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Field guide to improve crop water productivity in small-scale agriculture

The case of Burkina Faso, Morocco and Uganda

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Preface

By 2050, the worlds' population will reach 9.1 billion, which requires an increase of food production by 70 percent compared to 2005 (FAO, 2018). Nearly all the increase will occur in developing countries, where agriculture plays a major role to provide employment, income and to improve food security. One of the major challenges of increasing food supply is the limited water resources. Agriculture, as the largest driver of freshwater exploitation has, therefore, to be transformed into more resource efficient production (FAO, 2003).

Small-scale agriculture has been gaining importance in agriculture-drive development. Smallholders in Asia and Sub-Saharan Africa cultivate 80 percent of farmlands. Despite their dominance in the landscape, smallholders are still greatly exposed to poverty and hunger (Lipton, 2005). The need to enhance their agricultural production is an increasingly pressing issue, not only to raise their income and household food supply, but also to contribute to overall food security and poverty alleviation (FAO et al., 2019). However, small-scale agriculture development remains a challenge due to the multiple factors that must be taken into consideration, such as, the high diversity of small-scale schemes, the social disharmony over distributional issues, the varying water demands of multi-cropping systems and the heterogeneity of equipment used.

The world's limited freshwater resources are potentially threatened by the expansion of agriculture. Agriculture shares around 80 percent of the total water withdrawal in the developing world (AQUASTAT, 2019). Increasing the potential output per amount of water used is an appropriate practice to improve production efficiency while protecting water resources. Water productivity can be considered an effective strategy to tackle both water and food security concerns. Therefore, increasing the productivity of agricultural water use in a sustainable manner is essential to ultimately sustain the social and economic conditions of livelihoods. When shifting from rain-fed to irrigated farming systems, there are numerous pathways to increase water productivity along this continuum such as soil water conservation through zero or minimum tillage; supplemental irrigation; soil fertility maintenance; deficit irrigation; small-scale affordable management practices for water storage, delivery and application. Shifting to advanced irrigation technologies such as pressurized systems, however, has been the primary avenue for efficiency and productivity improvements. In all of the indicated systems, irrigation plays a crucial role in enhancing productivity and building resilience to climate change (Moyo et al, 2017).

Crop water productivity has grown into one of the major approaches to cope with water scarcity and advance crop-water relation. The number of conceptual frameworks and implication is ample, but there is always a growing need to review the step-by-step approach beyond. In this Field guide, practical pathways are presented to provide a comprehensive approach for assessing and improving crop water productivity in small-scale agriculture.

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Acronyms

AIW	Applied irrigation water	**G**	Soil heat flux
B	Biomass	**GDP**	Gross Domestic Product
B	Boron	**h**	Water height
Ca	Calcium	**Ha**	hectare
CAN	Calcium ammonium nitrate	**HI**	Harvest index
CCx	maximum canopy cover	**HIo**	Reference harvest index
CWP	Crop Water Productivity	**Ic**	intake characteristics of soil
CWR	Crop water requirement	**INI**	Initial Development phase
D	Average depth	**K**	Potassium
DAP	Diammonphosphat	**K2O**	Potassium oxide
DEV	Development phase	**Kc**	Crop coefficient
DI	Deficit irrigation	**Kr**	Empirical coefficient
DU	distribution efficiency	**L**	length of furrow
ea	Application efficiency	**LAT**	Late development phase
ERD	Effective rooting depth	**Mg**	Magnesium
ET	Evapotranspiration	**MH**	middle height
ETc	Crop evapotranspiration	**MID**	Mid-development phase
ETo	Reference evapotranspiration	**Mn**	Manganese
Fa	furrow or basin form	**n**	number
FAO	Food and Agriculture Organization	**N**	Nitrogen
Fe	Iron	**NaCl**	Sodium Chloride

P	Phosphorus
P2O5	Phosphorus pentoxide
pH	potential of Hydrogen
Q	discharge
ra	aerodynamic resistance
RD	Rood depth
RDI	Regulated deficit irrigation
RHmean	Mean relative humidity
Rn	Net radiation
Rs	Solar or shortwate radiation
rs	surface resistance
So	slope
S	Sulphur
SDI	Sustained deficit irrigation
SMD	Soil moisture deficit
SWC	Soil water content
t	time
TAW	Water holding capacity
Tdew	Dewpoint temperature
Tdry	Temperature of dry bulb
Tmax	Maximum air temperature
Tmin	Minimum air temperature
Tr	Crop transpiration
Twet	Temperature of wet bulb
Wd	Dry weight
WP	Water Productivity
Wspeed	Wind speed
WUA	Water User Association
Ww	Wet weight
Y	Yield
Ya	Attainable yield
Yp	Potential yield
Zav	Average Infiltrated depth
Ziq	low quarter of the field
Zn	Zink
Zr	Root zone storage
ΣTr	Cumulative amount of crop transpiration
p_a	mean air density
c_p	specific heat of the air
r_s	surface resistance
r_a	aerodynamic resistance
n	roughness coefficient
q_{jn}	inflow rate per unit

Introduction

Water productivity (WP) is influenced by many factors, therefore tackling the shortcoming needs careful review of the local conditions. In every case, the recommendations on WP must take the environmental, agronomic and socio-economic factors into consideration to be feasible and affordable for farmers. In most developing countries, farmers do not exploit all of the potential benefits of irrigation, thus, there are many opportunities to improve on-farm WP, since it is well below the attainable levels for the majority of crops. Many pathways for WP improvement are directly related to improving overall farm management (irrigation, fertilization, plant density, crop protection, etc.). However, there are also a number of factors outside the farm that have a strong influence in the WP. Such factor can be the irrigation design failures, insufficient storage pool, insufficient capacity for water re-use, climatic events, etc. (Bouman, 2007). This complexity of improving WP aspires the writing of this Field guide in a way to present a methodology and a process to enable farmers not only to understand but also to establish and update their own practices.

Water productivity per crops, called crop water productivity (CWP), is defined as amount of product over applied water amount. Usually, farmers are driven by enhancing the profitability of farming or improving the household food security, while paying less attention to water productivity (FAO, 1998). Nevertheless, the CWP measures introduced in the Field guide also contribute to land productivity, thereby increasing farming revenues through its effect on input management. The range of methods applied for water productivity changes can be conducted at different scales or levels such as plant, field, scheme, and catchment level, according to the objectives of the improvement. Besides, it can originate from various sources such as technical, technological, socio-economic, etc. The Field guide focuses on technical measures to improve CWP at field level, holding evidence of cost-efficiency and feasibility.

This Field guide differs from ordinary farmers' guidelines as it is based on locally conducted research and field experience. The Guide draws from field visits, protocol-driven data collection and analysis of production practices in three countries, Burkina Faso, Morocco and Uganda within the framework of FAO-conducted project "Strengthening Agricultural Water Efficiency and Productivity at the African and Global Level". In each country, WP experiments took place by ground-truth data collection, analysis and simulation, and validation by demonstration. The work involved national and international research institutes in order to obtain proper data and justify the recommendations by local experts. The recommendations – so called "CWP measures" – are geared towards helping farmers to improve their practices in the hope of increased water productivity. While the Guide provides a step-by-step approach to improve CWP and reach optimal irrigation and agronomic practices in each irrigation scheme, the successful outcome often depends on the farmers' willingness to embrace and adopt the recommended measures.

Smallholder agriculture and development issues in small-scale irrigation

Agriculture shares a large take in employment, and benefits of agriculture are particularly significant in low-income countries. In 2017, this sector employed 68 percent of total labour forces and accounted for 26 percent of GDP in low-income countries (FAO, 2108). However, despite its ample contribution to rural livelihood, small-scale farming face a growing challenges (Molden et al, 2007; Grassini et al, 2011; Ittersum et al, 2013).

Resource scarcity does not only refer to financial background, but also to the scarcity of natural resources. Land and water resources, in particular, have become scarcer and their sustainable management requires great attention. Since a large part of smallholders in developing countries are still living in poverty, costly development strategies are not always appropriate. While productivity growth is required to combat poverty and eradicate food insecurity, it might not be feasible to overcome the natural resource constraints. Alternative strategies are needed to generate such productivity: improved availability, distribution and sustainability of land and water resources, better crop varieties and facilitated access to other agricultural inputs, and improved land and water management practices, amongst other.

Infrastructure in small-scale agriculture is often underdeveloped or simply too poor to provide efficient water delivery services. Moreover, irrigation equipment is fixed and it does not allow much flexibility in the control of water distribution, while small-scale schemes gather large number of water users and any infrastructural development needs to achieve harmonized and equal benefits for every user. The difficulty of fulfilling all the needs often hinders the development programmes and leaves the schemes without the necessary investment.

Reaching *economic threshold* for the minimum subsistence is often difficult for small-scale farmers even through consistent increases in staple food productivity and smallholders have limited facilities to keep pace with the required productivity growth. Increased yields, for instance, require mechanization, an extended number of temporal employees and stable input markets. On the other side, staple crops are often sold at government-boosted prices or local markets that are too fragile to uptake the increased quantity. Furthermore, smallholders' plots are often too small to produce enough for the minimum poverty threshold, thus undermining the feasibility of the investment in agriculture and irrigation.

Heterogeneity of crop production is more significant in small-scale agriculture since farmers tend to diversify more and have more constraints in managing production inputs. Compared to large-scale production, the temporal and spatial patchwork of crops requires more flexible infrastructure and management to respond to the diverse crop requirements. This restrictive condition is one of the major constraints of irrigation development. Crop water demand varies greatly within the farm and the scheme, thus requiring flexible water services in terms of distribution, flow rate and flow control.

Preconditions such as human expertise, access to information and data, technological background, physical and economic access to markets and knowledge sharing are more difficult to establish. Farmers often have their own ways of farming in terms of agricultural and irrigation practices, land management, purchasing inputs and acquiring information. This results in an absence of general good practices that can instead be drawn from practical experience and theoretical learning.

The development of small-scale irrigation and smallholders' production is of paramount importance, but also limited by many factors. There is no 'one-size-fits-all' approach in developing improvement programmes, each implementation must be customized. In order to address the majority of the constraining factors, complex improvement programmes are required to address the above-mentioned challenges. Further issue of smallholders' programmes in developing countries is the data-scarce environment. In lack of solid database, definition of improvement framework might be inappropriate. Programme planning therefore evolves through the following steps: inception and mapping exercise, data acquisition and process, framework planning, pilot/demonstration phase formulation, scaling out and scaling up. In addition, improvement programmes must be designed in comprehensive manner taken into account the social, economic and environmental circumstances. Therefore, the Guide provides insight into the planning phases of the countries with different conditions through case studies.

The piloting involved three irrigation schemes in three countries: Ben Nafa Kacha in Burkina Faso, R3 Sector-Al Haouz in Morocco and Mubuku in Uganda. The three schemes present different types of open-canal irrigation systems with different conditions related to climate, practice and other agronomic indicators. Ben Nafa Kacha and Mubuku schemes apply two methods of surface irrigation: basin and furrow irrigation in traditional system; while in R3 Sector of Al Haouz, drip irrigation is applied. The Field guide discusses the options to improve CWP by analysing the main crops of the schemes' patterns and provides recommendations on optimal practices accordingly. The applied approach can be scaled-out only by considering their conditionality such as climate, soil, cropping patterns, equipment availability, input access and water availability.

Burkina Faso

Ben Nafa Kacha irrigation scheme is located in Sourou Valley, north-western part of Burkina Faso. The small-scale irrigation scheme occupies an area of 275 hectares, cultivated by 247 farmers. Agriculture is the only sector providing work and income for the rural population in the area. Close to the border with Mali, the farmers' only opportunity to support their families is to split the production partly to commercial purposes and to subsistence. Thanks to the availability of water resources that provide good conditions for irrigated agriculture, the region became one of the country's strategic area for agricultural production.

Morocco

R3 Sector-Al Haouz Irrigation Scheme in Marrakech-Safi region is of great importance in agricultural production. Due to growing population rates, agriculture became a strategic sector to absorb rural workers and generate income in the region. Nevertheless, the semi-arid basin is already overexploited, although water is at the core of further socio-economic development. Other sectors compete for water resources such as urban growth, industrial activities and tourism, thus requiring frequent reallocation according to varying water demands. In addition, Al Haouz is one of the country's most complex sites in terms of hydraulic network due to its continuous restructuring and development.

Uganda

Mubuku Irrigation Scheme in Kasese is promoted as a national high priority area due to its excellent climatic conditions for agriculture. The scheme was established as part of a governmental programme to promote productive use of the water resources. As the country's water potential remains largely unexploited, establishing small-scale irrigation schemes is a strategic pathway to decrease national food insecurity, while at the same time creating workplaces for rural population and reducing the import dependency. The scheme consists of 540 hectares of agricultural land cultivated by 167 farmers, of which an investigated Phase II consists of 254 hectare total area shared between 56 farmers.

What is crop water productivity?

In general terms, Water productivity per crops, called crop water productivity (CWP) refers to the agricultural production per unit volume of water. Many CWP analyses performed in different agricultural systems demonstrated that there are a number of factors, outside water, with a strong influence in determining the CWP. Looking at the numerator of CWP, yield is the result of genotype / environment / management, and therefore all components of these factors can indirectly affect CWP. Choice of cultivar, type of season, and the many agronomic management factors that affect crop production, influence yields and must be taken into consideration to achieve high CWP. Regarding the denominator, the environment (evaporative demand) is crucial in determining water use, which can also be partially managed by varying planting date and cultivar maturity. Additionally, changes in water delivery and irrigation system performance can contribute to high CWP and it has been shown how certain agronomic measures, such as adequate mineral fertilization, planting density and date, and crop protection measures are of paramount importance in optimizing CWP. It is, therefore, necessary to explore both engineering and agronomic measures besides the management of irrigation water to achieve optimal CWP in each situation.

The focus area of CWP measures are the following:

- Protocol of data collection and appraisal of farm practice;
- Estimation of crop water requirement per main crops based on analysis;
- Irrigation water monitoring and quantification at farm level;
- Creating optimal production practices for CWP.

Why to embrace crop water productivity?

Although it is widely agreed that water scarcity has been the main driver to develop the concept of CWP, its application is recommended even in areas that do not suffer from scarcity. The objectives of improving CWP can fall into the following categories (FAO, 1995):

- Combating water scarcity.
- Food security and nutritional diet.
- Employment increase in rural areas.
- Equity between water users.
- Environmental protection and water resource conservation.
- Water quality improvement.
- Productivity and profitability gains.

The scale of implementing CWP measures can be at plant, field, scheme and catchment level (Bastiaanssen and Steduto, 2016):

Enhancing CWP at plant level mainly considers the breeding technology including seedling vigour, increasing rooting depth or harvest index, and photosynthetic efficiency. Development of appropriate growing cycle while matching the expected water supply to requirement is one of the most significant improvement of water productivity at plant level. Breeding technology can also contribute to building resilience to climate change at field level such as improving drought avoidance by deeper root zones.

Enhancing CWP at field level requires improved practices in crop, soil and water management while bearing in evidence their interconnection. Practices to improve CWP can be numerous such as crop and cultivar selection, plant density, crop protection, nutrient management, tillage, land restoration, set-aside, irrigation scheduling, soil wetting etc. In addition, a relevant number of external factors exist that have a strong influence in CWP and in farmers' livelihoods. When farmers introduce new practices, they must be aware of the impact on other associated practices. Similarly, changing irrigation practices and applying new irrigation methods may affect both the runoff and evaporative losses. Therefore, improving CWP at field level requires a comprehensive approach, whereby farmers are the direct agents at field level. The present Field guide sets scope mainly on measures, which can be carried out at field level.

Enhancing CWP at scheme level rather concerns distributional issues. As small-scale irrigation schemes are often characterized by multi-cropping, crop water requirement varies in time and location. Equal distribution amongst farmers, while meeting the defined water demand, may help to ensure the match between water supply and demand. However, scheme management is responsible for the distribution, while farmers have a restricted room to contribute to the enhancement of CWP at scheme level.

Enhancing CWP at catchment level entails new scopes such as environmental and hydro-diplomacy issues. Interventions such as better land-use planning, data interpretation, trade-off between competing sectors may be effective tools to bring CWP at large-scale. However, improvement at catchment level does not necessarily results in production increase. Decision-makers are usually responsible for such complex interventions; therefore, the Field guide does not discuss improvement at catchment level.

From water productivity to crop water productivity

According to FAO, productivity is the ratio between a unit of output and input (FAO, 1998):

- output (numerator) is the amount or value of product.
- input (denominator) is the volume or value of water consumed (ET) or used.

There is no unique definition of WP, however many approaches have been elaborated and put in practice depending on the development objective. Nutritional water productivity, for instance, is becoming a key indicator of food security, while the 'jobs per drop' approach expresses the contribution of agricultural water use to employment. However, the current Field guide applies the most common 'crop per drop' approach referring to the amount of product, expressed as yield (kg/ha), per unit of water used or consumed (mm).

Key principles of improving WP are the following (FAO, 2012):

- Increasing marketable yield of crop per unit of water transpired.
- Reducing outflows and water losses, including the evaporation other than the crop stomatal transpiration.
- Increasing effective use of rainfall, stored water and water re-use.

The principles apply to all scale, from field to scheme and catchment. However, the methods of improving WP vary according to the selected scale. The current guidebook captures the field level, which requires a more restricted scope of WP: crop water productivity.

Crop water production is governed by transpiration. It is difficult to separate transpiration from evaporation though; therefore, evapotranspiration (ET) is used to calculate the amount of water consumed. Depending on the area, some correction should be considered to obtain accurate data. Leaching requirement in saline areas, for instance, must be always calculated as productive water amount, as well as evapotranspiration of cover crops, which are necessary to maintain soil fertility. One can define CWP as the ratio of yield to either water consumed (ET) or to water used. In the second case, water used by the crop includes Applied Irrigation Water (AIW) and the total rainfall. If the focus is on the use of irrigation water, it is not necessary to include the rainfall in the computation of CWP. However, it is crucial to define clearly the two components of CWP in each case. For the current Field guide, and since it was not possible to measure the amount of water actually consumed by the crops (ET), CWP was defined as the ratio of yield to AIW.

The underlying causes of low CWP can be numerous, and elaborating strategies for improvement requires a solid knowledge of local conditions including climatic and soil conditions, crop and irrigation management, input and seed supply, etc. Therefore, no universal solution exists, equally valid for all farms. The Field guide keeps this condition in evidence, and instead of providing only results, it guides through the analysis. While enabling the replication of the approach, it provides single country cases to better understand its implementation.

The framework behind

In light of the foregoing and under the framework of the project 'Strengthening Agricultural Water Efficiency and Productivity on the African and Global Level', the following methodological approach was followed to identify and implement optimal farming practices in order to demonstrate pathways to increase crop water productivity. The methodological approach was designed to perform the following steps:

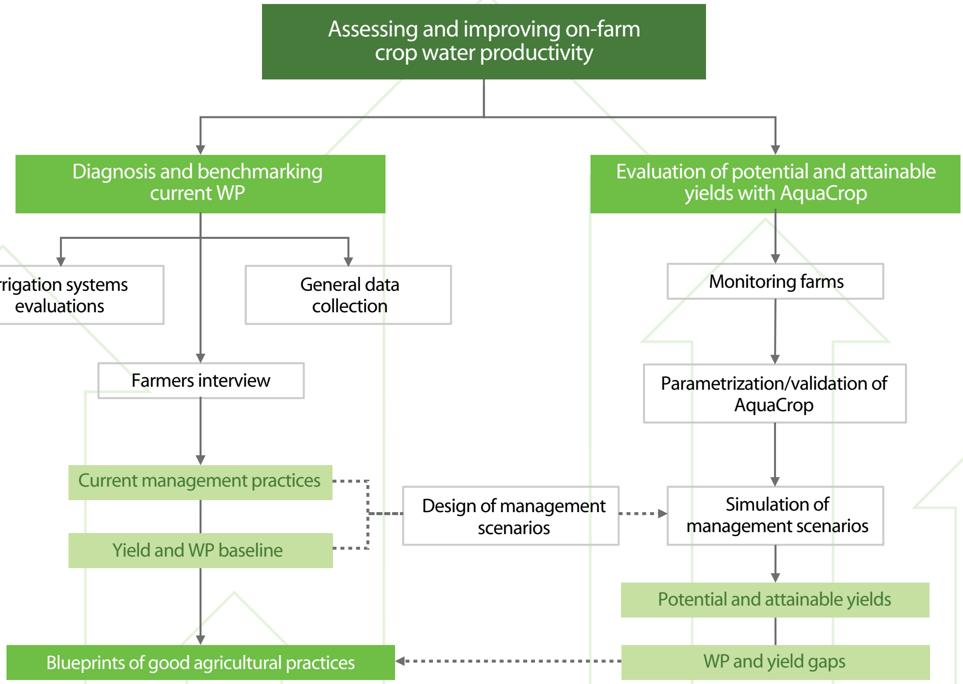
- Diagnosis and benchmarking of current agricultural productivity levels and of farming practices at farm level for major crops.
- Evaluation of potential and attainable yields with AquaCrop - field calibration of the FAO AquaCrop simulation model.
- Identification and delineation of optimal farming practices to improve the crop water productivity.
- Implementation of optimal farming practices in order to demonstrate their impact on the crop water productivity.

The schematized methodological approach creates synthesis between results acquired by locally conducted research and scientific approach.

1. Diagnosis and benchmarking of current crop water productivity

Diagnosing current agricultural productivity levels and identifying the limiting causes and the possible pathways to increase WP are the first steps for establishing the analysis. Water productivity is an outcome of how farmers manage their irrigation systems and of their agronomic practices on

Figure 1: Steps of performing crop water productivity analysis



Source: Elaboration of University of Cordoba

a day to day basis. Thus, a clear understanding of the detailed farmer practices is surveyed through: i) current conditions of farmers; ii) achievable conditions of farmers; and, iii) bridging the gap between current and desired conditions. Analyses of agricultural productivity levels and irrigation practices over irrigation schemes must be carried out. Instead of generalized datasets, observation of an entire season helps understanding the underlying issues of deficiencies.

Since farmers have different practices, productivity might vary considerably across the scheme. Differing performances among farmers in a scheme may be the first sign of different water management practices. Therefore, it is necessary to investigate the differences and establish cause-effect relationships. Based on a previous general data collection, farmers' interviews should be carried out to obtain detailed information on the agricultural productivity levels and farmers' specific management and constraints. This detailed data acquisition at farm level is completed to evaluate the performance of irrigation systems at farm level. Following the analysis of all collected data, the WP baseline and the current irrigation practices can be established; and a blueprint of good agricultural practices for the main crops can be produced while taking into account the socio-economic and technical level conditions.

Figure 2: Interview with farmers in Mubuku, Uganda

Table 1: Step-by-step implementation of diagnosis and benchmarking of CWP in pilot schemes

Step-by-step implementation in the project	
General data collection	For the diagnosis of the current productivity levels and the identification of limiting causes, it was necessary to collect the available general data about the selected irrigation schemes. Accordingly, a literature search of past work in the areas was carried out to identify the available information on soil and climate, water resources, cropping patterns, agronomic practices, main research centres and institutions, and relevant projects undertaken in the areas. The information found was verified by local stakeholders and information gaps were identified. Furthermore, and for a precise identification of the key information to be collected, discussion groups with main stakeholders were carried out in order to identify the major constrains and factors influencing CWP.

Farmers' interviews	Due to the need for a more detailed assessment beyond the general data collection, and given the lack of information about the irrigation and agronomic practices at farm level, it was necessary to conduct farmers' interviews in the irrigation schemes. The main objective of these interviews was to document current agricultural production levels and to describe on-farm irrigation and agronomic practices. The interviews were focused on water issues as well as on other production factors, in order to identify possible factors limiting production (pests, socio-economic issues, etc.), thus opening all avenues for improving WP. The inter-annual variability of management practices and production was also addressed through the interviews, and documented the strategies that farmers follow under different situations (e.g. water scarcity). These interviews also aimed at assessing farmers' perceptions of problems, threats, and risks, and how they approach their solution, since an important part of the work needed to identify the most desirable (and locally acceptable) pathways for increasing WP in the area.
Irrigation systems evaluations	The data acquisition for the diagnosis and benchmarking of current CWP was complemented with a number of irrigation system evaluations to assess the performance of the irrigation systems at farm level. Depending on the irrigation system (furrow, border, drip irrigation), different action protocols were established to obtain the performance indicators needed for the assessments.
Establishment of WP baseline and current practices	For the completion of the diagnosis and benchmarking phase, i.e. the evaluation of potential and attainable yields with AquaCrop, the data collected were processed and analysed. Once AquaCrop was parametrized, the model performance was evaluated by comparing the simulated results against the measured data for each crop (validation process). Afterwards, potential and attainable yields under different management scenarios were simulated. The yield and productivity gaps were also estimated, identifying the possible causes to reduce them in each case. As a previous step to the design of agricultural practices guidelines, the possible causes of the yield and productivity gaps were structured around the three major dimensions that directly affect them: irrigation water supply; irrigation management at farm level; and on-farm agricultural practices.
Generation of blueprints of good agricultural practices, and design of good agricultural practices	The analysis of the data generated in the monitoring fields linked to the diagnostic activities performed in the previous phase was carried out to generate the relevant information needed to design local guidelines on good agricultural practices. The guidelines were adjusted for the crops selected in each irrigation scheme, considering specific management practices on land preparation, sowing and plant density, fertilization, weed management, and pest and disease control. For the completion of the diagnosis and benchmarking phase, i.e. the evaluation of potential and attainable yields with AquaCrop, the data collected were processed and analysed. Once AquaCrop was parametrized, the model performance was evaluated by comparing the simulated results against the measured data for a crop in a particular case. This step is called model validation. Next, potential and attainable yields under different management scenarios were simulated. The yield and productivity gaps were also estimated, identifying the possible causes to reduce them in each case.

2. Evaluation of potential and attainable yields with AquaCrop model

The evaluation of potential and attainable yields with FAO AquaCrop model is the next step in the methodological approach. Crop models are useful tools to provide independent benchmarks for potential and attainable yields, encouraging sustainably increasing crop yields and productivity.

There is a broad range of models, from simple to more complex ones. The model accuracy and the requirements of parameters and inputs, which are not always available, are closely related. AquaCrop is a model of intermediate complexity that was developed by FAO to assess the yields of major herbaceous crops as a function of water supply[1]. Potential yield (Yp) is the yield of a cultivar growing under non-limiting nutrient- and water conditions; and with pests, diseases, and weeds effectively controlled. Yp for a specific cultivar only depends on the climatic conditions associated to location. Attainable yield (Ya) is defined as the maximum yield that may be achieved under optimum management, given the climatic and water supply constraints. AquaCrop model is used: i) to obtain an independent estimate of Yp and Ya (using long-series of weather data); ii) to identify the causes of gaps between yield levels (actual yields, Yp and Ya) and management options to reduce the gaps where feasible; and iii) to quantify the potential impact of implementing the proposed pathways for improving WP. Nevertheless, importance of local model parametrization and validation must be underpinned. Although AquaCrop is already calibrated for the main crops, some crop cultivars may require adjustment of parameters, in addition to phenology. In this regard, the parametrization and validation of the model should be done, employing data obtained from monitoring farms with different management practices. Data on weather, soil, crop development and management, applied irrigation water, final biomass and yield should be collected from the monitoring farms throughout the crop growing. Once the model is parametrized/validated, it can be used to assess the potential pathways for bridging yield and productivity gaps through the simulation of different management scenarios (Raes et al, 2012).

The tool behind

FAO-developed AquaCrop was applied as methodological background. AquaCrop is a crop growth model addressing environment and management issues on crop production. It simulates yield response of herbaceous crops to water, and it is particularly useful in water scarce conditions. AquaCrop is an effective tool for analysis and planning irrigation management. Amongst many applications, the following options were utilized in the project:

- Compared attainable to actual yields.
- Developed irrigation schedule for maximum production.
- Developed strategy to maximize water productivity.
- Supported decision-making on water allocation and policies.

The widely used AquaCrop is an open-source software that provides offline working mode for modelling. Its application is recommended for practitioners, extension services, organizations on agricultural development and farmer associations. Moreover, AquaCrop helps pooling the stakeholders together from farmers to decision-makers; while farmers play a crucial role in compiling reliable datasets under certain production conditions, scheme managers can draw

[1] Further explanation of AquaCrop model is provided in the next sub-chapter

optimal management practices from them. This iterative process contributes to develop production practices both at farm and at scheme level.

Another merit of AquaCrop is the systematic collection and review of production parameters. Since most of developing countries have to face data scarcity, AquaCrop helps establishing a comprehensive benchmark dataset based on potential production levels. Collected datasets are based on both observation and official statistics. The following groups of data need to be collected for the analysis:

- Climate data: minimum and maximum temperature, reference evapotranspiration (ETo), rainfall and CO2 concentration.
- Crop characteristics: plant density, crop development, green canopy cover evolution.
- Soil profile characteristics: soil survey and related maps.
- Groundwater table: salinity, depth below soil surface.
- Field management practices: soil fertility level and practices effecting water balance.
- Irrigation management practices: irrigation methods; application depth and time of irrigation events; salinity of the irrigation water.

Based on accurate datasets, the modelling goes through the following steps:

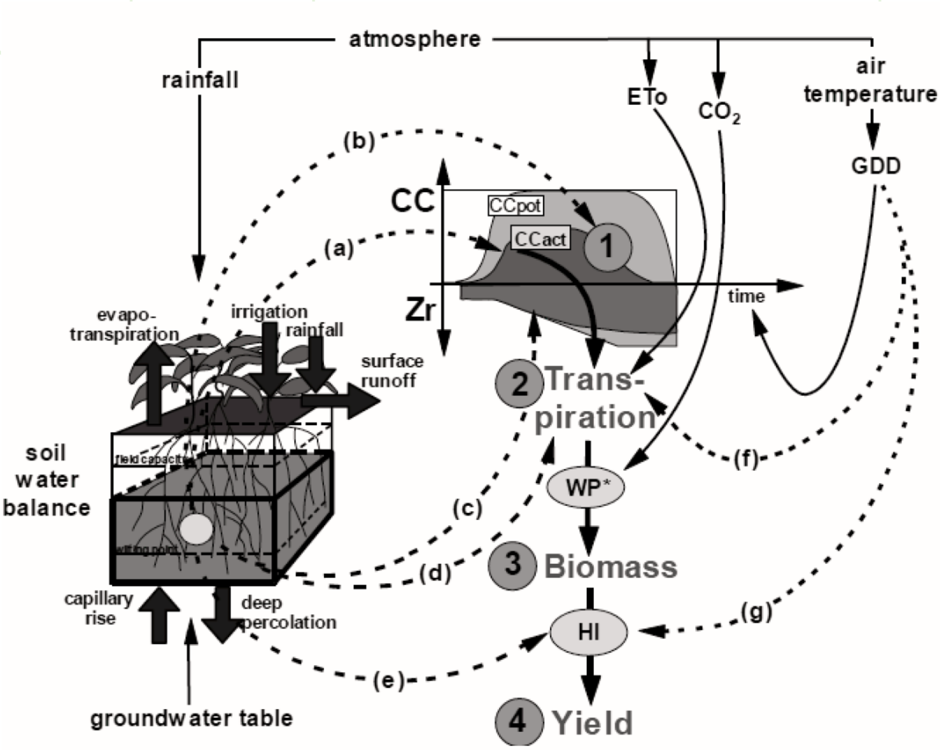
1. Measuring the development of green canopy cover: foliage is expressed through green canopy cover, which is the fraction of the soil surface covered by canopy. By adjusting the water content of soil profile, stress in root zone can be identified.
2. Crop transpiration: crop transpiration (Tr) is calculated from reference evapotranspiration (ETo) and crop coefficient (Kc). Kc is proportional to canopy cover, and it varies throughout the life cycle of the crop.
3. Above-ground biomass: the quantity of above-ground biomass (B) is proportional to the cumulative amount of crop transpiration (ΣTr). The conceptual equation of biomass production (B) separates transpiration from soil evaporation, while it applies water productivity normalized for climate:

$$B = WP * \sum\left(\frac{Tr_i}{ETo_i}\right)$$

4. Crop yield: the simulated biomass integrates all photosynthetic products assimilated by a crop during the season. Crop yield (Y) is obtained based on the harvestable fraction of above-ground biomass. The applied harvest index (HI) is obtained by adjusting the reference harvest index (HIo) with adjustment factor for stress effect.

The four steps of AquaCrop calculation scheme provide a transparent and easy-to-understand mechanism to simulate final crop yield (Figure 3). However, there are some limitations in the implementation. Amongst them, the assumption of a uniform field performance is the most difficult to overcome. Since small-scale irrigation schemes are often not uniformly managed due to the lack of technologies, significant difference can occur within a small plot. Seeding density, for instance, can differ across the plot due to manual application (Steduto et al, 2009).

Figure 3: Calculation scheme of AquaCrop with indication of the four steps



Source: FAO, 2015

AquaCrop differentiates between biomass water productivity and ET water productivity. While biomass WP refers to the biomass obtained by transpired water, ET water productivity is the relationship between crop yield and evapotranspiration. The following chapter provides interpretation about the currently applied definition.

Crop water productivity measures for improved irrigation practices

The Guide attempts to present a step-by-step approach for improved agricultural practices at small-scale derived from the pilot cases of Burkina Faso, Morocco and Uganda. However, the presented combinations of CWP measures are not universal as farms have commonly unique conditions with specific cropping patterns that can vary over time. The Field guide provides an integrated approach and presents the possible combinations of practices. The Guide sets scope on improving CWP at field level to provide solutions that actively involve farmers.

The Field guide is built on the following blocks:

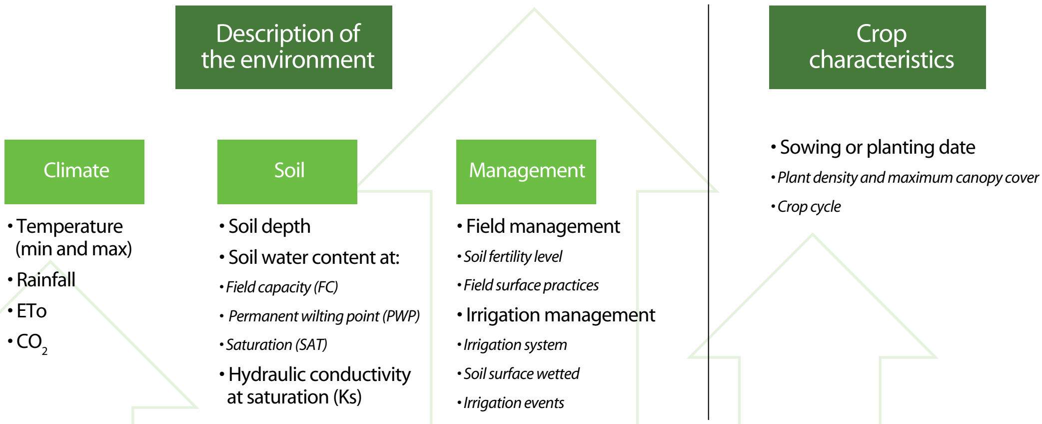
- Protocol of establishing case-specific diagnosis.
- Optimal practices to improve CWP: case studies.

The guide provides more than just an instruction material for practitioners. It offers a great potential for exchange of ideas among similar types of irrigation schemes and learning from others' experiences. Non-traditional learning of improving water-management is an iterative process where scheme managers are also invited.

Protocol of establishing case-specific diagnosis

The data collection protocol present the process of farm characterization to help the compilation of the necessary datasets to improve CWP. The AquaCrop calculation scheme categorizes data under four major groups: climate, crop, management and soil:

Figure 4: Input data of AquaCrop model



Source: FAO, 2019

While simulating attainable yields, AquaCrop considers canopy expansion, stomatal conductance, canopy senescence and harvest index as key indicators of water stress. The core of AquaCrop can be described with the following equations:

$$B = WP * \sum\left(\frac{Tr_i}{ETo_i}\right)$$

and

$$Y = B * HI$$

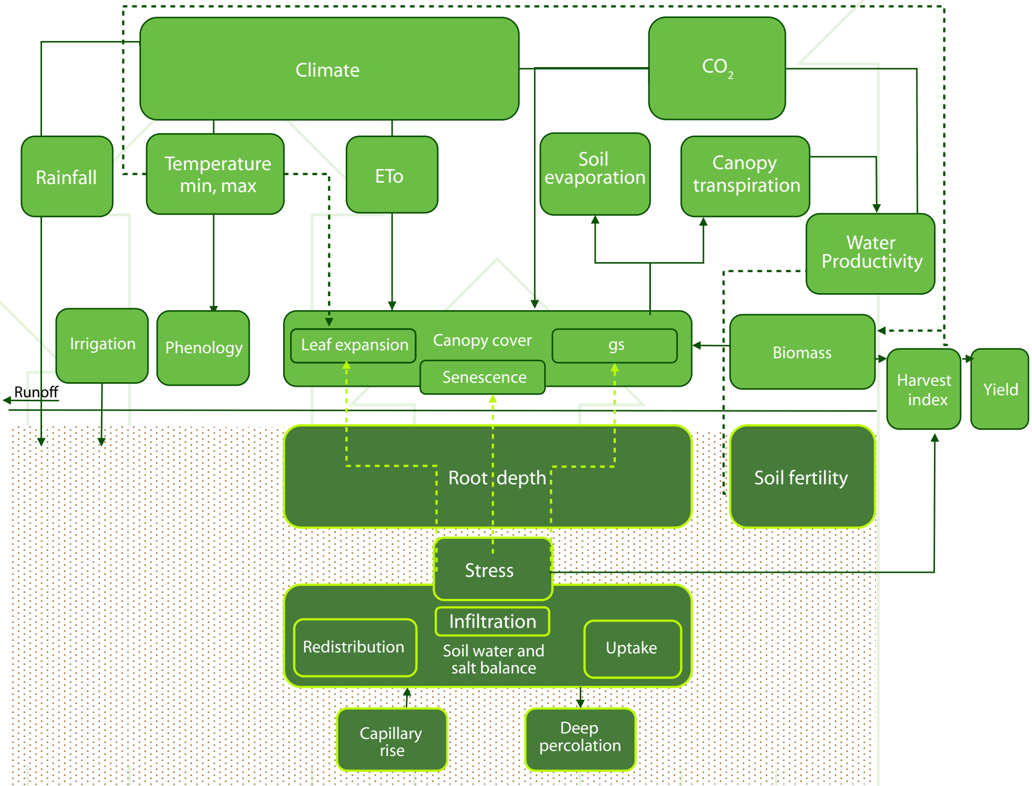
Where

WP is the water productivity in units of kg (biomass) m-2 (land area) mm-1 (water transpired), Y is the harvestable yield, B is the function of biomass, and HI is the harvest index.

The design of AquaCrop integrates the soil-plant-atmosphere continuum including soil, plant, atmosphere and management. Recording different management strategies while collecting data is particularly important because changes in fertilizing, mulching and other practices related to water can significantly affect the soil water balance, crop growth and development. The model, adapted from Steduto et al., can be described as following (Steduto et al, 2009):

Atmosphere refers to the climate component of AquaCrop. Calculation requires the data summarized in collection protocol: daily maximum and minimum temperature, daily rainfall, ETo and mean annual carbon dioxide concentration. Rainfall and ETo are inputs for water balance of the soil root zone, CO2 influences the canopy growth.

Figure 5: Calculation scheme of AquaCrop



Source: FAO, 2018

The crop has five major in-built parameters: phenology, canopy cover, root depth, biomass production and harvestable yield. The canopy cover expands, maintains and senesces depending on the rooting system, flowering, accumulation of above-ground biomass. Canopy cover directly reacts to water stress. The approach of calculating canopy cover instead of leaf area index distinguishes AquaCrop from other growth models. To simplify the simulation, changes in canopy can be inserted and the model will then convert them into a growth function. Green canopy is the basis to calculate transpiration and it is translated into proportional amount of biomass through normalized WP. Instead of traditional radiation-driven models, water-driven engine is applied in AquaCrop. After calculating the biomass (B), the yield is estimated through Harvest Index (HI). Reference HI must be provided for each crop as the harvestable portion of the biomass. The model enables the differentiation amongst varieties through the variation of timing and duration of development stages, differences in morphology, canopy size and growth, normalized WP and responses to different environmental factors (Raes, 2015).

The *transpiration*, as basis of the biomass production, is simulated separately from the soil evaporation and it is calculated as function from crop coefficient (Kc) adjusted for effects of stresses, canopy aging and senescence.

Water stress is one of the main functions of AquaCrop as it is constructed for the simulation of water-limited yields. AquaCrop has a novel approach that differentiates the effects of water deficit in three components: 1) reduction in expansion rate, 2) reduction in stomatal conductance, 3) acceleration of senescence. Water deficit is quantified in water stress coefficient (Ks) ranging on a scale from 0 (no stress) to 1 (full stress).

Soil-root system is entered into the simulation via effective rooting depth (ERD). ERD expresses the soil depth, in the cases where water uptake takes place. The ERD follows balancing approach involving infiltration, runoff, deep percolation, drainage, plan uptake, evaporation and transpiration.

Management practices distinguish field management and irrigation management options. The field management option includes the parametrization of soil fertility levels ranging from optimal to poor, field surface practices of mulching, soil bunds and time of forage cutting. The irrigation practices include two options: rain-fed and irrigation. Irrigation is further specified into application methods. One of the major strengths of the management modules is the option to input different scheduling methods or apply automatically generated schedule.

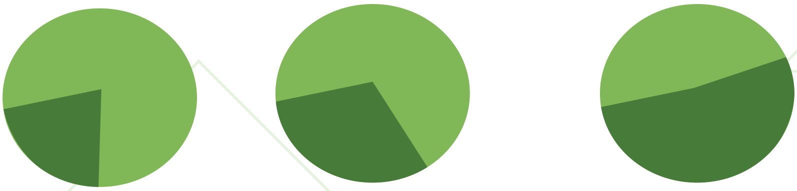
The simulation is performed according to the described steps. Although AquaCrop is already calibrated for the main crops, some crop cultivars may require further adjustments of parameters, in addition to phenology. In this regard, the parametrization and validation of the model were done with data obtained from monitoring farms with different management practices. This was particularly important for the local calibration of the fertility module of AquaCrop. Data on weather, soil, crop development and management, applied irrigation water, final biomass and yield should be collected from the monitoring farms throughout the crop growing season. Once the model is parametrized and validated, it can be used to assess the potential pathways for bridging yield and WP gaps through the simulation of different management scenarios.

In order to obtain sufficient data, the Guide provides further support through comprehensive data collection schemes. The following chapter consists of a stocktaking exercise to support data collection for water productivity analysis. Beyond AquaCrop, the designed data collection schemes are applicable to water productivity analysis based on other methods.

Protocol to obtain data for analysis

Improving CWP at farm level requires large amount of data. As most of the countries suffer from data scarcity, the Guide provides stocktaking exercise to support data collection. The set of surveys helps guiding through the necessary steps to establish sufficient background for analysis.

Figure 6: Chart flow of performing water productivity analysis



1. Selection and setup of monitoring farms

- Selection of monitoring farms
- Assignment of the management practices to each monitoring field
- Elaboration of the agronomic management guides

2. Climate data collection and processing

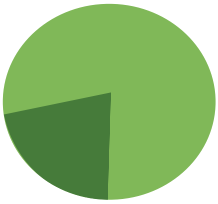
- Climate data collection
- Processing climate data

3. On-farm data collection and processing

- Design of protocols
- Validation of protocols with local stakeholders
- Soil sampling and analysis
- Crop data collection: crop development, canopy cover evolution and final biomass and yield
- Recording of applied irrigation water
- Processing of all data collected

The protocol covers three steps of evaluating potential and attainable yields with AquaCrop model: 1) Selection and setup of monitoring farms, 2) Climate data collection and processing, 3) On-farm data collection and processing. It is self-explanatory; however, additional information and references are inserted wherever collected data should be processed.

Selection and setup of monitoring farms



- Selection of monitoring farms
- Assignment of the management practices to each monitoring field
- Elaboration of the agronomic management guides

Crop Water Productivity analysis: Farmers interview for background data *to be completed by interviewing farmers Date: ……………………………………………………………….. Name:………………………………………………………………			
1. Farmer information			
1.1. Gender:	Male	Female	
1.2. Age:	Below 30	30-50	Above 50
1.3. When did you start farming?			
1.4. Total size of the land:			
1.5. Farm characteristics			
Field (crop)	*Field size (ha)*	*Soil characteristics*	*Crops/rotation*
1.			
2.			
3.			
1.6. What is your main crop and why that particular one?			
1.7. What has been your most consistent crop in terms of making a good profit?			

1.8. Level of education of household head:				
none	*primary*	*secondary*	*tertiary*	*university*
1.9. Is farming your only source of income? What percentage of your incomes comes from agriculture?				
1.10. How do you access agricultural markets?				
1.11. Do you have access to agricultural information? What type of information? Who provides it?				

2. Cropping practices		
2.1. What varieties do you grow and why?		
Crop	*Variety*	*Reason*
1.		
2.		
3.		

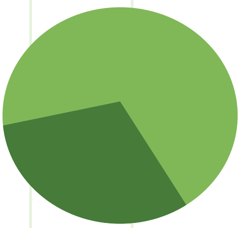
2.2. When do you sow each crop? When do you harvest? What is the row spacing? How many seeds do you use for sowing?			
Crop	*Sowing date*	*Harvest date*	*Plant density*
1.	*Month:* ☐ *At the beginning* ☐ *At mid* ☐ *At the end*	*Month:* ☐ *At the beginning* ☐ *At mid* ☐ *At the end*	*Plants/ha:* *or Row spacing (m):* *or Sowing rate (kg seeds/ha):*

2.	*Month:* □ *At the beginning* □ *At mid* □ *At the end*	*Month:* □ *At the beginning* □ *At mid* □ *At the end*	*Plants/ha:* *or Row spacing (m):* *or Sowing rate (kg seeds/ha):*
3.	*Month:* □ *At the beginning* □ *At mid* □ *At the end*	*Month:* □ *At the beginning* □ *At mid* □ *At the end*	*Plants/ha:* *or Row spacing (m):* *or Sowing rate (kg seeds/ha):*
2.3. Do you apply fertilization? Which crop? What type of fertilizer? What amount? When?			
Crop	*Fertilizer type*	*Amount (unit)*	*When*
1.			
2.			
3.			
2.4. Do you leave the crop residues in the field after harvest?			
2.5. How do you control weeds? Do you think weeds are affecting your production levels?			
2.6. What are the main pests and diseases? When have they appeared? Do you associate them with some factor? How do you control them?			
Crop	*Pest/Disease*	*Control method*	*Observations*
1.			
2.			
3.			

3. Production		
3.1. What is your production level (average, minimum and maximum) for each crop?		
Crop	*Production level*	*Comments*
	Average *Max.* *Min.*	

	Average *Max.* *Min.*	
	Average *Max.* *Min.*	
	Average *Max.* *Min.*	
3.2. In your opinion, what is the main constraint to reach higher production levels?		
Interviewer notes		

Climate data collection and processing



- Climate data collection
- Processing climate data

CLIMATIC STATION	
Name	
Code	
Longitude	*degrees, minutes, East or West*
Latitude	*degrees, minutes, North or South*

Altitude	*meters above sea level*										
Date	Temperature		Humidity					Wind	Solar radiation		
	Tmax **(°C)**	Tmin **(°C)**	RHmean (%)	Tdew **(°C)**	E (act) (kPa)	Tdry **(°C)**	Twet **(°C)**	Speed (m/s)	n (hour/ day)	Rs (MJ/ m^2.day)	Rn (MJ/ m^2.day)

Observation

Tmax (°C)	Maximum air temperature
Tmin (°C)	Minimum air temperature
RHmean (%)	Mean relative humidity
Tdew (°C)	Dewpoint temperature
e(act) (kPa)	Actual vapour pressure
Tdry (°C)	Temperature of dry bulb
Twet (°C)	Temperature of wet bulb
W. Speed (m/s)	Wind speed (x meters above soil surface)
n (hour/ day)	Actual duration of sunshine in a day
Rs (MJ/ m^2.day)	Solar or shortwave radiation
Rn (MJ/ m^2.day)	Net radiation

Climatic dataset is necessary to calculate the reference evapotranspiration (ETo) in order to compute the crop water requirement. The concept of evapotranspiration derives from two different types of water loss: evaporation from soil surface and transpiration from crop. The combination of the two determines the evapotranspiration rate (FAO, 1998).

Evaporation is the process when liquid water is converted into vapour and removed from surface. The degree of the vaporization depends on the difference between the water vapour pressure at evaporating surface and surrounding atmosphere. The climatic parameters determining the process are the solar radiation, air temperature, air humidity and wind speed. In case of soil surface, canopy cover and amount of available water at the surface are the influencing factors.

Transpiration is the vaporization of water contain of plant tissues and its removal to atmosphere. Vapour exchange with the atmosphere is through stomatal aperture. Similarly to evaporation, transpiration depends on energy supply, vapour pressure gradient and wind. However, transpiration is influenced by many other biological factors such as crop characteristics, environmental aspects, development state, and cultivation practices.

Evapotranspiration is the combination of evaporation and transpiration. At initial development stages, water is lost mostly through evaporation due to the lack of canopy cover. During the expansion of canopy, the soil gets shaded and transpiration becomes the driving water loss. In general, distinguishing evaporation and transpiration is difficult.

Evapotranspiration rate from reference surface determines the *reference evapotranspiration* (ETo). ET to a specific surface provides a reference against which ET from other surfaces can be measured. This enables the application at different location or season. ETo is computed from climatic parameters listed in the survey.

The widely-applied method to calculate ET_0 is constructed by Penman-Monteith. The Penman-Monteith form of the combination equation is:

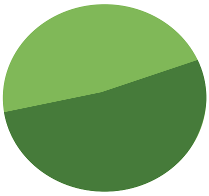
$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a c_\rho \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma(1 + \frac{r_s}{r_a})}$$

Where

R_n is the net radiation, G is the soil heat flux, $(e_s - e_a)$ represents the vapour pressure deficit of the air, p_a is the mean air density at constant pressure, c_a is the specific heat of the air, Δ represents the slope of the saturation vapour pressure temperature relationship, y is the psychrometric constant, r_s and r_a and are the (bulk) surface and aerodynamic resistances.

The FAO Penman-Monteith method overcomes the shortcoming of the Penman method and the need for local calibration of resistance factors when using the Penman-Monteith equation (Allen et al., 1998). To facilitate the estimation of ETo, FAO ETo Calculator has been embedded in AquaCrop. The program can handle daily, ten-daily and monthly climatic data. The data can be given in a wide variety of units and climatic parameters.

On-farm data collection and processing



- Design of protocols
- Validation of protocols with local stakeholders
- Soil sampling and analysis
- Crop data collection: crop development, canopy cover evolution and final biomass and yield
- Recording of applied irrigation water
- Processing of all data collected

1. Soil data	
Date	
Field code	
Area (m^2)	
Sub-sampling units	
Number of sub-samplings units (if applicable)	
Total number of sampling locations	
Number of sampling locations per sub-sampling units (if applicable): x // y // z	
Sampling depth (cm)	
Sampling depth interval (cm)	

Code	Sampling location	X UTM	Y UTM	Depth (cm)
1.				
2.				
3.				

Soil Water Content - SWC (*the table is complementary to the table of 1. General data)*

Code	Wet weight - Ww (g)	Dry weight - Wd (g)	Bulk density -ρd (g cm-3)	Gravimetric SWC θd (% wt)	Volumetric SW θw (% vol)
1.1				*=(Ww – Wd)/Wd*	= ρd**Gravimetric SWC*
1.2					
1.3					
2.1					

Figure 7: Infiltration test in Mubuku, Uganda

2. Crop data		
Field code		
Crop		
Planting method		
Plant density (plants/ m_2)		
Crop Development		
Planting/Sowing		
90% seedling emergence		
Maximum canopy cover (CCx)		
Start of flowering		
Duration of flowering		
Beginning of canopy senescence		

Physiological maturity						
Plant density (plants/ m2)						
Weeds, Pests and Diseases						
Name of incidence						
Date of onset						
Incidence rate						
Photo code						
Biomass yield						
Date						
Area (m^2)						
Spacing crop (m)						
Sampling size (m^2)						
Crop	Total fresh weight (g)	Fresh grain weight (g)	Total dry weight (g)	Dry grain weight (g)	HR grain (%)	
1.					*=(total dry weight – dry grain weight)/dry grain weight*	
2.						
3.						
MEAN						
Aboveground biomass (kg/ha)	*=mean of total dry weight/sampling size*10*					
Crop yield (kg/ha)	*=mean of dry grain weight/sampling size*10*					
Harvest index	*=crop yield/aboveground biomass*					

Many of the differences among crop cultivars are associated with the timing of developmental stages. Thus, for the cultivars used in the monitoring fields, the timing to reach a particular stage and/or its duration should be specified in AquaCrop. These stages are:

- Time to reach 90 percent seedling emergence
- Time to reach maximum canopy cover
- Time to the beginning of canopy senescence
- Time to the beginning of flowering (or the start of yield formation)
- Duration of flowering
- Time to physiological maturity

The parameters indicated above should be recorded throughout the growing season in all the monitoring fields.

3. Irrigation data			
When do you have irrigation water availability? Frequency?			
Please, describe your irrigation system			
Do you think that you apply irrigation water uniformly? If the answer is not, which do you consider the primary cause?			
Did you notice any runoff on your irrigated fields? In which crops? When?			
Please, describe the irrigation water management for each crop: Number of irrigations along the season and irrigation duration.			
Crop	*Month*	*No of irrigation per month*	*Irrigation duration*

How do you decide when to start irrigating, the frequency and the duration?
Under drought and/or water restrictions, what crops are your watering priorities?
In your opinion, what are the main difficulties in irrigation management?
Do you irrigate as efficiently as you think you could? How can you improve your irrigation management?
How can the government/irrigation scheme authorities/water agency assist growers to use more efficient irrigation practices?

4. Discharge monitoring		
Date		
Field code		
Area (m^2)		
Overflow depth (m)		
	Hour	Minute

Start time of irrigation						
Hour	Minutes	H_1(cm)	H^2(cm)	Q (m^3/s)	Volume (m^3)	Irrigation time (min)
Total volume (m^3)						
Water depth (m)						

Figure 8: Portable RBC flume to measure on-farm discharge

Measuring applied water requires season-long monitoring of irrigation. Although several devices are available to measure discharge in the irrigation system, on-farm irrigation requires separate equipment. However, this equipment is often expensive or not accessible directly for farmers, but a number of standardized process is available for discharge monitoring (Lorite et al, 2013). FAO-developed 'Field Guide to improve Water Use Efficiency in small-scale agriculture' provides several methodologies to obtain discharge data (Salman et al, 2019). Therefore, the current Guide does not include an in-depth discussion on discharge monitoring.

On-farm irrigation performance can be evaluated by two indicators: distribution uniformity and application efficiency (Brouwer, 2007; Saxton and Rawls, 2006). In case of surface irrigation, the following equation can be applied:

Distribution efficiency (DU) is defined as the ratio of the average infiltrated depth in the low quarter of the field (Z_{lq}) and to the average infiltrated depth (Z_{av}):

$$DU = 100\frac{\mathrm{ZIq}}{\mathrm{Zav}}$$

DU is a function influenced by many factors:

$$DU = f_j(q_{jn}, L, n, S_0, I_c, F_a, t_{co})$$

Where

q_{jn} is the inflow rate to the furrow or unit width of border or basin, L is the lengths of the furrow or border or basin, n is the roughness coefficient, S_o longitudinal slope of the field, I_c intake characteristics of the soil, F_a furrow or border of basin form, t_{co} time of cut-off.

The application efficiency ea is the ratio of the average depth added to the root zone storage (Zr) and the average depth applied (D) to the field:

$$e_a = 100\frac{\mathrm{Zr}}{\mathrm{D}}$$

$$e_a = f_2\,(q_\epsilon, L, n, S_0, I_c, F_a, t_{co}, SMD)$$

where

SMD is the soil moisture deficit.

The simulation process is considered data-demanding, but the presented protocol allows for flexibility by providing alternatives. The validation of the results needs to go through consultative process then. The simulated results are compared to the observations, the possible constraints of yield gaps are identified and good agricultural practices are established.

Enhancing Crop Water Productivity through improved practices: country cases

Drawing conclusions and lessons from the simulation output requires careful interpretation. Case study approach helps introducing the establishment of good practices and their implementation. Optimal agricultural practices were defined to enhance CWP in the pilot schemes through the following steps:

- Scheme characterization and compilation of comprehensive dataset.
- Parametrization and simulation through the AquaCrop model.
- Established good practices, monitoring of implementation and dissemination of results.

The country cases provide recommendations on agricultural practices while demonstrating the implementation of improvement strategies.

Based on the results of diagnosis, comparative analysis (using the FAO AquaCrop model) and demonstration actions in the irrigated area of the schemes, optimal practices were established with the aim of providing a comprehensive improvement strategy. The strategy considers the most aspect of agricultural production: resource efficiency, productivity, profitability. The introduced improvement strategy is piloted and proven to have a positive impact, not only on the WP of the crop, but also on agricultural production and water resources saving.

Optimal practices to enhance CWP in Ben Nafa Kacha, Burkina Faso

The development of irrigation in Burkina Faso is essential to strengthen food security and farmers' incomes. This is particularly the case in Sourou, where the majority of the population is employed in agriculture and household food security depends on agricultural productivity. However, the resource efficiency needs further improvement. In Ben Nafa Kacha, irrigation has multiple effects on farming outcomes. Firstly, water productivity should be increased in an area characterized by dry subtropical climate. Furthermore, irrigation has direct implication on the profitability since the system is supplied by large-capacity pumps. Withdrawing water through pumping is one of the considerable production costs; therefore enhancing water productivity is crucial. Many ways to improve WP are directly related to the management of irrigation at farm level. There is also a number of factors other than the water factor (fertilization, planting density, crop protection, etc.) that have a high influence on the WP and on the livelihoods of farmers.

Figure 9: Integrated management practices to improve Water Productivity

Source: FAO, 2019

The cropping pattern in Ben Nafa Kacha consists mainly of onion, maize and paddy rice irrigated by furrow or basin method. The agricultural production is distinguished into two seasons (humid and dry seasons), while there is only one irrigation campaign from October to April. Each farmer cultivates an average one hectare of land in multi-cropping system, and each farm is irrigated by one or two irrigation turns per week, except rice, where the filling of the basins lasts a month in October. The scheme applies only surface irrigation, namely furrow and basin irrigation.

Figure 10: Main canal of Ben Nafa Kacha, Burkina Faso

Table 2: Crop growth period of typical crops in Ben Nafa Kacha, Burkina Faso

DRY SEASON									
Crops	Length [Days]				RD [m]	MH [m]	Kc [-]		
	INI	DEV	MID	LAT			INI	MID	LAT
Paddy Rice	15	25	50	20	0.5	1.00	0.80	1.20	0.60
Onions	10	15	45	30	0.4	0.50	0.60	1.10	0.80
Green Beans	10	20	35	10	0.7*	0.40	0.60	1.10	0.90
Tomatoes	15	20	40	20	0.7*	0.60	0.40	1.20	0.80

HUMID SEASON										
Crops	Length [Days]					RD [m]	MH [m]	Kc [-]		
	NUR	INI	DEV	MID	LAT			INI	MID	LAT
Paddy Rice	15	15	25	55	20	0.5	1.00	0.80	1.20	0.60
Maize	-	15	30	55	30	0.7*	1.80	0.70	1.10	0.40

* Root depth limited by the soil depth (0.7 m)

Irrigation is managed by the local Water User Association (WUA) who is responsible for the operation and maintenance of the hydraulic structure, operation of the pumps and water distribution amongst secondary canals. According to the established discharge record, the average daily water supply is sufficient to meet the maximum crop water requirement. However, farmers often experience water shortages and waterlogging due to inadequate irrigation practices. Although the water supply is sufficient, water use efficiency and water distribution- application need to be further improved. The analysis identified temporal water oversupply in terms of duration and frequency of irrigation, while the applied water amount is not adjusted to the crop development stages. Water stress is also identified through the canopy development due to the difference between the water requirement per crop development stages and the fixed irrigation turns. Computed CWR indicates that paddy rice is the most water-demanding crop, while maize can be produced even under rainfed conditions.

Table 3: Crop water requirement in Ben Nafa Kacha, Burkina Faso

Crop	Sowing Period	Area [Ha]	CWR [m3]	CWR [m3/Ha]
Paddy Rice (humid season)	July	165	1 563 761	9 477
Onions	October	80	464 471	5 806
Paddy Rice (dry season)	February	165	1 622 446	9 833
Maize	May	110	298 630	2 715

Diagnosis

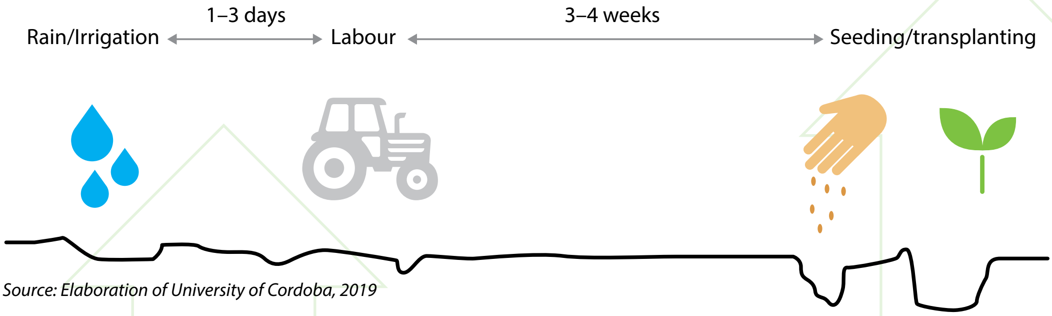
Preparation

Potential constraint: Insufficient seedbed

Proper seedbed preparation is essential for the proper establishment of the crop and, therefore, for optimal crop growth and development throughout the growing season, which has a significant impact on yield performance. Soil moisture condition is a critical factor in proper preparation of the seedbed.

Maize and onion

To ensure a good establishment of maize and onion cultiviation, the soil must be worked about three to four weeks before sowing/transplanting, allowing a partial decomposition of the organic matter. In addition, the preparation of seedling bed should be carried out one to three days after an irrigation/rain event, once the soil has been drained, which allows for a good soil moisture condition. Finally, the seeds/seedlings must be sown/planted in a thin, crumbled soil horizon, under which watered soil is consolidated.



Source: Elaboration of University of Cordoba, 2019

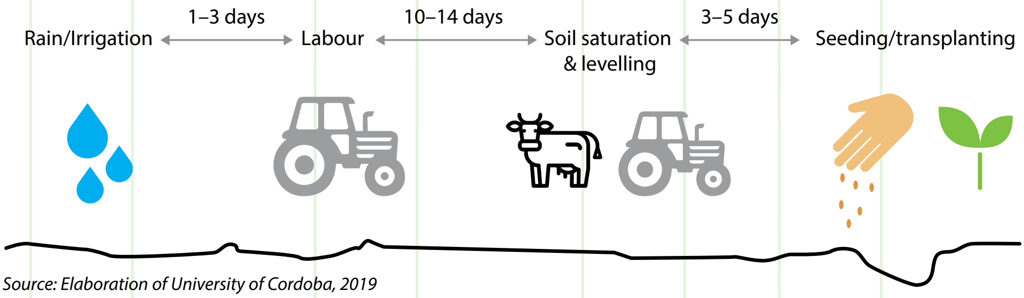
Rice

In the case of low land rice plantation, wet soil ploughing is particularly effective in clay soils and aims to develop a soil layer to reduce water loss by deep infiltration. Normally, a 15-20 cm ploughing is sufficient. Ideally, it is better to keep the soil dry for one to two weeks to allow the decomposition of the organic material. Mudding must be carried out shortly before transplanting followed by levelling. Flooding during at least three days is recommended to prevent weed growth, and to reduce fine soil and nutrient loss.

Potential constraint: Inappropriate seed rate

Complying with recommended seed rate is one of the most critical aspects of high yield. Planting more seeds than the optimal rate does not necessary increase yields, while reducing profitability. The following seed rate is recommended:

- Maize: 20–25 kg/ha
- Low-land rice: 40 kg/ha
- Onion: 4 kg/ha



Source: Elaboration of University of Cordoba, 2019

Potential constraint: Inadequate seed depth

Maize

One major factor defining plant success is seed depth. In order to ensure the development of a deep root system reaching sufficient water and nutrients, the planting depth of two to three cm is optimal for maize in medium-textured soils. The goal is to get the best possible settlement.

Potential constraint: Inappropriate transplanting date

Rice

For transplanting, the optimum age of the seedlings is between 15 and 21 days. The timing is crucial since the age of the transplanted plant greatly affects the forthcoming development stages (plant recovery, tillage, heading and yield).

Figure 11: Transplanting rice in Ben Nafa Kacha, Burkina Faso

Potential constraint: Poor quality of agricultural inputs

Appropriate and high-quality agricultural inputs should be used to improve plant production. Even if the quality inputs cost more, the investment return is guaranteed. Access to adequate inputs (seeds, fertilizers, pesticides, etc.) of good quality is currently facing limitations. A collective purchase through the cooperative or another local organization is recommended to improve access to input markets.

Management practices

Potential constraint: Rigid irrigation schedule

The irrigation supply must be adjusted to the water needs of the crop, which can be hardly achieved by rigid rotation. It is particularly important to respect the water demand at critical stages of crop development stages in case water supply is limited.

Seasonal rainfall covers almost all of the bulk water requirements of maize and partially of rice. Therefore, the current irrigation supply (discharge and duration) is sufficient to meet the water requirements of the crop. Irrigation is particularly important to ensure a timely supply during the flowering stages and grain-filling of both crops. However, during transplanting, the general criterion for irrigation is to maintain water level between 5 and 10 cm and to recover only the water losses. Currently, the design and equipment do not allow such water control in the fields.

The frequency and duration of irrigation water is more critical for onion production since onion is produced in the dry season and has a shallow root system. A weekly irrigation frequency is recommended, with two hours irrigation for a plot of 0.25 ha, and a discharge of 15 l/s. The rotation can be maintained throughout the production, although, the irrigation interval can be extended (e.g. 10 days) in the initial vegetative phase and in the final phase, when the bulb is mature.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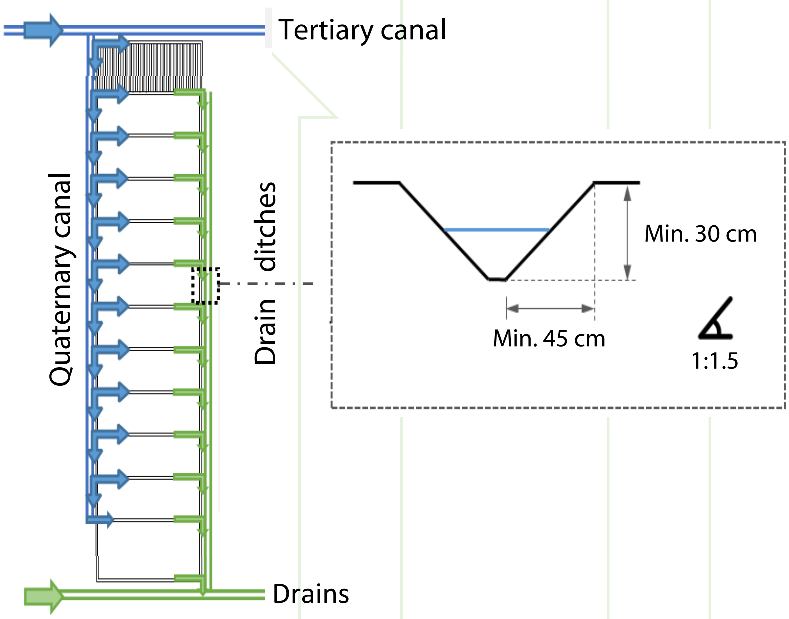
Potential constraint: Insufficient drain use

Drainage system at farm level must be properly maintained during the season, especially the ditches conveying runoff to the system-level drains. Ensuring good drainage at farm level is essential during the rainy season in heavy soils, because oversupply can result in massive waterlogging, which adversely affects the production by contaminating soil and water.

Figure 12: Main drain network in Ben Nafa Kacha, Burkina Faso



Source: Elaboration of FAO, 2019

Excess water must be conveyed through the furrows to drain ditches on the downstream side of the field. However, in certain cases, this is not enough and parallel drainage ditches need to be excavated. The cross section of the drainage canal can be trapezoidal or V-shaped, with a depth of 30 to 60 cm and a maximum lateral slope of 1:1.5. In addition, regular maintenance of drainage ditches, canals and their conjunction should be carried out to avoid blocks.

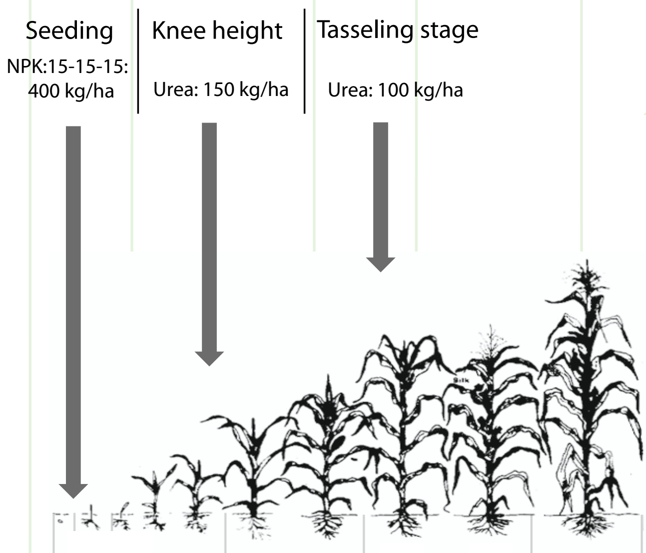
Potential constraint: Limited nutrient supply

The supply of nutrients often limits yields in the area. Applying the right nutrient at the right time is a key element in optimizing yields. Splitting nitrogen (N) applications during the growing season is highly recommended in order to provide sufficient nitrogen at time, as well as to reduce the economic and environmental impact of the loss of N. The amounts of recommended fertilizers were adapted to the formulations available in local markets.

Maize

For maize, the following split of inputs is recommended:

- At sowing: NPK 15-15-15 – 400 kg/ha
- At knee height: Urea – 150 kg/ha
- At tasselling stage: Urea – 100 kg/ha

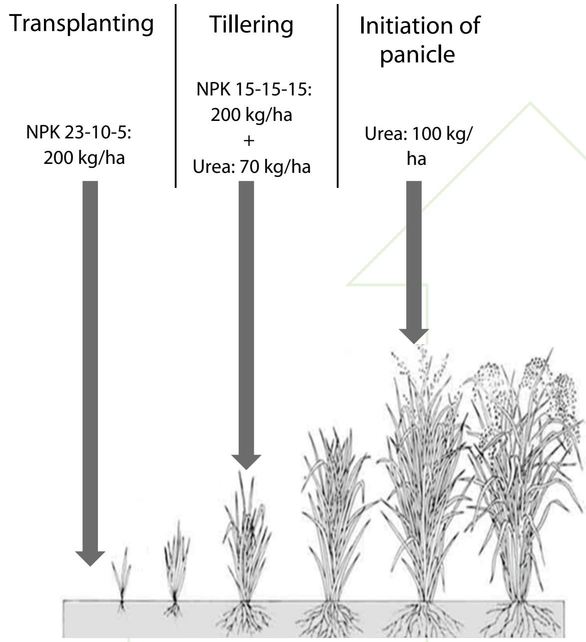


Source: University of Cordoba, 2019

Rice

For rice, the following split of inputs is recommended:

- At transplanting: NPK 23-10-5 – 200 kg/ha
- At tillering stage: NPK 15-15-15 – 200 kg/ha + Urea – 70 kg/ha
- At panicle initiation: Urea – 100 kg/ha

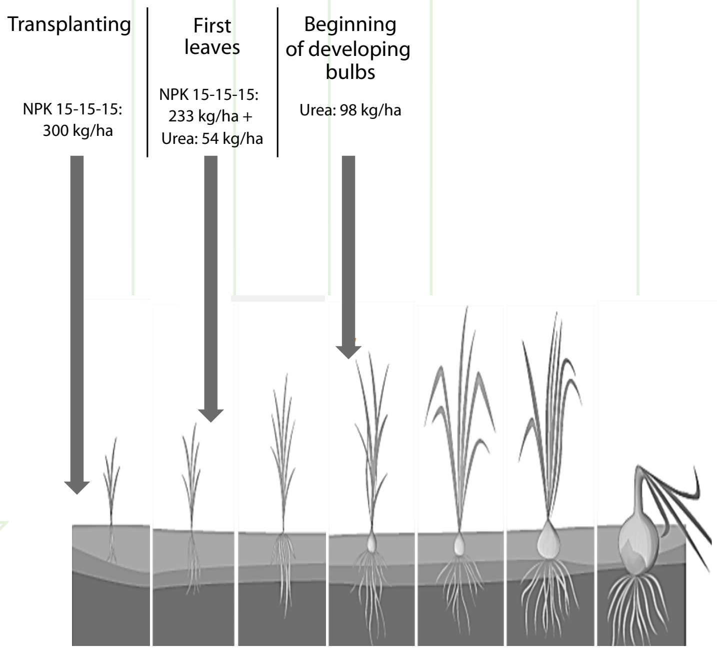


Source: University of Cordoba, 2019

Onion

For onion, the following split of inputs is recommended:

- At transplanting: NPK 15-15-15 – 300 kg/ha
- First leaf fall: NPK 15-15-15 – 233 kg/ha + Urea – 54 kg/ha
- Development of bulbs: Urea – 98 kg/ha



Source: University of Cordoba, 2019

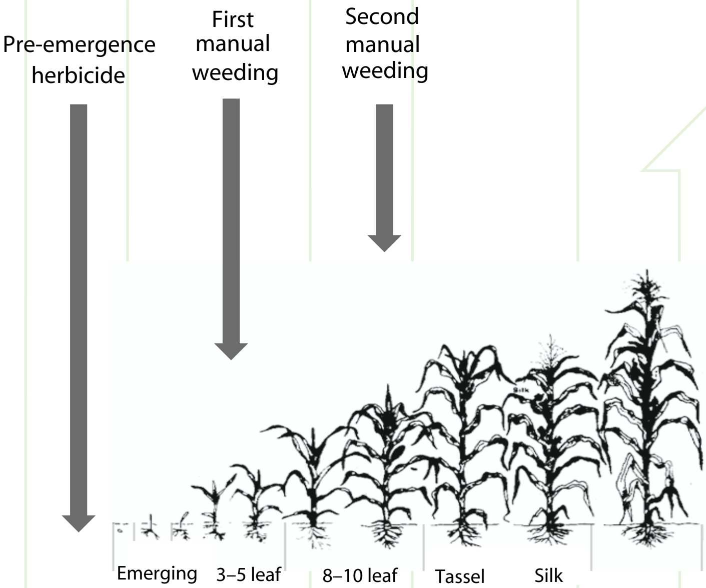
Potential constraint: Limited weed control

Proper weed control should be carried out during critical phases of crop growth through combining manual weeding with the application of a herbicide to prevent different types of weeds. The most critical period for weeding is during the settlement period until crops reach full coverage. In addition, the importance of weed removal before the second nitrogen spreading should be emphasized to minimize weed infestations that affect the yield of the crops.

Maize

For maize, the following weed control is recommended:

- Pre-emergence herbicide
- First manual weeding in the three–five leaf stage
- Second manual weeding before tasselling

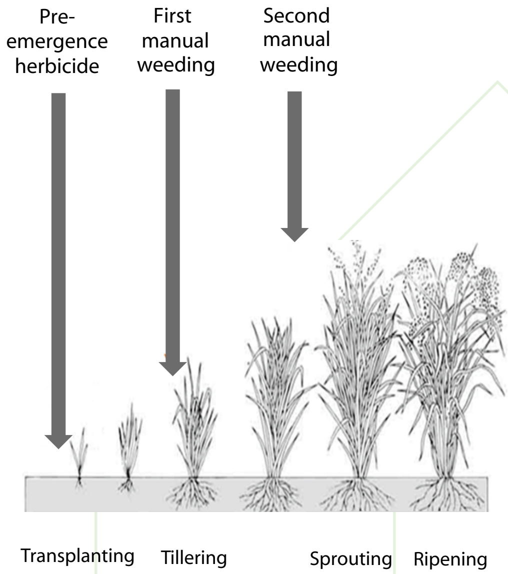


Source: University of Cordoba, 2019

Rice

For rice, the following weed control is recommended:

- Pre-emergence herbicide
- First manual weeding at tillering
- Second manual weeding before heading

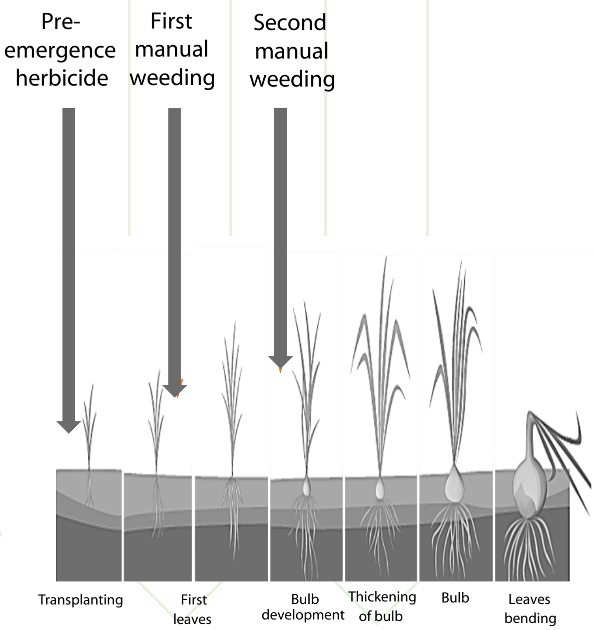


Source: University of Cordoba, 2019

Onion

For onion, the following weed control is recommended:

- Pre-emergence herbicide
- First manual weeding at first leaves
- Second manual weeding before bulb formation



Source: University of Cordoba, 2019

Potential constraint: Inappropriate insecticide

Insecticide application is required to effectively control pests and diseases. In addition, special attention should be paid to the most critical phenological stages, to avoid the appearance of insects and symptoms.

Cultivated fields should be checked about two weeks after planting and on a weekly basis to check that plants are emerging, detect signs of pests and diseases, and launch controls if necessary. Look for insects around and on the plants, and in the soil around the stem and roots; look for dead, dying and lying plants.

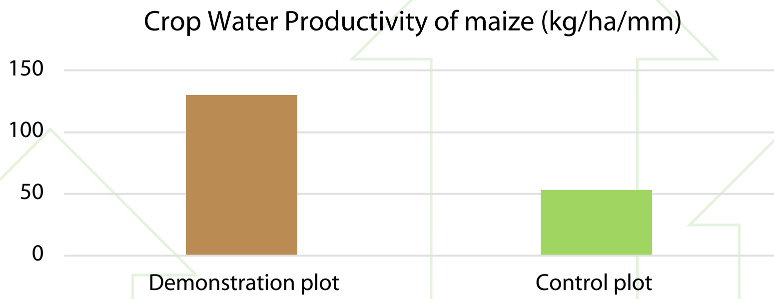
To manage the pests and diseases sustainably, insecticide applications need to be supplemented by other measures, such as:

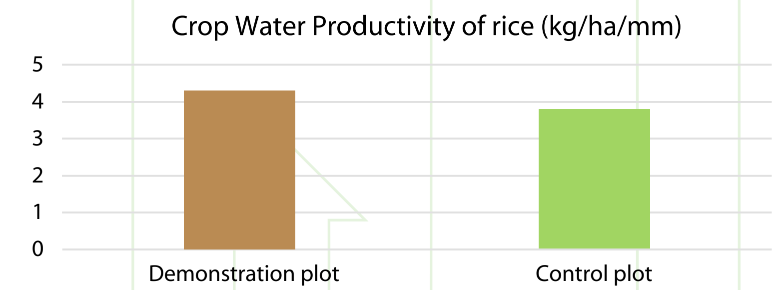
- Deep-ploughing through several weeks before planting
- Flood the rice plots for about two weeks to remove weeds
- Plant early at the beginning of the rainy season
- Treat seed with fungicides
- Improve soil conditions with proper fertilization
- Proper weeding
- Stubble management (removal of all crop residues, burning, ploughing and flooding after harvest) if there has been an intense attack.

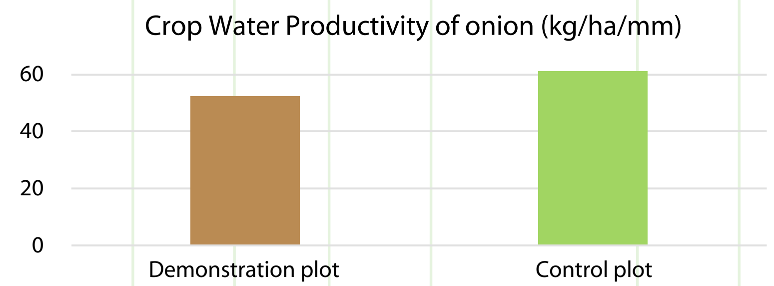
Results of implemented good practices

After a phase of **diagnostics and comparative analysis** *(benchmarking)*, the water productivity gains were assessed through AquaCrop. The implementation strategy was conducted in demonstration plots to provide effective means for dissemination. Three outputs were analysed as the result of improvement strategy: yield, applied water amount, and water productivity. The results show major improvement for rice and maize. The strategy has positive effect on the quality of the onion, which improved in terms of calibre and preservation. The quality increase greatly contributes to the marketability and long-lasting durability of the onion. Nevertheless, improvement, according to the objectives of quality, implies trading-off the productivity objectives.

Crop water productivity



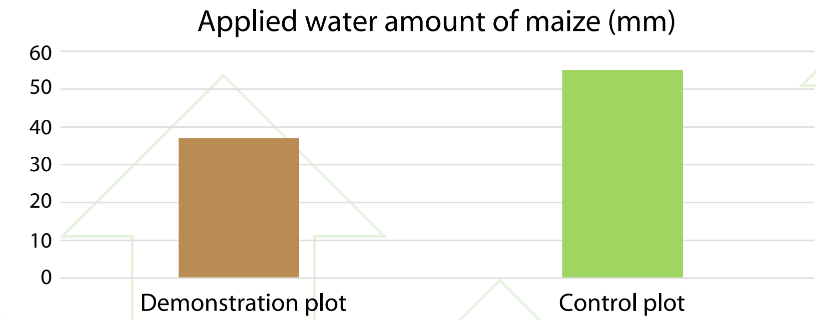


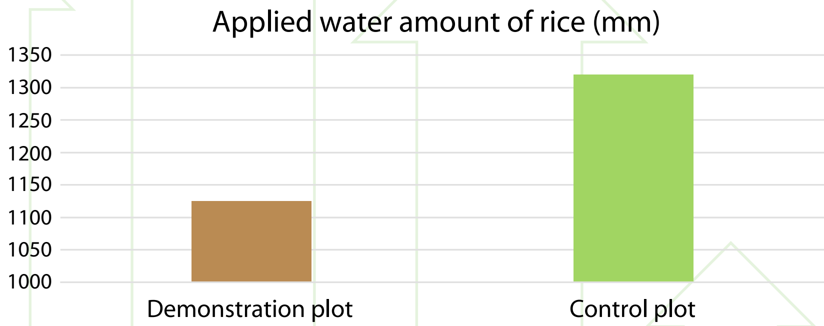


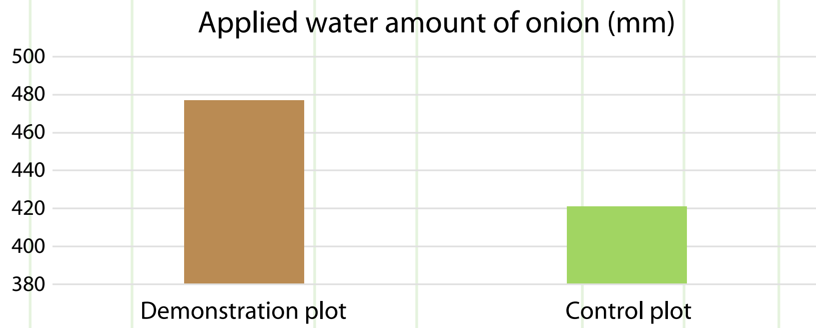
Source: Elaboration of FAO, 2019

The CWP of maize and paddy rice increased from 53 to 130 kg/ha/mm and from 3.8 to 4.3 kg/ha/mm respectively.

Applied water amount



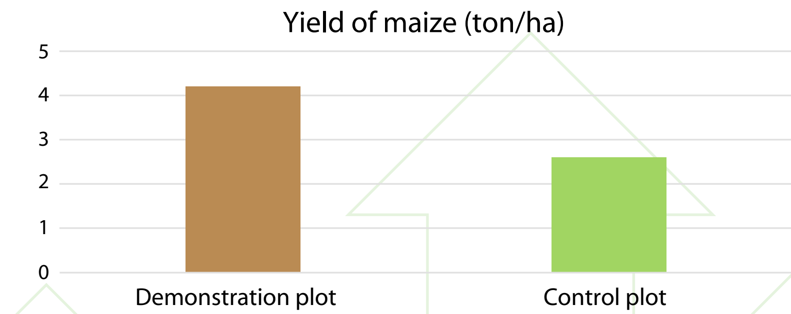


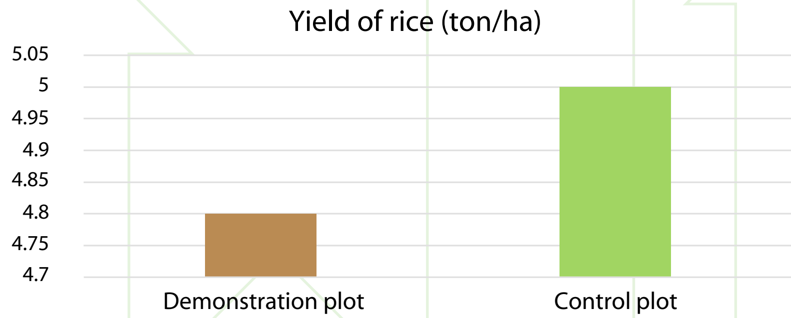


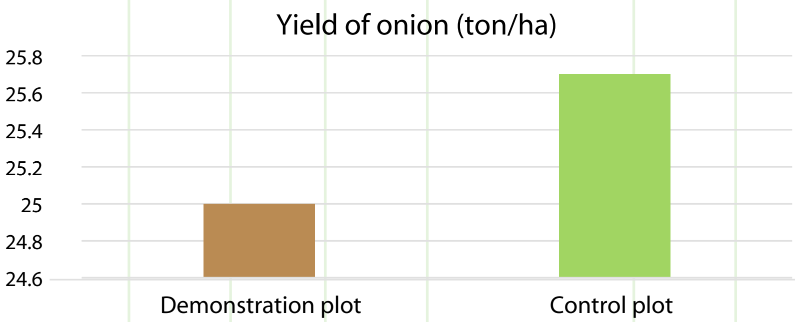
Source: Elaboration of FAO, 2019

The applied irrigation water reduced in the case of maize and rice. The improvement strategy resulted up to 18 mm water saving in maize plot and up to 195 mm water saving in paddy rice plots.

Yield







Source: Elaboration of FAO, 2019

Improvement strategy obtained significant increase in maize productivity resulting in more than 1.5 ton/ha yield gain. Rice and onion demonstration plots yielded similar amounts as the control plots, thus proving that current yields can be obtained even through more efficient resource use.

Optimal practices to enhance CWP in Mubuku, Uganda

The Mubuku irrigation scheme is approximately 540 ha cultivated by 167 farmers. Farmers are awarded with an average field size of eight acres (around 3.2 ha) under a long-term lease contract. The typical cropping pattern in Mubuku consists of rice, maize, onion in rotation in two seasons;

furthermore, tomato, beans and mango are produced randomly in small plots. Maize, rice and onion are the main crops that make up the 83 percent of the total cultivated area in the two seasons.

Table 5: Crop growth period of typical crops in Mubuku, Uganda

Crops	Length [Days]				RD [m][1]	MH [m]	Kc [-]		
	INI	DEV	MID	LAT			INI	MID	LAT
Maize	15	30	55	30	1.0–1.7	2.00	0.70	1.10	0.40
Rice	15	25	45	20	0.5–1.0	1.00	0.80	1.20	0.60
Onions	10	15	40	25	0.3–0.6	0.50	0.60	1.10	0.80
Beans	15	15	30	30	0.5–0.7	0.40	0.60	1.10	1.00
Tomatoes	30	60	30	30	0.7–1.5	0.60	0.40	1.00	0.80
Mangoes	60	90	120	95	2.0–4.0	6.00	0.72	0.75	0.78

Figure 13: Furrow irrigation evaluation in Mubuku

The peak period of water demand is April, May and July in the first season, and November and December in the second season. The scheme management does not restrict the selection and change of cropping pattern. There are two seasons per year, both of which are irrigation periods. River Sebwe provides sufficient water for irrigation; therefore, the scheme does not rely on groundwater resources. The scheme design applies surface irrigation with gravity conveyance. Although the conveyance efficiency is low, the applied water amount still greatly exceeds recommended water amount. It was also found that water distribution among divisions is not equal;

therefore, farmers' irrigation practices vary according to temporal water availability. Consequently, some farmers suffer from water shortage – particularly in downstream areas – and some farmers over-irrigate their plots. Crop water requirement of each crop was computed.

Table 6: Crop water requirement of typical crops in Mubuku, Uganda

Crop	Sowing PERIOD	Area [Ha]	CWR [m3]	CWR [m3/Ha]
Maize	March	50.00	175 492	3 510
Rice	March	33.00	119 152	3 611
Onions	January	23.00	98 903	4 300
Maize	September	69.00	230 982	3 348
Rice	September	53.00	180 959	3 414
Onions	June	10.00	40 404	4 040

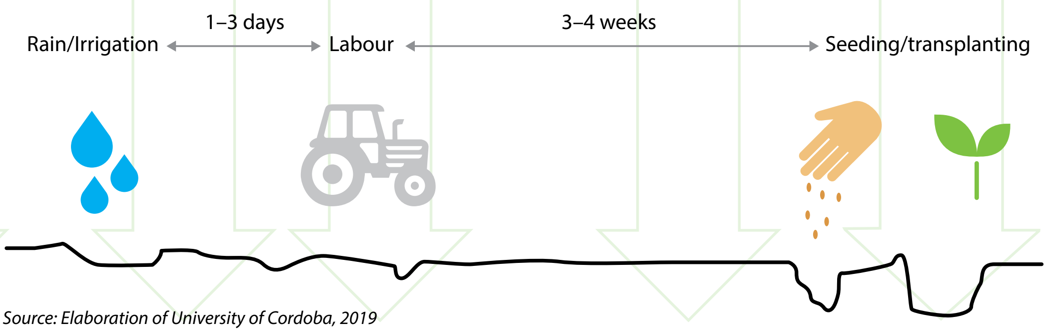
Diagnosis

Preparation

Potential constraint: Insufficient seedbed

Proper seedbed preparation is essential for the proper establishment of the crop and, therefore, for optimal crop growth and development throughout the growing season, which has a significant impact on yield performance. Soil moisture condition is a critical factor in proper preparation of the seedbed.

To ensure a good establishment of the cultivation of upland rice, maize and onion, the soil must be worked about three to four weeks before sowing/transplanting, allowing a partial decomposition of the organic matter. In addition, the preparation of the seedling bed should be carried out one to three days after an irrigation/rain event, once the soil has been drained, which allows for a good soil moisture condition. Finally, the seeds/seedlings must be sown/planted in a thin, crumbled soil horizon, under which watered soil is consolidated.



Source: Elaboration of University of Cordoba, 2019

Potential constraint: Inappropriate seed rate

Complying with the recommended seed rate is one of the most critical aspects of high yield. Planting more seeds than the optimal rate does not necessary increase yields while reducing profitability. The following seed rate is recommended:

- Maize: 20–25 kg/ha
- Upland rice: 50–60 kg/ha
- Onion: 4–5 kg/ha

Potential constraint: Inadequate seed depth

Maize

One major factor defining plant success is seed depth. In order to ensure the development of a deep root system reaching sufficient water and nutrients, the planting depth of 2–3 cm is optimal for maize in medium-textured soils. In sandy soil, maize seed should be planted more deeply (5 – 7 cm). Additionally, a depth of 2–4 cm is recommended for upland rice lines.

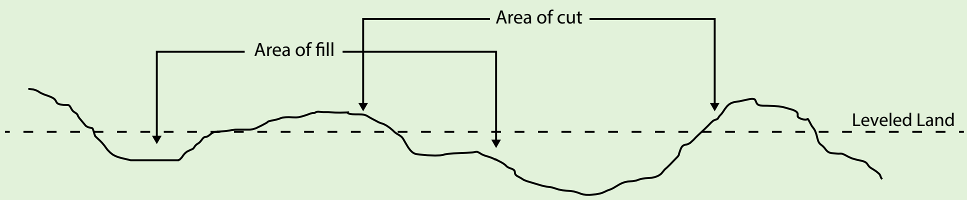
Rice

A depth of 2–4 cm is recommended for upland rice lines.

Potential constraint: Poor land levelling

Land levelling is essential to improve irrigation management at farm level. It improves the uniformity of irrigation water distribution and the application efficiency. In overall, proper land levelling improves the overall water productivity at farm level.

It is recommended that all farmers carry out land levelling regularly (every 2 –4 years). Two land leveling methods are recommended: the first method is to provide sufficient slope, which is adjusted to water application practices, and then, to level the field to its best condition with minimal earth movement while adjusting water application to the field condition. The second method is more viable to the conditions of Mubuku. While the first method may leave significant areas of the field without fertile topsoil, this latter method has economic consideration. Farmers should observe and identify the locations of high and low spots in the field and move soil from the high spots to the low ones. Ideally, this should be conducted with heavy machines (tractor), but it can also be performed manually (with a hoe or grid).

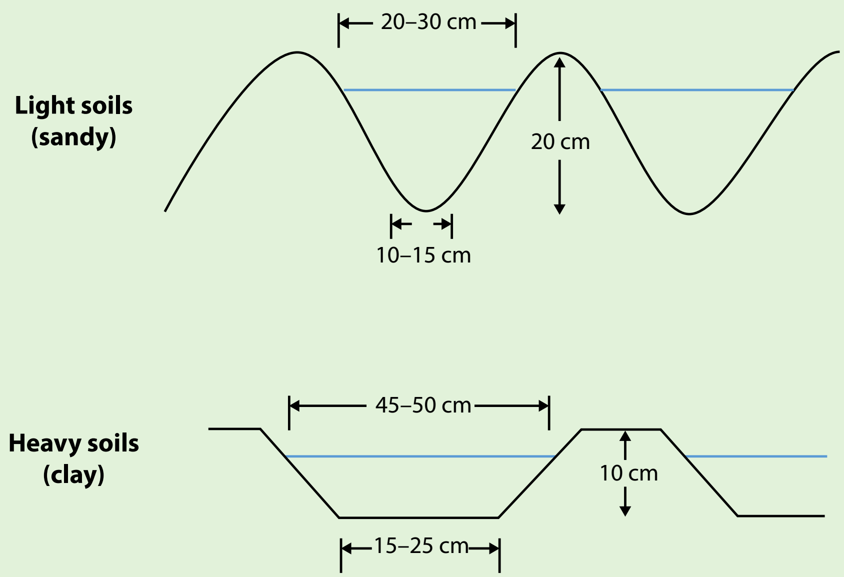


CROSS SECTION

Potential constraint: Inappropriate riding

Suitable dimension of the furrow is of great importance to evenly distribute water and control weed. Together with the levelling, riding improves irrigation uniformity.

In light soils, such as sandy soils with high infiltration capacity, narrow, deep V-shaped furrows are desirable to reduce the surface, through which water percolates. In heavy soils, such as clay soils with low infiltration capacity, wide, shallow furrows are required to obtain a large wetted area to facilitate infiltration.



Management practices

Potential constraint: Inappropriate maintenance of ditches

Proper maintenance of the conveyance infrastructure at quaternary level should be carried out regularly. Poor condition and maintenance lead to major water losses and insufficient water application at farm level.

Potential constraint: Unsuitable crop rotation

Suitable crop rotation is one of the determining factors of yield. Rotations improve soil fertility and is of great importance in pest management. Thus, crop rotation contributes to improved crop productivity. Nevertheless, it must be emphasized that the rotation needs to be consistent with farmers' objectives such as profitability issues.

Rehabilitation and re-profiling of quaternary canals should be carried out to maintain their original dimensions (60 cm wide and 30 cm deep; bottom slope should keep 0.05 percent grade), and conveyance should be improved by compacting the soil.

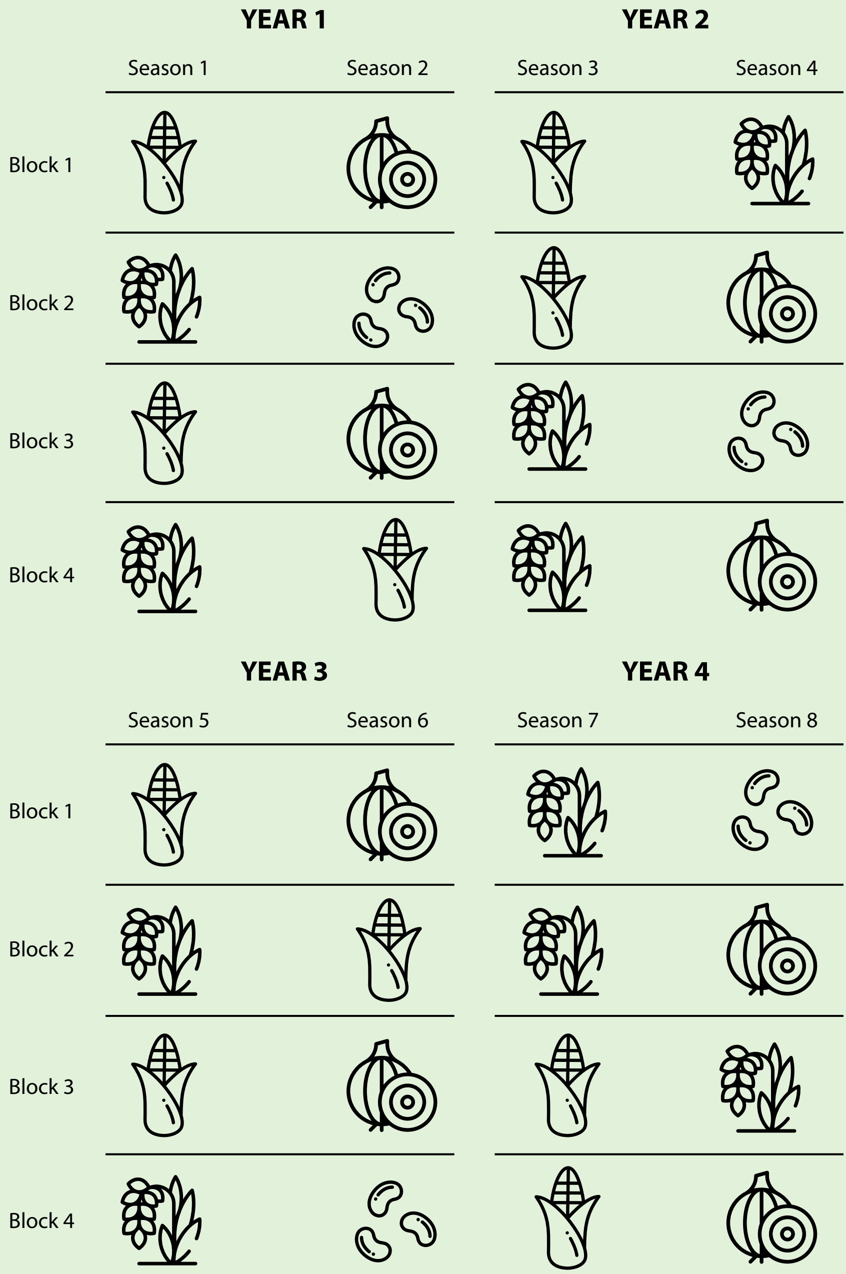
Potential constraint: Insufficient water application practices

Siphon tubes are effective tools for better control of furrow discharge flow, reducing the runoff and soil erosion problems. At the same time, they can reduce the irrigation duration, thus, allowing for higher irrigation frequency for crops, which require shorter irrigation intervals. Furthermore, siphons are easy to use and less labour intensive than other techniques to apply irrigation. However, this type of on-farm irrigation method requires training.

Potential constraint: Rigid irrigation rotation

The irrigation schedule should match the crop water requirement instead of relying on rigid irrigation schedule. It is particularly important to cover the irrigation requirement of critical growing stages. Sufficient water supply must be ensured in the most sensitive periods, such as flowering to avoid water deficit.

Despite the economic importance of cereals (maize and rice) and the contracts signed with the cooperative, they should be grown in rotation with other crops, such as onions or bush beans, which may provide both economic and environmental benefits. Rotational issues could be tackled by cropping beans before maize in order to improve soil fertility and weed management, and onion should be cropped after maize in order to exploit the residues of fertilization. The following rotation is recommended to improve productivity and water productivity.



Siphon tubes are efficient tools to control flows from field ditches to the furrows. The following recommendations help farmers to apply siphons appropriately:

- All siphons must deliver the same amount of water at time; thus, it is necessary to adjust the number of siphons to maintain constant water level in the ditch.
- The water depth in the ditch should be around 10–15 cm above the levelled ground to maintain a good siphoning head.
- All siphons should be placed perpendicular to the field ditch to avoid preferential flow into some siphons.

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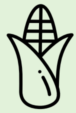
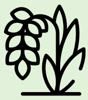
Potential constraint: Inappropriate drain use

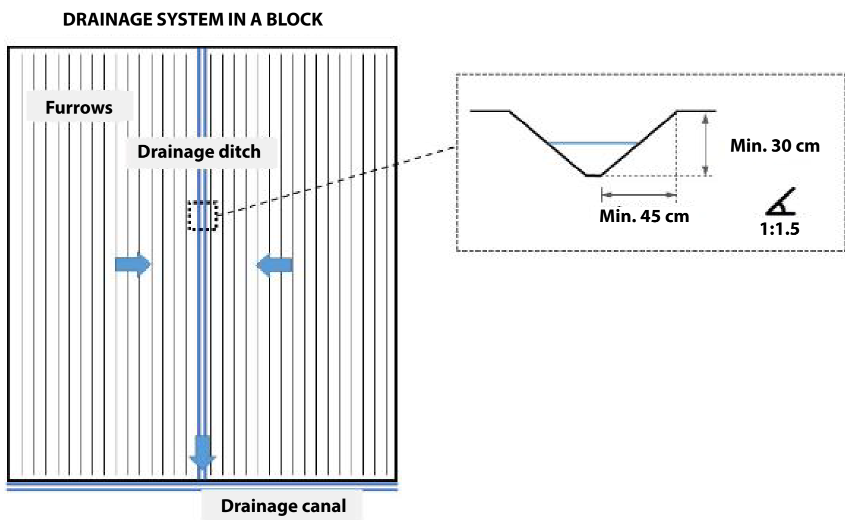
The drain ditches should be properly maintained during the season, in particular the connections to the general drainage system. Maintaining good drainage on farm is critical in case of heavy soils, since waterlogging has adverse effect on crop production.

In Mubuku Irrigation Scheme, seasonal rainfall covers more than half of the crop water requirements of maize and rice. Thus, the current irrigation supply (i.e. irrigation turn, flow discharge and duration) is sufficient to meet the crop water requirements. Irrigation is particularly needed to ensure sufficient supply during the flowering and grain filling stages of both crops.

In the case of onion, increase of irrigation frequency over current practice is necessary to ensure irrigation once a week. This is due to the fact that onion is cropped in the dry season and, in addition, it has a shallow root system. It is recommended that farmers increase irrigation frequency of onion, in particular during the bulb formation phase.

	Irrigation frequency	Critical stages
	Current	Flowing and grain filling
	Current	Flowering and grain filling
	Once a week	Bulb formation

Excess water should be conveyed through the furrows to the drains at the downstream side of the field. Nevertheless, in some cases, furrows are not sufficient to carry water, and parallel field drainage ditches should be excavated. The cross-section of the ditch could be trapezoidal or V-shaped, 30–60 cm depth and with a maximum side slope of 1:1.5. Furthermore, regular maintenance of the drainage ditches, canals and their connections should be carried out, avoiding the blockage by plants and sediments.



Source: Elaboration of University of Cordoba, 2019

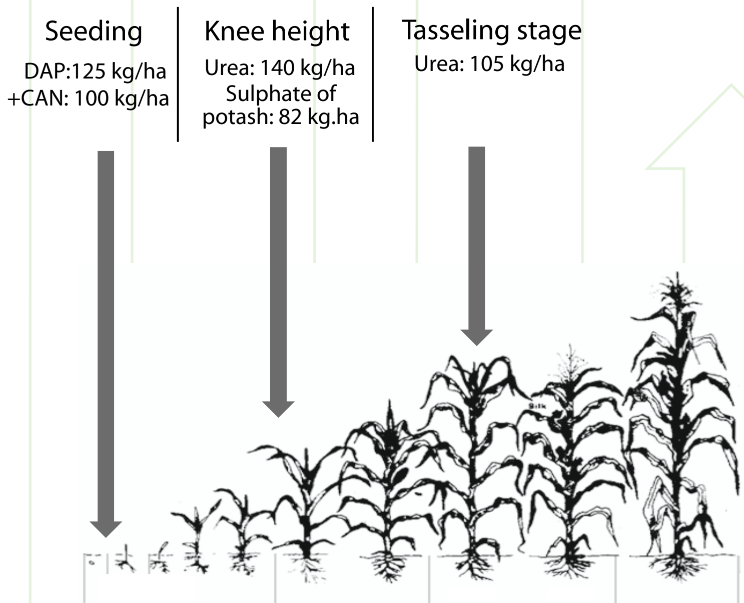
Potential constraint: Limited nutrient supply

The supply of nutrients often limits yields in the area. Applying the right nutrient at the right time is a key element in optimizing yields. Splitting nitrogen (N) applications during the growing season is highly recommended in the more coarse-textured soils in order to supply the crops with adequate nitrogen at all times while reducing the economic and environmental impact of nitrogen loss. The amounts of recommended fertilizers were adapted to the formulations available in local markets.

Maize

For maize, the following split of inputs is recommended:

- At sowing: DAP – 125 kg/ha + CAN – 100 kg/ha
- At knee height: Urea – 140 kg/ha + sulphate of potash: 82 kg/ha
- At tasselling stage: Urea – 105 kg/ha

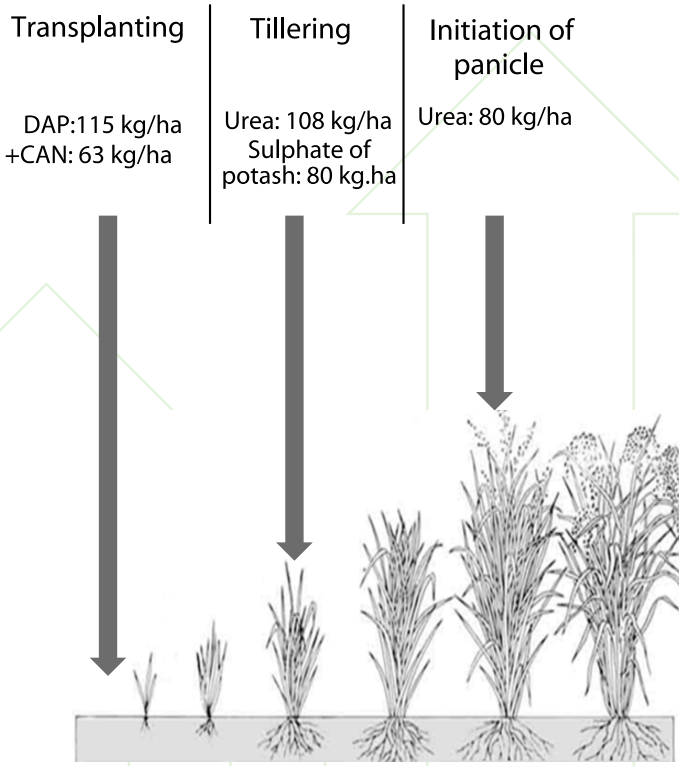


Source: University of Cordoba, 2019

Rice

For rice, the following split of inputs is recommended:

- At transplanting: DAP – 115 kg/ha + CAN – 63 kg/ha
- At tillering stage: Urea – 108 kg/ha + sulphate of potash: 80 kg/ha
- At panicle initiation: Urea – 80 kg/ha

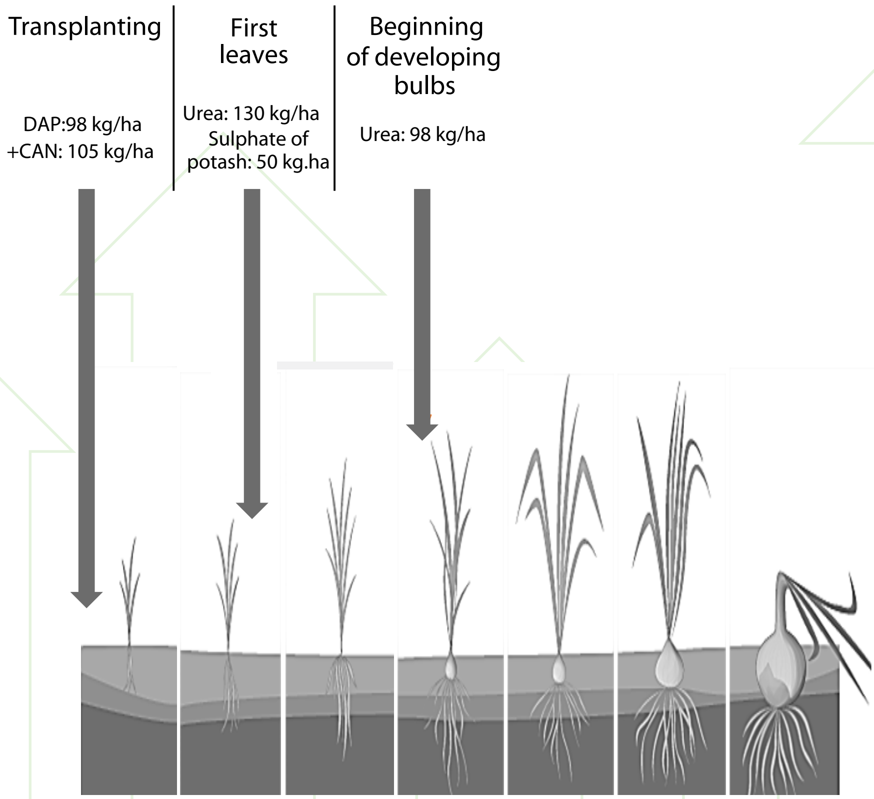


Source: University of Cordoba, 2019

Onion

For onion, the following split of inputs is recommended:

- At transplanting: DAP – 98 kg/ha + CAN – 105 kg/ha
- First leaf fall: Urea: 130 kg/ha + sulphate of potash – 50 kg/ha
- Development of bulbs: Urea – 98 kg/ha



Source: University of Cordoba, 2019

Potential constraint: Micronutrient deficiencies

In spite of their low requirements, critical plant functions are limited if micronutrients are unavailable. Micronutrient deficiencies can be detected by visual symptoms on crops. If deficiencies are detected, nutrients should be foliar-applied, as this method allows lower use rates of these expensive materials.

Some micronutrient deficiency symptoms

- **Mg:** Orange-yellow interveinal (older leaves first). Pale overall color. Green coloring remains patchy.
- **Zn:** Soft, droopy leaves and culms (younger leaves first). Stunted plants and poor tillering.
- **S:** Light green, pale leaves. Yellow upper leaves (younger leaves first). Stunted plants and reduced tillering. Delayed maturity.
- **Ca:** Yellow-necrotic split or rolled leaf tips (younger leaves first).
- **Fe:** Interveinal yellowing of emerging leaves (younger leaves first).
- **Mn:** Pale grayish green interveinal yellowing at the tip pf young leaves. Necrotic spotting. Shorter plants.
- **B:** White, rolled leaf tips of young leaves. Death of growth point if severe.

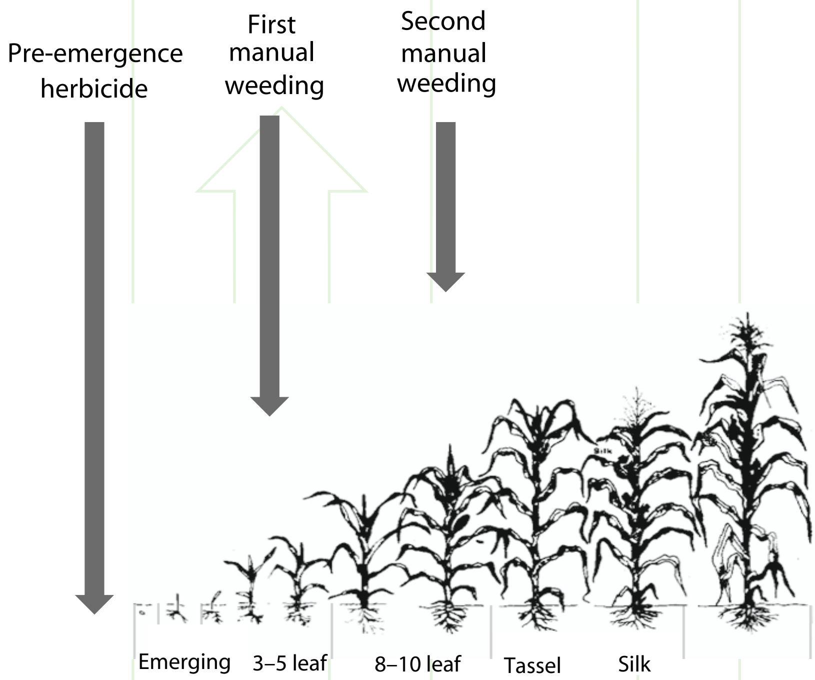
Potential constraint: Limited weed control

Proper weed control should be carried out during critical phases of crop growth through combining manual weeding with the application of an herbicide to prevent different types of weeds. The most critical period for weeding is the settlement until crops reach full coverage. In addition, the importance of weed removal before the second nitrogen spreading should be emphasized to minimize weed infestations that affect the yield of the crops.

Maize

For maize, the following weed control is recommended:

- Pre-emergence herbicide
- First manual weeding in the 3–5 leaf stage
- Second manual weeding before tasselling

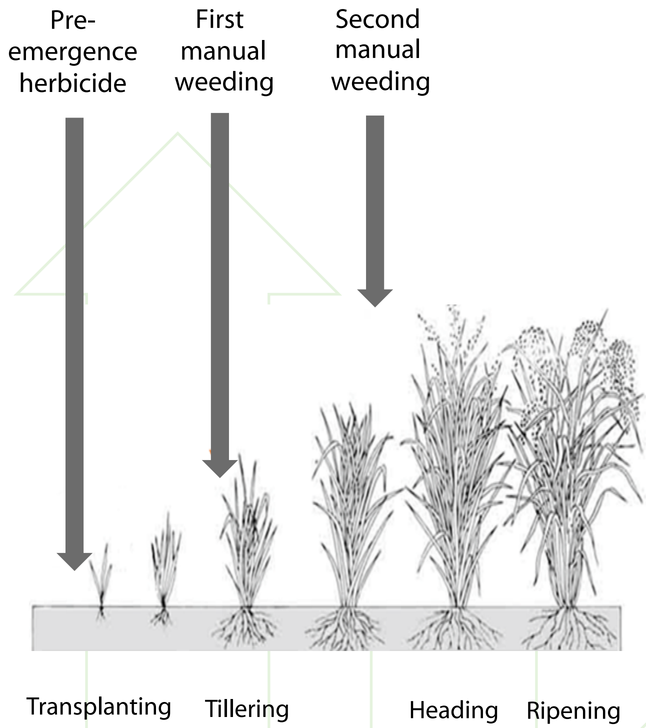


Source: University of Cordoba, 2019

Rice

For rice, the following weed control is recommended:

- Pre-emergence herbicide
- First manual weeding at tillering
- Second manual weeding before heading

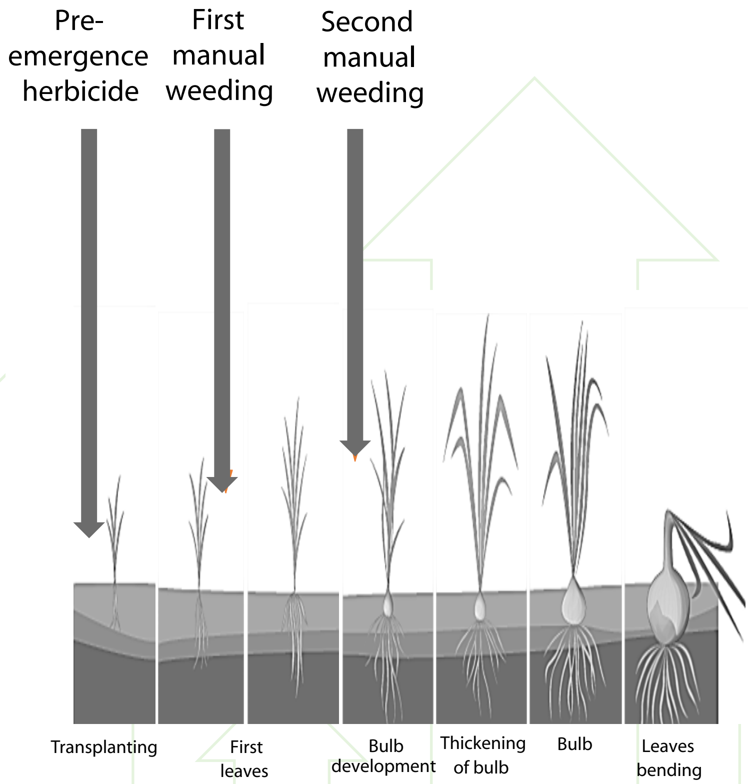


Source: University of Cordoba, 2019

Onion

For onion, the following weed control is recommended:

- Pre-emergence herbicide
- First manual weeding at first leaves
- Second manual weeding before bulb formation



Source: University of Cordoba, 2019

Potential constraint: Inappropriate insecticide

Insecticide application is required to effectively control pests and diseases. In addition, special attention should be paid to the most critical phenological stages to avoid the appearance of insects and symptoms.

Results of implemented good practices

After a phase of diagnostic and comparative analysis (benchmarking), the water productivity gains were assessed through AquaCrop. The implementation strategy was conducted in demonstration plots to provide effective means for dissemination. Three outputs were analysed as the result of improvement strategy: yield, applied water amount and water productivity. The results show major improvement for onion and maize. However, demonstration activities in rice plots faced difficulties at the time of implementation. Due to trade-related pest infestation, major damage occurred in the scheme and led to yield losses.

Cultivated fields should be checked about two weeks after planting and on a weekly basis, to check that plants are emerging, detect signs of pests and diseases, and launch controls if necessary. Look for insects around and on the plants, and in the soil around the stem and roots; look for dead, dying and lying plants.

To manage pests and diseases sustainably, insecticide applications need to be supplemented by other measures, such as:

- Deep-ploughing through several weeks before planting
- Flood the rice plots for about two weeks to remove weeds
- Plant early at the beginning of the rainy season
- Treat seed with fungicides
- Improve soil conditions with proper fertilization
- Proper weeding
- Stubble management (removal of all crop residues, burning, ploughing and flooding after harvest) if there has been an intense attack.

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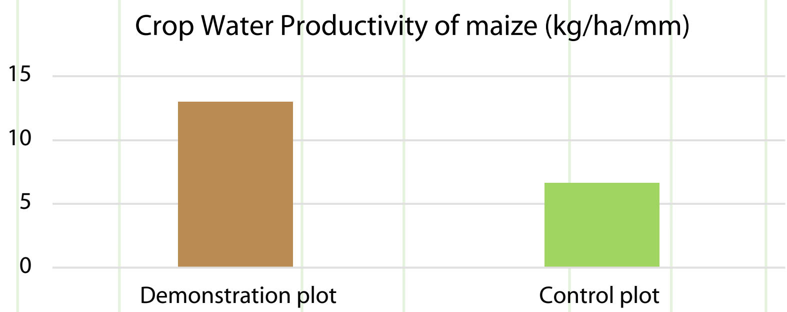
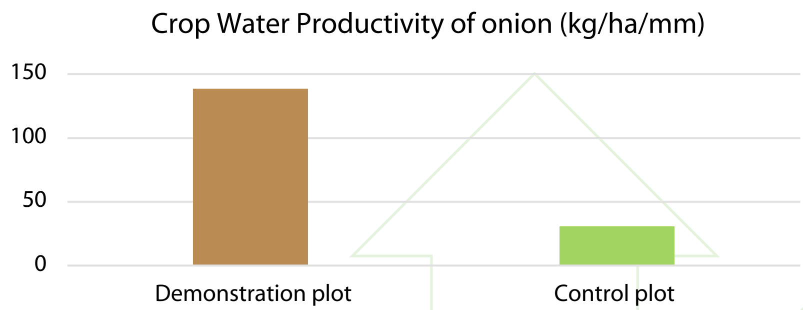
Crop water productivity

The CWP of maize and onion increased from 6.7 to 13.5 kg/ha/mm and from 31.7 to 139 kg/ha/mm respectively.



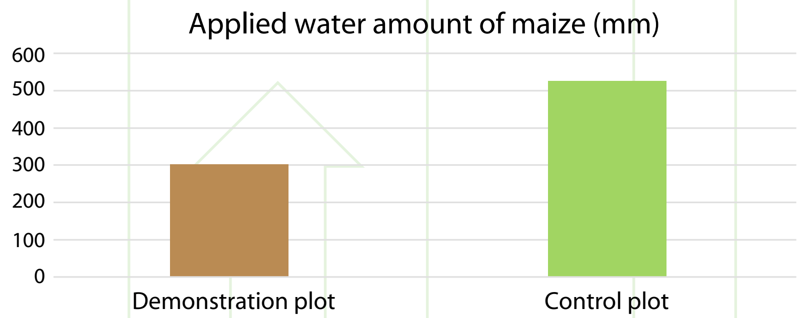
Source: Elaboration of FAO, 2019

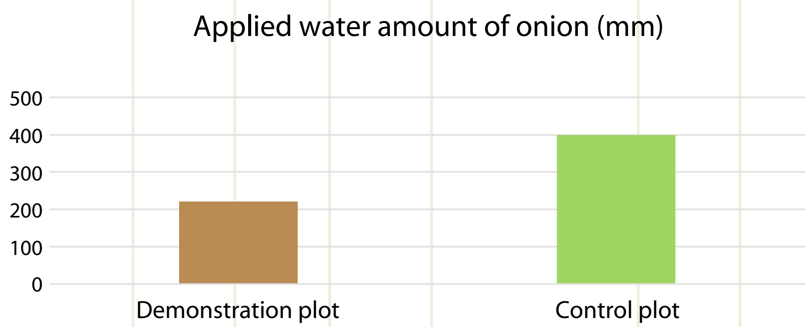


Source: Elaboration of FAO, 2019

Applied water amount

The applied irrigation water significantly reduced in the case of maize and onion. The improvement strategy resulted in up to 221 mm water saving in maize plot and up to 170 mm water saving in onion plots.

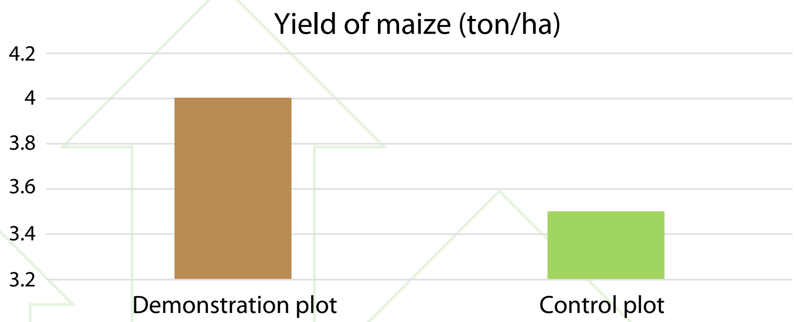


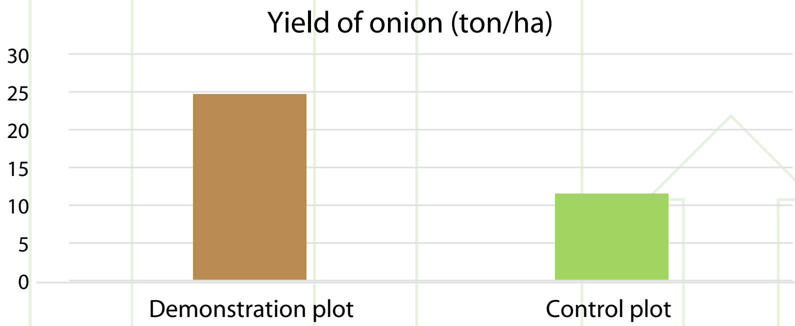


Source: Elaboration of FAO, 2019

Yield

Improvement strategy obtained significant increase in both maize and onion productivity resulting in 0.5 ton/ha yield gain of maize and 12.9 ton/ha yield gain of onion. The improvement strategy had a positive impact both on resource efficiency and productivity. Such result is consistent with both efficiency and socio-economic objectives, in order to support famers' efforts in transforming agriculture.





Source: Elaboration of FAO, 2019

Optimal practices to enhance CWP in R3 Sector-Al-Haouz, Morocco

Morocco is currently experiencing severe droughts, and consequently water scarcity. The situation exacerbated in 2017, when irrigation-cease was introduced in order to prioritize water use amongst sectors. Almost the whole area of R3 Sector (about 85 percent) is under surface irrigation (border irrigation). In the last few years, drip irrigation has been introduced, due to the subsidies provided by the government for irrigation modernization with the aim to increase water use efficiency at farm level (Plan Maroc Vert - Green Morocco Plan). Despite some flexibility to change the irrigation turns along the growing seasons (e.g. farms with cereals for seed production have priority access to water), the limited flexibility of the water service becomes an issue for farmers with drip irrigation systems. This, along with the fact that high-frequency irrigation system is used with high water demand crops during the period of highest atmospheric water demand, farmers seek alternative water supplies, such as groundwater. Thus, the groundwater resource of the R3 Sector is facing high pressure and the water-table level is decreasing by about 1 m per year. Increasing CWP by appropriate irrigation and agricultural practices is a key strategy to avoid wasteful water use or production failure.

Analysis involved olive experiments as the most produced cash crop in the region, making up to 78 percent of the irrigated area. In 2016, Morocco reached the goal of one million hectares of olive trees, thanks to the efforts made as part of the agricultural policy envisaged in the Plan Maroc Vert. About 35 percent of the olive area in the country is irrigated and over 90 percent of this area is irrigated using traditional flood irrigation. The upward trend that the sector is going through, both in Morocco and in the Mediterranean area, necessarily leads to an increase of production through intensive or super-intensive systems. These new production systems are also associated to the expansion of the drip irrigation system. Despite huge efforts towards intensification, traditions related to rainfed crop management know-how prevent farmers from the adoption of sustainable irrigation management practices. However, efficient and productive water management in the region hit by severe water shortages is of high importance. Olive growers have hardly exploited all of the potential benefits of irrigation; thus, there are many opportunities to improve on-farm WP. Many pathways for WP improvement are directly related to farm irrigation management. There are also a number of factors outside water (fertilization, plant health protection, pruning, etc.) that have a strong influence on WP and on farmers' livelihoods.

Figure 14: Canopy volume measurements in R3 Sector-Al Haouz, Morocco

The climate of this region is Mediterranean semi-arid, with an average annual precipitation around 250 mm, whereas the evapotranspiration demand is about 1 500 mm/year. The ETc for olive orchards is very variable and depends on several factors, with a range varying between 500–900 mm. As a first approximation, especially for surface irrigated orchards, it may be calculated using reference evapotranspiration (ETo), a crop coefficient (Kc) and an empirical coefficient (Kr) relating the ETc of an orchard of incomplete cover to the one of a mature orchard. According to the measurements taken in the area, the average canopy cover is 45 percent and, therefore, the reduction factor Kr is 0.9. Table 7 summarizes the monthly net irrigation requirements, given the monthly reference ET data, the effective precipitation and the recommended olive Kc for local conditions:

Table 7: Crop water requirement of olive in R3 Sector-Al Haouz, Morocco

Month	ETo (mm/month)	Kc	Kr	ETc (mm/month)	Effective Precipitation (mm/month)	Net Irrigation Requirements (mm/month)
January	56.4	0.55	0.90	27.9	43.9	0.0
February	68.6	0.55	0.90	34.0	14.6	19.4
March	110.4	0.65	0.90	64.6	40.9	23.7
April	130.2	0.65	0.90	76.2	19.7	56.4
May	158.1	0.65	0.90	92.5	27.2	65.3
June	175.2	0.55	0.90	86.7	0.0	86.7
July	217.3	0.55	0.90	107.6	0.0	107.6
August	210.8	0.55	0.90	104.3	0.0	104.3
September	153.6	0.65	0.90	89.9	11.8	78.0
October	110.4	0.65	0.90	64.6	6.9	57.7
November	67.8	0.65	0.90	39.7	61.1	0.0
December	54.6	0.55	0.90	27.0	20.4	6.6
Total	**1,513**			**815**	**247**	**606**

Based on the outcomes of the diagnosis, benchmarking and demonstration actions performed in the R3 Sector-Al Haouz Irrigation Scheme. The Field guide provides agricultural practices for improving WP in olive orchards, both traditional (surface irrigation) and intensive (drip irrigation) systems.

Diagnosis

Preparation

Potential constraint: inadequate border sizing

Border irrigation is the most common irrigation system in traditional olive orchards. In this system, the land is divided into narrow rectangular and usually long strips or borders, separated by earth bunds. Supply ditches are usually arranged at the upper end of the borders and drainage canals at the lower end. The water flows along the border forming a thin layer that gradually infiltrates as it advances. The proper irrigation supply depends on the borders dimensions, which is linked to the soil properties (infiltration characteristics). For borders with a slope of 0.3 percent, the following dimensions are recommended:

Table 8: Dimension of border irrigation in olive orchards

Type of soil	Width (m)	Length (m)
Sandy	10–12	50-80
Loam	10–15	100-200
Clay	10–15	150-300

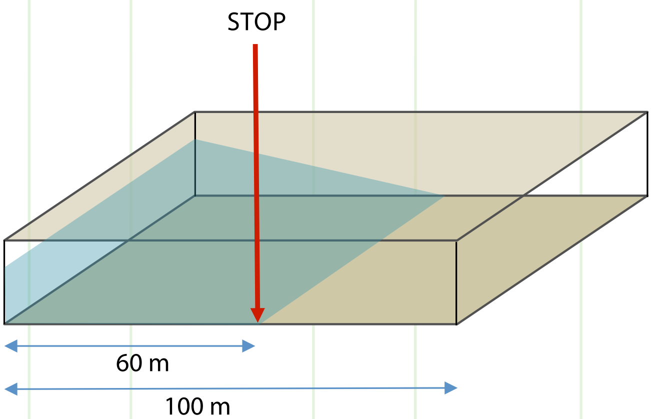
The two determining factors of efficient border operation are the discharge and the duration of flow. Lower discharge than required results in deep percolation losses near the field channel, especially on sandy soils. On the contrary, if the discharge is larger than required, the flow results in runoff along the border while reaching the end of the border without wetting the root zone sufficiently. Furthermore, large discharge leads to soil erosion. The duration of flow is particularly important to reach sufficient infiltration depth.

The time when the stream is turned off is another critical operational decision. If the flow is stopped too early there may not be enough water in the border to complete the irrigation at the far end. If it is left running for too long, water may run off the end of the border and be lost in the drainage system (FAO, 1998). There are no specific rules controlling this decision. However, as a guideline, the inflow to the border can be stopped as follows in function of the soil type:

- On clay soils, the inflow should be stopped when the irrigation water covers 60 percent of the border.

Figure 15: Border irrigation evaluation in R3 Sector

Figure 16: Irrigation duration of border irrigation in clay soil



Source: Elaboration of FAO, 2019

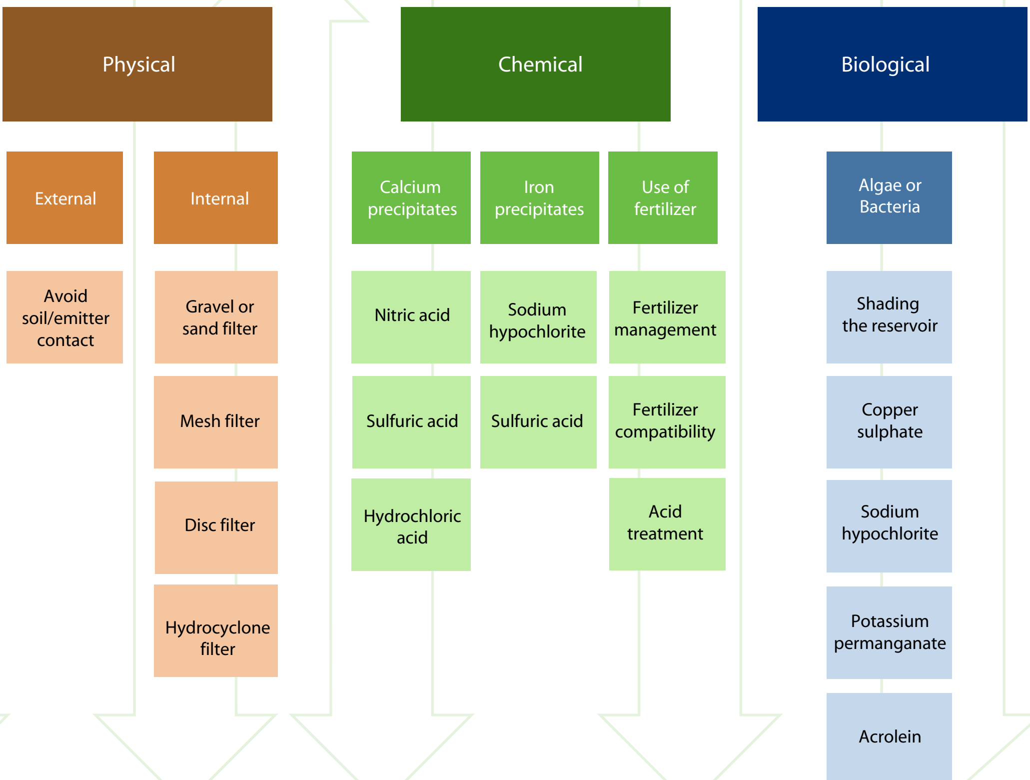
- On loamy soils, inflow should be stopped when 70 to 80 percent of the border is covered with water.
- On sandy soils, the irrigation water must cover the entire border before the flow is stopped.

In R3 Sector-Al Haouz Irrigation Scheme with a silty loam soil, the rule for an optimum irrigation operation is to stop the inflow when 90 percent of the border is covered with water. This will ensure a higher application efficiency and distribution uniformity.

Potential constraint: Poor drip maintenance

Localized irrigation, such as drip irrigation, enables the full control of flow and the adjustment of water supply to water requirement (Fereres et al, 1982). One of the main problems of localized irrigation is the emitter clogging, which causes a loss of uniformity and consequently an inhomogeneous tree development, and ultimately results in a reduction in production and WP. Therefore, it is very important to prevent the clogging of emitters (i.e. deposits of organic particles, minerals, salts that hamper the water flow) and other elements with very small water inlet sections, such as filter systems. Usually, when the degree of clogging is detected, it is already quite advanced. In these cases, the cleaning of emitters and pipes can be very expensive and, sometimes, the damage to the crop can be irreversible. For this reason, it is important to prevent the clogging before each irrigation season with the required dose of acid, chlorine or cleaner.

Figure 17: Type of clogging: prevention and treatment (adapted from IFAPA, 2010)



Further maintenance can help maximizing the benefits and lifespan of drip system:

Filtering equipment		
Before the irrigation season	**During the irrigation season**	**After the irrigation season**
Check the internal components: sand, meshes and discs, to verify their conservation status and change them if necessary. The exterior of the filters will also be painted if required	*Every two days:* Ensure that the filtering equipment and control valves operate correctly.	Wash and drain the filtering equipment
Verify the filtering system, including the automatic control system, if it exists	Check whether it is necessary to clean the filters, even those for automatic cleaning, by reading the pressure gauges at the inlet and outlet of the filters.	Examine the inside of filters and hydrocyclones to check for signs of deterioration (corrosion, wear, etc.)
In sand filters, check the sand level and the degree of dirt	*Monthly:* Remove the cover of the sand filters to inspect the level of sand and its dirt. If the cleaning of the sand is very frequent, it must be changed. Check if the valves that regulate the cleaning circuits are correctly adjusted Check for leaks in system connections Maintenance of the valves according to the manufacturer's recommendations Review the components of automatic control system, if it exists	Proper maintenance of valves
On disc filters, check that they are all the same color		*Filters with automatic cleaning system:* Disconnect the equipment. Check the status of the cables and electrical contacts
Check that the filtering circuit is in the filtering position and not in the cleaning position		
Filters with automatic cleaning system: Ensure that the electrical connections are clean and tight Verify that the electrical contacts are free of corrosion, dirt, dust and are not worn		

Maintenance of the irrigation network

Before the irrigation season	During the irrigation season	After the irrigation season
Open at the end of the pipelines and circulate the water to eliminate any element that may cause clogging	Check frequently for leaks and repair them if they occur Approximately once a month, perform a measure of uniformity (at least of the water flows)	Replace joints, elements or pieces of pipeline that have presented frequent problems of leakage or breakage during the irrigation season
Put the irrigation network in normal operation to check it for leakage		Drain the pipe network including the laterals
Measure the uniformity coefficient	Visually check the installation for signs of deterioration or damage caused by animals or vandalism Check frequently for leaks and repair them if they occur Approximately once a month, perform a measure of uniformity (at least of the water flows)	Open all valves
		Check for corrosion and consult the technician for possible measures to be taken Replace joints, elements or pieces of pipeline that have presented frequent problems of leakage or breakage during the irrigation season Drain the pipe network including the laterals

Maintenance of the emitters

Before the irrigation season	During the irrigation season	After the irrigation season
Check the existence of damaged or deteriorated emitters and perform test of emission uniformity	Check the system to verify that there are no damaged or deteriorated emitters	Inject a strong dose of acid, chlorine, or some cleaner, if there are problems of chemical or biological clogging
With the irrigation system working, verify visually that the emitters operate correctly	Verify the correct operation of the emitters	If possible, pick up the emitters lines, roll them up and store them until the next season
Prevent or treat problems of clogging with the required dose of acid, chlorine, or some cleaner	Prevent or treat problems of clogging with the required dose of acid, chlorine, or some cleaner	
	When fertigation is performed, always finish the irrigations with clean water, never with water and fertilizer	

Potential constraint: Rigid irrigation schedule

Morocco is currently facing sever water stress due to decreasing rainfall, dropping groundwater table and extended agricultural production. Therefore, irrigation schedule must take into account that water supply often does not cover the requirement. In R3 Sector, the irrigation water allocation is around 450 mm per year, while the requirement is around 600 mm (Table 7). Therefore, irrigation scheduling needs to be carefully designed to optimize water use. When water supply is insufficient, as in the pilot case, the only option is to apply less water than the orchard ETc requirements, a strategy known as deficit irrigation (DI). DI is a feasible strategy to maximize the productivity and revenue of water. Water deficit may lead to considerable yield loss, thus, it is important to consider the sensitivity of olive trees to water stress during each particular phenological phase. Yield is mainly determined by three main developmental processes: fruit set, fruit growth and oil accumulation in the fruit pulp. Nevertheless, vegetative growth is also important, because flowering originates in the axillary buds of one-year old wood; thus, the number of following year fruits directly depends on the amount of vegetative growth of the present year. With olive cultivar, a reduction in the number of olives may not be compensated by an increased size of individual olives. The sensitivity of these stages to water stress and their capacity to recover after a dry period should be analysed according to their impact on fruit and oil production. Water stress should be avoided from inflorescence development to fruit set. Moreover, the periods of initial fruit growth and of oil accumulation in the fall are sensitive to water deficit. On the contrary, the fruit growing period during summer can tolerate substantial water deficits (starting about 45–60 days after fruit set), provided that the tree recovers at the onset of the oil accumulation period. Olives blossom in late spring (later than many deciduous trees); thus, fruit growth is also delayed into the summer. Therefore, the risk of water stress occurring during these critical stages is significant under Moroccan climate (periods of water shortage). Nevertheless, even after several weeks of deficit, complete recovery of fruit growth occurs following irrigation. However, mild water stress during fruit development may have a positive effect on the pulp-to-pit ratio, an important quality feature in the olive fruit.

Table 9: Water deficit symptom of olives at different growing stages

Phase of vegetative- productive cycle	Period	Effect of water deficit
Vegetative growth	All year	Poor development of flower buds and next season's shoots
Flower bud formation	February–April	Decrease in the number of flowers; ovarian abortion
Flowering	May	Decrease in fertile flowers
Fruit set	May–June	Decrease in set fruit (increased alternate bearing)
Initial fruit growth	June–July	Reduction in fruit size (fewer cells/fruit)
Subsequent fruit growth	August–Harvest	Reduction in fruit size (smaller size of fruit cells)
Oil build-up	July–November	Lower oil content/fruit

Source: Orgaz and Fereres, 2001)

Two main approaches are recommended in the R3 Sector to introduce a Deficit Irrigation strategy: a) Sustained Deficit Irrigation (SDI), where a constant fraction of ETc is applied at regular intervals; and b) Regulated Deficit Irrigation (RDI), where the tree is stressed at those developmental stages where water deficits have the least negative impact on production. However, RDI strategy is recommended in the pilotarea. RDI suggests applying a fixed amount of irrigation water at regular intervals throughout the growing season. The amount of each irrigation should meet most of the ETc demand during spring and fall (critical periods), but it is quite insufficient to meet ETc during summer, when trees are insensitive to stress. This approach is the simplest for the design and management of the irrigation systems and works well in the case of soils with high water holding capacity (TAW = 160 mm/m). Another possible RDI strategy is to concentrate the water deficits from pit hardening until the end of the summer, ensuring a better supply during the sensitive periods (spring and fall).

Month	**Number of irrigation events**	
	Current practice	**RDI practice**
January	0	0
February	1	1
March	1	1
April	1	2
May	2	2
June	2	2
July	2	1
August	2	1
September	1	2
October	1	1
November	0	0
December	0	0

Potential constraint: Inappropriate fertilization

Olive trees tend to fruit better under conditions of low vigour, under minimal nutrition without being deficient. Additionally, excessive fertilization with nitrogen leads to a decline in oil quality. Nevertheless, to avoid nutrient deficiencies, a proper fertilization plan should be implemented. A lack of Nitrogen (N), Potassium (K) and Boron (B) are the common nutritional deficiencies in olives. Deficiencies of other nutrients are uncommon, but they should be verified.

Fertilicalc software was used to compile a fertilization plan for the R3 Sector. An olive orchard of eight years old and with a tree spacing of 10/5 m (200 trees/ha) has an expected production of 10 t/ha. It is necessary to know the fertility level of the soil by performing a preliminary analysis on the plot. The analysis results gave a silty loam soil with 14 mg/kg of P, 484 mg/kg of K and 1,46 percent content of organic matter. Thus, the nutrients requirements are:

Requirement of N	88 kg N/ha	0.44 kg N/tree
Requirement of P2O5	23 kg P2O5/ha	0.11 kg P2O5/tree
Requirement of K2O	58 kg K2O/ha	0.29 kg K2O/tree

Regarding fertilization schedule, the amounts of nitrogen, phosphorus and potassium to be applied throughout the season are not homogeneous; since they depend on the phenological stage.

Month	**% N**	**% P2O5**	**% K2O**
April	9	7.5	4
May	22	17	10
June	22	17	10
July	21	17	21
August	11	17	22
September	10	17	22
October	5	7.5	11

Foliar fertilization should be used only as a complement. The absorption of nutrients by the leaves is not always effective. Among the most important macro elements from the nutrition point of view of the olive tree, nitrogen and potassium are well absorbed by foliar application and the phosphorus has a very acceptable absorption. Similarly, the high foliar absorption of Na and Cl must be taken into account because the use of water with high levels of NaCl may cause toxicities. Unlike other mineral elements, Ca and Fe are very little absorbed by leaves, mainly iron. Therefore, it is advisable to apply this element to the soil to correct nutritive deficiencies.

In drip-irrigated olive orchards, fertigation allows the application of the nutrients required by the olive tree together with the irrigation water, which transports the fertilizers to the root system, allowing a continuous supply of nutrients throughout the irrigation season.

Potential constraint: Insufficient micronutrient

Regarding micronutrients, the fertilization plan should be oriented to cover their deficiencies, whose early detection is, thus, crucial.

Olive tree is sensitive to Boron deficiencies. Nevertheless, the symptoms of this deficiency can be confused with those caused by Potassium deficiency that are more common. Foliar diagnosis is essential. In case of diagnosed deficiency, it can be corrected by applying between 25 and 40 g of Boron per tree on the ground. On calcareous soils at high pH, the foliar application of soluble products at a concentration of 0.1 percent is preferred.

B deficiency

K deficiency

Iron deficiency is a nutrient imbalance that can affect olive orchards planted on very calcareous soils characterized by high pH. The affected trees show the characteristic symptoms of leaf chlorosis, low shoot growth and reduced production. These symptoms are the only way to detect this deficiency.

Fe deficiency

The majority of Moroccan olive orchards are planted on soils of limestone origin, so that Calcium is available in high quantities for trees. With regard to microelements such as Manganese, Copper and Zinc, the quantities required by the olive tree are very small and generally the tree finds them easily in the soil solution.

Ca deficiency

Source: Pastor, 2005

Potential constraint: Poor plant protection

Plant protection cannot be separated from agronomic practices and should be incorporated into the production system. Preventive protection measures (or indirect measures) should be prioritized. Preventive measures include all the practices concerning tree management and soil management (e.g. pruning, tillage, fertilization, irrigation, weed control, etc.), which help to maintain the stability of the agro-ecosystem (e.g. diversity of flora and auxiliary fauna). Monitoring and forecasting of noxious populations and determination of their harmfulness threshold are the other important pillars, which also define the set of direct management measures. Using different types of traps for insects and collection of plant organs samples (roots, shoots, stems, leaves, flowers, fruits, etc.) or on-site inspection are the methods to estimate the population level. Direct control is only undertaken if the population levels reach the harmfulness thresholds. Thus, pesticides are the last resort if preventive measures are inadequate.

Pest-Disease and importance (***)	Monitoring and forecasting methods	Intervention thresholds	Recommended management methods		
			Cultural practices	**Chemical treatment**	**Period of treatment**
Olive leaf spot***	20 leaves/tree on 20 trees	5% affected leaves	Prune properly to facilitate aeration in the canopy Decrease N fertilization and avoid K deficiencies	Bordeaux mixture or copper-based products	Before the first rains of autumn and spring
Sooty mould**	Check for presence of sap-sucking insects (scales, psyllid moth)	10% affected leaves; 5 to 10 larvae/leaf	Prune properly to facilitate aeration in the canopy Avoid tree stress	Mineral oil or copper-based products	End February, March
Verticillium wilt*	Visual inspection	Upon appearance of first symptoms decline in trees	Use resistant varieties Avoid excessive fertilization Disinfest tools Grub and burn infected trees	---	---
Olive fruit fly***	Counting of adults/trap	1 adult/trap/day, on average	Soil tillage under the canopy to bury the pupae Earlier harvesting in event of autumn infestation	Bait treatments, adult trapping	From June to September (one month at least before harvest)

Olive moth**	20 leaves/tree on 10 trees; funnel traps	5% flower cluster attacked; 20% infested fruit	Soil tillage under the canopy to reduce the 2nd generation Prune in winter to reduce larval populations	Bacillus thuringiensis (microbiological control), pyrethroids, dimethoate	Stage of 5% open flowers
Olive psyllid**	10 shoots/tree on 10 trees	> 10 larvae / flower cluster	Prune properly to facilitate aeration in the canopy Remove sprouts and suckers	Spray with dimethoate, deltamethrin	Beginning Mars, April

Currently, there is hardly any plant protection in the study area. It is recommended to implement preventive measures first and direct control after (if necessary) for the most common pests and diseases in the area, such as olive leaf spot, olive fruit fly and olive psyllid. In the future, and with the expansion of super-intensive systems with high irrigation frequency (drip), the verticillium wilt is expected to become a disease of high prevalence.

Potential constraint: Poor pruning operation

Pruning is one of the most important crop-growing techniques, since it can affect a multitude of productive factors, reducing the unproductive period, increasing production capacity, incidence of pests and diseases, harvesting costs, etc. These objectives should be prioritized depending on several factors, such as the type of planting, characteristics of the plant material and the physical environment, destination of the harvest, technical preparation, etc. Accordingly, different types of training and pruning exist (pruning for fruit production and rejuvenation pruning), which can support to extend in time the productivity of olive orchards to the maximum.

High-density cropping systems have been proposed in Morocco, using high-yielding varieties with limited vegetative development. However, highly intensive plantations create several potential problems. The pruning, in addition to the benefit of renewing the branches and improving production, reduces the risk of shading and eliminates the lower branches with lower productivity that hamper herbicide treatments. In this type of plantations, it is usually necessary to prune after the third year. Basic rules:

- Carry-out pruning once per year after harvesting.
- Avoid periods when temperature is low.
- Provide equipment in good condition (pruning shears, pruning saw, etc.).
- Apply sealing or healing products on cuts of more than 3 cm in diameter.
- Avoid the transmission of diseases through pruning tools. The tools must be sterilized (inflamed with alcohol) after the operations performed on diseased trees. It is advisable to prune these trees at the end.
- Be sure to make clean, soft and slightly tilted pruning cuts.

Potential constraint: Lack of special pruning practices

Special practices are often not followed by farmers, although, they have major benefits in terms of productivity, maintenance, harvesting and long-term plant health.

Training has the purpose of creating a structure of the tree able to support the weight of the harvest, with a good orientation and position of the main branches that captures the light and allows to maintain that structure in a prolonged way over time. At first, no cuts or shoot tipping are conducted, favoring the formation of a ball in the canopy. Finally, three main branches should be left with an approximate inclination of 45º in slightly precocious varieties, and almost 60º in very early varieties. The first branches of a plantation are always more productive than the branches from their renewal, in addition these first branches have a superior productive period.

Pruning of fruit production is recommended once the tree acquires the canopy volume adequate to the agronomic conditions (i.e. climate, soil and irrigation availability), namely keeping the canopy in an interval of volume, facilitating branch lighting and harvesting. The pruning interventions should be limited to eliminate internal water sprouts and secondary branches badly positioned. As far as possible, excessively spherical shapes should be avoided, and lobed shapes with protruding branches should instead be supported for larger radiation interception surface. The pruning can regulate the alternate bearing and reach average constant productions while optimizing the yield. However, the pruning should be limited to essential cases. The elimination of suckers from the base of the trunk can be done manually during the summer period, using adequate tools that do not generate major damage to the trunk.

When the plantation exceeded a certain number of years, its production capacity is reduced. The symptoms are significant: branches with absence of growth, yellowish leaves, wood with aged bark and a strong emission of water sprouts. These symptoms indicate that the branch is already exhausted and it needs to be replaced by another one. The rejuvenation pruning consists of eliminating main branches by their union with the trunk and replacing them with others coming from dormant buds, which exist in the trunk and do not sprout until the light falls directly on them. After removing the branch, the new buds appear just below the pruning cut. During the first and second year, selection of more vigorous and better positioned shoots should be selected. In rejuvenation pruning, the cuts usually have a high diameter, which delays the healing of the wound. In these cases, it is especially recommended the use of sealants or healing products that disinfect the wound and avoid sunburn.

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Field guide to improve crop water productivity in small-scale agriculture

The case of Burkina Faso, Morocco and Uganda

By 2050, the worlds' population will reach 9.1 billion, which requires an increase of food production by 70 percent compared to 2005 (FAO, 2018). Nearly all the increase will occur in developing countries, where agriculture plays a major role to provide employment, income and to improve food security. One of the major challenges of increasing food supply is the limited water resources. Agriculture, as the largest driver of freshwater exploitation has, therefore, to be transformed into more resource efficient production (FAO, 2003).

Small-scale agriculture has been gaining importance in agriculture-drive development. Smallholders in Asia and Sub-Saharan Africa cultivate 80 percent of farmlands. Despite their dominance in the landscape, smallholders are still greatly exposed to poverty and hunger (Lipton, 2005). The need to enhance their agricultural production is an increasingly pressing issue, not only to raise their income and household food supply, but also to contribute to overall food security and poverty alleviation (FAO *et al*., 2019).

The world's limited freshwater resources are potentially threatened by the expansion of agriculture. Increasing the potential output per amount of water used is an appropriate practice to improve production efficiency while protecting water resources. Water productivity can be considered an effective strategy to tackle both water and food security concerns. Therefore, increasing the productivity of agricultural water use in a sustainable manner is essential to ultimately sustain the social and economic conditions of livelihoods.

Crop water productivity has grown into one of the major approaches to cope with water scarcity and advance crop-water relation. The number of conceptual frameworks and implication is ample, but there is always a growing need to review the step-by-step approach beyond. In this Field guide, practical pathways are presented to provide a comprehensive approach for assessing and improving crop water productivity in small-scale agriculture. The Field Guide draws lessons learned in three countries (Burkina Faso, Morocco and Uganda) within the framework of FAO project "Strengthening Agricultural Water Efficiency and Productivity at the African and Global Level" funded by the Swiss Agency for Development and cooperation (SDC).

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