nutrients which are used by other crops. No external chemical inputs are used and pest control is achieved through the use of leaves of the walnut and neem, and the application of ash and cow's urine. The social and nutritional water productivity are also ensured as crop failure is balanced out and cash crop is combined with staples; and high mineral and protein crops provide beneficial home nutrition. In China, the simultaneous use of different rice varieties (glutinous and hybrid rice) was tested with promising results. Yields of glutinous rice were 89% greater and pest incidence was 94% lower than in monoculture systems. Hybrid (non-glutinous) rice yields were nearly equal to those

	of monocultures (Zhu et al. 2000) Another successful example of intercropping comes from mechanized wheat farming in the U.S. By using multiple wheat cultivars and wheat and barley intercropping, disease reduction was larger than with the application of fungicides (Vilich-Meller 1992; Kaut et al. 2008). Intercropping of cereal and legumes makes it possible to use significantly less fertilizer without having an impact on yields, as leguminous crops biologically fixate nitrogen. In India, nitrogen fertilizer savings of 35-44 kg/ha were registered when a leguminous crop preceded rice or wheat. Intercropping of soybean with maize saved 40-60 kg of nitrogen per hectare (Venkatesh and Ali 2007). Crops with different nutritional requirements, timing of peak needs and diverse and deeper root structures are grown on the same land simultaneously (Gliessman et al. 1985), thus optimizing nutrient and water use. Productivity in multiple cropping systems is expressed by land equivalent ratios, which is the ratio of the area under sole cropping to the area under intercropping needed to give equal amounts of yield at the same management level. It is the sum of the fractions of the intercropped yields divided by the sole-crop yields. <u>Intercropping systems in spate irrigation systems</u> Diversification of crops in spate irrigated areas is less of a successful given as in any other cropping system. As soils, nutrient and moisture management is distinctly different to any other, the underneath 'alternative' crops and vegetation provide specific suggestions for these areas to: increase land productivity; diversify to better sustain dependant livelihoods and allow for intercropping. In many spate systems, sorghum is a main staple crop, it can often easily be combined with early and uniform maturing mung beans, and other pulses like moth, bakla beans, chickpeas and kidney beans. Considering the main spate flooding have receded and the main crop has already reached vegetative stage. In spate irrigation areas of Pakistan wild edible mushrooms enter into symbiotic relations with sorghum. <u>Retaining wild crops:</u> There is a wide range of wild minor crops which have valuable benefits. The seeds are left in the soil and germinate usually after the area has been irrigated by the spate flow. They combine with the main crop that is grown during the spate seasons. Sanwak, cheena and smookha are examples. Bread and porridge are made with their seeds, their leaves and stems are used as roofing material and the whole plant serves as animal feed, especially in times of drought. Isagbol, a wild medicinal plant that grows from previous season seeds, provides treatment of chronic bacillary dysentery and constipation.
References:	Gliessman, S.R., 1985. "Multiple Cropping Systems: A Basis for Developing an Alternative Agriculture." In Innovative biological technologies for lesser developed countries: workshop proceedings. Congress of the U.S. Office of Technology Assessment. Washington, DC, pp. 67-83. Kaut, A.H.E.E., H.E. Mason, H. Navabi, J.T. O' Donovan, D. Spaner, D., 2008. "Organic and conventional management of mixtures of wheat and spring cereals". Agron. Sustain. Dev. 28, 363-371. Venkatesh, M.S., M. Ali, 2007. "Role of Legumes in Nitrogen Economy of Cereals/Cropping systems- The Indian Scenario". In Abrol, Y.P., N. Raghuram, M.S. Sachdev (eds.). Agricultural Nitrogen Use & its Environmental Implications. International Publishing House Pvt. Ltd., New Delhi, pp. 351-368. Vilich-Meller, V., 1992. "Pseudocercosporella herpotrichoides, Fusarium spp. and Rhizoctonia cerealis stem rot in pure stands and interspecific mixtures of cereals". Crop Prot. 11, 45-50. Zhu, Y., H. Chen, J. Fan, Y. Wang, Y. Li, J. Chen, J.X. Fan, S. Yang, et al., 2000. "Genetic diversity and disease control in rice". Nature 406, 718-722.
Additional sources	Ministry of Culture, Government of India. Parampara – Documenting efforts to conserve India's living traditions (https://paramparaproject.org/traditions_baranaja.html) Web resources: Improved Livelihood Opportunities in Spate Irrigation (http://spate-irrigation.org/wp-content/uploads/2020/05/Livelihood-opportunities-brochure-FINAL-1.pdf)

Intervention:	I 6-5: Agroforestry/shelter belts

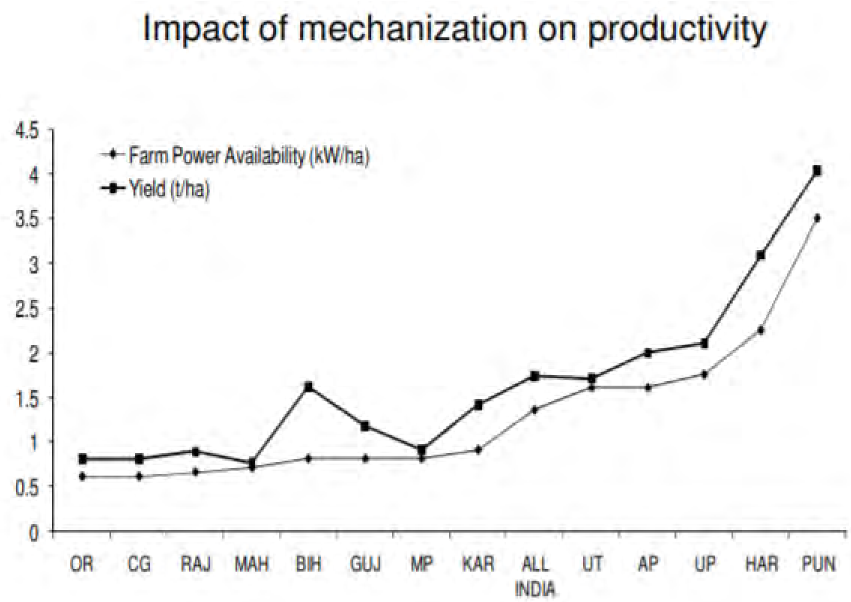
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas
Contributes to:	• Improved crop production (B or Y)
Description:	<u>Agroforestry:</u> Agroforestry is a land-use system in which woody perennials (trees, shrubs, palms, bamboos, etc.) are combined with agricultural crops and/or animals in the same land management units, in some form of spatial arrangement of temporal sequence. Agroforestry systems, if well managed, produce food, feed and fibre in proper balance. In agroforestry, trees are included in the cropping system or combined with livestock production in agro-silvo-pastoral systems. Benefits include biodiversity conservation, water and soil quality enhancement and carbon storage. By supporting a variety of complementary products (i.e., food, feed, fuel wood, timber and energy), agroforestry is an important means to increase smallholder incomes. Most importantly, agroforestry systems are modelled to maximize eco-efficiency – reducing the need for external inputs while enhancing nutrient cycling. The observed competition effect between trees and crops for radiation, topsoil water and nutrients, which might translate into lower crop yields, is outpaced by positive effects on soil moisture and nutrient improvement and the reduction of pest pressures. Recent studies on the productivity of temperate silvo-arable agroforestry systems show 20-60% higher productivity relative to the respective monocultures (van der Werf et al., 2007; Smith, 2010; Dupraz and Talbot, 2012). In Pakistan's spate irrigated areas the use of multipurpose trees and shrubs is the backbone of farming systems and are used for as windbreak, erosion protection, shading, timber, fodder, fencing, firewood, edible fruits, sand dune stabilization, honey, medicinal, charcoal, handicrafts (like from the Mazri plant), spate diversion, bird nesting and root use. In Pakistan, the most common multipurpose trees are Selam, Sedr, Ber, Arack, Jaal, Haleg, Date Palm, Dome, Athel, Daber, Jand, Karita, Kikar and Mesquite. The products (wood, fodder, fruit, etc.) of these trees provide income on top of the income of farming and can serve as a reserve fund. In case of drought and other harsh climate conditions, farmers' crops might die but the trees will survive. <u>Shelter belts:</u> Together with temperature and humidity, wind speed is one of the strongest drivers of evaporative losses from soil, plants, and surface water/moisture. As the air passes over surface, leaves, and water bodies or morning dew, it draws water along with it. Wind speed can however be drastically reduced by placing barriers in the way of oncoming air currents to serve as windbreaks, some of the most effective windbreaks are trees. Trees planted as windbreaks disrupt and lift incoming air currents, significantly reducing the wind force for a distance up to 10 times the height of the trees. This an important consideration for long-term planning, as the sheltered area of the field will expand horizontally as the windbreak trees grow vertically over the years. The effective height of young trees can be boosted by planting them on earth banks or bunds to add some height in the initial growth stages. The reduced wind speed, in turn, reduces evaporation but many other benefits are gained such as microclimate amelioration, timber and non-timber products (forage, fruit, etc.), ecological corridors and habitat, crop protection (reduced damage and blossom loss), reduced soil erosion, and of course carbon sequestration and cycling. <u>Considerations for shelter beds:</u> Gaps, both horizontal and vertical, in wind-break lines should be avoided as they will serve to funnel wind directly onto the field. Therefore, parallel rows of tree planting are recommended, with the tallest-growing species in the middle, and shorter-growing trees or shrubs on either side to close the gap between the trunks of the central trees, creating a homogenous barrier against the wind. Selection of tree species also warrants careful consideration, to be an effective and long-lasting wind breaker, trees should be deep rooting to offer stability against the force of oncoming winds. They should also have narrow canopies with small crowns to avoid being damaged by the wind themselves. When possible, trees should also be selected for their multifunctionality, such as the ability to produce fruit, fodder, of fix nitrogen in the soil. To avoid competition with crops for

	water, a shallow trench, or impermeable barrier can be placed between the windbreak and cropping areas, keeping root systems separated.
References:	Werf, W. van der, Keesman, K. Burgess, P. Graves, A. Pilbeam, D.. Incoll, L.D Metselaar, K. Mayus, M. Stappers, R. van den Keulen, H. Palma, J. Dupraz, C. 2007. "Yield-SAFE: A parameter-sparse, process-based dynamic model for predicting resource capture, growth, and production in agroforestry systems". Ecological Engineering 29(4), 419-433. Smith, J., 2010. Agroforestry: Reconciling Production with Protection of the Environment. A Synopsis of Research Literature. The Organic Research Centre, Elm Farm. Progressive Farming Trust Limited, Berkshire, UK. Dupraz, C., Talbot, G. 2012. Evidences and explanations for the unexpected high productivity of improved temperate agroforestry systems. 1st EURAF Conference, 9 October 2012, Session 1. INRA, Montpellier, France.
Additional sources	Web resources: Improved Livelihood Opportunities in Spate Irrigation (http://spate-irrigation.org/wp-content/uploads/2020/05/Livelihood-opportunities-brochure-FINAL-1.pdf)

Intervention:	I 6-6: Greenhouses and polytunnels
Application	• Irrigated areas
Contributes to:	• Improving water productivity (WP(ET)) • Improved crop production (B or Y)
Description:	Greenhouses and polytunnels are structures with walls and roof made mainly of transparent material, such as glass, in which crops are grown under regulated climatic conditions. The structures range in size from small sheds to industrial-sized buildings. The interior of a greenhouse exposed to sunlight becomes significantly warmer than the external temperature, protecting its contents in cold weather. Greenhouses and polytunnels provide a variety of advantages such as: (1) Longer growing season (even in cold climates) (2) Create an optimum growing environment (3) Suitable for a wide variety of plants (4) Protection of pests and diseases (5) Increased crop yield compared to conventional farming In high-tech greenhouses, all variables including: (sun)light composition and intensity, humidity, temperature, windspeed and integrated water and nutrient management. These systems allow for the optimal growing conditions in any given climate, be it that energy and water consumption may vary. High-tech greenhouses offer a near closed loop when it comes to water consumption as water that is transpired by plants or evaporated from planting substrates can be recollected (as condensation) and reused within the greenhouse. This making the systems a near optimum when it comes to water productivity, with the highest end performers noting a mere 1% of water required that would need to be '*freshly*' sourced from outside the greenhouse.
Additional sources	World Horti Center - the knowledge and innovation center for international greenhouse horticulture (www.worldhorticenter.nl)

Intervention:	I 6-7: Reel gardening
Application	• Irrigated areas • Rainfed areas
Contributes to:	• Improved crop production (B or Y) • Improved water productivity (WP(ET))
Description:	Reel Gardening is a biodegradable seed tape that can be planted straight into the ground. The tape contains high quality, non-chemically treated seeds. The seeds are held within the tape at the correct depth and distance apart for the plant to grow. The illustrations on the seed tape provide easy to follow instructions. The tape also provides information on where the plant is germinating and growing. This makes it easy for the users to irrigate only the spots where plants

	are grown and not the entire surface, which reduces irrigation water up to 80%. Hence besides easing seeding, it facilitates better germination and directed water application.
Additional sources	Web resources: Reel gardening (https://reelgardening.co.za/how-it-works-2/)

Intervention:	I 6-7: Reel gardening
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas
Contributes to:	• Improved crop production (B or Y)
Description:	Mechanized agriculture is the process of using agricultural machinery to mechanize the work of agriculture, greatly increasing farm productivity. Mechanization covers all levels of farming and processing technologies, from simple and basic hand tools to more sophisticated and motorized equipment. It eases and reduces hard labour, relieves labour shortages, improves productivity and timeliness of agricultural operations, improves the efficient use of resources, enhances market access and contributes to mitigating climate related hazards. Without mechanized agriculture, farm operations are either partially done or sometimes completely neglected, resulting in low yield due to poor growth or untimely harvesting or both. There is a positive correlation between application of improved technologies and the land productivity (figure below).  Impact of mechanization on production (Source: indiaagristat.com)
Additional sources	Web resources: Sustainable Agricultural Mechanisation, FAO (http://www.fao.org/sustainable-agricultural-mechanization/en/)

Intervention:	I 6- 9: Weed management
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas
Contributes to:	• Improving water productivity (WP(ET)) • Improved crop production (B or Y)
Description:	The time of tilling to remove weeds as well as applying herbicides is passé as not only the environmental impact bears concern for both, but also the increasing resistance of weeds to

herbicides (DiTommaso et al., 2016; MacLaren et al., 2020). Weeds are to be managed rather than controlled by means of: reduce herbicide rates (considering tillage systems, weed prevalence, crop stages and economic costs versus impact); integrated weed management practices; or considering certain weeds as beneficial and managing vegetational diversity in plots. Vegetational diversity (including that of weeds) also helps to decrease the risk of disease and pest epidemics, particularly for small-holder agriculture in many parts in Africa (Hillocks, 1998)[8]*.

Weeds if not properly managed can set farmers both a loss in land and in water productivity. Weeds may cause crops stress as they compete for water, light and nutrients; they may even affect the field micro-climate, influencing variables such as wind and, humidity. Not in the least, weeds can influence disease incidence either being a pest itself, a vector of a pathogen or acting as a reservoir of pathogens or its vector (Wisler & Norris, 2005). However, the old idea that particular plant species are weeds, needs to be abandoned and replaced with an understanding that weeds are 'value judgements' and the judgement needs to be made on a case by case basis if a particular plant or population are, or are not, judged to be causing harm' (Merfield, 2019).

Integrated Weed Management (IWM)

IWM aims to keep the crop ahead of the weeds, and thereby tip the competitive balance in favour of the crop. This is done by selecting or combining best cultural practices such as: varieties selection, planting dates, patterns and densities, availing nutrient and water (practices that may also be referred to as Integrated Crop Management).

Beneficial Weeds

In ascertaining beneficial cop weed interactions skills to identify weeds at an early stage in cropping seasons and specific knowledge of these interactions are required. A certain amount specific weeds may be beneficial whereas occurrence and spread of others is not. Examples of beneficial weeds include:

- Weeds that provide resources that attract and maintain pollinator populations can, as more than a third of all crops worldwide are dependent on pollinators, provide alternative non-crop resources and thereby help sustain their services to increasing food production (Kleiman et al., 2021)
- In corn production, maintaining a few villainous milkweed plants in the middle of a cornfield may help minimize crop loss from the destructive European corn borer (DiTommaso et al., 2016)
- Weeds (particularly in perennial crop settings) can if properly managed, mowing at regular intervals, preserve top soil and reduce the incidence of erosion and play a useful part in nutrient cycling

References:

iTommaso, A., Averill, K. M., Hoffmann, M. P., Fuchsberg, J. R., & Losey, J. E. (2016). Integrating Insect, Resistance, and Floral Resource Management in Weed Control Decision-Making. Weed Science, 64(4), 743–756. https://doi.org/10.1614/WS-D-16-00052.1

Hillocks, R. J. (1998). The Potential Benefits of Weeds with Reference to Small Holder Agriculture in Africa. Integrated Pest Management Reviews, 3(3), 155–167. https://doi.org/10.1023/A:1009698717015

Kleiman, B., Koptur, S., & Jayachandran, K. (2021). Beneficial Interactions of Weeds and Pollinators to Improve Crop Production.

MacLaren, C., Storkey, J., Menegat, A., Metcalfe, H., & Dehnen-Schmutz, K. (2020). An ecological future for weed science to sustain crop production and the environment. A review. Agronomy for Sustainable Development, 40(4), 24. https://doi.org/10.1007/s13593-020-00631-6

Merfield, C. N. (2019). Integrated Weed Management in Organic Farming. In Organic Farming (pp. 117–180). Elsevier. https://doi.org/10.1016/B978-0-12-813272-2.00005-7

Organic Farming - Global Perspectives and Methods, ISBN 978-0-12-813272-2

Wisler, G. C., & Norris, R. F. (2005). Interactions between Weeds and Cultivated Plants as Related to Management of Plant Pathogens. Weed Science, 53(6), 914–917.

[8] the study does mention that although vegetational diversity can be beneficial it is important that certain weed species may harbour important pests or diseases of local crops and therefore should be selectively removed

	http://www.jstor.org/stable/4046994
Additional sources	FAO – Integrated Weed Management (http://www.fao.org/agriculture/crops/thematic-sitemap/theme/spi/scpi-home/managing-ecosystems/integrated-weed-management/en/) eOrganic Community of Practice (https://eorganic.org/) Organic Farming - Global Perspectives and Methods, ISBN 978-0-12-813272-2

Intervention:	I 6-10: Eradication of invasive species
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas
Contributes to:	• Improving water productivity (WP(ET)) • Improved crop production (B or Y)
Description:	An 'invasive species" is defined as a species that is non-native to the ecosystem under consideration and whose introduction causes or likely to cause economic or environmental harm or harm to human life. Invasive species can be considered a pest as they are a major cause of crop loss and can adversely affect food security (Cook et al., 2011). With good planning, adequate techniques, and sustained effort, it is now possible to eradicate many types of invasive species, especially in the early stages of an invasion, or where a population is confined to an island or limited habitat. The eradication of invasive species can yield major economic benefits, by permanently removing the cause of damage to crops, livestock or native biodiversity, and obviating the need for costly perpetual control. The difference between eradication and control is only one of grade; these two strategies are part of a gradient of interventions, and both share the purpose of annulling or (if not feasible) decreasing the impact exerted by invasive species. The methods used to control or eradicate invasive species are: (a) mechanical removal of invasive species from an area; (b) construction of barriers to prevent their spread; (c) reduction of their population size by using biological means; or (d) by using biocides; or (e) by having recourse to autocidal approaches; and (f) habitat management (Gherardi & Angiolini, 2009). Eradication, that is the removal of every potentially reproducing individual of a species from an area where this behaves as invasive or the reduction of its population density below sustainable levels, is the best management option, since it removes the need for further control and ongoing financial and environmental costs. Low-cost tools such as the 'Tree puller' can be very useful. However, eradication is likely to be successful only in the earliest stages of an invasion, or in "island" systems of manageable size. Eradication is often difficult, particular in extensive land use such as in rainfed cultivation or rangelands. In intensive cultivation the re-emergence and reinfestation can be controlled. Before starting any eradication program, managers should be fully aware that (a) adequate funds and commitment exist to complete the eradication, (b) monitoring of the population size is feasible, and (c) eradication will be followed by the restoration or management of the community or ecosystem resulting from the removal of a "keystone" target species.
References	Cook, D.C., Fraser, R.W., Paini, D.R., Warden, A.C., Lonsdale, W.M., & De Barro, P.J. (2011). Biosecurity and Yield Improvement Technologies Are Strategic Complements in the Fight against Food Insecurity. PLoS ONE, 6(10), e26084. https://doi.org/10.1371/journal.pone.0026084 Gherardi, F., & Angiolini, C. (2009). Eradication and control of invasive species. In E. Gherardi, F., Gualtieri, M., Corti, C. (Ed.), Biodiversity Conservation and Habitat Management, Encyclopedia of Life Support Systems (EOLSS) (pp. 271–299).
Additional sources	Video: The Tree puller (https://thewaterchannel.tv/videos/the-tree-puller/) Web resources: https://www.invasivespeciesinfo.gov/what-are-invasive-species https://portals.iucn.org/library/sites/library/files/documents/SSC-OP-028.pdf https://portals.iucn.org/library/sites/library/files/documents/2018-030-En.pdf http://issg.org

7 Crop input management

List of interventions

I 7-1: Efficient fertilizer use

I 7-2: Integrated nutrient management

I 7-3: Smart fertilizers

I 7-4: Bio-fertilizers

I 7-5: Rock dust soil amendments

I 7-6: Micro-nutrients

I 7-7: Precision use of chemicals: fertigation

Intervention:	I 7- 1: Efficient fertilizer use
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas
Contributes to:	• Improved crop production (B or Y) • Improved water productivity (WP(ET))
Description:	Efficient fertilizer use can contribute to increase crop yields, efficient energy use in agriculture and reduced pollution. Most (89%) of the increased agricultural production over the coming decades is expected to come from agricultural intensification, bringing along more intensive use of fertilizer. In several regions, nutrient limitations set the major ceiling on yields (Bindraban et al., 1999; Breman et al., 2001). Fertilizer use is particularly low in many parts of Africa and this constrains land and water productivity (in sub-Saharan Africa, only 9kg/ha of external nutrients are used as compared to 73kg/ha used in Latin America, 10 kg/ ha in South Asia and 135 kg/ha in East and Southeast Asia) (Kelly 2006). Therefore, particularly in sub-Saharan Africa, the world's major agricultural frontier, a system of sustainable intensification is advocated (Pretty et al., 2006; Pretty et al. 2011; Tilman et al. 2011). With current rainfall patterns, improved soil fertility could double productivity in Africa (Molden et al., 2010), particularly if the appropriate dose and right type of fertilizer (responding to soil deficiencies, as can be evaluated by soil testing) are used. It is important is that fertilizers are used efficiently, as overuse contributes to influxes of nitrogen and phosphorus. These are negatively affecting many Earth systems in the form of groundwater pollution, eutrophication, reduced or depleted oxygen in water bodies causing extinction of species and land degradation (Rockström et al., 2009). Bio-fertilizers and other nutrient sources, if properly used, are often a credible alternative to chemical fertilizers. Bio-based fertilizers more over help to improve the soil structure - a very important advantage. They also have the advantage of being produced locally – generating job opportunities. There are several types of bio-based fertilizer: - Organic manure - Compost - Vermicompost - Green manuring - Bio-fertilizer
References:	Bindraban, P.S., Verhagen, A., Uithol, P.W.J., Henstra, P., 1999. A Land Quality Indicator for Sustainable Land Management: The Yield Gap. Report 106. Research Institute Agrobiology and Soil Fertility, Wageningen, The Netherlands. Breman, H., Groot, J.J.R., van Keulen, H., 2001. "Resource limitations in Sahelian agriculture". Global Environmental Change 11(1), 59-68. Kelly, V.A., 2006. Factors Affecting Demand for Fertilizers in sub-Saharan Africa. Agriculture and Rural Development Discussion Paper 23. The World Bank, Washington, DC. Molden, D., Oweis, T., Steduto, P. Bindraban, M.A. Hanjra, M.A., Kijne, J. 2010. "Improving agricultural water productivity: between optimism and caution". Agricultural Water Management 97(4), 528-535.

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Tilman, D., Balzar, C. Hill, J. Befort, B.L. 2011. "Global food demand and the sustainable intensification of agriculture". Proceedings of the National Academy of Sciences of the United States of America 108(50), 20260-20264.

Intervention:	I 7- 2: Efficient fertilizer use
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas
Contributes to:	• Improved crop production (B or Y) • Improved water productivity (WP(ET))
Description:	Integrated Nutrient Management (INM) uses complementary measures – both natural and man-made sources of soil nutrients and mechanical measures – while considerable attention is paid to timing, crop requirements and agro-climatic considerations (Gruhn et al. 2002). To support INM, real-time crop sensors for site-specific application of nitrogen are a breakthrough in precision agriculture (Singh et al. 2006). Also, the use of remote sensing methods to schedule nitrogen fertilization can help farmers to practice a more sustainable agriculture, minimizing risks of losing the harvest by providing an adequate rate of nitrogen when the crops' needs and at a specific location (Yousfi et al., 2020). The combination of mineral and organic fertilizers shows sustained yields in the long run compared to just mineral fertilization, as well as increased crop production per unit of synthetic fertilizer applied (Gruhn et al., 2000). Inorganic fertilizer combined with green manure leads to increased yields in rice-groundnut cropping (Prasad et al., 2002). They registered yield increases of 1.6 t/ha and 0.25 t/ha for rice and groundnut respectively.
References:	Gruhn, P., Goletti, F., Yudelman, M., 2000. Integrated Nutrient Management, Soil Fertility, and Sustainable Agriculture: Current Issues and Future Challenges. Food, Agriculture, and the Environment Discussion Paper 32. IFPRI, Washington, DC. Prasad, P.V.V., Satyanarayana, V., Murthy, V.R.K., Boote, K.J., 2002. "Maximising yields in rice-groundnut sequence through integrated nutrient management". Field Crops Research 75, 9-21. Singh, I., Srivastava, A.K., Chandna, P., Gupta, R.K., 2006. "Crop sensors for efficient nitrogen management in sugarcane: potential and constraints". Sugar Tech. 8(4), 299-302. Yousfi, S., Fernando Marin Peira, J., Rincón De La Horra, G., & V. Mauri Ablanque, P. (2020). Remote Sensing: Useful Approach for Crop Nitrogen Management and Sustainable Agriculture. In Sustainable Crop Production. IntechOpen. https://doi.org/10.5772/intechopen.89422

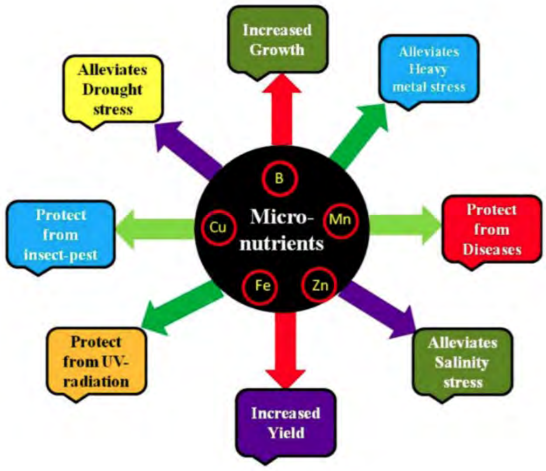
Intervention:	I 7-3: Smart fertilizers
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas
Contributes to:	• Improved crop production (B or Y) • Improved water productivity (WP(ET))
Description:	A smart nitrogen fertilizer incorporates a mechanism controlling nitrogen release based on crop requirements. This reduces unproductive losses, such as leaching and atmospheric emissions, while increasing nutrient-use efficiency and crop yields. These benefits may, under certain

	circumstances improve water productivity as the ratio between transpiration and yield (biomass) is improved as compared to cropping without or other fertilisers. The major mechanisms used are: 1) slow and control mechanisms; 2) nitrification inhibitors; and 3) urease inhibitors.
References:	Borgia, C., Evers, J., Kool, M., & van Steenbergen, F. (2014). Co-Optimizing Solutions: Water and Energy for food, feed and fiber. World Business Council for Sustainable Development.

Intervention:	I 7-4: Bio-fertilizers
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas
Contributes to:	• Improved crop production (B or Y) • Improved water productivity (WP(ET))
Description:	Biofertilizers are a fermented product made from cow dung, milk, sugars, ashes, and rock dust mixed with water. After a month of fermentation, the solution contains numerous minerals and compounds that feed and protect plants from insects and pathogens. Biofertilizers are a good alternative to chemical fertilizers for several reasons. Chemical fertilizers need to be bought, which means they depend on timely distribution and availability, and are a significant expense. Since biofertilizers are produced at home or on the farm, they are always available when needed and can be produced with locally available materials at minimal cost. Additionally, chemical fertilizers, while offering a short-term nutritional boost to the soil, over the long term degrade soil structure and soil biology thereby reducing the overall fertility and water holding capacity. Using chemical fertilisers leave the farmer dependent on buying and using more fertilizer every season! In contrast, biofertilizers nourish, regenerate, and reactivate the soil's life as the benefits build up with successive applications.
Additional sources	MetaMeta and RockinSoils. 2020. The biofertilizer manual - A step-by-step guide on how to make biofertilizer at home. as part of '*Green Future Farming Program (GFF)*'. Supported by IKEA Foundation.

Intervention:	I 7-5: Rock dust soil amendments
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas
Contributes to:	• Improved crop production (B or Y) • Improved water productivity (WP(ET))
Description:	Ground rock dust blends as a soil amendment may provide a more complete source of many plant-available elements and minerals, allowing for more wholesome plant growth and the production of higher quality, more nutrient-dense foods. The mechanism by which the rock dust is broken down also provides long-term improvements to soil fertility, reducing the resources needed to apply the amendment, thereby improving the overall sustainability of the growing operation.
Additional sources	Hunt, J., Hunt, A. J. (2017). Rock dust and biochar to remineralize soils. Pacific Biochar Benefit Corporation. Retrieved October 8, 2021, from https://pacificbiochar.com/rock-dust-and-biochar-to-remineralize-soils/.

Intervention:	I 7-6: Micro-nutrients
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas
Contributes to:	• Improved crop production (B or Y) • Improved water productivity (WP(ET))

Description:	In agriculture the usage of micro-nutrients by plants is often overlooked; be it that plants only require them in very little amounts, if deficient crop growth and quality will be affected. Each micronutrient plays a different role in a plant organism. The most important micronutrients are boron (B), iron (Fe), manganese (Mn), and zinc (Zn), besides also copper (Cu), chlorine (Cl) and molybdenum (Mo). The most common practice to maintain adequate amounts of micronutrients in the soil and thus enhance their uptake by the crops, is by direct application of chemical fertilisers or by applying organic fertilizers. The direct application of micronutrients to soils is the most common method, however it is known to decrease the availability as they react with soil minerals and organic matter and become unavailable to plants. However, when considering organic sources of micronutrients such as farm yard manure, compost, oil cakes, liquid organic manures, biofertilizers, animal manures and organically approved amendments, it is important to consider these within an entire farming approach. This including: cropping system management viz., green manures (one season in a year), crop rotation, intercropping and crop residues management as mulch (Anand et al., 2019). The organic fertiliser and amendment techniques have been fostered as the most feasible and sustainable approach to restore soil fertility (Masunaga & Fong, 2018). Micro-nutrients in adequate supplies increase the growth and yield of plants, thereby protecting the plants from adverse effects of various biotic and abiotic stresses (see figure below).  Response of micronutrients in different abiotic and biotic stresses (by (Tripathi et al., 2015)).
References:	Anand, M.R., Kumar, H.S., Kommireddy, P., & Murthy, K.N.K. (2019). Secondary and Micronutrient Management Practices in Organic Farming- An Overview. Current Agriculture Research Journal, 7(1), 04–18. https://doi.org/10.12944/CARJ.7.1.02 Masunaga, T., & Fong, J. (2018). Strategies for Increasing Micronutrient Availability in Soil for Plant Uptake. In Plant Micronutrient Use Efficiency (pp. 195–208). https://doi.org/10.1016/B978-0-12-812104-7.00013-7 Tripathi, D. K., Singh, S., Singh, S., Mishra, S., Chauhan, D. K., & Dubey, N. K. (2015). Micronutrients and their diverse role in agricultural crops: advances and future prospective. Acta Physiologiae Plantarum, 37(7), 139. https://doi.org/10.1007/s11738-015-1870-3

Intervention:	I 7- 7: Precision use of chemicals: fertigation
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas
Contributes to:	• Improved crop production (B or Y) • Improved water productivity (WP(ET))
Description:	With fertigation, fertilizers can be applied with irrigation water on demand during periods of peak crop demand at or near the roots and in smaller doses, which ultimately reduces losses while increasing yields and quality of product (Tilman et al. 2002). If properly designed and scheduled and also taking into consideration soil properties (Gärdenäs et al. 2005), fertigation

	systems allow for the more efficient application and use of nitrogen (Singandhupe et al. 2003; Hou et al. 2007) thereby reducing its leaching and runoff.
References:	Gärdenäs, A.I., Hopmans, J.W.Hanson, B.R. Šimunek, J. 2005. "Two-dimensional model for nitrate leaching for various fertigation scenarios under micro-irrigation". Agricultural Water Management 74, 219-242. Hou, Z., Li, P., Li, B., Gong, J., Wang, Y., 2007. "Effects of fertigation scheme on N uptake and N use efficiency in cotton". Plant and Soil 290, 115-126. Singandhupe, R.B., Rao, G.G.S.N., Patil, N.G., Brahmanand, P.S., 2003. "Fertigation studies and irrigation scheduling in drip irrigation system in tomato crop (Licopersiconesculentum L.)". European Journal of Agronomy 19, 327-340. Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. "Agricultural sustainability and intensive production practices". Nature 418, 671-677.

8 Pest and disease control

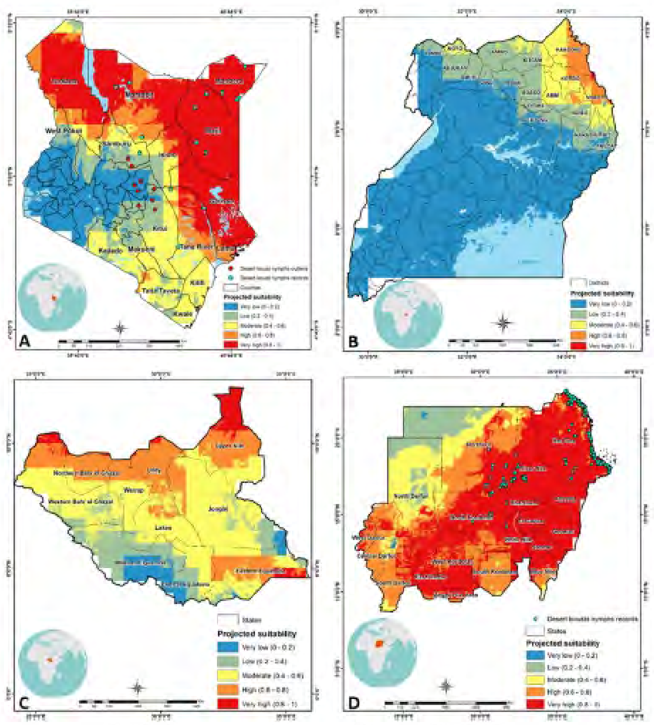
List of interventions
I 8-1: Plant disease control
I 8-2: Desert locust control
I 8-3: Integrated Pest Management (IPM)
I 8-4: Nanotech pesticides
I 8-5: Ecologically based rodent management
I 8-6: Precision use of chemicals: chemigation

Intervention:	I 8-1: Plant disease control
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas
Contributes to:	• Improving water productivity (WP(ET)) • Improved crop production (B or Y)
Description:	As plant diseases come in all shape, sizes, intensity and ferocity measures to tackle them are plentiful. However, only since the discovery of the causes of plant diseases in the early nineteenth century, our growing understanding of the interactions of pathogen and host has allowed us to distil general principles of plant disease control (Plant Disease Management Strategies). Outlined by a committee of the US National Academy of Science in 1968 are the following **Traditional Principles of Plant Disease Control** 1. Avoidance—prevent disease by selecting a time of the year or a site where there is no inoculum or where the environment is not favourable for infection. 2. Exclusion—prevent the introduction of inoculum. 3. Eradication—eliminate, destroy, or inactivate the inoculum. 4. Protection—prevent infection by means of a toxicant or some other barrier to infection. 5. Resistance—utilize cultivars that are resistant to or tolerant of infection. 6. Therapy—cure plants that are already infected. An important consideration though is that the steps imply a goal of zero disease, which in most cases is not feasible. The principles should therefore be fitted into an overall strategy based on (disease specific) epidemiological principles, ie. that of studying the distribution (frequency, pattern) and determinants (causes, risk factors) of crop related states and events, looking at not only the disease itself but particularly looking at the cropping environments and pathways in which diseases (or inoculum[9]) spread. Some examples that follow from the considering of the above principles are provided below (from (Akanmu et al., 2021; Berger, 1977) (Organic Growers School). 1. Exclusion / or control of disease by reduction of initial inoculum (selection of): treatment of seed with hot water or chemicals to kill seedborne pathogens; seed indexing and certification; crop rotation, changing the planting area of crops every season will help prevent disease, especially soil-borne pathogens; deep ploughing of crop refuse is used to minimize losses to Septoria on wheat; heat therapy of crops, e.g. used to control sugarcane ratoon stunt 2. Protection / control of disease by slowing the rate of infection (selection of): alter the microclimate of a crop: maintain good airflow between plants, by ensuring adequate spacing, minimal weeds, and varied architecture (i.e have tall and short plants together); sow or plant crops at a time of year that is less favourable for disease; plant spacing and row planting, considering that rows oriented in the direction of prevailing winds (or with

[9] Inoculum: the portion of the pathogen responsible for infection is called inoculum. The inoculum may be spore, mycelium or any other part of the fungus, but in bacteria and virus the entire body behaves as inoculum. (Study Notes on Inoculum | Plant Pathology (biologydiscussion.com))

	east-west orientation for sunlight penetration) create drier and less favourable conditions; where sequential planting takes place ensuring crops that are harvested later are not in the prevailing winds of those harvested earlier (as disease is usually maximal when crops are harvested); timing the application of organic (organic materials or biological control) or chemical fungicides so that they are synced with infection rates 3. Control of the disease by shortening time of exposure: crop transplantation, the setting of vigorous plants with a well developed root system ensures quicker establishment of the crop and shorten the time to maturity; use of short season varieties; strive for healthy soils and maintain adequate moisture (not too much) to avoid any slowdown of crop growth are the most common techniques to shorten the exposure of crops to pathogens; control of weeds that if part of the same family as the crop can transmit and/ or harbour diseases for current standing crops or next season. Finally, as a lot is to be said about the control of plant diseases and many of the above measures need to be considered jointly; approaches such as the Biorational Approach described by (Akanmu et al., 2021) can provide comprehensive (plant health) guidance to 'new' ways in sustainable agricultural practice.
References	Akanmu, A.O., Babalola, O.O., Venturi, V., Ayilara, M.S., Adeleke, B.S., Amoo, A E., Sobowale, A.A., Fadiji, A.E., & Glick, B.R. (2021). Plant Disease Management: Leveraging on the Plant-Microbe-Soil Interface in the Biorational Use of Organic Amendments. Frontiers in Plant Science, 12. https://doi.org/10.3389/fpls.2021.700507 Berger, R.D. (1977). Application of Epidemiological Principles to Achieve Plant Disease Control. Annual Review of Phytopathology, 15(1), 165–181. https://doi.org/10.1146/annurev.py.15.090177.001121
Additional sources	Jones, R.A.C. 2021. Global Plant Virus Disease Pandemics and Epidemics. Plants, 10, 233. https://doi.org/10.3390/plants10020233

Intervention:	I 8-2: Desert locust control
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas
Contributes to:	• Improving water productivity (WP(ET)) • Improved crop production (B or Y)
Description:	Creating resilience to desert locust invasions requires measures taken (a) in-between invasions, (b) in the runup to the invasions, and (c) during invasions. **A. Early warning: strengthening existing systems using near-real-time 'big data' and cross cutting machine learning modelling approach** Current early warning systems track locust hopper bands and swarms in real time. Their hands can be strengthened by the application of 'big data' and machine learning models to accurately predict future locust breeding sites. icipe and MetaMeta are piloting a process that entails: 1. establishing what environmental conditions are conducive to locust breeding, through analysis of bio-climatic (temperature and rainfall) and bio-physical (sand and moisture contents) are conducive to locust breeding, through analysis of historical data 2. identifying areas with similar current and future conducive conditions



A graphical representation of the projected model for desert locust breeding sites in Kenya (A), Uganda (B), South Sudan (C), and Sudan (D) based on environmental conditions and breeding pattern linkages from Morocco. The breeding sites found in Sudan (647) and Kenya (28) are historical (from 2013 to 2019) and actual (2020) records, respectively, used for measuring the developed model performance.

B. Biopesticide: minimizing environmental impact using insecticides based on natural oils

Pesticides continue to be the main pushback against advancing swarms. Beyond a certain swarm strength, chemical fertilizers are the only viable option given their quick kill time. However, their negative impact on the environment and non-target species can be limited significantly by targeting hopper bands and nascent swarms with biopesticides. Use of biopesticides is already being widely promoted. The ones currently in use are based on fungi spores with mineral oils (diesel/kerosene) as solvent. Environmental impact can be further reduced by using biopesticides based in essential (plant) oils. A team of scientists from University Graz has developed prototypes that are ready for field testing.

C. Catching locusts for the animal food industry

Here is a novel idea for fighting back against locusts: catch them and feed them to chickens. This is precisely what has been tried out in parts of Pakistan with some success. Local communities were encouraged to catch locusts at night (when they are not flying but resting on the ground), and sell them to poultry feed manufacturers. The insects make for a good, protein-rich feed. On average, 1 community in Punjab province was able to catch 7 tonnes of locust per night, and individuals could make about 120 dollars for one night's catch upon selling it off. This way, the swarm was contained, while creating livelihood opportunities.

Additional sources	www.thewaterchannel.tv / Conference "Insects to feed the world"

Intervention:	I 8-3: Integrated pest management (IPM)
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas
Contributes to:	• Improving water productivity (WP(ET)) • Improved crop production (B or Y)

Description:	Integrated pest management (IPM) as opposed to single pest control methods is a strategy that combines a larger range of cultural, biological, mechanical, and chemical tools and practices. It relies on a deep understanding of pathogen life cycles and plant-pathogen interactions. By rationalizing chemical interventions and doses, IPM aims to use resources more efficiently, reducing costs and environmental and health externalities. IPM includes four steps: 1) setting an action threshold; 2) monitoring and identification of pests; 3) prevention; and 4) control. Prevention methods encompass several practices using pest-resistant crops, including rotations, intercropping, and using certified and pest-free planting material. These methods can be highly effective and cost-efficient while preserving the environment and human health. Similarly, any method for early monitoring and pest detection is crucial in preventing the outbreak of devastating diseases and avoiding cost-intensive measures. Once the threshold for action has been reached, various control methods are available, starting with the least risky pest control methods, such as pheromones for pest mating or mechanical control. If these are not working, then, targeted pesticides may be applied. Broadcasting and nonspecific pesticides are the last resort (US EPA n.d). Several studies confirm the potential and profitability of this approach (Dasgupta et al., 2007; Pretty et al., 2011). IPM has found wide application in Asia and Africa, often promoted in farmer field schools as part of programs aimed at social and human development. Rice yields in Mali have been reported to rise from 5.2 to 7.2 t/ha and in Senegal from 5.19 to 6.84 t/ha, with up to 90% reductions in pesticide use (Pretty et al., 2011).
References	Dasgupta, S., Meisner, C., Wheeler, D., 2007. "Is Environmentally Friendly Agriculture Less Profitable for Farmers? Evidence in Integrated Pest Management in Bangladesh". Review of Agricultural Economics 29(1), 103-118. Pretty, J.N., Toulmin, C., Williams, S., 2011. "Sustainable Intensification in African Agriculture". International Journal of Agricultural Sustainability 9, 5-24. US EPA (US Environmental Protection Agency), n.d. "Integrated Pest Management (IPM) Principles".
Additional sources	Borgia, C., Evers, J., Kool, M., & van Steenbergen, F. (2014). Co-Optimizing Solutions: Water and Energy for food, feed and fiber. World Business Council for Sustainable Development.

Intervention:	I 8-4: Nanotech pesticides
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas
Contributes to:	• Improving water productivity (WP(ET)) • Improved crop production (B or Y)
Description:	Despite global pesticide use of 2.5 million tonnes every year, production losses as a consequence of plant pests remain in the order of 20-40% (FAO 2011). Oerke (2006) estimates total losses* of 28% for wheat, 37% for rice and 31% for maize. Conventional pesticides are strongly associated with environmental degradation and health hazards. This is due to pesticide toxicity, non-biodegradability, the impreciseness of some formulations, and leaching and other losses during application. This combination of side effects and low efficiency is the imperative for rethinking conventional pesticide use, the aim being to halve current losses. Breakthroughs in pesticide control are expected in the field of nanotechnology. Nanotechnology refers to a range of techniques for manipulating materials, organisms and systems at a scale of 100 nano meters or less. Nano pesticides contain nanoscale chemical substances. The theoretical advantages are: 1) increased efficacy, stability or dissolvability in water as compared to larger-scale molecules of the same chemical substances and 2) controlled release of pesticides due to the nanoencapsulation of pesticide substances. Some smart pesticides can release their active ingredient only when inhaled by insects (Kuzma and VerHage, 2006). Nano pesticides are also better combined with genetically engineered insecticide-producing crops and genetically engineered herbicide tolerant crops. Nano pesticides are still in the experimental stage: one issue to be resolved is precautionary concerns on the release of the particles in a larger environment.

References:	FAO (Food and Agriculture Organization of the United Nations), 2011. Looking ahead in world food and agriculture: perspective to 2050. Conforti, P. (ed.). Food and Agriculture Organization of the United Nations, Rome, Italy. Kuzma, J., VerHage, P., 2006. Nanotechnology in Agriculture and Food Production: Anticipated Applications. Woodrow Wilson International Centre for Scholars, Project on Emerging Nanotechnologies Oerke, E.C., 2006. "Crop losses to pests". Journal of Agricultural Science 144, 31-43
Additional sources	Borgia, C., Evers, J., Kool, M., & van Steenbergen, F. (2014). Co-Optimizing Solutions: Water and Energy for food, feed and fiber. World Business Council for Sustainable Development.

** Globally, cereal crops losses from weeds are estimated at 8-11%; from animal pests 8-15%; from pathogens 9-11% and from virus strains 1-3%*

Intervention:	I 8-5: Ecologically based rodent management
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas
Contributes to:	• Improving water productivity (WP(ET)) • Improved crop production (B or Y)
Description:	To safeguard local food supplies an immediate priority is to control the loss of the current harvest by drastically reducing rodent damage. Both in the field and in storage. At the same time, it is essential to combat rodent vectored diseases, which amount to over 60 different diseases. For example, the Lassa-and Hanta viruses are brought by rodents. Chemical control is currently the primary driver of "Integrated Pest Management" (IPM) for rodents. This generally provides effective control in the short term, regardless of the rodent species. However, governments are concerned about the use of chemicals, especially when they are striving to provide clean and green food products for their domestic and export markets. In developing countries, the challenge is first to develop a good understanding of the ecology of the pest species and then assess the efficacy of using traditional and new methods of rodent control. This will enable adoption of management actions that are more environmentally sound and sustainable (environmentally and culturally). Therefore, Ecologically Based Rodent Management (EBRM) which promotes integrated control mechanisms could greatly improve agricultural production standards in quantity and quality and improves healthy living conditions.
Additional sources	www.rodentgreen.com

Intervention:	I 8-6: Precision use of chemicals: chemigation
Application	• Irrigated areas • Rainfed areas • Spate irrigated areas
Contributes to:	• Improved crop production (B or Y) • Improved water productivity (WP(ET))
Description:	Chemigation is a technique developed over the last three decades that consists of incorporating any chemical (e.g., fungicide, insecticide, herbicide, fertilizer, soil and water amendments) into the irrigation water. Chemigation allows for a more precise application of agro-chemicals, thus reducing energy use (fewer chemicals, less tractor movements) and increasing yields (Burt, 2003). A chemigation system typically includes an irrigation pumping station, a chemical injection pump, a reservoir for the chemical, metering and monitoring devices, a backflow prevention system and safety equipment. Progress in equipment technology leads to increased precision and effectiveness. The latest chemigation systems are designed to work with different chemicals simultaneously. The chemical's distribution uniformity is related to irrigation uniformity, which is dependent on a number of factors (i.e., wind, pressure differences in the emitting lines, clogging of emitters, unlevelled soils and soil infiltration rate).

References:	Burt, C.M. (2003). Chemigation and Fertigation Basics for California. http://www.itrc.org/reports/pdf/chemigationbasics.pdf
Additional sources	Borgia, C., Evers, J., Kool, M., & van Steenbergen, F. (2014). Co-Optimizing Solutions: Water and Energy for food, feed and fiber. World Business Council for Sustainable Development.