Compendium on Climate-Smart Irrigation

Concepts, evidence and options for a climate-smart approach to improving the performance of irrigated cropping systems

GACSA
GLOBAL ALLIANCE FOR
CLIMATE-SMART AGRICULTURE

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FOREWORD

Irrigation plays an important role in global food security, helping to produce 40 percent of crops worldwide on just 20 percent of the world's cultivated area. It is also the major single water user globally, accounting for about 47 percent of water abstracted from surface and groundwater resources, and faces a number of challenges, mainly linked to its dependence on water as a key resource. The expansion of irrigated areas and the shift towards more water intensive foods, coupled with growing water demand by other sectors make water an increasingly scarce resource in many regions of the world. Scarcity and competition for water are expected to be exacerbated by climate change, as rainfall amounts are projected to decline, particularly in dry areas, and rising temperatures will increase crop evapotranspiration rates and hence water demand by irrigation. At the same time, irrigation contributes to climate change, for example through greenhouse gas (GHG) emissions from fossil fuel powered water pumping, intensive use of mineral fertilizers, and the fossil fuel powered machinery and automation used at all stages, from the cultivation of crops through to the final phase of value chains.

A holistic and coordinated approach is needed to address these interlinked challenges and support the transition to irrigation systems that are productive and profitable while, at the same time, being resilient and well adapted to climate change, minimizing GHG emissions and ensuring the sustainable use of water resources. Such a shift will also support progress towards several interlinked goals on the 2030 Agenda for Sustainable Development, in particular Sustainable Development Goal (SDG) 6: Ensure availability and sustainable management of water and sanitation for all; SDG 2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture; and SDG 13: Take urgent action to combat climate change and its impacts.

The Compendium on Climate-Smart Irrigation proposes such a holistic and integrated approach, building on the three pillars of climate-smart agriculture (CSA), namely (i) Sustainably increasing agricultural productivity and incomes; (ii) Adapting and building resilience to climate change; and (iii) Reducing and/or removing GHG emissions, where possible. The compendium provides a comprehensive overview of the challenges and issues for sustainable irrigation development, both related and unrelated to climate change. It discusses the options and opportunities for each CSA pillar, identifies potential synergies and trade-offs between the different objectives of CSA, and underscores the importance of inclusive processes engaging stakeholders across different sectors and institutional levels.

I hope that the Compendium on Climate-Smart Irrigation will stimulate dialogue and significant progress towards the identification and implementation of sustainable solutions for the irrigation sector, which safeguard its fundamental role for food security while responding effectively to the challenges of climate change. Coordination and alignment between agriculture, climate change, water, energy and other sectors will be crucial for the design of sound and inclusive policies, as well as regulatory frameworks to support the adoption of climate-smart irrigation practices by farmers, and ensure the sustainable and equitable use of water resources in the long term.

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PREFACE

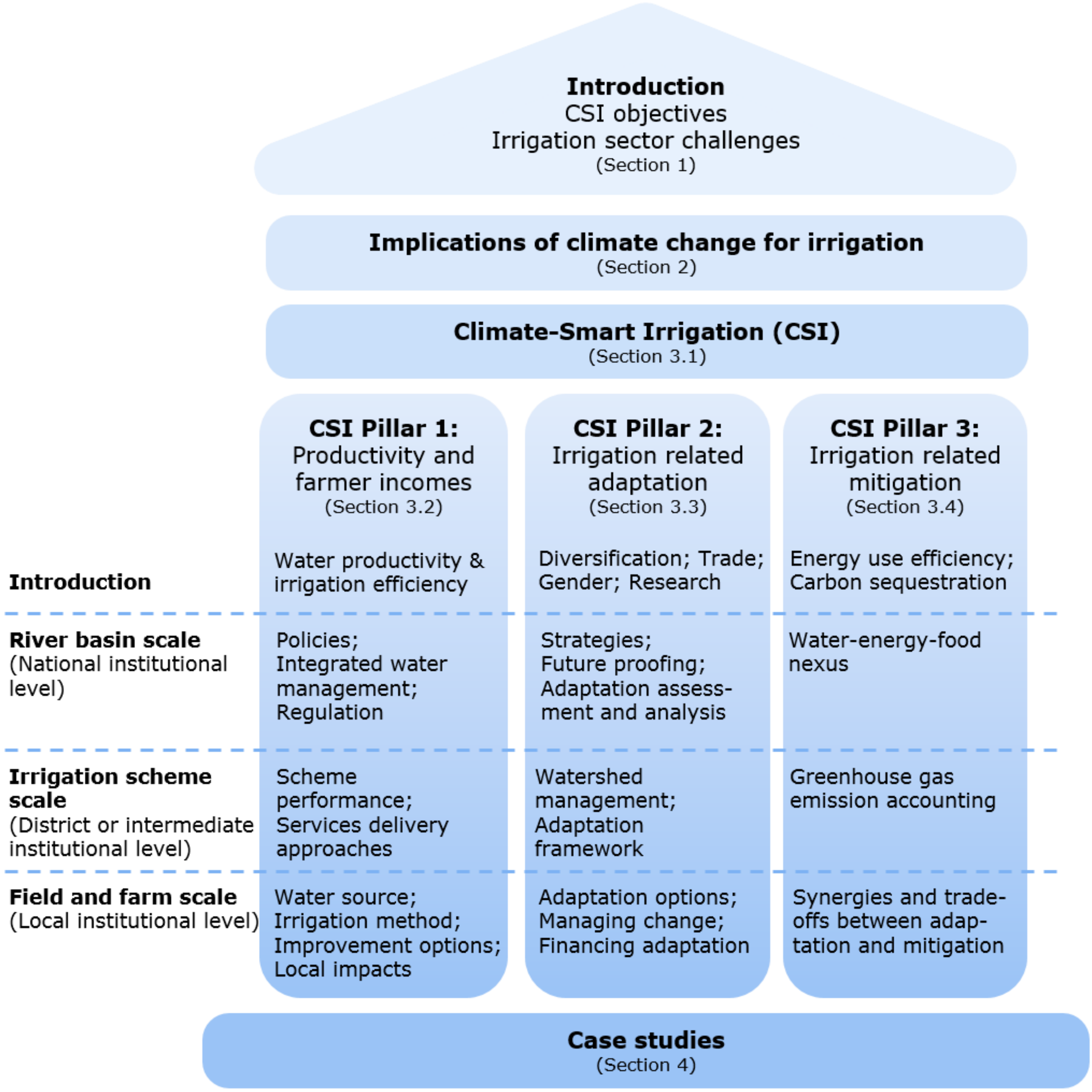
The idea for the Compendium on Climate-Smart Irrigation (CSI Compendium) was born from a global survey among agricultural development practitioners conducted by the Food and Agriculture Organization of the United Nations (FAO) and the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) in 2014. This survey identified water resources management as one of the priority areas for the development of knowledge products on climate-smart agriculture. FAO's Climate-Smart Agriculture Sourcebook (2013 and 2017) provides an overview of water management for CSA. Since the irrigation sector is the biggest water user within agriculture and, therefore, a central player in the management of water resources, we decided to focus on irrigation and assess in more detail the specific challenges and options for a climate-smart approach to this subsector.

Rather than giving climate change the high priority it deserves, irrigation sector policy-makers, professionals and practitioners continue to focus their energies on responding to more immediate challenges (e.g. irrigation schemes that are underperforming). This does not mean that they are in denial of the scientific evidence or the potential hazards and risks posed by climate change. Similarly, it does not mean that they are failing to recognize the imperatives for taking urgent action and/or modifying existing policies and practices. Instead, the relatively slow response can be attributed to the fact that responding to the climate challenge is far from easy for most people involved in the sector. Or to put it another way, they can only change their practices if and when there is political and public support for institutional reforms and relevant shifts in irrigation policies and practices. In addition, they can only change their practices if they are confident that new practices will generate a reliable and sustainable return on investments. The motivation behind this compendium is: to argue the case for irrigation policies and practices that are climate-smart; to raise awareness of what can be done to make irrigation policies and practices climate-smart; and to provide practical guidance and recommendations that are well referenced and, wherever possible, based on lessons learned from practical action.

The CSI Compendium develops the concept of climate-smart irrigation (CSI) as an integral part of CSA and intends to complement the existing literature and guidance on CSA published by the Global Alliance for Climate-Smart Agriculture (GACSA), FAO, CCAFS, the World Bank, Cornell University, and others. In the first section, the compendium presents the objectives of CSI, as derived from the three pillars of CSA, and puts CSI in context with 'good irrigation practice' (see diagram below). This is followed by a brief overview of tendencies in the expansion of global irrigated area, and a summary of challenges faced by irrigated agriculture, both related and unrelated to climate change. The second section focuses in more detail on the specific implications of climate change for irrigation. The third section is structured according to the three CSA pillars. Each of the subsections provides an introduction to the objectives, concepts and approach of CSI related to the respective CSA pillar, followed by a discussion of the key instruments, methods, tools and practices, as relevant at three different spatial scales – and institutional levels:

- River basin scale – national institutional level;
- Irrigation scheme scale – district or intermediate institutional level;
- Field or farm scale – local institutional level.

The order of scales, starting from the largest, highlights the need to consider impacts of irrigation activities at a local scale on other water uses and users, including environmental flows, at larger scales, such as that of the irrigation scheme or river basin. The fourth and last section of the CSI Compendium presents case studies that illustrate selected issues discussed in the preceding chapters.



Introduction
CSI objectives
Irrigation sector challenges
(Section 1)

Implications of climate change for irrigation
(Section 2)

Climate-Smart Irrigation (CSI)
(Section 3.1)

	CSI Pillar 1: Productivity and farmer incomes (Section 3.2)	**CSI Pillar 2:** Irrigation related adaptation (Section 3.3)	**CSI Pillar 3:** Irrigation related mitigation (Section 3.4)
Introduction	Water productivity & irrigation efficiency	Diversification; Trade; Gender; Research	Energy use efficiency; Carbon sequestration
River basin scale (National institutional level)	Policies; Integrated water management; Regulation	Strategies; Future proofing; Adaptation assessment and analysis	Water-energy-food nexus
Irrigation scheme scale (District or intermediate institutional level)	Scheme performance; Services delivery approaches	Watershed management; Adaptation framework	Greenhouse gas emission accounting
Field and farm scale (Local institutional level)	Water source; Irrigation method; Improvement options; Local impacts	Adaptation options; Managing change; Financing adaptation	Synergies and trade-offs between adaptation and mitigation

Case studies
(Section 4)

Diagram: Structure of the Compendium on Climate-Smart Irrigation

Under each CSI pillar some key words and highlights of the discussion are included for the respective spatial scale.

LIST OF ACRONYMS

ADB	Asian Development Bank
AFOLU	Agriculture, forestry and other land uses
AQUASTAT	FAO's global water information system
C	Carbon
CA	FAO’s Comprehensive Assessment of Water Management in Agriculture
CBO	Citizen- or community-based organization
CC	Climate change
CEAPRED	Center for Environmental and Agricultural Policy Research, Extension and Development
CH_4	Methane
CO_2	Carbon dioxide
CSA	Climate-smart agriculture
CSI	Climate-smart irrigation
EIT	Economies in transition
EPA	United States Environmental Protection Agency
FAO	Food and Agriculture Organization of the United Nations
FL	Field level
GCM	General circulation model
GFA	Global Framework for Action to cope with water scarcity in agriculture in the context of climate change
GHG	Greenhouse gas
GIS	Geographic information system
GWA	Gender and Water Alliance
HKH	Hindu Kush Himalaya
ICID	International Commission for Irrigation and Drainage
ICIMOD	International Centre for Integrated Mountain Development
IFES	Integrated Food-Energy Systems
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
IRWR	Internal renewable water resources
IS	Irrigation scheme
IWMI	International Water Management Institute
IWRM	Integrated Water Resources Management
IRRI	International Rice Research Institute
Kc	Crop coefficient for estimating evapotranspiration
LOS	Level of service
MASSCOTE	Mapping System and Services for Canal Operation Techniques
MASSMUS	Multiple uses of water services in large irrigation systems
MOOC	Massive Open Online Course
N_2O	Nitrous oxide

NAP	National Adaptation Plan
NAPA	National Action Plan for Adaptation
NAS	National Adaptation Strategy
NDVI	Normalized Difference Vegetation Index
NENA	Near East and North Africa
NGO	Non-governmental organization
O&M	Operation and maintenance
OECD	Organisation for Economic Co-operation and Development
PEA	Political economy analysis
PES	Payments for environmental services
PDIA	Problem-Driven Iterative Adaptation
R&D	Research & development
RAMSAR	Convention on Wetlands of International Importance especially as Waterfowl Habitat
RI	Regulatory instruments
RDI	Regulated deficit irrigation
RCP	Representative concentration pathways
RMV	Resilient Mountain Villages
SDA	Services delivery approach
SDG	Sustainable Development Goal
SI	Sustainable intensification (Elsewhere SI also refers to supplemental irrigation)
SLM	Sustainable land management
SOLAW	FAO’s State of Land and Water Resources
SPIS	Solar-powered irrigation systems
SSA	Sub-Saharan Africa
UAV	Unmanned aerial vehicle
UGB	Upper Guardiana Basin (Central Spain)
UNESCO	United Nations Educational, Scientific and Cultural Organization
ULRP	Urmia Lake Restoration Program
VDC	Village development committee
VRI	Variable rate irrigation
WA&A	Water accounting and auditing
WaPOR	FAO portal for monitoring water productivity estimated from remotely sensed data
WFD	Wetting front detector
WP	Water productivity
WWF	World Wide Fund for Nature

EXECUTIVE SUMMARY

Climate-smart irrigation aims and objectives

Climate-smart irrigation (CSI) is an important integral component of climate-smart agriculture. The aims and objectives of CSI include:

- Increasing the productivity of irrigated cropping systems and incomes derived by farmers in ways that minimize risks of trade-offs or externalities that may be politically, socially or environmentally unacceptable.
- Closing the gap between *potential crop yields* and *actual crop yields* achieved by farmers in different agroclimatic contexts.
- Increasing the resilience of irrigated cropping systems and related value chains to current and potential future climate change impacts and other sources of immediate and longer-term risk and uncertainty.
- Adapting irrigated cropping systems and related value chains to anticipated climate change in ways that take advantage of new opportunities that may arise as a result of climate change, and reduce its direct or indirect negative impacts.
- Reducing greenhouse gas emissions for each calorie or kilo of food, fibre and fuel that is produced by irrigated cropping systems up to and beyond the farm gate.
- Identifying and prioritizing opportunities for reducing GHG emissions from irrigated cropping systems at different scales, from accessing sources of water through to growing crops, post-harvest operations and the final phase of value chains.
- Improving the environmental sustainability of irrigated cropping systems and value chains while safeguarding the basic human water requirements of rural and urban water users; the livelihoods of women, children and poor or marginal social groups; and the functionality of aquatic ecosystems.

CSI context

There is increasing evidence that climate change is impacting regional and seasonal rainfall patterns, and the frequency and severity of extreme weather events. This has major implications for farmers who are already using irrigation, as well as farmers who hope to adopt irrigation as part of their climate change adaptation strategy.

While climate change predictions are subject to uncertainty, the expectation is that annual rainfall will increase in the tropics and higher latitudes but decrease in the already dry arid to semi-arid mid-latitudes, and in the interior of large continents. As a consequence, it is expected that water scarce areas of the world will become drier and hotter.

Climate change is not taking place in the context of pristine watersheds or river basins. Rather, the norm is that climate change is impacting watersheds and river basins that have already experienced centuries of development, land use change and degradation or depletion of environmental resources. In many of these watersheds and basins, consumptive water use is already outstripping sustainable supply.

Irrigation underpins food supplies in many countries that have large and/or rapidly increasing populations, for example China, India, Indonesia and Pakistan. However, in recent years, there are signs of a decline in expansion of irrigated areas for reasons that include the unsustainable consumptive use of water by irrigation. In these countries, the scope for increasing the area equipped for irrigation may be limited, and focus should be on improving water productivity.

The CSI context and focus can also be differentiated and determined by the magnitude of the yield gap between actual and potential crop yields. In countries or regions that are characterized by low-input farming and wide yield gaps, the focus of CSI is likely to be on sustainable intensification of crop production systems. In countries or regions that are characterized by relatively intensified farming and relatively narrow yield gaps, some further yield gap closure may still be possible, but increases in potential yields are needed if production is to be increased substantially. In such cases, the focus of CSI is likely to be on improving the sustainability and reducing the GHG emissions of existing crop production systems.

CSI rationale

Irrigation plays a major role in stabilizing agricultural production by supplementing rainfall and retained soil moisture during occasional or prolonged dry spells, and extending cropping into dry seasons and into arid and semi-arid areas. In most regions, scope exists for improving the performance of existing irrigation systems or schemes, and for improving the design and implementation of new irrigation systems or schemes by adopting CSI principles.

Irrigation hardware (i.e. infrastructure) that is well designed, constructed, operated and maintained is an important and necessary part of CSI strategies and practices aimed at increasing the productivity of irrigated cropping systems and the incomes of farmers, without having a negative impact on the environment or other water users. Similarly, irrigation hardware is often a necessary component of successful climate change adaptation and mitigation. However, good irrigation hardware alone is rarely sufficient to achieve desired outcomes. Irrigation software is also needed, e.g. policies, institutions, water governance and management, land and water tenure, farmer know-how, markets and access to credit. Or to put it another way, effective adaptation and mitigation is as much about irrigation software as it is about irrigation hardware.

Climate change is best conceptualized as a cascade of risks from direct or indirect impacts (e.g. on water sources for irrigation, irrigation related infrastructure, and irrigated cropping systems), through to socio-economic and environmental impacts (e.g. on value chains, livelihoods and environmental flows). Understanding this cascade of risks, as well as the vulnerabilities to them, is fundamental to effective climate change adaptation and mitigation.

CSI is not a set of ‘one size fits all’ practices that can be universally applied. Rather, it consists of irrigation hardware and software that is embedded in local contexts, policies, institutions and practices. Good irrigation practices, in particular, are an essential element of CSI and are typically founded on the accumulation of knowledge, know-how and lessons learned often over a long period of time.

Evidence informed planning is also fundamental to good irrigation practice. Planners and/or farmers should have a good understanding of the comparative advantages, limitations and suitability of different irrigation methods. They should also be aware that the performance of irrigation schemes is just as much a function of the farmer and irrigation scheduling procedures as of the irrigation methods or equipment that are used. When planning and implementing irrigation schemes it is important to note that farmers, planners, ecologists, politicians and the general public often have different or even contradictory perspectives and views on what constitutes good irrigation practice.

CSI approach

As a general rule, it is recommended that CSI projects and programmes focus initially on improving the performance, productivity and profitability of existing irrigated crop production systems. This entry point is recommended in part because improved productivity and profitability generate stakeholder interest and buy-in, and in part because irrigation systems where farmers have adopted good irrigation practices tend to be more resilient to climate change than systems that, for one reason or another, are underperforming. There is also a significant risk that investment in CSI adaptation and/or mitigation will be ineffective if farmers are lacking in, for example, crop husbandry and water management know-how, and/or irrigation systems are not performing well because sources of water are, for example, being overexploited or systems are not well maintained.

The intended outcomes of this first phase of the CSI approach include: 1) Irrigation systems and practices in a specified area that are productive, profitable, sustainable and non-polluting; 2) Farmers who are competent, capacitated and financially secure; and 3) Safeguards are in place that protect environmental flows, ensure that poor and marginal social groups have equitable access to water, and that gender issues are taken into account.

In the second phase of the CSI approach, adaption and mitigation strategies build on good irrigation practices by: identifying and evaluating additional opportunities for reducing exposure to climate change; improving the resilience of irrigated crop production systems; and reducing GHG emissions per unit of product. Typically, CSI adaptation strategies are developed in parallel with mitigation strategies, with the aim of identifying and maximizing potential synergies and minimizing potential trade-offs.

CSI adaptation should be perceived as a continuum of approaches, including: 1) Activities that aim to address underlying causes of vulnerability; 2) Measures explicitly targeting climate change impacts; and 3) Efforts to improve resilience at landholding, irrigation scheme and river basin scales. Typically, adaptation strategies aim to: 1) Make effective and efficient use of rainfall, for example by adjusting cropping seasons and taking advantage of seasonal weather forecasting; 2) Increase water availability for irrigated crop production; 3) Improve efficiency and productivity of irrigated cropping systems; and 4) Improve the resilience of irrigated cropping systems and value chains.

It is anticipated that changes in rainfall amounts and patterns will have a major impact on the availability and accessibility of surface and groundwater resources for irrigation. However, projections of these changes under different climate change scenarios are relatively uncertain, compared with changes in temperature, especially at local scales. In this context, no- and low-regret measures that have the potential to deliver benefits regardless of future rainfall trends are in many cases likely to be preferable CSI adaptation options.

CSI mitigation strategies involve, for example: 1) Reducing the use of non-renewable energy, e.g. used to pump, treat and distribute irrigation water; 2) Applying organic and inorganic fertilizers in ways that minimize GHG emissions; 3) Managing soils, cropping systems and irrigation regimes with a view to maximizing the potential of soils to act as carbon sinks; and, 4) Recognizing that, at basin scale, intensification of irrigated cropping may be justified and offset, for example, by reductions in rates of land use change from forestry or rangeland to rainfed or irrigated agriculture.

GHG emissions occur at all stages of an irrigated crop production system, from the source of irrigation water through to the cultivation of crops and to the end of value chains. It is also notable that GHG emissions are often exacerbated by, for example, unsustainable water resource use, poor farming practices and post-harvest crop losses up to and beyond the farm gate. A key point is that the main causes and magnitude of GHG emissions should be identified, quantified and mapped (in space and time) when developing CSI mitigation strategies.

CSI challenges

Implementing the CSI approach may prompt stern resistance from some stakeholders who are happy with their irrigated cropping system, would prefer not to take the risk of changing their irrigated cropping system, and/or, are yet to be convinced by arguments that the irrigation sector should take climate change seriously. This can be pre-empted to some extent by developing and implementing a targeted awareness-raising strategy and government programmes that provide financial or fiscal incentives.

Another challenge is that many farmers have limited or no interest in using water more efficiently or productively. For example, farmers located in a water scarce region may not experience water scarcity because: 1) Their landholdings are located near a canal offtake (rather than at the tail end); or 2) They have access to a high-yielding well.

A major challenge for CSI is that improvements in irrigation practices at field scale often translate into net increases in total consumptive water use at irrigation system or river basin scales. The underlying cause is that the more productive and profitable an irrigated cropping system is, the more farmers want and are able to upscale or intensify this system. In such cases, it is important to pay attention to options for managing and regulating intersectoral demand for water.

A powerful narrative, associating low efficiency in irrigation systems with a low level of water charges (or tariffs), has widely promoted the idea that raising water charges leads to major improvements in irrigation efficiency and water productivity. This narrative draws on evidence from the urban water supply and energy sectors, but can be highly misleading when extended to irrigated agriculture.

Another popular narrative is that improvements in irrigation efficiency save and free up water for other uses and users. The evidence from research and hydrometric monitoring shows that this is not always the case.

CSI monitoring and evaluation

On the basis that "We can't manage what we don't measure", CSI projects and programmes require robust monitoring systems that provide reliable information on the benefits and trade-offs of CSI across a range of different contexts and spatial and temporal scales. It is recommended that these systems take advantage of recent advances in the design and functionality of environmental sensors, cyber-technologies and informatics. It is also recommended that GHG accounting and water accounting/auditing are used in tandem as an integral part of CSI related monitoring and evaluation systems that: 1) Inform decision-making at different levels; 2) Underpin lesson learning and iterative improvements to CSI adaptation and mitigation strategies; and 3) Provide a sound basis for dialogue with other sectors that also consume water or influence water quality or availability (in space and time).

1. INTRODUCTION

1.1 Brief introduction to climate-smart agriculture

1.1.1 What is climate-smart agriculture?

Climate-smart agriculture (CSA) is often defined as "*agriculture that sustainably increases productivity, enhances resilience (adaptation), reduces or removes greenhouse gases where possible and enhances achievement of national food security and development goals"* (FAO, 2013a). In addition, CSA aims to strengthen livelihoods and food security, especially of smallholders, by improving the management and use of natural resources and adopting appropriate methods and technologies for the production, processing and marketing of agricultural goods. To maximize the benefits and minimize the trade-offs, CSA takes into consideration the social, economic and environmental context where it will be applied. Repercussions on energy and local resources are also assessed.

CSA is based on three main pillars (CCAFS, 2017):

1) **Productivity:** CSA aims to sustainably increase agricultural productivity and incomes from crops, livestock and fish, without having a negative impact on the environment. This, in turn, will raise food and nutritional security. A key concept related to raising productivity is sustainable intensification.
2) **Adaptation:** CSA aims to reduce the exposure of farmers to short-term risks, while also strengthening their resilience by building their capacity to adapt and prosper in the face of shocks and longer-term stresses. Particular attention is given to protecting the services that ecosystems provide to farmers and others. These services are essential for maintaining productivity and our ability to adapt to climate changes.
3) **Mitigation:** Wherever and whenever possible, CSA should help to reduce greenhouse gas emissions. This implies that we reduce emissions for each calorie or kilo of food, fibre and fuel that we produce, that we avoid deforestation from agriculture, and that we manage soils and trees in ways that maximize their potential to act as carbon sinks and absorb carbon dioxide (CO_2) from the atmosphere.

1.1.2 What is the climate-smart agriculture approach?

CSA is not a set of practices that can be universally applied, but rather an approach that involves different elements embedded in local contexts. CSA relates to actions both on-farm and beyond the farm, and incorporates technologies, policies, institutions and investment.

Different elements of climate-smart agricultural systems include (FAO, 2017a):

- Management of farms, crops, livestock, aquaculture and capture fisheries to balance near-term food security and livelihoods needs with priorities for adaptation and mitigation.
- Ecosystem and landscape management to conserve ecosystem services that are important for food security, agricultural development, adaptation and mitigation.
- Services for farmers and land managers to enable better management of climate risks/impacts and mitigation actions.
- Changes in the wider food system, including demand-side measures and value chain interventions that enhance the benefits of CSA.

While the CSA approach pursues the triple objectives of sustainably increasing productivity and incomes, adapting to climate change and reducing greenhouse gas emissions where possible, this does not imply that every practice applied in every location should produce 'triple wins'. Rather, the CSA approach seeks to promote synergies, reduce potential trade-offs and maximize benefits in any given societal or biophysical context, and over a range of different temporal and spatial scales.

CSA's rationale is based in part on the fact that the majority of the world's poor live in rural areas, and agriculture is their most important source of income. Developing the potential to increase productivity and incomes from smallholder crop, livestock, fish and forest production systems will be the key to achieving global food security over the next 20 years. Climate change is expected to hit developing countries the hardest. Its effects include higher temperatures, changes in precipitation patterns, rising sea levels and more frequent extreme weather events. All these pose risks for agriculture, food and water supplies. Resilience is therefore a predominant concern. Agriculture is a major source of greenhouse gas emissions. Mitigation can often be a significant co-benefit of actions to strengthen adaptation and enhance food security, and mitigation action compatible with national development priorities for agriculture is therefore an important aspect of CSA.

CSA is built upon a knowledge base that largely already exists, and a range of sustainable agricultural approaches – such as *sustainable intensification*, *conservation agriculture*, *water-smart agriculture* and *sustainable land management*.

So how does CSA differ from existing approaches and paradigms? The differences boil down to three essential features:

- **A focus on climate change:** Like many existing approaches, CSA is based on principles of increased productivity and sustainability. But it is distinguished by a focus on climate change, explicitly addressing adaptation and mitigation challenges while working towards food security for all. In essence, CSA is sustainable agriculture that incorporates resilience concerns, while at the same time seeking to reduce greenhouse gas emissions.
- **Outcomes, synergies and trade-offs:** To develop interventions that simultaneously meet the three challenges of productivity, adaptation and mitigation, CSA must not only focus on policies, technologies and practices, but also on the outcomes of interventions beyond farm level. In so doing, it must consider the synergies and trade-offs that exist between productivity, adaptation and mitigation, as well as the interactions that occur or may be needed at different institutional levels. For instance, CSA interventions at farm/community level may affect social and ecological systems locally, and at the wider watershed or basin scales. Likewise, a CSA intervention that aims to increase productivity should also consider how this may affect adaptation and mitigation, and how all three CSA pillars can best be addressed and/or optimized. All this requires farmers and other decision-makers to understand the synergies and trade-offs that exist between the three pillars, and between different sectors. To help people make informed decisions – from the farm to parliament – CSA focuses on developing metrics and prioritization tools that bring these synergies and trade-offs to the fore.
- **New funding opportunities:** Currently, there is an enormous deficit in the investment that is required to meet food security. By explicitly focusing on climate change, CSA opens up new funding opportunities for agricultural development, enabling the sector to tap into climate finance for adaptation and mitigation.

1.2 Brief introduction to climate-smart irrigation

1.2.1 What is climate-smart irrigation?

Climate-smart irrigation is good irrigation practice for a given agroclimatic and societal context that takes explicit account of challenges and opportunities that may result directly or indirectly from different facets of climate change. Climate-smart irrigation pays explicit attention to the three CSA pillars, as evidenced by the following versions of the three pillars:

1) **Productivity:** CSI aims to increase agricultural productivity and incomes derived from irrigated cropping systems up to and beyond the farm gate, without having negative impacts on the environment or other water users and uses (in space and time). CSI also aims to: 1) Improve the sustainability of irrigated cropping systems and value chains, and 2) Ensure safeguards are in place regarding women, children and poor or marginal social groups.
2) **Adaptation:** CSI aims to reduce the exposure of farmers, their irrigation systems and related value chains to short-term risks, while also strengthening their resilience by building their capacity to adapt and prosper in the face of shocks and longer-term stresses. Particular attention is paid to

improving the resilience of ecosystem services, infrastructure and support systems (e.g. extension services, water governance systems, sources of credit) that are needed to maintain productivity and improve the ability of farmers to adapt to climate change.

3) **Mitigation:** CSI aims to reduce greenhouse gas emissions for each calorie or kilo of food, fibre and fuel that is produced by irrigated cropping systems up to and beyond the farm gate. This can involve: reducing the non-renewable energy needed to pump, distribute and treat irrigation water, using solar pumps where appropriate, minimizing use of agrochemicals, and managing soils and irrigation systems in ways that maximize their potential for acting as carbon sinks.

1.2.2 What differentiates climate-smart irrigation from good irrigation practice?

Farmers have used irrigation for many thousands of years to overcome constraints on crop growth and quality that are caused by spatial and temporal variability in rainfall and/or soil water characteristics (e.g. soil depth, hydraulic conductivity and water retention properties). Over time, the development, adaptation and adoption of *good irrigation practices* for given agroclimatic and societal contexts have played a central role in: 1) Stabilizing agricultural production by supplementing rainfall and retaining soil moisture during occasional or prolonged dry spells, and 2) Extending cropping into dry seasons and/or arid/semi-arid areas.

Arguably, *good irrigation practices* have always been climate-smart because, by definition, they are based on: 1) A sound knowledge of spatial and inter- and intra-annual rainfall variability and crop water requirements; 2) A good understanding of the hydraulic properties of different soil types; and 3) Lessons learned regarding measures for mitigating, for example, the impacts of extreme weather events such as unseasonal or prolonged droughts.

Typically, *good irrigation practices* are founded on a mix of technical and non-technical measures, know-how and lessons learned relating to the different elements of an irrigation system. Put simply, these elements include:

- **A reliable source of water,** e.g. a spring, a river or an aquifer. Reliability of water sources may also be dependent on policies and institutions responsible for regulating and protecting the integrity (quality and quantity) and sustainability of natural resources, aquatic ecosystems, etc.
- **Infrastructure to extract and convey water** from the source to where it is needed, when it is needed and with a quality that meets agreed standards, e.g. pumps, canals, pipes, valves (or gates), storage tanks and water treatment systems. Policies and institutions for managing and maintaining public and private conveyance systems may also be needed.
- **Infrastructure to distribute water uniformly** across a field and/or an irrigation scheme according to certain schedules, e.g. pumps, canals, pipes, control devices, night-storage tanks, weather or soil sensors, etc. Institutions such as service-oriented irrigation management systems and water user associations (WUA) may also be required.
- **Drainage infrastructure** is often needed to reduce the risks of waterlogging and soil salinization. Policies and institutions may be needed to ensure that adequate attention is paid to constructing and maintaining drainage systems.
- **Access to land and water.** Farmers require some kind of land and water tenure that gives them rights to use both resources and, just as important, the incentives to invest in activities aimed at improving the productivity and resilience of their irrigation systems. Policies and institutions may also be needed, e.g. to ensure land and water rights are respected, to adjudicate if and when disputes occur, etc.
- **Cropping systems** that are well adapted to relevant biophysical factors (e.g. agroclimatic conditions, soils, extreme events, etc.) and societal factors (e.g. markets, policies, labour availability, social and political economy shocks and risks, etc.). Policies and institutions may be needed

PHOTO 1: Women selling produce at a market in a village in southern India
An important element of good irrigation practice is to connect farmers to markets, ensuring income and returns on investment for farmers and income-generating opportunities for traders.

Photo credit: Charles Batchelor

to support farmers and farming systems, e.g. extension services, banking or credit services, suppliers of seeds and agrochemicals, suppliers of irrigation and agricultural equipment, etc.

- **Value chains** that connect farmers to markets, ensure returns on investment and minimize risks of high post-harvest losses (see **PHOTO 1**). Policies and institutions may be needed to support farmers, traders and other intermediaries along value chains (e.g. trading standards legislation, cooperatives, etc.).

Typically, different stakeholders have different perspectives on what constitutes *good irrigation practices*. From a farmer perspective, the main constituents or attributes of good irrigation practice could be: crop productivity, profitability and minimal risk. By contrast, good irrigation practices from a national and basin level perspective could include: policy objectives are achieved; consumptive use of water by irrigation is sustainable (e.g. not leading to groundwater overdraft); levels of pollution are within acceptable limits; levels of damage to aquatic ecosystems are also acceptable; and intersectoral conflicts between irrigation and other water uses are mediated and resolved.

1.2.3 What are the value additions of climate-smart irrigation relative to good irrigation practices?

As stated earlier, good irrigation practices are based on a range of activities that are well adapted to a given agroclimatic and societal context. Other attributes include: good crop husbandry; good irrigation scheduling; good maintenance of infrastructure; sustainable and efficient use of water sources, and so on. The reality is that actual irrigation practices often fall short of good practice in some or many respects. As a consequence, a necessary first step in implementing CSI is often to tackle the root causes of current poor irrigation practice and performance, the rationale being that climate-smart investment (e.g. aimed at improving resilience and reducing GHG emissions) will be of limited value if irrigation schemes are underperforming. It should be noted that the underlying causes of poor irrigation performance may be complicated, and outside the control of farmers.

Notwithstanding issues over what constitutes good irrigation practice, the following are examples of potential value additions of CSI:

- **Explicit attention to climate change adaptation and mitigation:** More specifically, CSI pays explicit focused attention to CSA pillars 2 and 3. CSI also pays explicit attention to CSA pillar 1, but this is already a central component of good irrigation practices and, as such, it does not differentiate CSI from good irrigation practice.
- **Explicit attention to climate change related institutional reform:** Typically, effective mainstreaming of climate change adaptation and mitigation into planning processes requires sector reform and capacity-building at all institutional levels, but particularly at decentralized level. A shift towards intersectoral planning is also required if intersectoral sustainability, equity and efficiency goals are to be achieved. The CSI concept could play a role in leveraging sector and institutional reform that is based on, for example, the Water-Energy-Food (WEF) nexus concept or similar.
- **Leveraging funds.** The CSI concept can also play an important role in leveraging funds for irrigation improvement and making effective use of these funds by improving farmer income and water productivity at the same time as reducing the vulnerability and carbon footprint of irrigated cropping systems.
- **Improved irrigation related planning and management:** CSI recognizes that trend analysis and modelling based on historic climatic, hydrological and agricultural data and statistics can no longer be relied upon to underpin irrigation related planning and management. As a consequence, CSI adopts different methods when planning and managing irrigation schemes. For example, less emphasis is put on time series analysis and relatively more emphasis is placed on

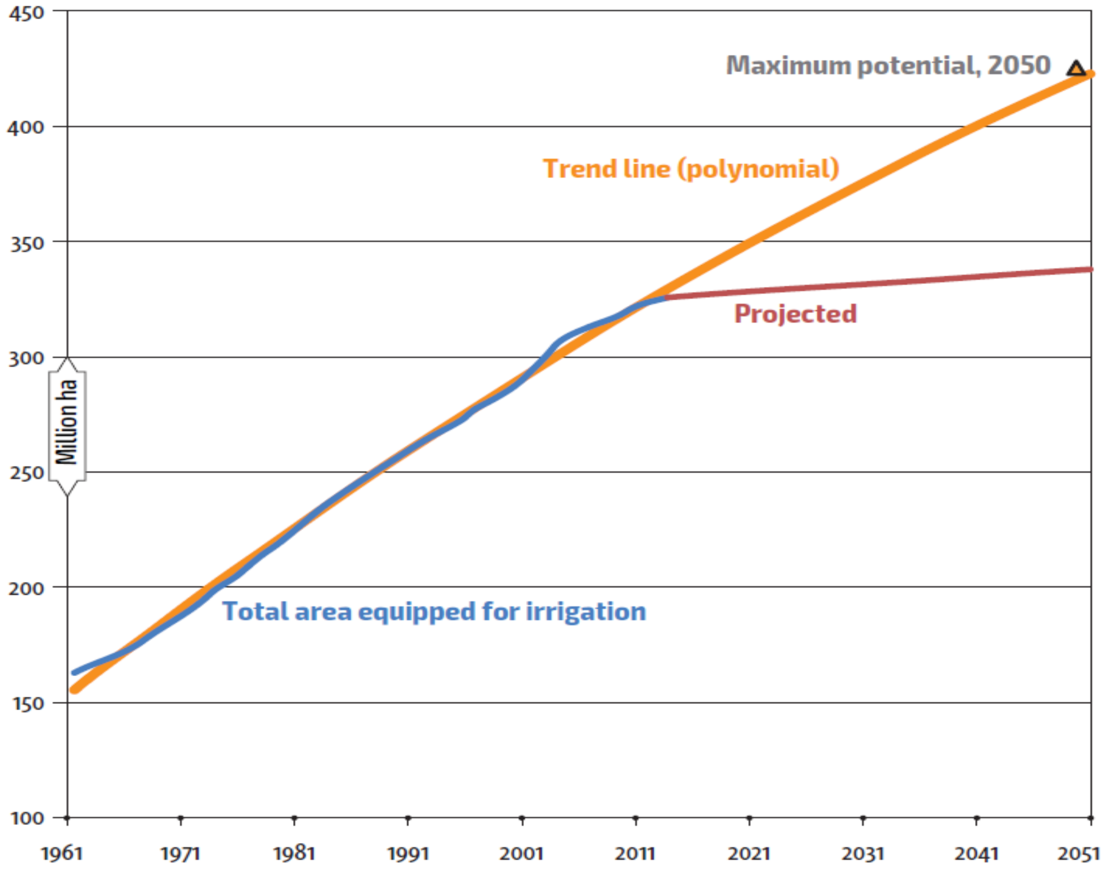


FIGURE 1: Trends and projections in total land equipped for irrigation to 2050

Source: FAO, 2017b

scenario building and analysis. A key point here is that future conditions, while uncertain and difficult to predict, may generate irrigation related opportunities as well as challenges.

- **Development of improved coping strategies.** There is a risk that traditional irrigation related coping strategies will fail as a result of the direct or indirect impacts of climate change. For example, reservoirs may be too small to meet increasing water demands of irrigation and other uses. Similarly, flood events may exceed the capacity of spillways on dams or lead to severe waterlogging due to insufficient capacity of drainage systems. The CSI concept can play a central role in the development of new coping strategies that enhance the resilience and adaptation of irrigation systems to climate change, which brings with it an increased frequency of extreme events (e.g. floods and droughts).
- **High impact, low probability outcomes or impacts.** Many potential outcomes and impacts of climate change are difficult to predict because they have not been experienced before (Taleb, 2008). While the probability of these outcomes or impacts may be low, the risk is that they will disrupt existing irrigation practices and best efforts to improve the resilience of irrigation systems. In such situations, disaster preparedness is crucial if loss of life and livelihoods are to be avoided. CSI can play a role in establishing appropriate procedures and building the capacity of staff to take necessary decisions and preventative actions, should unpredicted climate change related events occur.

1.3 Current status and future trends in global irrigation development

In 2013, the global land area equipped for irrigation was around 325 million ha (FAO, 2017b) (see **FIGURE 1**). During the period between 1961 and 2009, the area equipped for irrigation globally grew at an annual rate of 1.6 percent. FAO has projected that the global area equipped for irrigation may further increase at a relatively low annual rate of 0.1 percent.

Factors that influence area equipped for irrigation globally include:

- **Water scarcity:** With the doubling of irrigated area, water withdrawal for agriculture has been rising sharply, and this is having an effect on the rate of expansion of area equipped for irrigation. Globally, agricultural water withdrawal represents 70 percent of all withdrawals (FAO, 2011a). However, as water resources are very

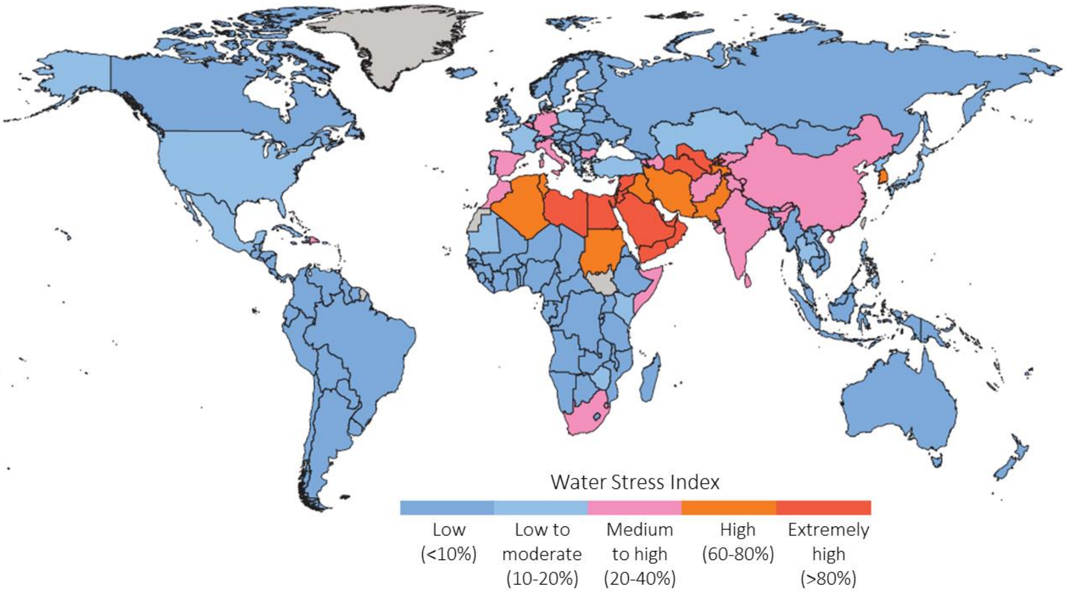


FIGURE 2: Freshwater withdrawals as a percentage of total renewable resources

Source: FAO, 2017b

unevenly distributed, the impact of these withdrawals varies substantially between countries and regions (see **FIGURE 2**). An increasing number of the world's river basins have reached conditions of water scarcity through the combined pressure of agriculture and other sectors. FAO (2011a) estimates that more than 40 percent of the world's rural population lives in river basins that are classified as water scarce.

- **Demand for water is outstripping supply:** Estimates of incremental water requirements to meet future demand for agricultural production under climate change vary from 40 to 100 percent of the extra water needed without global warming. The amount of ground or surface water required for irrigation depends on modelling assumptions related to the expansion of irrigated area – between 45 and 125 million ha. One consequence of greater future water demand and likely reductions in supply is that the emerging competition between the environment and agriculture for raw water will be much greater, and the matching of supply and demand consequently harder to reconcile (FAO, 2011a). The regions that cause most concern are the Near East and Northern Africa (NENA), where water withdrawals are already near or above total renewable resources, and where precipitation is low. In Northern Africa, pressure on water resources due to irrigation is extremely high, resulting in unsustainable use of groundwater.
- **Increased private investment in groundwater-based irrigation:** The large-scale public surface irrigation systems built during the Green Revolution dominated the landscape until the early 1980s and had a profound impact on the flow of many rivers. Over the past 30 years, private investment in groundwater-based irrigation has been stimulated in part by the reduced costs of drilling boreholes and submersible pumps. While this has produced major benefits (e.g. improved rural livelihoods and improved food security), the trade-off has been depletion of aquifers in many countries, including China, India and the United States of America (USA). In contrast, it is notable that access to credit has constrained the investment in irrigation of indebted and/or risk averse farmers.
- **Agricultural intensification and risk reduction:** The amount of land needed to produce food for one person decreased from 0.45 ha in 1961 to 0.22 ha in 2009. During the same period, the extent of irrigated land more than doubled, increasing from 139 to 301 million ha (FAO, 2011a). By providing farmers with access to water, irrigation has been a key factor in agricultural intensification and risk reduction. Continued expansion in areas equipped for irrigation is expected in areas that are well endowed with surplus water resources, as farmers in these areas increasingly look to gain greater control over production factors, secure higher returns and reduce risks of crop failure.
- **Environmental degradation:** Increased use of land, irrigation and agrochemicals played a major role in the growth of agricultural production during the Green Revolution. However, it is now recognized that the gains were often accompanied by negative effects on agriculture's natural resource base, including land degradation, salinization of irrigated areas, over-extraction of groundwater, the build-up of pest resistance and the erosion of biodiversity. Agriculture has also damaged the wider environment through deforestation, the emission of GHGs and nitrate pollution of water bodies (FAO, 2011a).
- **Population increase, urbanization and changing diets:** As the global population heads for more than 9 billion people by 2050 (under medium growth projections), the world is rapidly becoming both urbanized and increasingly wealthy. Food preferences are changing to reflect this, with declining trends in the consumption of staple carbohydrates, and an increase in demand for luxury products – milk, meat, fruits and vegetables – that are heavily reliant on irrigation in many parts of the world (FAO 2011a).
- **Changing flow regimes:** About 40 percent of the world's irrigation is supported by flows originating in the Himalayas and other large mountain systems (e.g. Rocky

Mountains in the western USA and Tien Shan in Central Asia). The loss of glaciers worldwide has been one of the strongest indicators of global warming. Notwithstanding long-running debates over the rate of glacier recession, the contribution of snowmelt to runoff is important in terms of base flows and timing of peak flows, but is more variable in its proportion of total runoff. The impacts on some river systems (such as the Indus) are likely to be significant, and will change the availability of surface water for storage and diversion, as well as the amount of groundwater (FAO, 2011a).

- **Low-income trap:** In most low-income countries, agriculture remains the major employer. Smallholder farmers are often caught in a trap of low earnings, low savings and low investments, which results in low levels of production and productivity. Small farm sizes, fragmentation of landholdings and limited access to equipment and inputs prevent farmers from connecting to value chains and taking advantage of economies of scale. Poor infrastructure, in terms of transport, access to electricity and irrigation, all serve to keep smallholder farmers in this trap. Higher food prices may boost productivity and create employment, but may also increase wage costs and lower competitiveness (World Bank, 2014). Addressing structural constraints remains the key priority for improving agriculture's capacity to create decent employment opportunities.

1.4 Irrigation sector challenges in the face of climate change

In facing up to climate change, the irrigation sector is encountering a great many challenges. Some of these are generic, and also relevant to the agricultural sector in general, and to other sectors. Others are more specific to the irrigation sector. The following list provides an overview of the climate change related challenges, while the rest of the report focuses on how best the irrigation sector can respond to these challenges.

1.4.1 Uncertainty

There is no escaping the fact that uncertainty and climate change go hand-in-hand. Despite decades of ever more exacting science on different aspects of global warming, great uncertainty remains on just how much warming will occur and, more specifically, on rates of atmospheric warming over different land surfaces. There is even more uncertainty in the global climate and modelling systems that are used to predict the effects of greenhouse gas emissions on rainfall and other climate variables, at various spatial and temporal scales. This uncertainty is linked: to inadequacies in the way the models describe complex physical processes; problems of scale;[1] and quality of information used to develop, calibrate and/or drive these models. It is also highly unlikely that some uncertainties will be reduced significantly in the near future given, for example, the lack of observations of past changes relevant to some aspects of both climate forcing[2] and climate change (RS & NAS, 2014).

Climate change may impact the irrigation sector directly as a result of spatial and temporal changes in rainfall that reduce (or in some cases increase) the fraction of rainfall that is consumed by irrigated agriculture. Climate change may also directly impact the irrigation sector via the availability of surface and groundwater (in space and time) and the frequency of extreme events (e.g. floods and droughts). However, the ways in which changes in future rainfall amount and intensity affect surface runoff and groundwater recharge depend on simultaneous changes in evapotranspiration and, just as importantly, on changes in a multitude of additional factors that include land use, land management and land cover, cropping intensity of rainfed and irrigated crops, and groundwater levels. It has to be recognized that changes in land use

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[1] Many physical processes are scale dependent and, as a result, uncertainties are unavoidable if data or model outputs are upscaled or downscaled.

[2] *Climate forcing* (also known as *radiative forcing*) results from imbalances in the Earth's energy budget resulting from increases in greenhouse gases and particles in the atmosphere, and/or changes in the nature of the Earth's surface.

systems and associated change in the patterns of demand for and use of water may be induced by climate change and/or a wide range of semi-dependent causal factors, such as increasing demand for agricultural commodities and changes in government policies.

To make the situation even more complicated, there are possible feedback loops that have the potential to exacerbate (or possibly reduce) potential climate change impacts. Such feedback loops, resulting in part from adaptation (or possibly maladaptation) measures to climate change are not fully considered in current predictions. As a consequence, the prediction with any certainty of the impact of climate change on, for example, the frequency and severity of extreme events (e.g. flooding of droughts) in space and time becomes highly complex and challenging. It is therefore highly unlikely that reliable forecasts of changes in water supply and demand will be available in the foreseeable future, particularly at the scales at which irrigation sector planning generally takes place. For this reason, the challenge, as is discussed later in the compendium, is to develop water sector strategies and plans that are robust across a range of plausible future scenarios.[3]

When attempting to manage uncertainty (e.g. using scenario building and analysis), it is important to note that, arguably, uncertainty linked to understanding the underlying science is less significant than uncertainty linked to the wider political economy of climate change adaptation and mitigation. The following are examples of sources of uncertainty that are linked to the wider political economy of climate change:

- Uncertainty linked to potential trade-offs between food security, energy security and water security (in space and time).
- Uncertainty linked to system behaviour and, more specifically, the ability of systems to adapt to and cope with (or even prosper from) climate change impacts.
- Uncertainty in the perceptions (or mental models) that institutions or people have of climate change and, as important, the scientific evidence that underpins current understanding of climate change. These are and will continue to be diverse, ambiguous and difficult to reconcile.
- Uncertainty in political and financial commitment to climate change mitigation and adaptation (e.g. as part of the 2015 Paris Agreement (see EC, 2017)).
- Uncertainty in the outcomes resulting from implementation of climate change adaptation and mitigation strategies. While the expectation is that outcomes will be positive, the reality is that some outcomes may be perverse. Note that taking an adaptive approach to implementing strategies can reduce the risk of perverse outcomes.

1.4.2 Sector reforms

In many countries, meeting climate change related challenges may require reforms, for example, to the agriculture, irrigation/water and energy sectors, and possibly broader reforms to the ways in which sectors: coordinate and their policies, programmes and expenditure; share information; monitor outcomes; and resolve potential conflicts. More specifically, in order to improve food security and at the same time adapt to changing climatic conditions, policies and practices are required that result in more productive agricultural production systems which use inputs more efficiently, have less variability in their outputs, and are more resilient to risks, shocks and long-term climate variability.

From California to China’s eastern provinces, from Jordan to the southern tip of Africa, an estimated two-thirds of the global population – more than 4 billion people – lives with severe water shortages for at least one month each year (FAO, 2016a). Although, overall, there will be sufficient water in a changing climate to satisfy the demand for food at global level, a growing number of regions will face increasing water scarcity. Indeed, significant parts of the world are already struggling with physical water scarcity (**FIGURE 3**) (FAO, 2016a). In addition, demand for water by other sectors is also

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[3] Ideally, different types of scenario building should be used. This includes scenario building that are 1) Predominantly *descriptive*, i.e. scenarios describing possible trajectories starting from what we know about current conditions and trends, and 2) Predominantly *normative,* i.e. scenarios that are constructed with a view to achieving a shared vision or national or international norms.

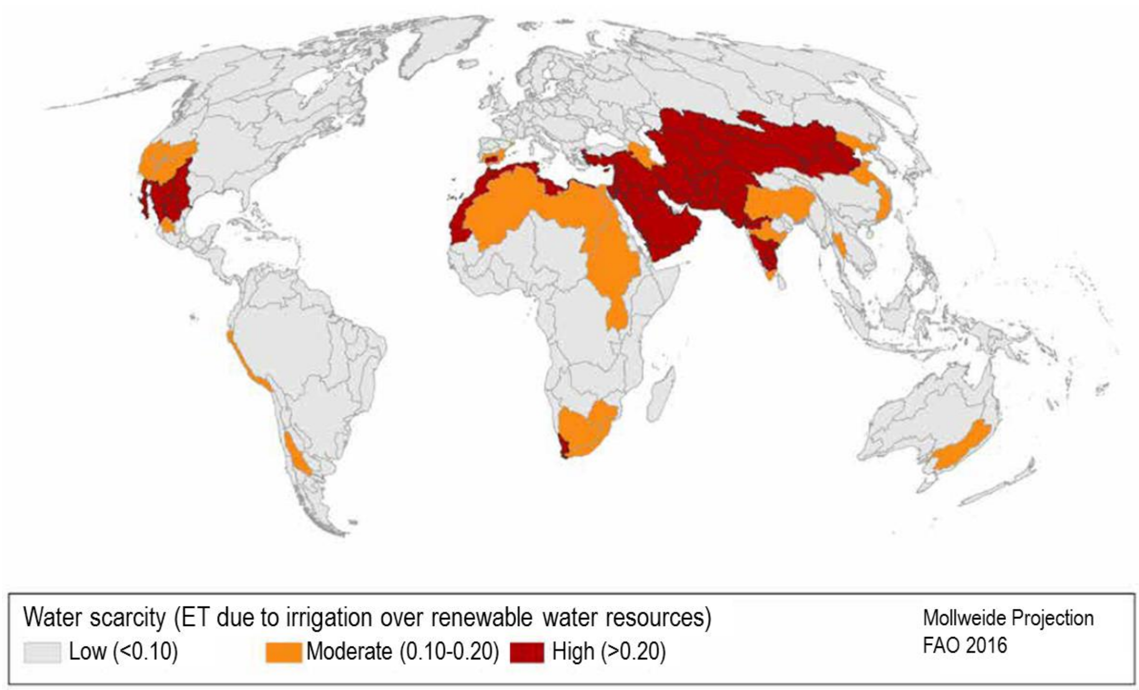

FIGURE 3: Global map of physical water scarcity by major river basin

Source: FAO, 2016a

increasing, albeit starting from a lower base. For example, the following demand increases were projected from manufacturing (+400 percent), thermal electricity generation (+140 percent) and domestic use (+130 percent). In the face of these competing demands, there will be little scope for increasing water allocations to the irrigation sector in many parts of the world (OECD, 2012).

Intersectoral planning and management that take account of climate change induced risks and opportunities are fundamental to the development of resilient irrigated cropping systems that are well adapted to specific agroclimatic and societal contexts. Similarly, the challenge of sustainable, efficient and equitable management of water is generally only possible when there is good intersectoral dialogue, stakeholder engagement and sharing of information horizontally at each institutional level, and vertically between institutional levels. Nested planning processes overcome a number of challenges by ensuring that planning at any given scale informs and is informed by planning at other institutional levels.

There is general agreement that integrated and intersectoral approaches to managing water are becoming more important as a result of increasing competition for limited water resources. This said, many countries have attempted to introduce integrated approaches but, in many cases, with limited success.

To respond to these challenges in a coordinated and effective manner, FAO and a broad range of partners have developed the *Global Framework for Action to Cope with Water Scarcity in Agriculture in the Context of Climate Change* (GFA). The GFA calls for urgent action to cope with water scarcity in agriculture in the context of climate change, and growing sectoral and intersectoral competition for water resources (FAO, 2016a). It recognizes the intricate links between climate change, water scarcity, sustainable agriculture and food security – and the importance of addressing these holistically. Its objective is to strengthen the capacities of vulnerable countries to adapt agriculture to the impacts of climate change and water scarcity and, thereby, to reduce water related constraints to achieving the food security and sustainable development goals of those countries.

The GFA is based on the premise that a sustainable pathway to food security in the context of water scarcity lies in maximizing benefits that cut across multiple dimensions of the food–water–climate nexus, enabling sustainable agricultural production while reducing vulnerability to increasing water scarcity, and optimizing the climate change adaptation and mitigation benefits (**FIGURE 4**) (FAO, 2016a).

1.4.3 Efficiency/productivity conundrum

Efficient and sustainable use of resources is one of the guiding principles of CSI, given that the irrigation sector is both a major consumer of water (e.g. through evapotranspiration) and energy (e.g. for pumping water, producing agrochemicals and operating machinery). As a consequence, pumped irrigation water that is not consumed productively, and crop failure or losses, represent a loss of both water and energy. As might be expected, climate change strategies often include measures aimed at reducing water losses and/or improving the efficiency and productivity of irrigated cropping systems.

A major challenge here is that many losses of pumped water are not real losses when viewed, for instance, from farm, irrigation scheme or river basin scales. For example, pumped water that is ‘lost’ as deep percolation to an aquifer can be pumped and reused locally, and pumped water that is ‘lost’ as drainage can be reused within a large irrigation scheme downstream. The net effect is that, in many (possibly most) cases, the potential for reducing water losses is much less than anticipated. In contrast, return flows in the form of deep percolation or drainage reuse do represent a real waste of energy. This said, return flows often have a lower water quality than the original pumped water, and, in some cases, these flows may be difficult to recover and reuse.

The conundrum is that many water professionals believe that there is huge scope globally for improving the efficiency of irrigated agriculture and freeing up water for other uses. The evidence from research and field measurements shows that this is not the case. The benefit at the local ’on-farm’ scale may appear dramatic, but when properly accounted at basin scale, total water consumption by irrigation tends to increase instead of decrease. (Molle and Closas, 2017).

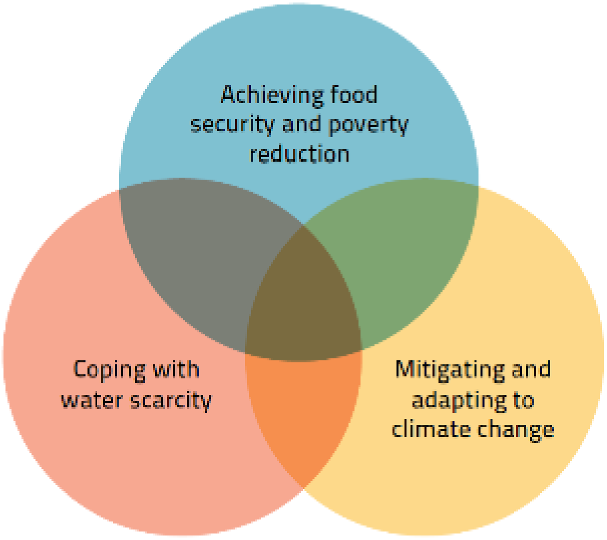

FIGURE 4: The focus of the Global Framework for Action (GFA) in a nutshell

Source: FAO, 2016a

The solution to these problems in areas experiencing increasing water scarcity is relatively simple in conceptual terms: less water must be consumed, and whatever water is available should be used as productively as possible. However, the politics of this solution are far from simple, because choices have to be made regarding who should reduce water use, and choices made are likely to have economic, social and food security implications[4] (Molle and Closas, 2017). The challenge of improving efficiency and productivity is also complicated by the fact that this is not necessarily a high priority for farmers. Farmers in both rainfed and irrigated settings may have more important priorities that relate to, for example, reducing risk, reducing labour requirements and/or maximizing returns (Wichelns, 2014).

1.4.4 Evidence informed planning

Similar to CSA, CSI is not based on or built around a single technology or practice that can be applied universally. It is an approach that requires site-specific assessments that inform decisions related to both irrigation hardware, i.e. infrastructure, and software, e.g. policies, institutions, water governance and management, land and water tenure, farmer know-how, markets and access to credit. In many cases, the starting point is an assessment of existing irrigation policies and practices and identification of underlying causes of good

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[4] Particular consideration should be given to who is paying for irrigation improvement and/or expansion, since this may influence the gross and net profit margins experienced by farmers and their level of interest in irrigation improvements and/or expansion.

and/or poor irrigation performance. Note that assessments can benefit from using approaches such as: 1) Modernizing irrigation management – the Mapping System and Services for Canal Operation Techniques (MASSCOTE) approach (Renault *et al.*, 2007), and 2) Water accounting and auditing (WA&A) (Batchelor *et al.*, 2017).

A key CSI principle is that irrigation improvement or modernization should be based on adaptive approaches that make incremental improvements to irrigation hardware and software as and when new information or evidence becomes available. Challenges here include building and financing the necessary capacity for evidence informed planning and management; improving monitoring systems; and overcoming resistance to change from planning and management systems that are based on a limited number of 'one size fits all' options.

1.4.5 Resistance to change

While there are strong arguments for irrigation sector reform in many countries, the experience of a number of reform programmes is that progress is very slow and that opportunities for making even incremental changes envisaged as part of CSI are often transient or short-lived. Typical challenges faced by sector reform programmes include:

- **Lack of political will or broad support for change.** In many situations, political will is lacking and the reform process relies heavily on a lone champion, who may or may not have sufficient political support to see the reforms implemented.
- **Resistance from middle managers.** Resistance from this intermediate level can be passive or aggressive, but experience has shown that these middle managers can be the level at which reform processes stall.
- **Vested interests.** Often, special interest groups have a vested interest in opposing and/or slowing down reform. The effect that they can have on a reform process depends on how motivated they are, and how quickly and effectively they mobilize opposition to reform.
- **Hostile public opinion**. Many reforms have limited public support, even when they are in the broader national interest. The media often plays a critical role in influencing public opinion either for or against reform.
- **Silent majority**. Potential beneficiaries of reform often have limited opportunities and/or power to influence reform processes. In addition, they tend not to be organized or fully aware of what they stand to gain or lose. This is in contrast to those with vested interests, who are often a minority that is acutely aware of what is at stake.

1.4.6 Resilience

A central aim of CSI is to improve the resilience of irrigation schemes, whether these be large publicly funded schemes or small privately funded and owner operated schemes. Resilience can be described as the capacity of systems, communities, households or individuals to prevent, mitigate or cope with risk and recover from shocks. At first approximation, resilience is the opposite of vulnerability. However, resilience adds a time dimension. A system is resilient when it is less vulnerable to shocks over a period of time, and when it has the ability to recover from them.

Adaptive capacity is an essential element of resilience. From a resilience perspective, adaptive capacity encompasses two dimensions: recovery from shocks and iterative responses to gradual change. Crucial elements of improving resilience include management of known risks, whether climatic or not, and preparedness for future, uncertain risks and changes (FAO, 2013a). Improving and maintaining the resilience of irrigation schemes, irrigated cropping systems and relevant value chains is particularly challenging because these are often complex and vulnerable to many different aspects of climate change (e.g. see **FIGURE 5**).

1.4.7 Water related beliefs and misconceptions

Decision-making based on beliefs and misconceptions is commonplace in the water and irrigation sectors. For example, beliefs and misconceptions relate to the effects of deforestation, afforestation and other land use changes on the hydrology of river basins. Some typical examples of the disparities between popular narratives and the findings of decades of detailed research are listed in **TABLE 1**. Unfortunately, some of these popular narratives are prevalent in the media and climate change adaptation plans. A key challenge is therefore to replace beliefs and misconceptions with facts and evidence that stand up to scrutiny when developing and implementing climate change mitigation and adaptation plans.

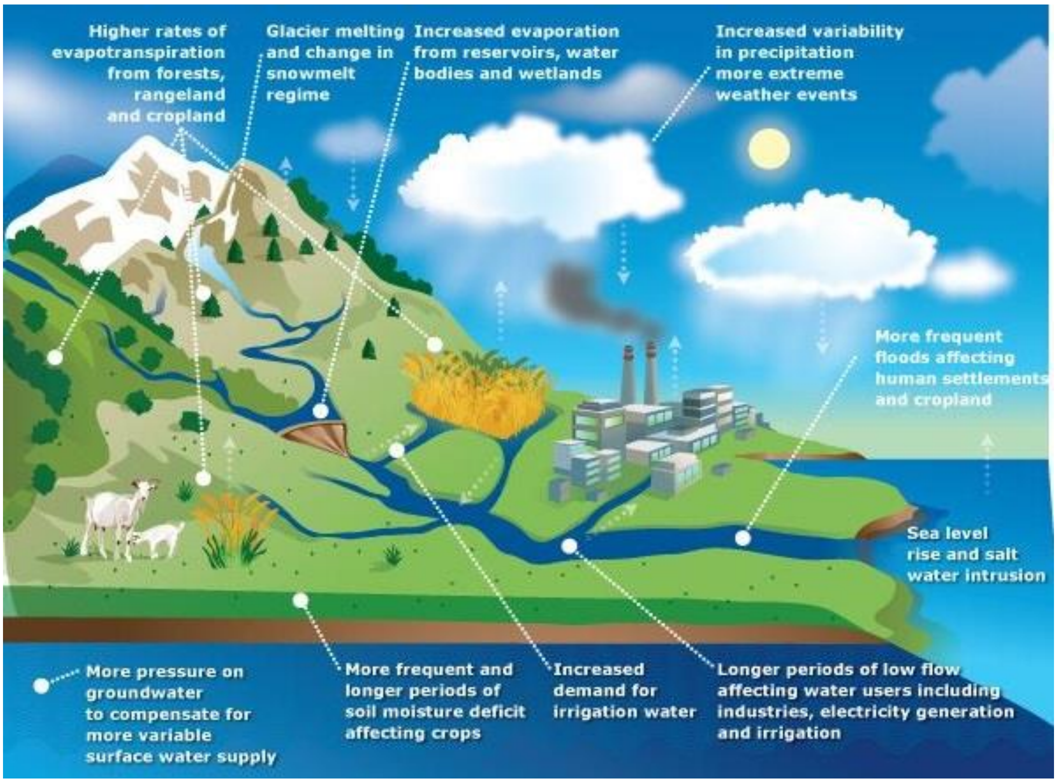

FIGURE 5: Effects of climate change on the elements of the water cycle and their impacts on agriculture

Source: FAO, 2017a

TABLE 1: Typical disparities between scientific consensus and public beliefs/misconceptions

Forest-water relationships	Popular narrative	Key findings
Forests and rainfall	*Forests increase rainfall (and conversely, the removal of forests decreases rainfall).*	The clearing of forests is highly unlikely to reduce total rainfall, and conversely, there is no evidence that reforestation increases rainfall. Caveat: In the few locations where occult precipitation[5] occurs, the clearing of cloud forests can cause a reduction in net precipitation.
Forests and water yield	*Forests increase water yield (and conversely, the removal of forests decreases water yield).*	For annual rainfall regimes greater than about 500 mm per year, forests use more water than shorter forms of vegetation because deeper root systems, higher Leaf Area Indices and greater rainfall interception lead to higher evapotranspiration. Taller forms of vegetation are also associated with greater surface roughness than shorter forms, which induces greater turbulence, leading to higher transpiration. Hence humid forested catchments yield lower total volumes of water (for wells, springs and streams) than humid catchments covered by shorter forms of vegetation.
Forests and floods	*Forests reduce floods (and conversely, the removal of forests increases floods).*	(1) Increases in peak (flood) flows as a result of cutting trees are observable for small- to medium-sized rainfall events in relatively small catchments – less than about 10 km^2. (2) The major determinants of large-scale flooding at all catchment scales are rainfall amount and intensity, antecedent rainfall and catchment geomorphology – not vegetation type.

After: FAO and CIFOR, 2005; Ong et al., 2006; Hamilton et al., 2008; Gilmour, 2014

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[5] 'Occult precipitation' is precipitation in liquid (fog drip) and solid (rime) forms that are induced when clouds or fog encounter trees or other vegetation.

This is not always easy since facts and evidence do not necessarily change opinions. Many beliefs are deep-seated, and holders of them have a tendency to reject any facts or evidence that challenge or are inconsistent with these.

1.4.8 Reducing GHG emissions

The challenge of mitigating GHG emissions is complicated by the fact that a number of different gases are involved, and processes of GHG emission and capture are a result of natural and anthropogenic activities, some of which relate to agriculture, forestry and other land uses (AFOLU) and land and water management practices (FAO, 2017a). As a consequence, measuring and monitoring GHG emissions with confidence is a challenge.

FIGURE 6 indicates how land use and management can influence a variety of ecosystem processes, which in turn can affect GHG fluxes such as photosynthesis, respiration, decomposition, nitrification/denitrification, enteric fermentation, and combustion. Note that these processes involve transformations of carbon and nitrogen, driven by biological (activity of microorganisms, plants and animals) and physical processes (combustion, leaching, and runoff) (Tubiello *et al.*, 2015). Production factors that have an important influence on total agricultural GHG emissions include (FAO, 2013a):

- **Extent of the area of interest** given that cultivation of new areas, in general, requires either deforestation or grasslands being converted to croplands, which would induce higher carbon dioxide (CO_2) emissions.
- **Energy used and associated CO_2 emissions** that result from pumping and pressuring water for irrigation, from operating machinery and transporting goods, products and labour up to and beyond the farm gate.
- **Levels of fertilizer usage**, given that fertilizers are an important source of CO_2 and nitrous oxide (N_2O) emissions.
- Food losses up to and beyond the farm gate effectively **increase CO_2 emissions per unit of product** that is consumed and/or reaches end users.
- **Number and type of livestock**, given that livestock are an important source of methane (CH_4) and N_2O emissions.

GHG emissions resulting from AFOLU include (Tubiello *et al.*, 2015):

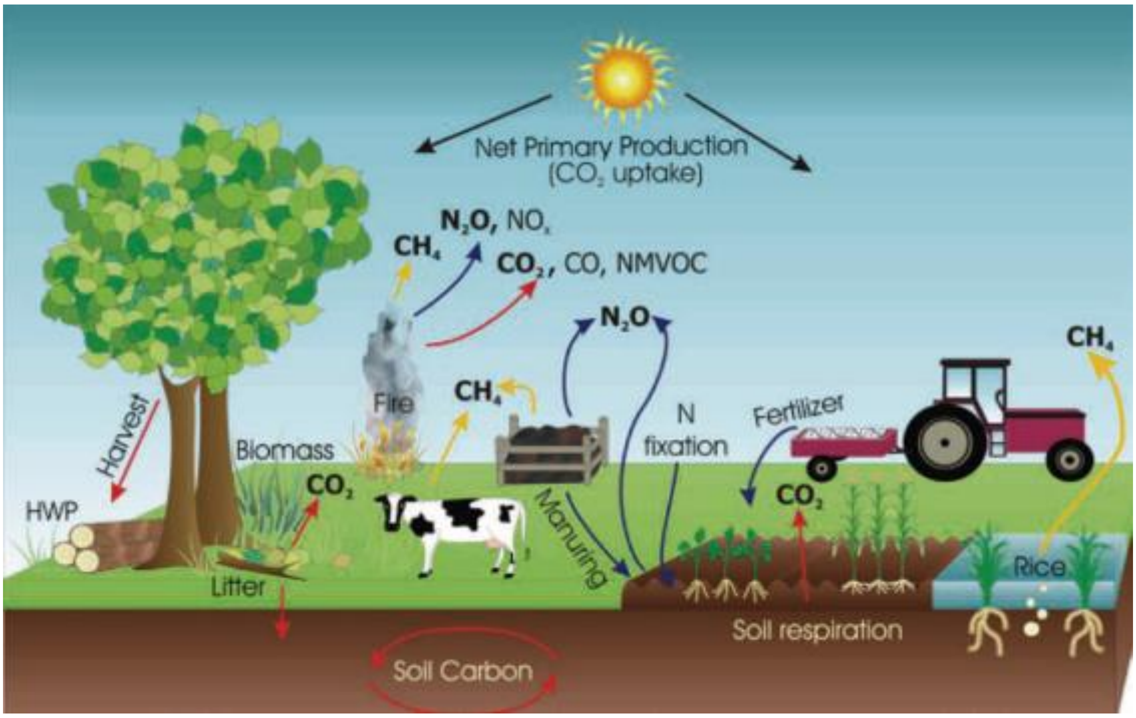

FIGURE 6: GHG emission sources/removals and processes in managed ecosystems

Source: IPCC in Tubiello et al., 2015

- CO_2 emissions and removals resulting from carbon (C) stock changes in biomass, dead organic matter and harvested wood/timber.
- CO_2 from cultivated organic soils.
- non-CO_2 emissions from, for example, burning crop residues on all managed land.
- CH_4 emissions from rice cultivation.
- N_2O emissions from all managed soils.
- CO_2 emissions associated with liming and urea application to managed soils.
- CH_4 emissions from livestock enteric fermentation.
- CH_4 and N_2O emissions from manure management systems.

Greenhouse gas fluxes can be estimated in two ways:

- As net changes in carbon stocks over time (used for estimating most CO_2 fluxes).
- Directly, as gas flux rates to and from the atmosphere (used for estimating non-CO_2 emissions and some CO_2 emissions).

The Climate-Smart Agriculture Sourcebook (FAO, 2017a) lists two major ways in which agricultural production can contribute to mitigation of climate change, which are in line with the 'food security first' objective. The first is to improve efficiency by decoupling production growth from GHG emissions growth. This involves reducing emissions per kilogram of food output (included in this calculation are the effects of emissions from reduced deforestation per kilogram of food). The second way is to enhance soil carbon sinks. The Intergovernmental Panel on Climate Change (IPCC) estimated that the greatest part of the technical mitigation potential of agricultural GHG emission (89 percent of a total of 5 500 to 6 000 Mt CO_2-eq per year) lies in soil carbon sequestration (Metz *et al.*, 2007). The mitigation potential for non-CO_2 emissions was estimated at 2 percent for NO_2 and 9 percent for CH_4, corresponding to approximately 1 and 6 percent of the estimated 8 200 Mt CO_2-eq of annual agricultural non-CO_2 emissions from agriculture by 2030, respectively. This means that the greatest GHG mitigation potential in agriculture is linked to managing land carbon stocks. This involves enhanced soil carbon sequestration, reduced tillage, improved pasture and rangeland management, restoration of soil organic matter, and restoration of degraded lands. About 70 percent of this identified potential lies in developing countries, 20 percent in Organisation for Economic Co-operation and Development (OECD) member countries, and 10 percent in economies in transition (EIT) countries. A third way would involve changes in consumption patterns (note that this option is not discussed in detail in the Climate-Smart Agriculture Sourcebook; FAO 2013a).

1.4.9 Synergies and trade-offs

Ideally, climate change mitigation and adaptation strategies for the irrigation sector should be synergistic, with few if any trade-offs or negative externalities that are not politically, socially and environmentally acceptable. This is often a major challenge given that: 1) It can be difficult to integrate both mitigation and adaptation within a common analytical and/or planning framework because spatial and temporal scales of most interest are often different; 2) Mitigation and adaptation strategies are often developed independently of each other, in part because different institutions are involved and/or funding comes from different sources; and 3) Simplistic assumptions are made that strategies will be win-win in nature, regardless of the agroclimatic, societal or political context.

More positively, many potential intersectoral synergies exist that encompass both climate change mitigation and adaptation. For example, potential synergies exist between climate-smart energy generation (e.g. using solar panels) and climate-smart irrigation (e.g. using solar pumps). Similarly, many potential trade-offs exist, for example, between use of CSI to produce biofuels and use of CSI to produce agricultural commodities for human consumption. Less obvious trade-offs exist between the health sector and CSI, for example: water storage tanks, ponds and reservoirs are often constructed as part of CSI. While this infrastructure may be necessary to ensure that CSI is productive and cost-effective, it can create breeding grounds for mosquitoes and lead to increases in malaria and other waterborne diseases. It is notable that this and other health related trade-offs may be exacerbated, in some regions, if anticipated increases in temperature and/or rainfall occur.

Interrelated actions at different institutional levels can also be synergistic and/or result in trade-offs. For example, management decisions at irrigation scheme level may result in access to irrigation services that are more sustainable, reliable and equitable. However, the trade-off may be that some farmers in the scheme may have to accept a reduction in their own water supply and/or level of service. In addition, trade-offs often exist between financial support for immediate actions aimed at upgrading the poor performance of irrigation schemes and financial support for actions aimed specifically at improving resilience to climate change, i.e. there are insufficient funds available to both upgrade the performance and the resilience of irrigation schemes at the same time.

Finally, an important trade-off that is often overlooked exists between the uptake of CO_2 from the atmosphere by plants as part of photosynthesis and the loss of water vapour from leaves as transpiration. The ratio of water loss to carbon gain (referred to as the transpiration efficiency) is a key characteristic of ecosystem functioning that is central to the global cycles of water, energy and CO_2. A key consequence of this ratio is that any intensification of irrigated or rainfed land use that increases vegetative cover is likely to increase consumptive water use, assuming that evapotranspiration is not limited by a soil moisture deficit.

1.5 Key messages

- Climate-smart irrigation is an important **integral component** of climate-smart agriculture**.**
- Climate-smart irrigation is not a set of practices that can be universally applied. Rather, it is an approach that involves different elements embedded in local contexts, policies, institutions and practices.
- Farmers have used irrigation for many thousands of years to overcome constraints on crop growth and quality that are caused by spatial and temporal **variability in rainfall** and/or soil water characteristics (e.g. soil depth, hydraulic conductivity and water retention properties). There is increasing evidence that rainfall variability is increasing as a result of climate change.
- Over time, the development, adaptation and adoption of **good irrigation practices** in given agroclimatic and societal contexts has played a central role in: 1) Stabilizing agricultural production by supplementing rainfall and retained soil moisture during occasional or prolonged dry spells, and 2) Extending cropping into dry seasons and/or arid/semi-arid areas.
- Typically, **good irrigation practices** are founded on a mix of technical and non-technical measures, knowledge, know-how and lessons learned relating to the different elements of irrigation systems from the source of water to the final phase of value chains.
- There is no escaping the fact that **uncertainty** and climate change go hand-in-hand. Despite decades of ever more exacting science, the rates and impacts of climate (in space and time) are uncertain.
- Farmers, planners, ecologists, politicians and the general public have **different perspectives** on what constitutes good irrigation practice.
- Since 2009, there has been a marked decline in the rate of expansion of the global **area equipped for irrigation**.
- A key CSI principle is that irrigation improvement or modernization should be based on adaptive approaches that make **incremental improvements** to irrigation hardware and software, as and when new information or evidence become available.

2. IMPLICATIONS OF CLIMATE CHANGE FOR IRRIGATION

2.1 Expected changes in global climate and sea levels

2.1.1 Global warming

It is likely that countries around the world will face climate change impacts that affect a wide variety of sectors, from water resources to ecosystems to human health (EPA, 2016). Global warming of just a few degrees will be associated with widespread changes in regional and local temperature and precipitation, as well as with increases in some types of extreme weather events. It is anticipated that these and other changes (such as sea level rise and storm surges) will have serious impacts on human societies and the natural world (RS & NAS, 2014) (See **FIGURE 7**).

Both theory and direct observations have confirmed that global warming is associated with greater warming over land than oceans, moistening of the atmosphere, shifts in regional precipitation patterns and increases in extreme weather events, ocean acidification, melting glaciers, and rising sea levels (which increases the risk of coastal inundation and storm surge) (RS & NAS, 2014). Already, record high temperatures are outpacing record low temperatures, wet areas are becoming wetter as dry areas are becoming drier, large rainfall events are becoming more intense, and snowpacks (an important source of seasonal river flow and freshwater for many regions) are decreasing. The level of these impacts is expected to increase with greater warming and to threaten food production, freshwater supplies, coastal infrastructure, and the welfare of the huge population currently living in coastal and other low-lying areas. Even though certain regions may realize benefits from global warming, the overall long-term consequences will be negative and/or disruptive.

Assessments of the potential impacts of climate change on the irrigation sector indicate that water availability (in the form of precipitation, surface water and groundwater) will be a critical factor. Substantial adaptation will be needed to ensure adequate supply and efficient utilization of what will, in many instances, be a declining and increasingly contested resource (After Turral *et al.*, 2011). However, the long-term climatic risks to irrigated lands, irrigation infrastructure and relevant value chains are difficult to predict with any certainty. While global circulation models can project temperature and pressure variables with a high

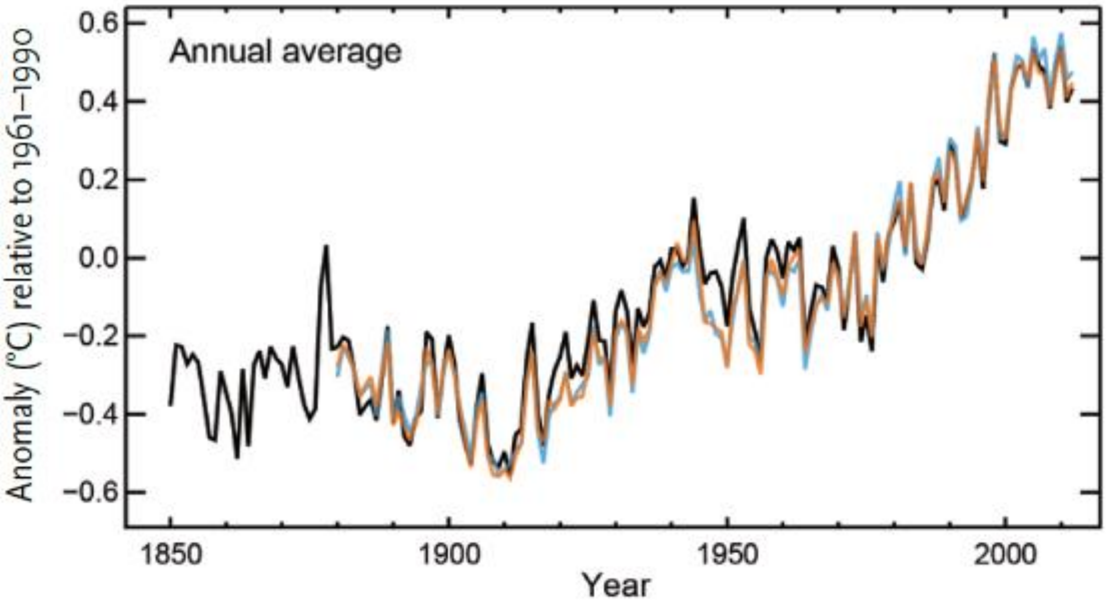

FIGURE 7: Change in global average surface temperature between 1850 and 2012 relative to average surface temperature from 1961 to 1990

Temperatures combine measurements from land and ocean surfaces.

Source: IPCC in RS & NAS, 2014

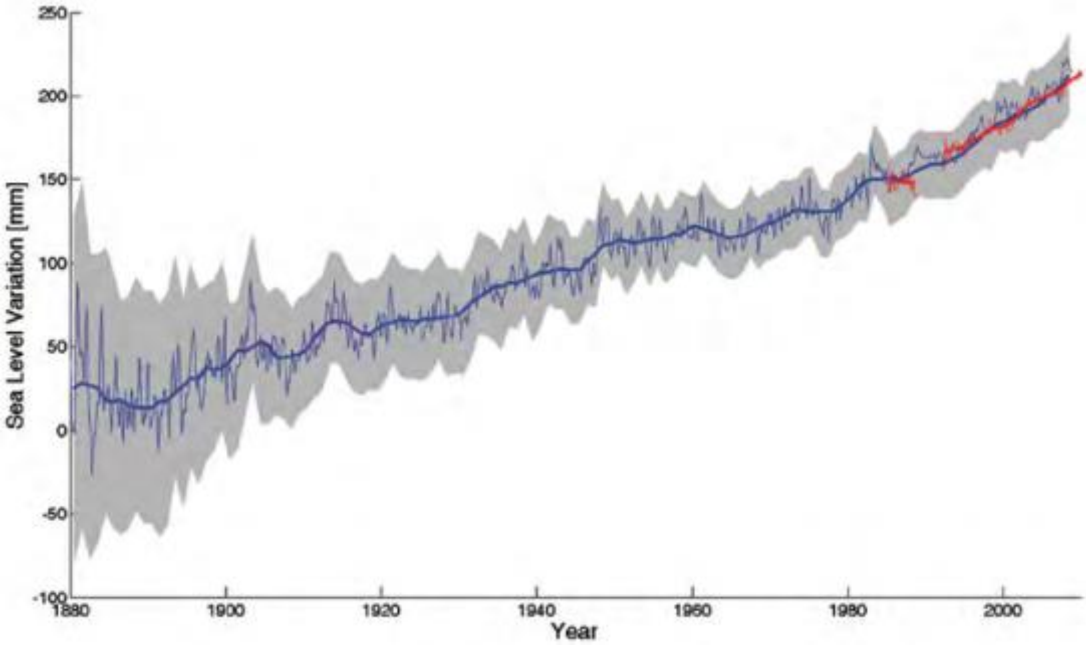

FIGURE 8: Estimated change in global average sea level between 1880 and 2012

The grey shaded area represents uncertainty of estimates, which decreases over time as number of tidal gauge sites increase.

Source: Shum and Kuo in RS & NAS, 2014

degree of 'convergence', the same cannot be said of water vapour in the atmosphere. Hence the levels of risk associated with rainfall and runoff events can only be determined with provisional levels of precision.

2.1.2 Changes in climate

Rainfall is predicted to rise in the tropics and higher latitudes, but decrease in the already dry semi-arid to arid mid-latitudes and in the interior of large continents. As a consequence, it is expected that water scarce areas of the world will generally become drier and hotter (Turral *et al.*, 2011). Both rainfall and temperatures are predicted to become more variable, with a consequent higher incidence of droughts and floods, sometimes in the same place. Runoff patterns are harder to predict as they are governed by land use as well as uncertain changes in rainfall amounts and patterns. Substantial reductions (as much as -40 percent) in regional runoff have been modelled in southeastern Australia and in other areas where annual potential evapotranspiration exceeds rainfall. Notably, relatively small reductions in rainfall will translate into much larger reductions in runoff, for example, a 5 percent reduction in precipitation in Morocco will result in a 25 percent reduction in runoff (Turral *et al.*, 2011). In glacier-fed river systems, the timing of flows will change, although mean annual runoff may be less affected.

It is notable that climate change can lead to a change in the mean (average) of a climatic variable, such as rainfall, and/or its variability (UK-US Taskforce, 2015). Changes in variability are just as important as changes in the average. To give an example, climate change may result, on average, in an area getting wetter; however, if the variance is also increasing, it is possible for both floods and droughts to become more common. As extreme weather is often associated with the highest impacts on the functioning of irrigation systems, it is important to understand exactly how the shape of the distribution of climatic variables will change relative to the mean. While there is currently incomplete understanding of how extreme weather events are changing, there is nonetheless good evidence that these events, from intense storms to droughts, floods and heatwaves, are increasing in frequency and severity.

2.1.3 Changes in sea level

Long-term measurements of tide gauges and recent satellite data show that global sea level is rising, with best estimates of the global average rise over the past two decades centred on 3.2 mm per year. The overall observed rise since 1901 is about 20 cm (see **FIGURE 8**). This sea level rise has been driven by (in order of importance): expansion of water volume as the ocean warms, melting of mountain glaciers in most regions of the world, and losses from the Greenland and Antarctic ice sheets. All of these result from a warming climate. In addition, fluctuations in sea level also occur due to changes in the volume of water stored on land. The amount of sea level change experienced at any given location also depends on a variety of other factors, including whether regional geological processes and rebound of the land weighted down by previous ice sheets are causing the land itself to rise or sink, and whether changes in winds and currents are piling ocean water against some coasts or moving water away (RS & NAS, 2014). From an irrigation sector perspective, changes in sea level and storm surges threaten delta and other coastal or low-lying areas which, in many regions, are the location of highly productive irrigation schemes (e.g. the Nile Delta).

The sea level nearer to the equator is projected to be higher than the global mean of 100 cm at the end of the century. In Southeast Asia for example, sea level rise is projected to be 10–15 percent higher than the global mean (World Bank, 2014). Coupled with storm surges and tropical cyclones, this increase is projected to have devastating impacts on coastal systems.

In addition to the effects on climate, excess carbon dioxide in the atmosphere can be taken up by the ocean and lead to ocean acidification that can have a negative impact on some marine organisms (such as corals and some shellfish). However, marine acidification has the potential to influence the cycling of nutrients and many other elements and compounds in the ocean (RS & NAS, 2014). This in turn could shift the competitive advantage among species, with as-yet-to-be-determined impacts on marine ecosystems

2.2 Expected direct and indirect impacts of climate change

It is becoming increasingly apparent that climate change has the potential to impact all aspects of a functioning irrigation system. This includes: the **supply side** (e.g. delivery of irrigation services); the **demand side** (e.g. demand for irrigation services); irrigation **hardware** (e.g. irrigation infrastructure) and irrigation **software** (e.g. irrigation policies and institutions); and all the main elements of a functioning irrigation system from the source of water through to the consumption and/or sale of produce from irrigated agriculture. There is also growing recognition that some climate change impacts will be direct and relatively obvious, for example, the immediate consequences of floods, droughts and heatwaves. Other impacts are likely to be indirect and to have a cascading effect on human health, the environment and development.

TABLE 2 summarizes typical direct and indirect impacts of climate change on the main elements of a functioning irrigation system, i.e. sources of irrigation water, irrigation infrastructure, demand and access to irrigation services and irrigation value chains. The list provided in **TABLE 2** is not exhaustive, and focuses more on biophysical than on societal impacts.

2.3 Relative impacts of climate change and irrigation development

Across much of the world, climate change is not taking place in the context of pristine watersheds or river basins. Rather, the norm is that climate change is impacting watersheds and river basins in which many centuries of development, land use change and possibly degradation of environmental resources have already occurred. Hence, from an irrigation development perspective, it is important to consider whether the expected impacts of climate change are likely to exacerbate existing irrigation related challenges (e.g. competition for limited water resources) or alleviate these challenges (e.g. as a result of possible increased rainfall).

It is also important to recognize that the policy imperative in many regions is to expand the area under irrigation and/or to intensify production within existing schemes, with a view to achieving outcomes that include improved food security, improved rural economies and improved farmer income. In some cases, new investments in irrigation development are made by the public sector. While in many areas, new investments are predominantly made by the private sector, e.g. the widespread private investment in groundwater-based irrigation in South Asia. In either case, new investments in irrigation should take into account the impacts of climate change on local water availability and incorporate them into system planning and engineering design (Medeiros DuBois *et al.*, 2012).

In arid and semi-arid areas, climate change will place additional burdens on already overstretched water resources. In these areas, the irrigation sector will need to respond to the challenges posed by increasing human pressures on these resources, as well as to emerging climate change related challenges. In other places, climate change will be the main driver of change and will require specific climate change related responses. **TABLE 3** presents the relative importance of climate change and irrigation development in relation to different elements of the hydrological cycle. The relative impacts of climate change will vary from one agricultural system to another, but it is important that adaptation and mitigation strategies take into account the overall context in which they are to be implemented.

2.4 Relative impacts of climate change on public and private irrigation schemes

Typically, irrigation schemes are categorized according to: size, nature of the water source (e.g. surface or groundwater), and whether schemes are operated publicly or privately (Snellen, 1996). However, categorization according to size at global level is complicated by the fact that schemes considered large-scale in, for example, sub-Saharan Africa, would be considered small- or medium-scale in South Asia. Similarly, categorization on the nature of the water source does not, for example, recognize the very different characteristics of major public surface water schemes based on dams in the USA and relatively small community-managed tank irrigation schemes in southern India or Sri Lanka.

Therefore, for the purpose of evaluating climate change impacts, it is more useful to categorize irrigation schemes according to whether they are: 1) **Public irrigation schemes**, in which government has a dominant financial interest and management responsibility; or 2) **Private irrigation schemes**, in which farmers (or private companies) have a dominant financial interest and management responsibility. This said, it should be noted that hybrid arrangements are common. For example, governments often take an interest in private irrigation by facilitating irrigation development, providing incentives and/or regulating demand for water in one way or another. It is also common for governments to turn over responsibility for operation and maintenance of irrigation schemes to the private sector.

From a CSI perspective, it is important to note that public irrigation tends to be supply-driven and incorporate political or social objectives, while private irrigation tends to be demand-driven and incorporate financial objectives (e.g. returns on investments). **TABLE 4** lists some additional differences between public and private irrigation which, depending on the context, may be relevant to climate change mitigation and adaptation.

While there are many potential differences between small and large irrigation schemes, there is limited evidence to suggest that small-scale irrigation is more or less likely than large-scale irrigation to achieve intended outcomes (Snellen, 1996). Nevertheless, it can be argued that where irrigation institutions – public or private – are relatively weak and where there is a lack of capacity to plan, implement, operate and manage large schemes, attention should focus on smaller developments. Smaller schemes are more conducive to farmer management and control, and market limitations for the crops produced often make such schemes the only viable choice. On the other hand, there are many examples of the development of small public irrigation systems globally that have overstretched the logistical and staffing capabilities of irrigation agencies, and have eventually failed. In theory, larger contiguous irrigation developments should encourage more government support, attract better management, be easier to organize, and should therefore enjoy better prospects for sustainability and effective climate change mitigation and adaptation.

TABLE 2: Examples of possible direct and indirect climate change impacts on the elements of a functioning irrigation system

Sources of irrigation water		**Irrigation infrastructure**		**Irrigation demand & access**		**Irrigation value chains**	
Direct	**Indirect**	**Direct**	**Indirect**	**Direct**	**Indirect**	**Direct**	**Indirect**
▪ Decreased rainfall in some areas and increased rainfall in others ▪ Increased inter- and intra-annual rainfall variability ▪ Increased frequency of extreme events (e.g. floods, droughts) ▪ Increased or decreased runoff and/or groundwater recharge ▪ Increased or decreased water stored in glaciers or snowpack	▪ Increased or decreased demand for irrigation leading to unsustainable use of water resources ▪ Increased or decreased intersectoral competition for water sources ▪ Rising sea levels leading to saline intrusion and inundation of delta, coastal and low-lying areas ▪ Intensification of rainfed agriculture leading to reductions in runoff coefficients	▪ Increased or decreased investments in storage, treatment and bulk transfer infrastructure ▪ Increased investments in flood protection and re-engineering of e.g. spillways ▪ Increased investment in land levelling, in-field irrigation equipment etc. ▪ Increased investment in water management and irrigation scheduling infrastructure	▪ Increased incidence of e.g. illegal connections to pipelines ▪ Increase in private investment in infrastructure for accessing alternative or additional sources of water ▪ Increased use of solar pumps as part of CC mitigation ▪ Increased investment in metering and monitoring equipment (e.g. web sensors, unmanned aerial vehicles (UAVs) as part of water regulatory systems	▪ Increased demand for irrigation at policy and farmer levels ▪ Greater incentives to increase efficiency and productivity of water uses and users ▪ Increased use of a range of water demand management approaches ▪ Increased attention to irrigation 'software', e.g. improved governance, extension services	▪ Improvements in food security ▪ Improved rural economy and rural livelihood opportunities ▪ In some contexts, increased gap between irrigation demand and access ▪ Increased risk of negative externalities or trade-offs, e.g. tail-ender problems, reduced environmental flows, capture of benefits by elites etc. ▪ Increased risks of pollution of surface and groundwater	▪ Potential changes to the value chain needed to take account of changes to crops and cropping systems prompted by CC ▪ Increased expenditure on hardware and software needed to improve economic, social and environmental sustainability and resilience of value chains ▪ Improved preparedness for extreme events	▪ Increased attention to reducing 'wastage' and loss of virtual water along the field-to-fork value chain ▪ Increased attention to ensuring equitable risk and profit sharing along the value chain ▪ Improved climate change related risk management along value chains and attention to social and environmental safeguards, e.g. linked to woman and children

TABLE 3: Relative impacts of climate change and irrigation development on elements of the water cycle

Elements of the water cycle	**Expected impacts from**	
	Climate change	**Irrigation development activities**
Annual precipitation	▪ Rainfall is expected to rise in the tropics and higher latitudes, but decrease in the already dry semi-arid to arid mid-latitudes and in the interior of large continents.	▪ No or minor impact.
Inter-annual variability in precipitation	▪ Expected to increase everywhere.	▪ No or minor impact.
Intra-annual variability in precipitation	▪ Expected to increase everywhere.	▪ No impact.
Extreme events (e.g. floods, droughts and heatwaves)	▪ Expected higher incidence of droughts, floods and heatwaves.	▪ Widespread development of irrigation systems is expected to moderate impacts of small to medium flood events, but have a less moderating influence on major flood events. ▪ Unsustainable use of ground or surface water is expected to exacerbate the impact of droughts over time. ▪ Irrigation is expected to moderate the local severity of heatwaves (as a result of decreases in the Bowen Ratio in irrigated areas).
Soil moisture	▪ Climate change is expected to make good soil management more of a challenge, especially in areas that have not adopted conservation agriculture (e.g. as a result of increased frequency of high intensity rainfall events, loss of organic matter, etc.).	▪ Depending on irrigation and soil management practices, irrigation is expected to have a positive or negative impact on soil hydraulic characteristics.
Snowpack and glacier melt	▪ Rising temperatures and changes in albedo are expected to accelerate snowpack and glacier melt with initial increases in river flow followed by decreases.	▪ No impact.

Evapotranspiration	▪ Increased air temperature is expected to increase evapotranspiration by increasing the vapour pressure deficit. Increased or decreased rainfall and cloud cover may increase or decrease evapotranspiration via changes in solar radiation reaching the land surface.	▪ Increases in the area under irrigation and in the intensity of irrigation (e.g. single, double and triple cropping) will increase evapotranspiration relative to rainfed crops and cropping systems. ▪ Actual evapotranspiration from irrigated crops will be close to potential evapotranspiration when irrigation systems are well managed and maintained.
River discharge	▪ Increased variability in flow regimes is expected as a result of increased inter- and intra-annual rainfall variability. ▪ Amplified decrease in runoff is expected in areas with decreased annual rainfall. In contrast, runoff may increase in areas experiencing increased annual rainfall. ▪ Seasonal changes are expected in river discharge, e.g. in base flows during dry seasons. ▪ Some changes are expected in the nature and severity of water quality problems, e.g. as a result of increased temperatures.	▪ Increased diversions of surface water for irrigation are expected to deliver benefits (e.g. improved food security, rural economies, etc.), but with significant trade-offs locally and downstream (e.g. reduced water for environmental flows and other water uses and users, particularly in water scarce areas. ▪ Construction of small, medium and large reservoirs, increased area under irrigation and intensification of rainfed agriculture are expected to impact river discharge and patterns of surface water availability and use in space and time. ▪ Intensification of irrigated agriculture along with urbanization is expected to increase levels of pollution in river systems.
Groundwater	▪ Increased variability in groundwater recharge is expected as a result of increased inter- and intra-annual rainfall variability. ▪ Similar to river discharge, an amplified decrease in groundwater recharge is expected in areas with decreased rainfall and an increase in recharge in areas experiencing increased annual rainfall. ▪ Some changes in the levels of natural and anthropogenic contaminants in groundwater are expected as a result of climate change (CC) induced changes in surface water chemistry (e.g. increased salinity).	▪ Increased extraction for groundwater-based irrigation is expected as competition for surface water increases, and as the capital and recurrent costs fall in real terms, or as a result of subsidies. ▪ Increased and unsustainable groundwater extraction is expected to lead to falling groundwater levels and reductions in river discharge. ▪ Unsustainable groundwater extraction is expected to increase the incidence of arsenic and fluoride in groundwater.

Wetlands and lakes	▪ Increased variability in the water balances (inflow and outflows) of wetlands and lakes is expected as a result of increased or decreased annual rainfall and increased variability. ▪ Increased groundwater extraction is expected to impact the ecological functionality of wetlands and lakes and, in extreme cases, to result in their drying up. ▪ Changes in rainfall regimes and increased temperatures are expected to alter the buffering capacity of wetlands and lakes in terms of nutrients, sediments and river flows. ▪ Rising temperature is also expected to lower water quality in lakes as a result of e.g. lower oxygen concentration.	▪ Increased diversion of surface water and increasing extraction of groundwater, along with expansion and intensification of irrigation schemes and cropping systems, is expected to have a negative impact on the ecological integrity and functionality of wetlands and lakes. ▪ Increased engineering of water courses (e.g. construction of dams and canalization of rivers) and increased levels of pollution are also expected to have a negative impact on the goods and services provided by wetlands and lakes. ▪ Shallow groundwater tables, waterlogging and poorly drained irrigation schemes can be expected to raise the incidence of many waterborne diseases such as malaria, filariasis, yellow fever, dengue and schistosomiasis.
Seas and oceans	▪ The rate of sea level rise over the past two decades was around 3.2 mm per year, but it is expected that this rate may accelerate. ▪ The severity and frequency of storm surges are also expected to increase in coming decades, along with increasing inundation of delta, coastal and low-lying areas. ▪ Saline intrusion into groundwater is expected to be an increasing problem for coastal aquifers, and aquifers along tidal estuaries and watercourses. ▪ Sea level rise is expected to have a diverse range of impacts, including damage to coastal infrastructure that is relevant to agricultural value chains, e.g. roads, bridges, storage facilities, processing and packaging plants.	▪ Expansion and intensification of irrigation areas in delta, coastal and low-lying areas is expected, in many cases, to exacerbate impacts of sea level rise. ▪ Increased irrigation, watershed development and engineering (e.g. construction of dams) are expected to reduce sediment loads in delta areas. This is expected to have a negative impact on delta geomorphology and ecosystems. ▪ Increasing levels of salinity in irrigation water in delta, coastal and low-lying areas are expected to impact crop yields and farmer incomes. ▪ Increasingly severe storm surges are expected to increase the risk of crop failure, abandonment of irrigation schemes and loss of life.

After: Turral et al, 2011; FAO, 2017a

TABLE 4: Typical differences between public and private irrigation re climate change impacts

Public irrigation	Private irrigation
In public irrigation, it is the government that plans, finances and implements, and in most cases farmers effectively receive a subsidized service.	In private irrigation, although government may sometimes facilitate development or provide incentives, farmers take their own investment decisions, pay, implement, operate and maintain, and carry the risks.
Public irrigation is essentially supply driven and may incorporate political, social and environmental objectives.	Private irrigation is demand-driven and reflects financial objectives and priorities of farmers (e.g. self-supply, risk aversion, minimizing costs, etc.).
Public irrigation is better placed to make large 'no-regrets' irrigation investments that are expensive and relevant to CC mitigation and adaptation at landholding, irrigation scheme and basin scales (e.g. re-engineering water storage and bulk transfer systems).	Private irrigation is better placed to make relatively small 'no-regrets' irrigation investments that are relevant to CC mitigation and adaptation at landholding and irrigation system scales (e.g. solar panels and pumps).
Irrigation management decisions need to be based on official guidelines and procedures that tend not to be revised very often.	Irrigation management decisions are more likely to be reactive, adaptive and rapid.
Public irrigation scheme implementation and management tend to have relatively better access to specialist skills and experience (e.g. in engineering, hydrology, irrigation agronomy).	Private irrigation scheme implementation and management tend to rely on accumulated knowledge, lessons learned, artisanal support and possibly inputs from extension officers.
Farmers may participate in decision-making, but often only passively (e.g. as part of a water user association). Similarly, farmers may have official responsibility for operation and maintenance (O&M) (e.g. at the tertiary canal system level), but they may not exercise this.	Farmers are more likely to participate actively in decision-making, either individually or collectively. If farmers have invested in an irrigation system, they are more likely to undertake regular and timely O&M and capital maintenance activities.

2.5 Potential climate change impacts by region

Climate change already affects the agriculture sectors in many regions of the world, and it is expected that impacts will be amplified in the years and decades ahead (FAO, 2016b). A large body of evidence points to a prevalence of negative outcomes, with many agricultural systems becoming less productive and direct effects on agricultural production, which will have economic and social consequences, and finally, an impact on food security. Just as importantly, impacts will affect food security in all four of its dimensions: access, availability, utilization and stability. At each stage of the transmission chain, the severity of impact will be determined by both the shock itself and by the vulnerability of the system or population group under stress (FAO, 2016b).

Demand for water is outstripping sustainable supply in many regions of the world. In some but not all regions, this trend is likely to be exacerbated by climate change. Many organizations and studies are using modelling to predict increasing water scarcity or stress over various time horizons. **FIGURE 9** is an example of predicted water stress for 2040 that was generated using an ensemble of climate models and socio-economic scenarios (Maddocks *et al.*, 2015). This figure shows that 14 of the 33 likely most water stressed countries in 2040 are in the Middle East. The region, already arguably the least water secure in the world, draws heavily upon groundwater and desalinated seawater. While they will probably not face the same extreme water stress as the Middle East, global superpowers such as China and the USA face water risks of their own. For example, areas such as the southwestern USA and China’s Ningxia Province could see water stress increase by 40 to 70 percent.

Impacts of climate change experienced by individual farmers using irrigation may be a result of a combination of many factors, some of which may be local in nature, while others may affect the whole region. It is also possible for a farmer to live in a desert and experience no water scarcity because he or she is lucky enough to have a high-yield well. In contrast, a farmer in an area that is well endowed with water resources can experience a high level of water scarcity because his or her borehole has failed, and the hydrogeology is such that well deepening is not an option. The important point here is that there is a high level of heterogeneity and serendipity in the nature and severity of climate change within regions. With this in mind, **TABLE 5** lists some typical climate change impacts that may be experienced by farmers.

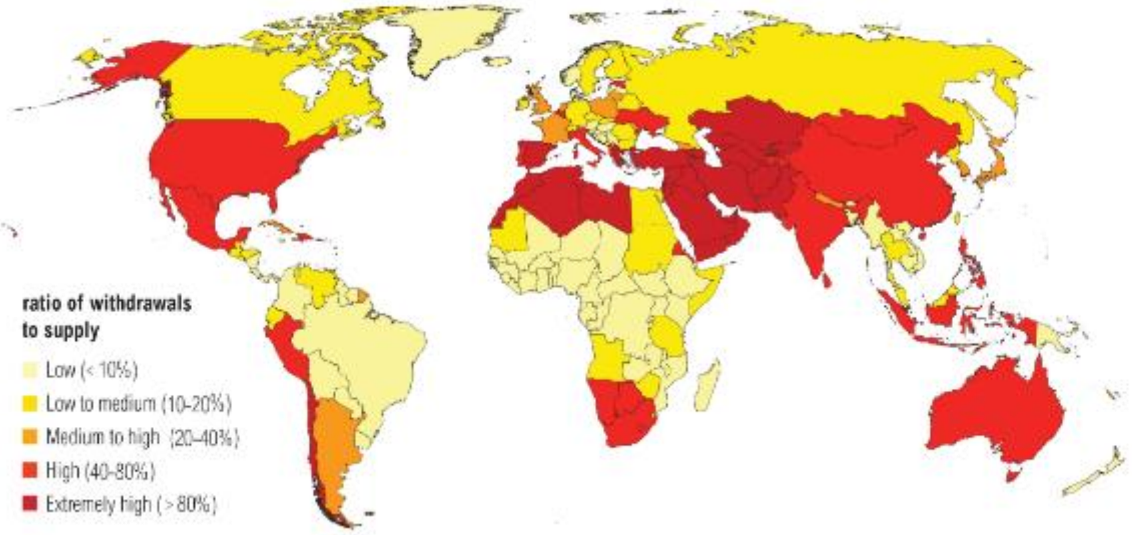

FIGURE 9: Projected water stress by country in 2040

Note that projections are based on a business-as-usual scenario using SSP2 and RCP8.5

Source: WRI, Maddocks et al., 2015

TABLE 5: Typical impacts of climate change by region

Potential climate change impacts by region	
Africa	▪ Africa may be the most vulnerable continent to climate variability and change due to multiple existing stresses and low adaptive capacity. Existing stresses include poverty, food insecurity, political conflicts, and ecosystem degradation. ▪ By 2050, between 350 and 600 million people in Africa are projected to experience increased water stress due to climate change. ▪ Climate variability and change is projected to severely compromise agricultural production, including access to food, in many African countries and regions. ▪ Much of southern Africa is likely to be drier, but rainfall is expected to increase in East and West Africa. ▪ Frequency of extreme events and extreme wet and dry years is likely to increase. ▪ Towards the end of the 21st century, projected sea level rise will likely affect low-lying coastal areas with large populations, including Liberia, Mozambique and Senegal.

Potential climate change impacts by region	
Near East & North Africa	▪ As one of the world’s most water scarce regions, the Near East and North Africa is particularly vulnerable to climate change. ▪ Income and employment may be lost as a result of more frequent droughts in rural areas, and of floods and sea surges in urban and coastal areas. ▪ Higher temperatures and reduced precipitation will increase the occurrence of droughts, an effect that is already materializing in North Africa. ▪ An additional 80–100 million people are estimated to be exposed to water stress by 2025, which is likely to result in increased pressure on groundwater resources, already being extracted in most areas beyond the aquifers’ recharge potential. ▪ Agricultural yields, especially in rainfed areas, are expected to fluctuate more widely.
Asia	▪ Climate change is projected to reduce freshwater availability across Asia, particularly in semi-arid areas. ▪ With population growth and rapid increase in groundwater-based irrigation, increasing water scarcity could adversely affect more than 1 billion people by 2050. ▪ Increased flooding from the sea and, in some cases, from rivers, threatens coastal areas, especially heavily populated delta regions in South and Southeast Asia. ▪ Impacts of climate change on crop yields are likely to vary dramatically depending on region, crop type, and regional changes in temperature and precipitation. However, by the mid-21st century, climate change could increase crop yield up to 20% in East and Southeast Asia, while reducing yields by up to 30% in Central and South Asia. ▪ Agricultural zones shift northwards as freshwater availability declines in South, East and Southeast Asia.
Oceania	▪ Water security problems intensify with a 1° C global average warming in southwestern and southeastern Australia, and in northern and some eastern parts of New Zealand. ▪ Pacific island farmers face longer droughts, heavier rains and an increased risk of sea surges. ▪ Sea level rise, more severe storms and coastal flooding will affect some coastal area of Australia and New Zealand. ▪ Increased drought and fire are projected to cause declines in agricultural and forestry production over much of southern Australia and the northern and eastern parts of New Zealand.
North America	▪ Reduced rainfall restricts water availability as irrigation demand increases in North America. ▪ Warming in western mountains will decrease snowpack, increase winter flooding, and reduce summer flows, exacerbating competition for already over-allocated water resources. ▪ Moderate climate change in the early decades of the 21st century is projected to increase aggregate yields of rainfed agriculture in northern areas, but temperature increases will reduce corn, soy and cotton yields in the Midwest and South by 2020. ▪ Crops that are near the warm end of their suitable range, or which depend on highly utilized water resources, will likely face major challenges. High emissions scenarios project reductions in yields by as much as 80% by the end of the century. ▪ Climate change will likely increasingly stress coastal communities and habitats, worsening the existing stresses of population, development and pollution on infrastructure, human health and the ecosystem.

Potential climate change impacts by region	
Europe	▪ Wide-ranging impacts of climate change are already being documented in Europe, including retreating glaciers, sea level rise, longer growing seasons, species range shifts, and heatwave related health impacts. ▪ In Southern Europe, higher temperatures and drought may reduce water availability, hydropower potential, summer tourism and crop productivity, hampering economic activity more than in other European regions. ▪ In Central and Eastern Europe, summer precipitation is projected to decrease, causing higher water stress and increased demand for irrigation. ▪ In Northern Europe, climate change is initially projected to bring mixed effects, including some benefits such as reduced demand for heating homes and greenhouses, increased crop yields, and increased forest growth. However, as climate change continues, negative impacts are likely to outweigh benefits. These include more frequent winter floods and higher risk of storm surges in coastal areas.
Central & South America	▪ By mid-century, increases in temperature and decreases in soil moisture availability are projected to cause savannah to gradually replace tropical forest in eastern Amazonia. ▪ In drier areas, climate change will likely worsen drought, leading to degradation and desertification of agricultural land. The productivity of livestock and some important crops such as maize and coffee is projected to decrease in some areas, with adverse consequences for food security. In temperate zones, soybean yields are projected to increase. ▪ Sea level rise is projected to increase risk of flooding, displacement of people and salinization of drinking water sources. ▪ Changes in precipitation patterns and the melting of glaciers are projected to significantly affect water availability for agriculture, energy generation and urban uses. ▪ There is an expected risk of more frequent violent storms and hurricanes.

After: EPA, 2015; FAO, 2016b; Verner and Biroscak, 2010

2.6 Potential climate change impacts on food security

Irrigation and drainage are playing a major role in improving global and regional food security[6] by creating and maintaining soil conditions that are close to optimum for crop production under conditions that include insufficient or erratic rainfall (Turral *et al.*, 2011). From a farmer perspective, adoption of irrigation and drainage has made an important contribution to increasing crop yields and mitigating the risks of failed investment and associated hardship that can result from crop failure.

Some frequently quoted statistics state that irrigation and drainage play a central role in the production of 40 percent of the world's food from just 20 percent of cultivated area (FAO, 2016d). In addition, it is notable that irrigation underpins food supplies in many countries that have large and/or rapidly increasing populations, e.g. China, India, Indonesia and Pakistan. However, in recent years, there are signs of a decline in expansion of irrigated areas for reasons that include the unsustainable consumptive use of water by irrigation. The inference that can be drawn is that irrigation will continue to be an important component of strategies aimed at improving and maintaining global and regional food security. However, unsustainable use of limited water resources is a major threat to food security in some regions. In these areas, the emphasis has to be on reducing the consumptive use of water by agriculture, at the same time as improving the efficiency and productivity of irrigation schemes and cropping systems. In regions that are not experiencing water scarcity, expansion of

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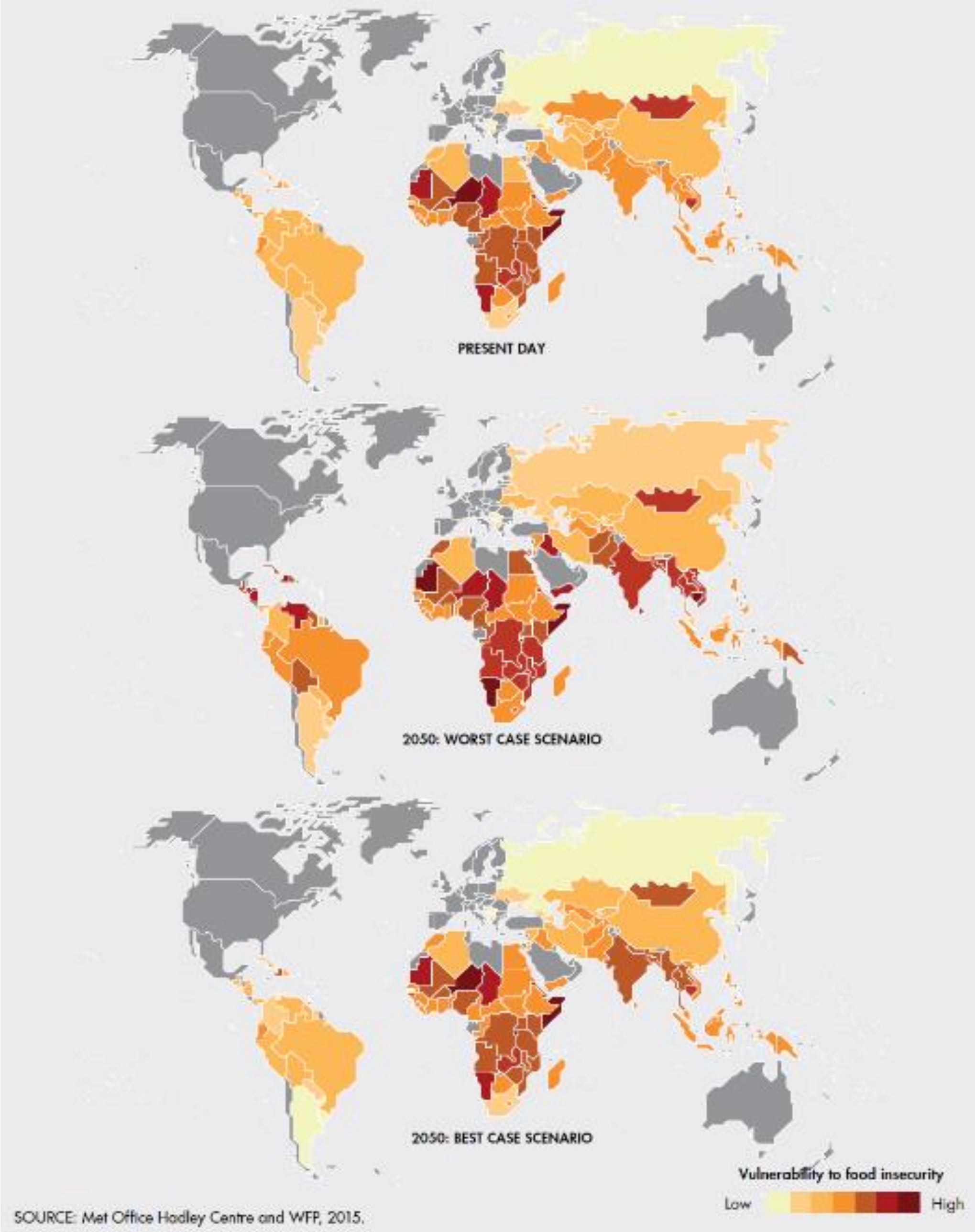
[6] FAO (2006a) uses the following definition of food security: "*A situation that exists when all people, at all times, have physical, social, and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life*".



SOURCE: Met Office Hadley Centre and WFP, 2015.

FIGURE 10: Vulnerability to food insecurity at present day and projected to 2050 under worst case and best case scenarios

Source: Met Centre Hadley and WFP in FAO, 2016b

irrigated areas and increases in the consumptive use of water by agriculture may be feasible.[7] However, strategies in these areas should consider factors that can influence environmental sustainability in the short, medium and long terms. Some of these factors are likely to be directly or indirectly related to climate change, while others may be unrelated.

FIGURE 10 presents the regional vulnerability of food security in 2015 and in 2050 under two different climate change scenarios: a worst case scenario, with high emissions (RCP 8.5) and no adaptation, and a best case scenario, with low emissions (RCP 2.6) and high levels of adaptation (FAO, 2016b).[8] In this diagram, vulnerability is defined by a composite index

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[7] Water scarcity is defined here as an imbalance between supply and demand of freshwater in a specified domain (country, region, catchment, river basin, etc.) (FAO, 2012a).

[8] RCPs are *representative concentration pathways*. For more information on RCPs see e.g. Moss *et al.* (2008).

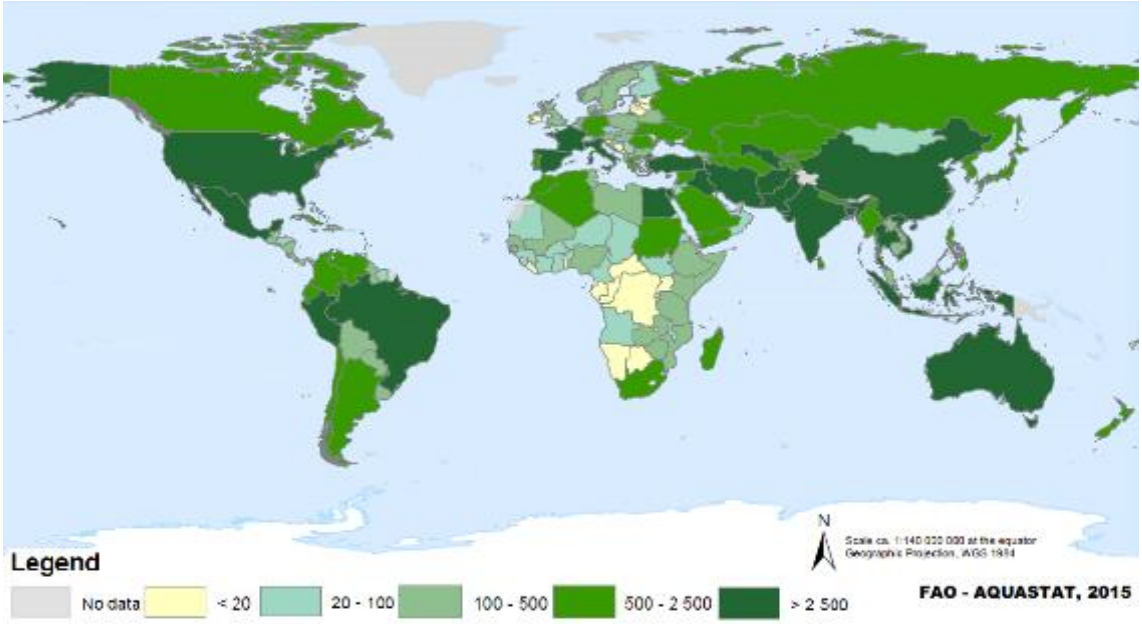

FIGURE 11: Area equipped for irrigation by country. Unit: 1 000 ha

Source: FAO, 2016d

based on measures of exposure, sensitivity and adaptive capacity. The highest vulnerabilities are seen in areas of sub-Saharan Africa and South and Southeast Asia, where millions of people are likely to face greater risk of food insecurity as a result of climate change by the 2050s. The increase in vulnerability is dramatic under the worst case scenario. Under a best case scenario, vulnerabilities are greatly reduced, and for some countries, they actually decrease from 2015 levels.

2.7 Potential climate change impacts on global distribution of irrigation

The global distribution of area equipped for irrigation in 2015 is presented in **FIGURE 11**. Ninety-nine percent of this area is under *full control irrigation*, which is the sum of surface irrigation, sprinkler irrigation and localized irrigation. The remaining 1 percent includes, for example, spate irrigation and cultivated wetlands. A striking feature of this map is the limited area equipped for irrigation in Africa, compared with Asia. This feature is reinforced by the fact that around 40 percent of the area equipped globally is located in two Asian countries: China and India.

The area under the three different full control irrigation technologies is presented in **FIGURE 12**. The three technologies are characterized as follows (FAO, 2016d):

i. ***Surface irrigation*** comprises a group of application techniques where water is applied and distributed over the soil **surface** by gravity. It is by far the most common form of **irrigation** throughout the world, and has been practiced in many areas virtually unchanged for thousands of years. Surface irrigation includes techniques such as furrow, border strip and basin irrigation. It also includes submersion irrigation of rice.

ii. ***Sprinkler irrigation*** consists of a pipe network, through which water moves under pressure before being delivered to the crop via sprinkler nozzles. The system basically simulates rainfall, in that water is applied through overhead spraying.

iii. ***Localized irrigation (or micro-irrigation)*** consists of water being distributed under low pressure through a piped network, in a predetermined pattern, and applied as a small discharge to each plant or adjacent to it. Localized irrigation includes techniques such as drip, mini-sprinklers, bubbler and tapes.

Globally, around 86 percent of the area equipped for full control irrigation is under surface irrigation, 11 percent is under sprinkler irrigation and 3 percent is under localized irrigation. It is notable however that the value

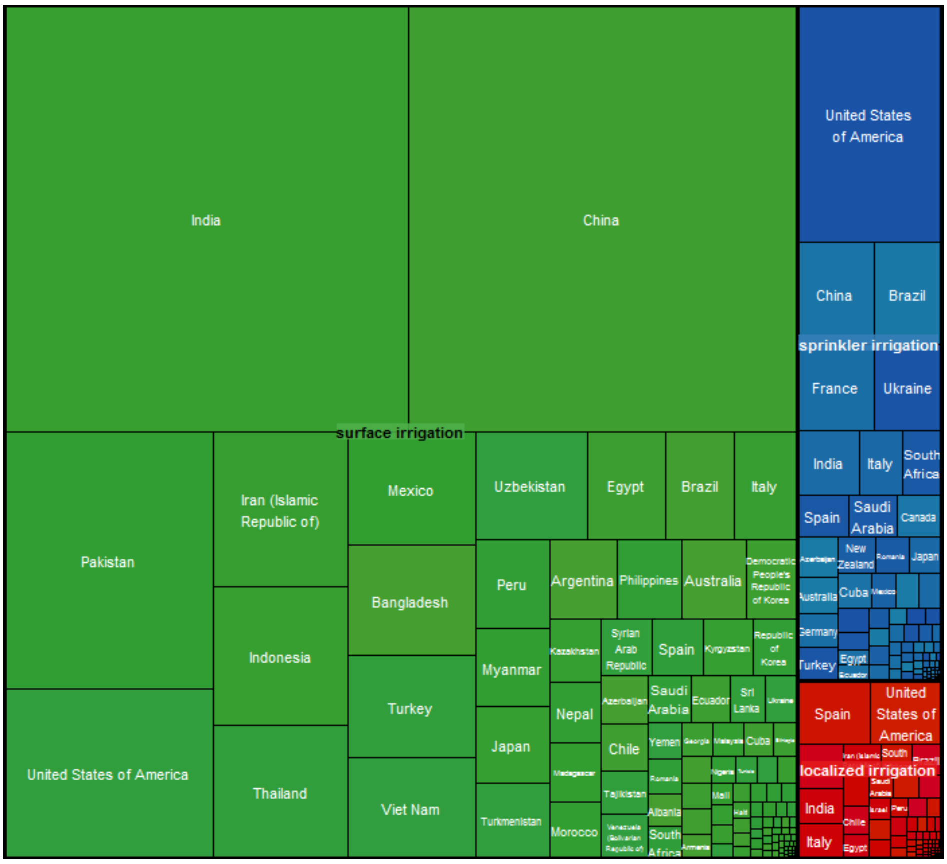

FIGURE 12: Full control irrigation technologies by country

Surface irrigation is still the most widely used irrigation technology. Colour coding: Green - surface irrigation; blue - sprinkler irrigation; red - localized irrigation. *Source: FAO, 2016d*

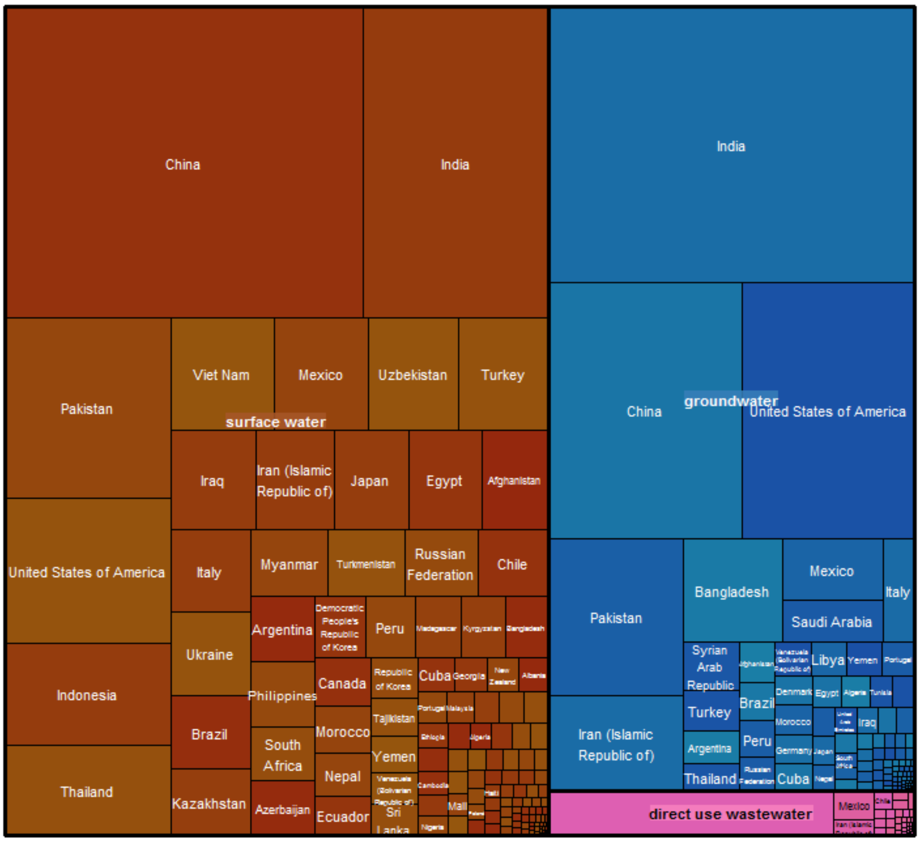

FIGURE 13: Area equipped for irrigation according to source of irrigation water.

Surface water is the main source of irrigation water, followed by groundwater, while wastewater represents only a small fraction. Colour coding: brown - surface water; blue – groundwater; pink - municipal wastewater. *Source: FAO, 2016d* of crops produced per unit area and per unit of water consumed tends to be higher for some, but not all localized and sprinkler irrigated crops.

FIGURE 13 presents the area equipped for irrigation according to the main source of irrigation water. Globally, around 60 percent of the area equipped for irrigation is irrigated using surface water from rivers, lakes and reservoirs (pumping or diversion), 38 percent uses groundwater (shallow wells or deep tube wells), and 2 percent relies on direct use of municipal wastewater (i.e. with no or little prior dilution with freshwater during most of the year).

There is increasing evidence that climate change is impacting irrigation related practices and outcomes at farm, irrigation scheme and river basin levels (see Lake Urmia case study, **Section 4.3**). For some time, climate change adaptation strategies have advocated irrigation practices with the potential to increase irrigation efficiency ('crop per drop') and productivity ('cash per splash').

Increasingly, policies are being developed and implemented that aim to mitigate climate change, for example, by subsidizing the costs of solar pumps used to supply water to irrigation schemes (see Schnetzer and Pluschke, 2017). However, there is limited evidence that climate change has become a major driver of irrigation investment at global level. Arguably, at national level, more important drivers include economic development, poverty reduction and growing demand for agricultural commodities as a result of increasing population and purchasing power. In contrast, at farm level, there is evidence in some regions that farmers are factoring perceived shifts in rainfall into their risk management and coping strategies. This said, factors such as profitability, access to markets, and access to credit and labour are a higher priority than potential climate change impacts. However, this may change as and when climate change impacts become more pronounced.

2.8 Key messages

- There is increasing evidence that climate change has **major implications** for farmers already using irrigation, and farmers who hope to adopt irrigation as part of their climate change adaptation strategy.
- There is **increasing evidence** that climate change is impacting regional and seasonal rainfall patterns, and the frequency and severity of extreme weather events.
- Rainfall is predicted to rise in the tropics and higher latitudes, but **decrease in the already dry semi-arid to arid mid-latitudes and in the interior of large continents**. As a consequence, it is expected that water scarce areas of the world will generally become drier and hotter.
- Changes in **rainfall variability** are just as important as changes in the average. For example, climate change may result, on average, in an area becoming wetter; however, if the variance is also increasing, both floods and droughts may become more common.
- Climate change is not taking place in the context of pristine watersheds or river basins. Rather, the norm is that climate change is impacting watersheds and river basins that have already experienced **centuries of development**, land use change and degradation or depletion of environmental resources.
- From an irrigation development perspective, it is important to consider whether the existing and anticipated impacts of climate change are likely to **exacerbate existing irrigation related challenges** or **alleviate these challenges.**
- Low-lying irrigation schemes in delta and other areas are threatened by **rising sea levels** and increased frequency of storm surges.
- Irrigation and drainage are playing a major role in improving and conserving **global and regional food security** by maintaining soil conditions that are close to optimum for crop production. From a farmer perspective, adoption of irrigation and drainage has played a major role in increasing crop yields, mitigating the risks of failed investment and associated hardship that can result from crop failure.

- Irrigation and drainage play a central role in the production of 40 percent of the world’s food from just 20 percent of the world’s cultivated area.
- It is also notable that irrigation underpins food supplies in many countries that have large and/or rapidly increasing populations, e.g. China, India, Indonesia and Pakistan. However, in recent years, there are signs of a decline in expansion of irrigated areas for reasons that include the **unsustainable consumptive use** of water by irrigation.
- Globally, around 86 percent of the area equipped for full control irrigation is under surface irrigation, 11 percent is under sprinkler irrigation and 3 percent is under localized irrigation.
- Globally, around 60 percent of the area equipped for irrigation is irrigated using surface water from rivers, lakes and reservoirs, 38 percent uses groundwater and 2 percent relies on direct use of municipal wastewater.

3. CLIMATE-SMART IRRIGATION

3.1 Introduction and overview

This section is structured around the three CSI pillars, namely: productivity, adaption and mitigation. Each subsection is organized according to three spatial scales and institutional levels that are typically central to irrigation related decision-making and climate change adaptation and mitigation (see **FIGURE 14**). These are:

- Field or farm scale (or Local institutional level);
- Large irrigation scheme scale (District or intermediate institutional level);
- River basin scale (or National institutional level).

These scales were selected to highlight and reflect different challenges and opportunities that exist at different spatial scales and institutional levels. It is also important to note that: 1) Decisions and decision-making processes are distinctly different at these three institutional levels; 2) Decisions made are often influenced by dialogue and interactions between stakeholders horizontally at each level, and vertically between levels; and 3) Power asymmetries exist between stakeholders at each level and between institutional levels. Depending on the context, additional spatial scales and institutional levels may be relevant to irrigation related climate change adaptation and mitigation. Examples include spatial scales and institutional levels that are related to value chains or to international or transboundary waters.

In each section, options are highlighted that have potential to deliver positive outcomes relative to the CSI pillars. Most of the options discussed are generic, well proven and applicable in a wide range of biophysical and societal contexts. However, the practical reality is that achieving positive outcomes in terms of improving productivity and climate change adaptation and mitigation requires changes in policies at national level, changes in governance systems at intermediate level, and changes to irrigation practices at farm level. The key point here is that strong linkages exist in both directions between farm, irrigation scheme and river basin levels (Turral *et al.*, 2011). Stakeholders at farm and irrigation scheme levels will respond to changes in water policy at

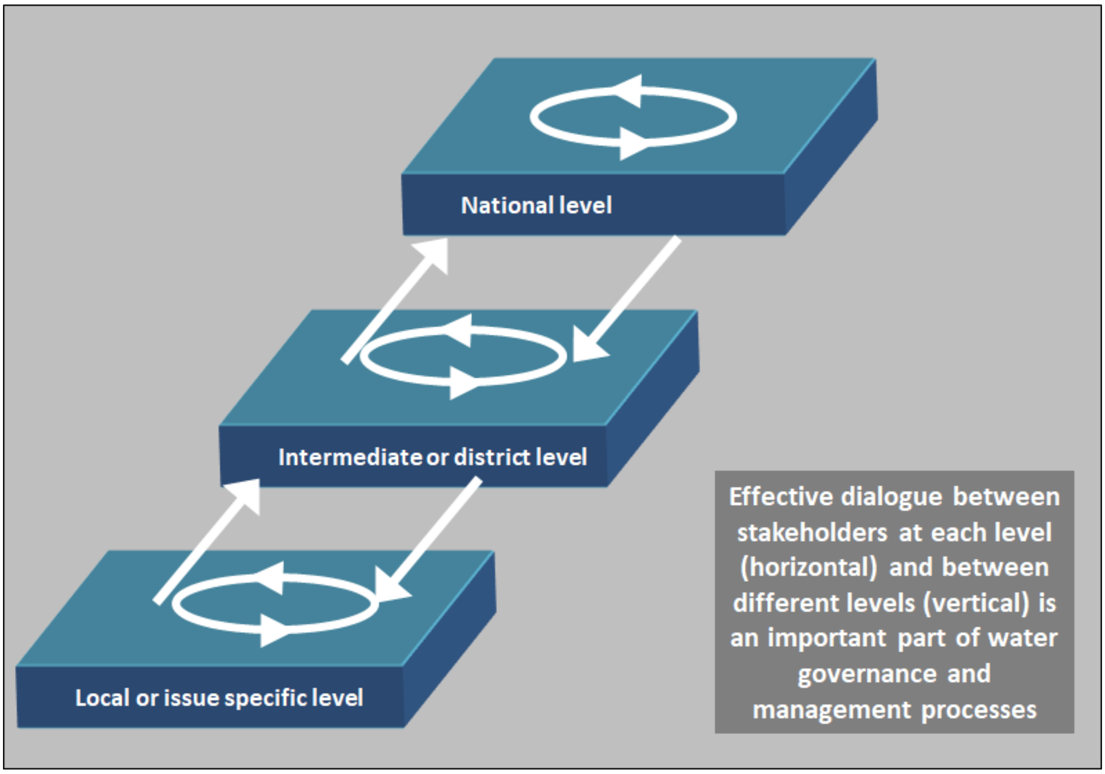

FIGURE 14: Typical stakeholder dialogue levels and interactions

national and basin scale, especially if, for example, these changes influence government expenditure and/or water allocations that benefit the stakeholder.

Irrigation hardware (i.e. infrastructure) that is well designed, constructed, operated and maintained is an important and necessary part of strategies and practices aimed at increasing water productivity of irrigation schemes and cropping systems, and the incomes of farmers, without having a negative impact on the environment. Similarly, irrigation hardware is often a necessary part of successful climate change adaptation and mitigation. However, good irrigation hardware alone is rarely sufficient to achieve desired outcomes. **Irrigation software** is also needed. That includes, for example, effective policies, institutions, governance, statutory and/or customary rights to land and water, access to finance, crop husbandry and irrigation agronomy know-how, water management skills/experience, extension and other support services, and links to value chains.

When developing strategies for implementing CSI, it is important to recognize that irrigation policy formulation and implementation already involves entwined and complex choices and trade-offs between irrigation and ecosystem health. The likelihood is that, in the coming decades, these choices will become even more complex, and potential trade-offs or externalities may become even more severe (Turral *et al.*, 2011). Hence steps should be taken to identify and quantify potential trade-offs and externalities as an integral part of CSI strategy development and planning processes.

3.2 CS1 Pillar 1: Increased agricultural productivity and farmer incomes

3.2.1 Introduction and overview

The stated aim of CSI Pillar 1 is to increase agricultural productivity and incomes derived from irrigated cropping systems up to and beyond the farm gate, without having negative impacts on the environment or other water users and uses (in space and time). This is achieved in part by adopting the sustainable intensification (SI) concept. SI has been defined as a form of production wherein "*yields are increased without adverse environmental impact and without the cultivation of more land*." In this sense, the term denotes an aspiration of what needs to be achieved, rather than a description of how SI can be achieved, and more specifically whether the starting point should be conventional high input farming, or smallholder agriculture, or approaches based on organic methods (Garnett and Godfray, 2012). Therefore to some extent, any increase in water productivity is consistent with the aims of SI, i.e. more crop per drop. In theory at least, there should be no need to cultivate more land. In practice, however, when farmers increase productivity and profitability as a result of improved irrigation practices, they are inclined – if water is not a limiting factor – to increase their cropping intensity and/or, if land is not a limiting factor, the area under irrigated cropping.[9] The end result is that they increase their net production, their net water use and their annual income. In areas facing increasing water scarcity, this process of intensification may not be sustainable locally (e.g. as a result of groundwater overdraft), or at the watershed or basin scales, since there can be significant downstream trade-offs such as reduced environmental flows and less water availability for other water users and uses (including irrigation).

It is almost axiomatic that irrigation improves crop yields, compared with rainfed agriculture. However, the gap between *potential crop yields*[10] and *water limited crop yields*[11] varies enormously. Potential crop yield depends on location, since it relates to weather, but is independent of soil related factors. These are assumed to be physically and chemically favourable for crop growth (Sadras *et al.*, 2015). The climate factors that influence

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[9] This phenomenon is linked to the Jevons Paradox and often referred to as the rebound effect.

[10] *Potential crop yield* is the yield of a crop cultivar "*when grown in environments to which it is adapted; with nutrients and water non limiting; and with pests, diseases, weeds, lodging, and other stresses effectively controlled*" (Evans and Fischer 1999).

[11] *Water limited crop yield* is similar to potential crop yield, except that yield is also limited by water supply, and hence influenced by soil type (water holding capacity and rooting depth) and field topography.

BOX 1: Water productivity

Increasing the water productivity (WP) of irrigated agriculture is viewed as an important element of CSI because WP improvements have the potential to increase production per unit of water consumed. This enables a more efficient use of water resources, particularly important where these resources are limited. A potential cobenefit of increasing WP is a reduction in energy used, e.g. for pumping groundwater.

Water productivity for a specified domain can be defined and derived as:

$WP = Y_{Actual} / Q_{Consumed}$

Where Y_{Actual} is the actual crop yield and $Q_{Consumed}$ is the volume of water that is consumed to produce this yield. A significant advantage of the WP parameter is that any absolute increase in water consumption equates unequivocally with an absolute increase in water depletion within a specified domain. This forces explicit consideration of any increase or decrease in water consumption in terms of a reallocation of actual water use within the hydrological domain (van Halsema and Vincent, 2012). In contrast, considerable confusion and questionable interpretations occur when the definition and value of the denominator in the above equation is replaced by total water use (or total water applied).

The WP concept can also be applied in a wider sense, by attributing different values to the ‘product’ in the numerator. For example, as part of water valuation approaches, the numerator can be expressed in monetary terms (e.g. US dollars). The attractiveness is that this provides a method to compare the value of products per unit of water consumed (van Halsema and Vincent, 2012). However, there are some potential pitfalls or challenges associated with economic water productivity analysis (see **BOX 2:**).

potential crop yield include radiation, ambient CO_2 concentration, temperature and vapour pressure deficit. It is also notable that potential crop yield provides a benchmark for crops where irrigation, the amount and distribution of rainfall, or a combination of both ensure that water deficits do not constrain yield. In contrast, water limited yields provide a benchmark for rainfed crops. The difference between potential crop yield and water limited yield gives an indication of the increase in productivity that is possible by optimizing water supply in any given agroclimate. Guidance on estimating potential and water limited yields can be found in Sadras *et al.* (2015).

In general, there are significant gaps between *actual crop yields*[12] that are achieved by farmers and *attainable crop yields*.[13] One of the aims of policies and practices linked to CSI Pillar 1 is to close the gap between actual crop yield and attainable or potential crop yields, whether this be as a result of increasing the area equipped for irrigation or by improving the water productivity of existing irrigation schemes (see **BOX 1**). The challenges of closing yield gaps and maintaining food security can also be addressed from a crop production perspective.

BOX 3 summarizes the options and opportunities that may apply in regions with relatively wide or narrow yield gaps. It is also notable that methodologies are being developed for mapping water productivity at regional and national scales. For example, FAO and partners have created the WaPOR portal for monitoring

BOX 2: Potential pitfalls of economic WP analysis

- Economic WP values do not necessarily equate to crop yield WP values, i.e. maximum net income of a farmer may be achieved at lower levels than maximum yield productivity.
- Economic WP values are susceptible to the vagaries of the markets and economy.
- Methodological complications arise for extension of WP to non-consumptive production processes such as hydropower, fisheries, recreation and biodiversity (to some extent).
- Additional water valuation methods need to be deployed to capture broader societal benefits of water use (e.g. jobs, food security, poverty reduction, etc.).

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[12] *Actual yield* reflects the current state of soils and climate, average skills of the farmers, and their average use of technology.

[13] *Attainable crop yield* is the best yield achieved through skillful use of the best available technology. Some studies use attainable yield as an approximation to either potential crop yield or water-limited crop yield (Hall *et al.* 2013).

BOX 3: Productivity improvement in regions with wide and narrow yield gaps

The concepts of potential and actual farm crop yields and the yield gap between them can be used to identify and assess current and future opportunities for food supply to satisfy increasing demand. Using these concepts, the world regions can be differentiated somewhat simplistically into two groups according to typical yield gaps:

Wide yield gap regions characterized by: low-input farming with wide yield gaps. For these regions, crop intensification through yield gap closure is essential for reducing rural malnutrition and poverty, and curtailing the likelihood of high food prices. For success, intensification must be complemented by strategies aimed at removing the institutional and infrastructural barriers faced by farmers.

Narrow yield gap regions characterized by: more or less strongly intensified farming with relatively narrow yield gaps. For these regions, some further yield gap closure is still possible, but increases in potential yields are needed if production is to be substantially improved. However, the potential for enhancing potential yields in the near term is considered to be limited.

For all regions, sustainable intensification of cropping, predominantly on existing arable lands, is the best way forward. Combining sustainability with intensification is not a contradiction and is, in fact, essential. Sustainability requires the efficient use of all inputs in cropping, and husbandry of the soil and agricultural biodiversity that are also needed to continue to raise productivity. For regions that offer unused potential for irrigation, as e.g. in sub-Saharan Africa, it is clear that irrigation should be part of any programme aimed at improving food security, addressing climate change and improving the incomes and livelihoods of farmers.

Source: Fischer and Connor, 2018

water productivity derived from remotely sensed data.[14]

Increasing productivity is often based on engineering quick fixes which, for example, involve modernizing irrigation schemes by switching from surface irrigation to localized irrigation. While this can work, the outcomes are often disappointing because insufficient attention is paid to farmer preferences or capacity development. Similarly, attempts at institutional quick fixes, particularly when driven by outside agencies, often have disappointing outcomes (Merrey and Cook, 2012). In both cases, iterative adaptive approaches that have a high level of stakeholder engagement are more likely to succeed (Andrews *et al.*, 2013).

There is a widely held belief that improvement in water productivity is an important objective of farmers. The reality is that: "*farmers in both rainfed and irrigated settings must address a complex set of issues pertaining to risk, uncertainty, prices, and opportunity costs, when selecting activities and determining optimal strategies"* (Wichelns, 2014). If farmers either collectively or individually are not experiencing water scarcity, even though they may live in a semi-arid area, their main objectives may be, for example, to reduce risk, meet self-supply requirements and/or increase profit rather than to improve water productivity.

Improving water productivity and efficiency of irrigation schemes and cropping systems is a typical element of development, agricultural

BOX 4: Different perceptions of water savings

For many (possibly most) farmers, concepts of irrigation efficiency and water productivity are linked to maximizing the farms' economic productivity rather than saving water, except perhaps when their own allocated resources may be inadequate. Instead, they aim for the best use of a potentially limited water supply, attempting not to over or under-irrigate, while minimizing any non-beneficial losses. This is often described as 'applying the right amount of water at the right time in the right place'. Any water 'saved' would be allocated to additional crops. In contrast, water regulatory authorities or similar institutions, whose prime objective is to balance the water needs of all water users (including the aquatic environment) generally view increasing water efficiency as a means of saving water and promoting environmental sustainability.

Source: Knox et al., 2012

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[14] http://www.fao.org/in-action/remote-sensing-for-water-productivity/resources/en/

and climate change adaptation and mitigation policies, particularly in areas experiencing increasing water scarcity and/or river basins that have reached or are approaching a closed status.[15] While this to be commended, in terms of policy interventions there is a tendency for policies to be financed and implemented on a 'one-size-fits-all' basis. Or to put it another way, only limited attention is paid to matching policy interventions with specific biophysical and societal contexts.

Initiatives aimed at improved water productivity are hindered by: 1) Confusion over what constitutes a water saving (see **BOX 4**), and 2) A widely held belief that by adopting water saving irrigation technologies, water can be freed up for alternative uses locally or downstream in the case of rivers, or further down a canal system in the case of a large irrigation scheme (Perry and Steduto, 2017). In both cases, an evidence informed understanding is needed of how different policies, activities and technologies impact crop yields and consumptive water use (in space and time). In most cases, this is best provided by using water accounting and auditing (Batchelor *et al.*, 2017).

Policies and decisions taken at the river basin scale and/or national level can and do influence irrigated crop production and value chains in a number of ways, at some or all scales and levels. As a general rule, sustainable improvements in the productivity of irrigation schemes and farmer incomes are more likely to be achieved by adopting approaches that involve: 1) Planning that differentiates between water uses that are consumptive and non-consumptive in space and time (see **BOX 5**); 2)

BOX 5: Water accounting terminology

Understanding how different interventions impact resource use requires a clear set of accounting terminology, since in the analysis of water systems, stakeholder perspectives affect how different flows are labelled and valued. Note that in the context of irrigation, stakeholders include: farmers, environmentalists, operators of infrastructure (including operators of water storage and bulk water transfer systems), environmentalists and people and organizations with a stake in irrigation value chains.

The following neutral set of labels is applicable at any scale, to any type of water use:

All the water used for any purpose goes to one or more of the following categories:

1. Consumptive use:
    - 1.1. Beneficial consumption, e.g. evapotranspiration from irrigated or rainfed crops, forestry, rangeland or wetlands (but not necessarily from bare soils).
    - 1.2. Non-beneficial consumption, e.g. evaporation from lakes, reservoirs, irrigation channels, roads and wasteland.
2. Non-consumptive use:
    - 2.1. Recoverable flows, e.g. deep drainage (or percolation) to groundwater; surface water return flows from irrigated areas.
    - 2.2. Non-recoverable flows, e.g. environmental flows that discharge into the sea; water, agricultural and urban wastewaters than cannot be treated and reused at an economic cost.
3. Change in storage, e.g. increase or decrease in reservoir storage, groundwater levels or residual soil moisture during a specified time period.

These accounting terms allow a clearer definition of the issues and options we face in irrigated agriculture. Headlines claiming, say, "50 percent water savings through better technology" invariably refer to a narrow 'local' perspective of water applied to the field, failing to account for return flows that recharge aquifers or contribute to downstream river flows. If the underlying aquifer is saline, or outflow goes straight to the sea, then savings are real, but only a complete set of water accounts will reveal whether real water savings are achieved, so that water can be released to other users with no negative effects.

Source: Perry, 2007

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[15] River basins are said to be 'closed' or are 'closing', when total consumptive water use exceeds or is approaching the amount of renewable water available.

Constructive dialogue between stakeholders at the same institutional level, and between institutional levels; 3) Good enough governance at all levels (Grindle, 2007); 4) ‘Getting the basics right’ by, for example, ensuring that activities are planned, properly sequenced and completed on time (EC, 2008); 5) Some form of integrated planning (ADB, 2107); 6) Reform processes that aim to build on existing institutions (Merrey and Cook, 2012); and 7) Incremental improvements that are based on well managed monitoring and evaluation (M&E) systems.

3.2.2 River basin scale (National institutional level)

Policies

In many regions of the world, a high priority is given to increasing the area under irrigation and/or improving the performance and productivity of existing irrigated areas. Typically, the underlying policy goals are some combination of: economic development, improved food security, improved water security, improved rural livelihoods, reduced energy demand for pumping water, environmental sustainability and reduced risk of environmental pollution. Typically, achievement of these policy goals involves: 1) Improved water governance; institutional development (e.g. establishment of river basin agencies, commissions or organizations); and adoption of services delivery models (e.g. in the delivery of irrigation services); 2) Public and private investment in, for example, infrastructural expansion, rehabilitation and/or modernization; 3) Improving irrigation efficiency (see **BOX 6**) and water productivity; and 4) An integrated approach to managing water resources, in some cases along with energy and food as part of a nexus approach.

From an international policy perspective, the United Nations adopted the Sustainable Development Goals (SDGs) in 2015 to “end poverty, protect the planet, and ensure prosperity for all”. Achievement of the SDG

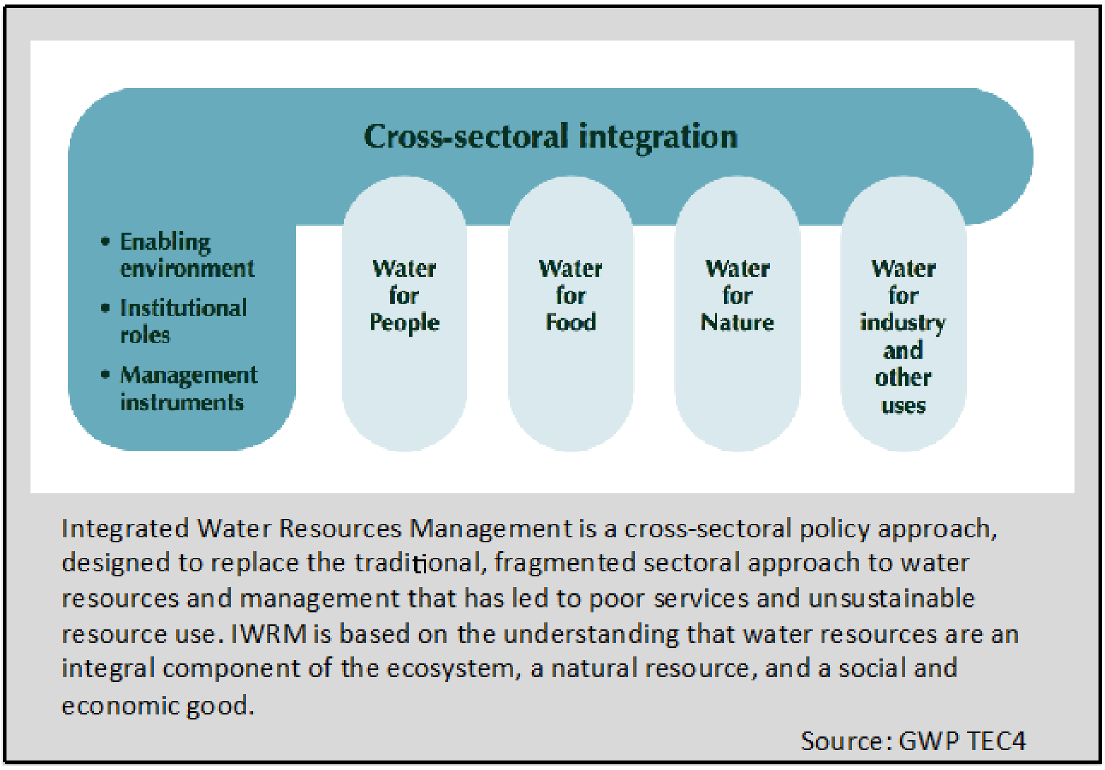
BOX 6: Irrigation efficiency

Generically, ‘water efficiency’ is a dimensionless ratio that can be calculated at any scale and used for different classes of water supply and use (e.g. an interbasin transfer system, a town water supply network). In the agricultural sector, it is referred to as irrigation efficiency (IE) and is used to assess and monitor system losses that can be classified as non-beneficial water use fractions that may be non-recoverable (e.g. evaporation from a canal) or recoverable (e.g. seepage from unlined canals). At the national, basin and large irrigation scheme scales, there are good reasons for improving irrigation efficiency. For example, less energy is required for pumping water when it is used more efficiently. Lower levels of water abstraction or diversion for irrigation can also reduce impact on the availability for other water users, and uses of the same water source (e.g. a reservoir or an aquifer). This in turn can reduce the risks that the water source is overexploited, aquatic ecosystems are damaged, and farmers and other users have inequitable access to water (e.g. at the tail-end of the supply system). However, these benefits may be negated where downstream water users have grown dependent on return flows (e.g. deep percolation, leakage from supply systems), or where increased irrigation efficiency prompts: more profitable crop production, an expansion in the irrigated area, an increase in cropping intensity (e.g. a single to double or triple cropping), and, thus, a major increase of consumptive water use at the national, basin and large irrigation scheme scales.

The attractiveness of irrigation efficiency as an indicator is embedded in its constituent parts that distinguish conveyance efficiencies from application efficiencies. The net result for a specified domain is that IE neatly distinguishes the irrigation engineering/ management efficiency from the farmer/agronomic efficiency (van Halsema and Vincent, 2012). However, it should be noted that IE estimates are less comparable than sometimes implied because they are scale dependent, both in time and space – this hampers comparison of IE values, across scales, time frames and localities (Van Halsema and Vincent, 2012). In this compendium, IE for a specified domain, is defined as a ratio:

$$IE = Q_{BC} / Q_{TWA}$$

where Q_{BC} is the volume of water beneficially consumed as evapotranspiration, or possibly as leaching to prevent salinization, and Q_{TWA} is the total volume of water applied.



Integrated Water Resources Management is a cross-sectoral policy approach, designed to replace the traditional, fragmented sectoral approach to water resources and management that has led to poor services and unsustainable resource use. IWRM is based on the understanding that water resources are an integral component of the ecosystem, a natural resource, and a social and economic good.

Source: GWP TEC4

FIGURE 15: Cross-sectoral integration in IWRM

Source: Global Water Partnership in Batchelor and Butterworth, 2014

goals (e.g. zero hunger, no poverty, progress in the fight against climate change) will require greater attention to food production by the irrigation sector. More specifically, Goal 6 (sustainable access to clean water and sanitation) has several targets that are specific to irrigation. These include: increasing **irrigation efficiency** and ensuring sustainable withdrawal to address the problem of water scarcity; implementing **integrated water resources management at all levels**; improving water quality; restoring and improving water dependent ecosystems; and, strengthening the participation of local communities in improving water and sanitation management (ADB, 2107).

Integrated approaches to water resources management

An important aim of integrated approaches to water resources management (or 'water management') is to ensure that sectoral plans that have the potential to impact water supply or demand are: well aligned and, ideally, mutually supportive. Sectoral plans should also: 1) Ensure water is allocated according to agreed priorities; 2) Take explicit account of potential intersectoral competition or conflict over limited water resources (in space and time); 3) Seek to minimize potential trade-offs; and 4) Ensure that water resources are managed sustainably and environmental flows are protected.

Integrated Water Resources Management (IWRM; see **FIGURE 15**) has been a dominant water management paradigm in rich and poor countries for more than two decades. This is despite the fact that IWRM has attracted considerable controversy and criticism (Martinez-Santos *et al.*, 2014). In particular, the IWRM implementation process has been criticized for being formulaic, prescriptive, top-down and, all too often, based on a standard package of measures that typically includes (but is not limited to): development of a national water policy; legislation to support IWRM; establishment of an independent water regulatory authority; and creation of river basin agencies, typically with some element of stakeholder engagement (Batchelor and Butterworth, 2014). There has also been criticism of the fact that IWRM tries to be holistic but is often seen as an end in itself, rather than as a means of achieving important goals (van Koppen and Schreiner, 2014), e.g. securing water service delivery, environmental sustainability and/or effective operation and maintenance of water supply, storage and treatment infrastructure.

Concerns relating to the way the IWRM concept has been interpreted and implemented led to the development of the concept of light IWRM (Moriarty *et al.*, 2004). In contrast to prescriptive top-down IWRM (Shah and van Koppen, 2006), light IWRM aims to be problem focused, opportunistic and adaptive/iterative when applying core IWRM principles, especially at the water users level. The intended outcome of applying light IWRM is a system of managing water resources and water services delivery that has developed incrementally over many years and, as a result, is better adapted or tailored to the political economy of a given area. It is also argued that light IWRM has fewer problems with buy-in, because even quite limited initial successes can help to convince sceptics that this is an approach that is worth serious consideration.

The light IWRM concept was piloted with some success in the Near East and North Africa (Moriarty *et al.*, 2010). However the concept of light IWRM has not been adopted widely or picked up by organizations that promote IWRM. This said, it is encouraging that the central elements of light IWRM are gaining traction under other headings. For example, there is overlap between the principles of light IWRM and those underpinning the increasingly popular Problem-Driven Iterative Adaptation (PDIA) framework (Andrews *et al.*, 2013; Rao, 2014). Both approaches aim to: engage with a broad set of actors and not just specialists; identify and solve specific problems rather than deliver generic best practice solutions; and move forward via short iterative cycles of learning and adaptation. It is worth noting that light IWRM and PDIA also adopt principles of good enough governance (Grindle, 2007), getting the basics right (EC, 2008) and reform processes that aim to build on existing institutions.

There is no doubt that implementing holistic integrated approaches to managing water, land and other natural resources is politically challenging and not necessarily desirable in all contexts (e.g. in areas that are well endowed with water resources). It is also important to recognize that there are different types or levels of integration (see **BOX 7**). Some types are unisectoral and can be handled very well within the water sector, or within individual water sector line departments (e.g. integrated management of surface and groundwater or integrated delivery of water services to different users and uses). Other types of integration are intersectoral and necessitate the water sector working cohesively with other sectors (e.g. with the agriculture, local government, power sectors). A problem here is that, from an institutional perspective, it is rare for the water sector to work cohesively. In most countries, responsibilities for managing water resources and for delivering water services are split across different line departments (e.g. water resources, rural development, public health engineering, irrigation, planning, local government). In contrast, the power and agriculture sectors tend to each be the remit of just one line department.

Although it is not the only factor, the level of water scarcity in a region can have a strong influence on the need for and potential benefits of adopting integrated approaches to managing water, land and other natural resources. In areas that are well endowed with water resources and where sustainable water supply

BOX 7: Different types or levels of integration

- **Vertical intersectoral integration:** e.g. nested planning across institutional levels and spatial scales involving different line departments and other stakeholders.
- **Horizontal intersectoral integration:** e.g. stakeholder dialogue and concerted action at one institutional level that involves, say, the water, energy and agriculture sectors.
- **Unisectoral integration:** e.g. integrated planning management of water services delivery systems for a range of different water uses and users.
- **Integration along value or supply chains:** e.g. mapping and managing water use and productivity from the 'field to the fork'.
- **Transboundary integration:** e.g. river basin organizations or initiatives involving riparian countries.
- **Integrated assessments or monitoring systems:** e.g. use of water accounting and auditing to monitor biophysical and societal trends in water supply, demand and services delivery.
- **Multistakeholder learning processes:** e.g. communities of practice, learning alliances, quality improvement collaboratives.

BOX 8: Some key differences between integrated approaches to water management under different water scarcity conditions

Relatively low water scarcity	Relatively high water scarcity
Bias towards using unisectoral approaches to solving problems	Bias towards using multisectoral approaches to solving problems
Multisectoral integration needed to tackle challenges that include: pollution, flooding, environmental sustainability, climate change, biodiversity protection and cost efficiency of services delivery	Multisectoral integration needed to tackle additional challenges that include: managing competing demands for water, equitable services delivery, conflict resolution, maintaining water security during droughts
Relatively easy to achieve consensus via multistakeholder processes	Relatively difficult, if not impossible, to achieve consensus via multistakeholder processes
Possibility of win-win solutions to some challenges	Few win-wins available. Most solutions have significant negative trade-offs or externalities
Politics and political economy factors relatively less important	Politics and political economy factors are often of crucial importance
Not so important to get the water accounting and auditing right	Very important to get the water accounting and auditing right

exceeds demand even during periods of prolonged drought, integrated approaches may not be needed as much as is the case in areas of increasing water scarcity (see **BOX 8**). This said, even in areas of limited water scarcity, there may still be arguments for some level of integration processes based on, for example, joint lesson learning; alignment of planning processes; sharing of monitoring information among key stakeholders; and the alignment of long-term strategies.

During the past 4-5 years, the Water-Energy-Food nexus approach has gained traction as an alternative or complementary approach to IWRM (Mohtar, 2016). A key difference between the two approaches is that IWRM always starts with water resources when considering interrelationships between water, land, food and energy, whereas the nexus approach can start from different perspectives (e.g. water, food or energy) (Hoff, 2011). While the nexus approach has significant merit, it has also attracted criticism for being unnecessarily limiting and prescriptive, for example, by not explicitly highlighting interlinkages with climate change, poverty and pro-poor development. More recently the nexus approach has been criticized for: 1) Paying more attention to technological solutions than, say, the politics and political economy of resource management; 2) Focusing more on the national level than the local level when examining the synergies and trade-offs of resource use; and 3) Being somewhat slow to recognize trends emerging at local level, e.g. the increase in privately funded, groundwater-based irrigation, initially in South Asia and more recently in sub-Saharan Africa (Dowd-Uribe *et al.*, 2018; Dessalegn and Merrey, 2015).

In recent years, ecosystem approaches to integrated natural resource planning and management at the basin scale have emerged (e.g. Pegram *et al.*, 2013). A positive attribute of these approaches is the explicit attention that is paid to maintaining ecosystem functions and services. A concern, however, is that ecosystem approaches tend to bring ecosystem functionality to the forefront regardless of the contexts or challenges. In some extreme cases, ecosystem functionality is regarded as an end in itself rather than, say, improved water security or improved performance of irrigation systems (After Molle, 2008).

Regulation and oversight

At policy level, water is usually regarded as a public good (CA, 2007). As a consequence, national governments have a duty to sustain its availability and quality. A significant challenge is that farmers using irrigation enjoy the benefits of water use while passing on environmental and social costs linked to unsustainable use or pollution of surface and groundwater. In such situations, national governments need oversight provided by

BOX 9: Types of regulatory instruments

Economic instruments: e.g. prices, tariffs, subsidies, incentives, tradable permits, water markets, taxes.

Direct controls: e.g. quotas, management rules, standards & norms, water rights, permits, groundwater sanctuaries or conservation zones.

Encouraged water productivity improvements: e.g. promotion of practices and technologies that improve production per unit of consumptive water use.

Encouraged self-regulation: e.g. social policing, community management.

Indirect management: e.g. energy pricing, energy quotas, groundwater markets, limiting credit.

monitoring systems and appropriate policies and regulatory frameworks.

CSI aims to increase the productivity and incomes generated from irrigated cropping systems and irrigated agriculture value chains without having negative impacts on the environment or other water users and uses (in space and time). A major challenge for CSI is that improvements in water productivity at field scale often translate into net increases in total consumptive water use at irrigation system or river basin scales. This phenomenon can be explained by the rational economic reasoning that the more productive an activity is, the more a farmer wants to upscale it (Ahmad *et al.*, 2007). Another challenge for CSI is that many farmers have no interest in using water more efficiently or productively. For example, farmers may be located in a water scarce region or zone but do not experience scarcity because their landholdings are located near a canal offtake (rather than at the tail end), or because they have access to a high-yielding well. Hence the lesson learned is that, as competition for water resources increases and the demand for good quality water outstrips supply, regulating and managing demand for water becomes increasingly important if sustainable development goals are to be met. However, regulating the water use of large numbers of farmers is not easy. In fact, there are very few examples globally of successful regulation of groundwater use for irrigation (Closas and Molle, 2016).

Regulation and standard setting are carried out in the public interest and, as such, are necessary functions of government (Svendsen and Wester, 2005), but other tasks may be fulfilled by commercial or hybrid public-private organizations. Regulation can also be initiated and used at local level, for example, as an important component of decentralized collective management of groundwater resources (Steenbergen, 2002). Institutions that have responsibility for designing and operating regulatory systems have a wide range of regulatory instruments. These instruments fall into five main groups: direct economic instruments, direct controls, encouraged water conservation, encouraged self-regulation, and indirect management (see **BOX 9**). In practice, effective regulation of water use often requires a mix of instruments.

Molle and Turral (2004) argue that demand management through pricing is often effective in managing domestic supply, but this is not the case in the agricultural sector. In part, this is because the elasticity of water use is very low at low prices; when the cost of water is less than five percent of income, even a doubling may not change behaviour. In part, it is also because raising tariffs to find a degree of elasticity is almost certainly politically impossible, not least because this is likely to hit poor farmers much harder than farmers who have larger landholdings, are more professional and more commercially savvy. According to Molle and Turral (2004), direct controls adapted to the local context appear to be the easiest and most efficient means of reducing water use. Direct controls have two overwhelming advantages over economic instruments. First, they ensure a degree of transparency and equity in the face of scarcity. Second, they are directly effective in bringing use into line with available resources. This adjustment by users is made easier if supply is gradually, rather than abruptly, decreased, and if the reduced supply is both predictable and dependable.

Experience worldwide has shown that reforms which involve regulation and modifications to long-established water use patterns will be resisted, particularly if they cut across existing rights, be they customary or legal. This is because social attitudes to water, and in particular the belief that groundwater is a private resource, do not change quickly, irrespective of government views on ownership. It follows that water resource management is as much about managing people as it is about managing water. Consequently, water resource management systems need to be flexible and responsive to the changes in user behaviour that they engender. The view of Shah *et al.* (2007) is that attempting to impose regulatory reform such as pricing and new forms of organization in informal local economies is ill advised, not because they are not needed, but because they will fail. The advice of Shah *et al.* is to focus attention on four areas:

- Improving water infrastructure and services through investment and better management.
- Promoting institutional innovations at higher levels that reduce transaction costs and rationalize incentive structures.
- Focus demand management on formal large-scale sectors such as urban and industrial water use.
- Use indirect instruments to achieve public policy goals in the informal sector.

In other words, rather than attempting to impose new institutional arrangements and water management practices (e.g. water pricing), the focus should be on promoting and facilitating innovation at local levels while, at the macro-level, the focus should be on putting effective infrastructure and institutions in place on the basis that over time, as the economy develops, the formal water sector will expand and the informal water sector will contract (Merrey and Cook, 2012).

3.2.3 Irrigation scheme scale (District or intermediate institutional level)

Irrigation scheme typology

There are fundamental differences between: public and privately managed schemes; cash crop and food grain production; and the humid tropics and arid areas (CA, 2007). It is important to recognize that irrigation plays different roles in different climatic contexts by supplying full, partial or supplementary irrigation. A simple typology of irrigation schemes is presented in **TABLE 6** with the aim of making sense of the huge complexity and diversity that exists in irrigation design, management and primary objectives.

TABLE 6: Simple typology of irrigation schemes

Type	Description
1	Large-scale public irrigation systems in dry areas, growing mostly staple crops. Typically public funds provided to meet some or all capital, capital maintenance and O&M costs.
2	Large-scale public paddy irrigation systems in humid areas. As in Type 1, typically public funds provided to meet some or all capital, capital maintenance and O&M costs.
3	Small- to medium-scale community-managed systems. Typically public funds will meet some capital and recurrent costs, but the percentage contribution of users may be higher than for Types 1 and 2.
4	Commercial privately managed systems, producing for local and export markets. Typically privately funded but may benefit from public investment in, for example, dams and interbasin transfers.
5	Farm-scale individually managed systems, producing for local markets. Typically privately funded but may benefit from public investment in infrastructure, extension services or subsidized power supplies.

After: CA, 2007

Performance of irrigation schemes

During the past 50 years, there has been considerable public investment in large-scale surface irrigation as part of global and regional efforts to address issues related to economic/social development and food security (CA, 2007). Private and community-based investment in developing countries, particularly in groundwater pumping, has grown rapidly since the 1980s, propelled by cheap drilling technology, rural electrification, and relatively inexpensive submersible pumps (see **PHOTO 2**). More specifically, rapid expansion of groundwater-based irrigation has transformed the rural economy in many regions of the world and led to significant increases in agricultural productivity and farmer incomes (Scott and Shah, 2004). However, these positive outcomes have been associated with significant trade-offs that include unsustainable utilization of groundwater and deteriorating water quality. India and Mexico are two of the largest users of groundwater in the world, and both have struggled to overcome the problem of groundwater overdraft that is as much political, social and economic as it is technical.

Rehabilitation, modernization, and a range of institutional reforms that include irrigation management transfer and participatory irrigation management have been advocated over the past 20 years as ways of improving the delivery of irrigation services, reducing recurrent costs, and boosting the productivity of large irrigation schemes. While the results from performance assessment have been mixed, there is general agreement that the majority of large publicly funded irrigation schemes have underperformed as a result of limitations in governance, water productivity, innovation, financing and modernization (ADB, 2107).

Another reason for underperformance is the emphasis of the irrigation sector in many countries on engineering solutions that have worked well in the past. In countries experiencing increasing water scarcity and falling groundwater levels, there is a fundamental need to shift from solutions centred on irrigation hardware to solutions that consider both irrigation hardware and software.

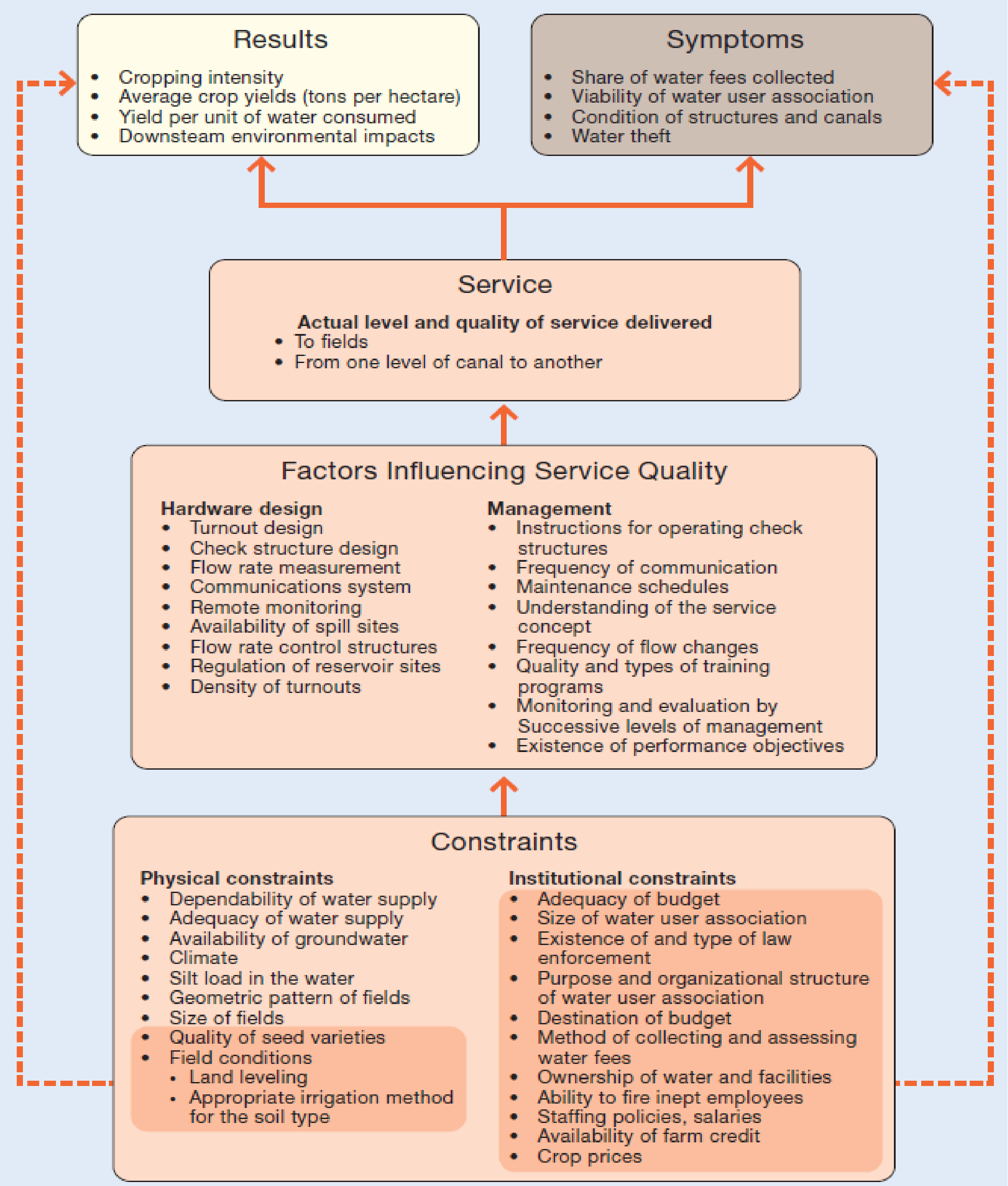


FIGURE 16: Factors affecting the performance of irrigation schemes

Source: CA, 2007

PHOTO 2: Privately funded groundwater-based irrigation in southern India

These small-scale irrigation schemes have improved farmer incomes and food security in semi-arid areas. However, in many areas, this practice has contributed to unsustainable use of groundwater.

Photo credit: Charles Batchelor

TABLE 7: Main conditions for success and reasons for failure of institutional reforms

Conditions for success	**Reasons for failure**
▪ Strong political backing. ▪ A clear role for the different stakeholders. ▪ Support for the empowerment of institutions at all levels (including water user associations and local governments). ▪ The autonomy of the water user associations. ▪ The legal framework needed to accommodate the proposed changes in authority. ▪ Capacity-building of the people governing the transferred system. ▪ Functioning infrastructure. ▪ Success in recovering operation and maintenance costs.	▪ Lack of political support. ▪ Resistance of public agencies and water users. ▪ Insufficient resources. ▪ Poor water quality. ▪ Lack of proper involvement of water users. ▪ Transfer of dilapidated or badly designed infrastructure that is dysfunctional and needs major improvement.

After: CA, 2007

FIGURE 16 lists typical physical and institutional constraints and typical hardware and management factors that can influence levels of irrigation service delivered to farmers and the performance of irrigation schemes.

In recent decades, irrigation sector reforms have been based on the assumptions that active water user participation will result in improved responsiveness and performance of irrigation schemes, and that water users will be increasingly interested in and empowered to manage their irrigation services, thereby enabling the state to retreat from providing and financing its provision. While the results of irrigation management transfer are mixed, much has been learned in regard to formation

BOX 10: Level of service (LOS)

Typically, an irrigation sector LOS has seven elements:

- **Seasonal supply volume** (quantity, seasonal variability, and quality of water);
- **Delivery or service point conditions** (channel capacity, offtake flow rate, offtake elevation);
- **Scheduling and flexibility of supply** (continuous flow, rotation, on-order, on-demand);
- **Reliability** (control and operation of structures to supply the intended quantity and flow consistently);
- **Predictability and dependability** (services provided according to an agreed schedule and agreed level of service);
- **Equity** (often viewed as 'tail-ender' water supply problems, where water is not distributed to the lower end of canals because of insufficient hydraulic control); and
- **Cost** (normally a trade-off versus the other elements, determining the willingness of farmers and the government to invest).

After: ADB, 2017

of water user associations and the potential roles that they can play (see for example Garces-Restrepo *et al.*, 2007).

Sectoral reforms in irrigation management cannot succeed in a vacuum, and depend heavily on broader reforms in governance and transparency at national level, and on agricultural policies (CA, 2007). Some of the main conditions for success and reasons for failure of institutional reforms are presented in **TABLE 7**.

Services delivery approach

The irrigation sector's services delivery approach (SDA)[16] is used mainly on large publicly funded irrigation schemes. The aim of SDAs is to provide farmers with a level of service (LOS) that meets the requirements of their irrigated cropping systems. The LOS of an irrigation system is critical to the efficient use of water and to increasing food production. A well determined LOS will deliver the allocated water flexibly, reliably and equitably throughout the entire design command area, according to crop water needs (ADB, 2107). In some cases, it will also introduce a degree of water scarcity to encourage farmers to produce more with less (see **BOX 10**).

Modernization of irrigation during the past 40 to 50 years has involved a series of reforms based on different paradigms and/or theories of change (CA, 2007). This included an early assumption that farmers were failing to respond to new irrigation opportunities, which led to emphasizing training and on-farm infrastructure development. Next came attempts to transfer responsibilities to farmer organizations (irrigation management transfer). This was followed by an emphasis on increasing interactions and dialogue among water users that led to the creation of river basin organizations. More recently, the focus has been on irrigation modernization based on the services delivery approach. A consequence has been a change in the roles of managers of irrigation schemes, from being the person responsible for an entire production system to being a services delivery manager (Ertsen, 2009).

The transformation to service delivery approaches and the devolution of responsibilities to water user associations and farmers is a worldwide phenomenon (Merrey and Cook, 2012) that has had its ups and downs and associated difficulties. However, the net result is that farmers are now acknowledged as being active and important stakeholders in irrigation management and development. However, the way in which they should be treated by irrigation management agencies has been the subject of intense debate. Within this context, in recent years FAO has shifted the debate on modernization somewhat, putting more emphasis on modernization as an attempt to improve the ability of the system to respond to user demands (Ertsen, 2009).

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[16] Note that service delivery approaches are also referred to as services oriented management (SOM)

In response to a growing interest in service delivery approaches, FAO developed the MASSCOTE approach, which stands for Mapping System and Services for Canal Operation Techniques (Renault *et al.*, 2007; Facon *et al.*, 2008). MASSCOTE provides a systematic methodology for assessing and improving the performance of irrigation systems (see **FIGURE 17**; Renault *et al.*, 2007).

FIGURE 17: Steps in the MASSCOTE approach

Source: After Renault et al., 2007

In this context, it is important to recognize that typically, water supply infrastructure for large irrigation schemes is designed and constructed for the sole or, at least, the primary purpose of growing crops (including food, fibre and fodder crops). Similarly, institutional development in the irrigation sector focuses primarily on crop production and ensuring that irrigation infrastructure: 1) is well managed and maintained (e.g. by water user associations at local level), and 2) delivers irrigation services that are reliable and meet the requirements of farmers. The reality in many cases is that irrigation infrastructure delivers many additional services, for example, water for some domestic uses, water for livestock, water for backyard gardening, water for recreation and water that sustains aquatic ecosystems. These multiple uses are recognized in the multiple-use water services (MUS) concept. This can be used to identify and integrate demands for MUS into the overall management of large irrigation schemes, for example through FAO's Mapping Systems and Services for Multiple Uses of Water Services (MASSMUS) approach, which complements that of MASCOTTE (Renault *et al.*, 2013).

Scope for improving the performance of irrigation schemes

Scope for improving the performance of irrigation schemes lies in policies and activities that include (After ADB, 2107):

- Improved governance that leads to improved delivery of irrigation services and explicit attention to sustainability, equity, trade-offs and social and environmental safeguards. Improved governance should also take explicit account of lessons learned (see **BOX 11**).
- Life-cycle cost financing of existing irrigation schemes that pays as much attention to recurrent costs of O&M as to capital costs. Also, financing that funds both rehabilitation

BOX 11: Typical lessons learned from evaluations of irrigation schemes

A recent ADB evaluation found six factors common to successful projects and missing from others:

- Sufficient financing for sustainable O&M.
- Adequate asset management.
- Adequate institutional capacity, and retention of trained staff.
- Appropriate design, good quality construction, and use of modern technologies.
- Strong institutions willing to undertake reforms step by step.
- Awareness of issues, commitment to change, willingness of government to become the lead change agent, and community involvement.

Source: ADB, 2017

and modernization (see **BOX 12**).

- Improved water productivity at scheme level, i.e. producing more food with less water.
- Wariness of chasing 'crop per drop' and water savings because, in many cases, these 'water savings' are illusory, since 'saved' water was previously used by downstream or groundwater users. These users may face adverse impacts as a consequence of the modernization works, and the overall river basin water productivity may be unchanged.
- Explicit attention to restoring and protecting aquatic and other ecosystems, which in many cases are already degrading as a result of intensification of irrigated and rainfed farming system to the detriment of ecosystem functionality.
- Identifying and resolving water conflicts, and ensuring that priority needs are met even during prolonged periods of drought or subsequent to other extreme events.

BOX 12: Difference between irrigation modernization and rehabilitation

FAO defines irrigation modernization as a process of technical and managerial upgrading of irrigation schemes combined with institutional reforms, if required, with the objective of improving: 1) Resource utilization (e.g. labour, water and other natural resources, energy and finances), and 2) Delivery of appropriate irrigation services to farms.

Irrigation rehabilitation, in contrast, tends to deal only with certain parts of an irrigation system (e.g. the infrastructure). As a consequence, rehabilitation tends not to take the opportunity of systematically upgrading all the elements of an existing irrigation scheme.

3.2.4 Field or farm scale (Local institutional level)

'Save and Grow' model

FAO's recommended approach to sustainable crop production intensification is based on the Save and Grow model. This model promotes*: "productive agriculture that conserves and enhances natural resources. It uses an ecosystem approach that draws on nature's contribution to crop growth, such as soil organic matter, water flow regulation, pollination and natural predation of pests. It applies appropriate external inputs at the right time and in the right amount to improved crop varieties that are resilient to climate change and use nutrients, water and external inputs more efficiently. Increasing resource use efficiency, cutting the use of fossil fuels and reducing direct environmental degradation are key components of the approach, saving money for farmers and preventing the negative effects of overusing particular inputs. This approach has been extended to other agriculture sectors"* (FAO, 2016b).

While principles underpinning the Save and Grow model are sound, uptake by farmers has, for various reasons, been rather slow. In some cases, farmers are forced into adopting unsustainable practices by poverty, insecure land tenure and a lack of knowledge (SOLAW, 2011). In other cases, farming systems and value chains have become increasingly market driven. While this has delivered benefits to farmers and consumers, only limited attention has been paid to environmental sustainability and protection of ecosystems. There is also an increasingly large group of farmers who acknowledge that: 1) current practices are inherently unsustainable, and 2) climate change has the potential to exacerbate this problem. However, they have yet to modify their practices for reasons that include: 1) They cannot afford the capital and recurrent costs of changing their irrigation practices in many cases because they are already in debt; 2) They are reluctant to take the risk of changing practices that have served them well for many decades and/or generations; and 3) They prefer not to take immediate action. In the latter case, they may have decided to: 1) Wait until they are affected personally by environmental degradation or climate change (e.g. a reduction in profitability; 2) Abandon farming and migrate to an urban area at some time in the future; or 3) Give up farming when they are too old to carry on. Note that the average age of farmers is increasing in many countries, as rural youth seek less onerous employment and livelihood opportunities in urban areas. The average age of farmers in the USA and other developed countries borders on 60. In Africa, the average age is also about 60, despite the fact that 60 percent of Africa's population is under 24 years-of-age. So as farmers are getting older – and many of them are women with less access to productive resources, especially in developing countries – this raises questions about future prospects for increasing farm productivity (FAO, 2014a).

Local level impacts of irrigation

Through increased productivity, irrigation delivers secondary benefits for the rural economy at all levels, including increased productivity of rural labour, promotion of local agro-enterprises, and stimulation of the agriculture sector as a whole. The overall multiplier effect on the economy has been estimated as being in the range 2.5 to 4 (CA, 2007). It is also argued that the impacts of irrigation at local level should be viewed in the context of rural development, rather than simply agricultural development. Road systems, education, health, and the entire way of life in rural areas are often transformed by shifting from rainfed to irrigated farming.

Given that rainfed cropping relies entirely on rainfall, productivity is dependent on the agro-climatic factors that include inter- and infra-annual rainfall variability, soil physical properties and crop rooting depth. In contrast, irrigated cropping relies on a combination of rainfall (if significant) and artificial application of water using various methods and systems. Typically, the relative impact of irrigation on productivity is most apparent wherever rainfall is non-existent (e.g. during a dry season), or insufficient to meet crop water requirements on a regular basis (e.g. during a wet season in a semi-arid area). However, in addition to improving yields, irrigation is also used to reduce risk of crop failure, improve the quality of agricultural products and ensure returns on agricultural investments. It is also important to note that supplemental irrigation can have a major impact if used during drought periods, particularly if application of water coincides with critical crop development stages (Nangia *et al.*, 2018).

When considering productivity, it is important to recognize that the desired impact at local level may differ between policy-makers and farmers. The desired impact of policy-makers is often to achieve the maximum level of productivity and farmer incomes, whereas the desired impact of farmers could be, for example, to minimize risks of crop failure.

Sources of water

Farmers need access to reliable sources of water (quantity and quality), if their irrigation systems are to improve productivity and their incomes. Typically, farmers access irrigation water from canals or pipelines that deliver water as part of a publicly funded irrigation system, or they may be able to access groundwater (e.g. using boreholes or shallow hand dug wells) or surface water (e.g. withdrawn from a spring, stream or lake). As mentioned earlier, the reduced costs of drilling and submersible pumps have contributed to increased investment by farmers in their own boreholes and pumps in many countries.

In some cases, farmers have access to unconventional sources such as treated wastewater, drainage water or desalinated water. It is notable that around 90 percent of wastewater produced globally is untreated (ICID, 2017), and use of this for irrigation can represent a health hazard for farmers and consumers of the produce grown with it. The quality of water used for irrigation can also influence crop yield and, in the long term, soil fertility and soil productivity. For example, the physical and mechanical properties of soils such as structure (stability of aggregates) and permeability are very sensitive to the exchangeable ions present in the irrigation water.

In many cases, the access of farmers to water sources is determined by statutory or customary water rights or water tenure. In the absence of rights or tenure, farmers may not be able to access any water, or not in periods when it is needed for irrigation. Lack of water rights or tenure is a major disincentive in investments that are likely to improve productivity and farmer income (Hodgson, 2016).

Drainage and waterlogging

Drainage of irrigated land serves two purposes: to reduce waterlogging and manage or reduce salinization (Ritzema *et al.*, 1996). Lack of drainage can be a serious impediment to increased agricultural productivity. Drainage problems are serious on about 100 to 110

BOX 13: Influence of agroclimatic conditions on selection of irrigation method

While consideration of the agroclimatic conditions is fundamental to the selection of an irrigation method and its effective implementation, irrigation methods are often selected and/or promoted with limited consideration of the agroclimatic context. Hence, the following checklist highlights agroclimatic factors that should have a bearing on the selection of irrigation methods:

Soil type:	Sandy soils have low water storage capacity and a high infiltration rate. They therefore need frequent but small irrigation applications, in particular when the sandy soil is also shallow. Under these circumstances, sprinkler or localized irrigation is more suitable than surface irrigation. On loam or clay soils all three irrigation methods can be used, but surface irrigation is more commonly found. Clay soils with low infiltration rates are ideally suited to surface irrigation. When a variety of different soil types is found within one irrigation scheme, sprinkler or localized irrigation are recommended, as they will ensure a more uniform water distribution.
Slope:	Sprinkler or localized irrigation are often preferred over surface irrigation on steeper or undulating lands as they require little or no land levelling. An exception is paddy rice grown on terraces.
Climate:	Strong winds will have a negative impact on the distribution uniformity of irrigation water and on the efficiency of sprinkler irrigation. Under very windy conditions, localized or surface irrigation methods are preferred. In areas of supplementary irrigation, sprinkler or localized irrigation may be more suitable than surface irrigation because of their flexibility and adaptability to varying irrigation demands.
Water availability:	Irrigation efficiency is generally greater with sprinkler and localized irrigation than with surface irrigation. So these methods are preferred when water is in short supply. However, it must be remembered that efficiency is just as much a function of crop cover duration, evaporative demand and standard of water management as of the method used.
Water quality:	If the irrigation water contains dissolved salts, localized irrigation is particularly suitable, as less water is applied to the soil than with surface methods. Sprinkler systems are generally more efficient than surface irrigation methods in leaching salts.

Source: Brouwer et al., 1989

million ha of irrigated land that is mainly located in the world's semi-arid and arid zones. At present, about 20 to 30 million ha of irrigated land have been seriously degraded by the build-up of salts and 0.25 to 0.5 million ha are estimated to be lost from production every year as a result of salinization (ICID, 2017).

Selection of an irrigation method

To choose an irrigation method, the farmer must have a good knowledge of the advantages and disadvantages of the various irrigation methods available. He or she must also know which methods best suit local conditions and preferred cropping systems. The selection process is complicated by the fact that, in many cases, there is no single best solution, i.e. all methods have their advantages and disadvantages (Brouwer *et al.*, 1989). The suitability of generic irrigation methods (i.e. surface, sprinkler and localized) depends on factors that include:

- **Agroclimatic conditions** (see **BOX 13**).
- **Type or nature of crop or cropping system**, e.g. full cover or row crops.
- **Main aims of using irrigation**, e.g. to supplement rainfall, improve the quality of produce.
- **Previous irrigation experience**, i.e. in some cases it may be advisable for a farmer with know-how of surface irrigation to modernize his or her surface irrigation system rather than switch to, say, localized irrigation.
- **Availability of labour inputs**, e.g. some irrigation methods require higher inputs for O&M than others.
- **Water storage**. Will farm ponds or reservoirs be needed?

- **Scheduling equipment**. Will sensors and control equipment be needed to schedule irrigation effectively, e.g. to make better and more effective use of rainfall?
- **Availability of markets**. Is there a market for increased crop production?
- **Water harvesting**. Is the plan to use *in situ* water harvesting or water conservation measures to enhance effective rainfall and, thereby, reduce the irrigation water requirements?
- **Capital costs (per ha)**. What is the capital cost of modernizing or replacing the existing irrigation scheme or developing a new scheme? What are the expected lifespan and potential capital maintenance of the main components of the irrigation scheme?
- **Recurrent costs (per ha)**. What are the costs of O&M, energy, labour, repairs?
- **Benefits**, e.g. financial, social, environmental?
- **Government policies**. Are government grants available for irrigation modernization or similar? Are regulations in place that cap the water available for irrigation?

Advantages and limitations of irrigation methods relative to CSI pillars

TABLE 8, **TABLE 9** and **TABLE 10** give an overview of the advantages and limitations of surface, sprinkler and localized irrigation relative to the three pillars of CSI. **TABLE 8** and **TABLE 9** refer to popular variants of surface and sprinkler irrigation, while **TABLE 10** provides information that relates to most variants of localized irrigation. The information provided includes:

- A brief description of the irrigation methods or variants.
- An overview of the relative suitability of the irrigation methods or variants to crops and agroclimates.
- Some typical advantages of the irrigation methods or variants relative to the CSI pillars.
- Some typical limitations of the irrigation methods or variants relative to the CSI pillars.

While **TABLE 8**, **TABLE 9** and **TABLE 10** do not provide analysis of an exhaustive list of irrigation methods and all their variants, these tables highlight the comparative suitability, advantages and limitations of the major irrigation typologies and some popular variants. The following inferences can be drawn:

- None of the irrigation methods considered in the tables is ideal for all circumstances or contexts. Or to put it another way, all the irrigation methods and variants considered have their advantages and limitations relative to the three CSI pillars.
- In terms of agricultural productivity and farmer incomes, localized irrigation systems are often singled out as the irrigation method that achieves the highest levels of productivity for some crops at least. Reasons for this include the fact that soil evaporation can be limited and water and fertilizer can be applied precisely, often directly into the crop root zone. However, the capital and recurrent costs of using localized irrigation systems are relatively high and they are not suitable for all crops. As a result, many farmers prefer to use other methods of irrigation.
- As the most popular method of irrigation globally, surface irrigation deserves more attention in climate change adaptation and mitigation strategies as an option that can contribute to achieving the aims of the three CSI pillars. Specific advantages include: energy requirements for pressurizing water are relatively low, and it is relatively adaptable at farm and field levels. It is notable that surface irrigation is considered to be very inefficient. However, the reality is that the irrigation efficiency and water productivity can be relatively high if return flows are taken into account, and if systems are well designed, maintained and managed.
- Low energy precision application (LEPA) sprinkler irrigation is another irrigation method or variant that warrants more attention in climate change adaptation and mitigation strategies. This is because it combines some of the advantages of localized irrigation (e.g. precision application) and surface irrigation (e.g. it is relatively adaptable at field and farm level). In addition, relative to other sprinkler irrigation variants, LEPA systems can deliver

good irrigation uniformity, even under windy conditions.

Regarding irrigation related adaptation, travelling gun systems have the advantage of being relatively flexible in terms of whether or not they are used for supplemental or full irrigation. Travelling gun systems also have a relatively low capital cost, and can be converted into a LEPA system by replacing the gun with a boom to which droptubes are attached. The net result is a sprinkler variant that has LEPA benefits and that can be used for supplemental irrigation across a large area, or for full irrigation on a small area.

Irrigation scheduling

Irrigation scheduling is used to match the water applied (irrigation plus effective rainfall) to crop water requirements during different phases of the growing season. Typically, the aims of irrigation scheduling from a farmer's perspective include:

- Minimizing risk of crop failure that may result from, for example, water stress, waterlogging or soil salinization.
- Achieving good crop yields and quality and minimizing costs, e.g. cost of pumping water, and thereby realizing a good return on financial and other investments.
- Improving irrigation efficiency and/or water productivity when access to water is limited.

In the case of large irrigation schemes, farmers tend to have limited control over irrigation scheduling unless they have a night storage tank, or possibly an alternative source of water. In these cases, decisions relating to the timing, duration and volume of irrigation applied may be made by the manager of the scheme or by a water users association. When irrigation water is available on demand, for example from the farmer's own borehole, he or she can decide when and how much water is applied.

Many methods are used to inform irrigation scheduling decisions. These have different advantages, disadvantages and costs. Estimating crop water requirements on the basis of meteorological data is one of the more common and, for many applications, most effective means of irrigation scheduling (Allen *et al.*, 1998). Such methods combine crop water requirement estimates with crop and soil data to calculate irrigation requirements, e.g. using water budget-based models as in CROPWAT[17] or AquaCrop (Steduto *et al*., 2012; FAO, 2017c; Raes *et al.*, 2018). Soil sensors are widely used for irrigation scheduling, especially in greenhouses. Soil sensors detect when soil dries to a point at which irrigation is required. Plant sensors can also be used to monitor plant water status, either directly (e.g. measurements of growth) or indirectly (e.g. infrared thermometry). However, the reality is that most farmers globally schedule irrigation on the basis of accumulated knowledge and real-time information on daily rainfall. In practice, this means that farmers apply a fixed number of irrigations and a set volume or depth of water, depending on the crop, cropping season, soil type and rainfall.

Regulated deficit irrigation (RDI) has been promoted as a means of increasing irrigation efficiency and productivity, partly by making more effective use of rainfall. In effect, this is a form of irrigation scheduling that aims to meet the full water requirements of the crop during developmental stages, when plant yield and quality are most sensitive to water stress, but less water is applied during less drought sensitive phenological phases (EIP-AGRI, 2016). In principle, RDI can also help to control excessive vegetative growth or improve quality, e.g. relating to higher dry matter content, soluble solids content or storability.

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[17] http://www.fao.org/land-water/databases-and-software/cropwat/en/

TABLE 8: Typical advantages and limitations of surface irrigation relative to the CSI pillars

Irrigation method	Description	Suitability	Typical advantages relative to CSI pillars	Typical limitations relative to CSI pillars
Basin irrigation systems	A basin is a horizontal area of land surrounded by earthen bunds that is flooded during irrigation. Basin irrigation, in one form or another, is the most common type of surface irrigation.	▪ Basin irrigation is suitable for many field crops including paddy rice, alfalfa and cereals. ▪ Basin irrigation is generally not suited to crops that cannot withstand waterlogged conditions for periods longer than 24 hours, e.g. root and tuber crops such as potatoes, cassava, beet and carrots, which require loose, well drained soils.	▪ **Pillar 1:** Basin irrigation systems are relatively cheap and easy to manage. If properly designed and managed, basin irrigation systems make effective use of rainfall and minimize deep percolation losses. ▪ **Pillar 2:** The size, shape and bund heights of basins are also flexible and adaptable. ▪ **Pillar 3:** Similar to other surface irrigation methods, basin irrigation does not require a pressurized water supply and therefore has relatively low energy requirements.	▪ **Pillar 1:** Precision levelling is required for uniform water distribution. If low or high areas exist, uneven infiltration occurs and distribution uniformity, crop productivity and farmer income are likely to be reduced. ▪ **Pillar 2:** Bunds can be destroyed by large rainfall events that may increase in frequency and severity.
Furrow irrigation systems	A furrow irrigation system consists of furrows and ridges. The water is applied by means of small channels or furrows, which follow a uniform longitudinal slope. Water can be diverted from the field canal or the tertiary canal into furrows by means of siphons placed over the side of the ditch or canal bank, and be allowed to flow downstream along the furrow.	▪ Furrow irrigation is suitable for many crops, especially row crops e.g. maize, sugarcane, potatoes, onions, tomatoes, etc. ▪ Uniform flat or gentle slopes are preferred for furrow irrigation. These should not exceed 0.5%. Usually a gentle furrow slope of around 0.05% is created to assist drainage following irrigation or excessive rainfall with high intensity. ▪ Furrows can be used on most soil types. However, as with all surface irrigation methods, very coarse sands are not recommended, as percolation losses can be high.	▪ **Pillar 1:** High application uniformity can be attained with a properly designed and managed system. ▪ **Pillar 2:** Similar to basin irrigation, furrow irrigation is adaptable and relatively easy to manage, particularly at the field scale. ▪ **Pillar 3:** Similar to other surface irrigation methods, furrow irrigation does not require a pressurized water supply and therefore has relatively low energy requirements.	▪ **Pillar 1:** Typically, surface drainage must be provided to divert high rainfall events off fields and reduce the risk of waterlogging. ▪ **Pillars 1 & 2:** Relatively large flows and applications of water are needed to ensure irrigation uniformity along furrows. ▪ **Pillar 3:** Except on uniform flat fields, extensive land preparation is required for initial installation. The risk is that this will release soil organic carbon.

Borderstrip irrigation systems	Borderstrips are strips of land with a downward slope but little or no cross slope. The aim is to facilitate an even rate of water advance down the slope. Borderstrips can vary from 3-30 m in width and from 60-800 m in length. Typically, they are separated by parallel dykes or border ridges.	▪ Borderstrip irrigation is generally best suited to the larger mechanized farms, as it is designed to produce long uninterrupted field lengths for ease of machine operations. ▪ Borderstrip irrigation is suited to full cover crops, e.g. pasture, alfalfa etc. ▪ Borderstrip slopes should be uniform, with a minimum slope of 0.05% to provide adequate drainage and a maximum slope of 2% to limit problems of soil erosion. ▪ Deep homogenous loam or clay soils with medium infiltration rates are preferred. Heavy, clay soils can be difficult to irrigate with border irrigation because of the time needed to infiltrate sufficient water into the soil. Basin irrigation is preferable in such circumstances.	▪ **Pillar 1:** Relatively high application efficiencies can be achieved on soils with average infiltration rates when systems are properly designed, maintained and managed. ▪ **Pillar 2:** Borderstrip systems can be used in rotation with other methods and systems of applying water, including sprinkler and furrow irrigation systems. ▪ **Pillar 2:** Water with relatively high sediment loads can be used to irrigate borderstrips. ▪ **Pillar 3:** Similar to other surface irrigation methods, borderstrip irrigation does not require a pressurized water supply and therefore has relatively low energy requirements.	▪ **Pillar 1:** Good distribution uniformity requires intensive in-field water management (or costly automation). ▪ **Pillar 2:** Uniform light applications of water are difficult to apply. As a consequence, borderstrip irrigation is relatively less flexible and adaptable in this regard than other surface irrigation methods. ▪ **Pillar 3:** Creating uniform slopes often involves land levelling and release of soil organic carbon.

After: Stewart and Nielsen, 1990; USDA, 1997; Brouwer et al., 1989; Savva and Franken, 2001; Bjorneberg, 2013

TABLE 9: Typical advantages and limitations of sprinkler irrigation relative to the CSI pillars

Type	Description	Suitability	Typical advantages relative to CSI pillars	Typical limitations relative to CSI pillars
Periodic move systems	Periodic move sprinkler irrigation systems are moved to an appropriate position and operated for a specified length of time with the aim of applying a required depth of water. The laterals, pipes and/or sprinkler are then advanced to the next set position.	▪ Periodic move systems are best suited to sandy soils with high infiltration rates, although they are adaptable to most soils. ▪ Periodic move systems are suitable for fields that have not been levelled. ▪ Periodic move systems are suited to a range of field crops, but are difficult to use in tall crops, such as maize or sugarcane.	▪ **Pillar 1:** Periodic move systems have a relatively low capital cost. ▪ **Pillar 1:** Periodic move systems can improve irrigation uniformity and water productivity in undulating terrain and/or unlevelled fields. ▪ **Pillar 2:** Periodic move systems can be used adaptively, e.g. to establish crops that are subsequently irrigated by a surface irrigation system. ▪ **Pillar 3:** Well managed periodic move systems can improve productivity and reduce GHG emissions per unit of product.	▪ **Pillar 1:** Periodic move systems require labour to move laterals, pipes and sprinklers, often several times a day. ▪ **Pillar 2:** Periodic move systems are not ideal for frequent light irrigation and precise irrigation scheduling. ▪ **Pillar 3:** Periodic move systems require pressurized water, and typically use more energy for pumping than surface irrigation systems. ▪ **Pillar 3:** Irrigation uniformity and efficiencies may be low when wind velocities and evaporation rates are high. This can result in additional pumping costs and energy usage.
Solid set systems	A fixed or solid set sprinkler irrigation system can irrigate an area without the need to move pipes, laterals or sprinklers.	▪ Solid set systems are best suited to sandy soils with high infiltration rates, although they are adaptable to most soils. ▪ Solid set systems are suitable for fields that have not been levelled. ▪ Solid set systems are suited to a range of field crops, but tend to be used for higher value crops or orchards.	▪ **Pillar 1:** Solid set sprinkler systems can be automated and have relatively low labour requirements. ▪ **Pillar 1:** Solid set sprinkler systems can improve irrigation uniformity and water productivity in undulating terrain and/or unlevelled fields. ▪ **Pillar 2:** Solid set systems can be adapted, e.g. for frost protection, crop cooling, humidity control, bud delay, crop quality improvement, dust control and chemical application. ▪ **Pillar 3:** Well managed solid set systems can improve productivity and reduce GHG emissions per unit of product.	▪ **Pillar 1:** The capital cost of solid set systems is relatively high. ▪ **Pillar 2:** The additional in-field infrastructure may inhibit adaptability in terms of cropping systems and in-field operations. ▪ **Pillar 3:** Solid-set systems require pressurized water and typically use more energy for pumping than surface irrigation systems ▪ **Pillar 3:** Irrigation uniformity and efficiencies may be low when wind velocities and evaporation rates are high. This can result in additional pumping costs and energy usage. ▪ **Pillar 3:** Solid set systems require pressurized water, and typically use more energy for pumping than surface irrigation systems

Centre pivot system	A centre pivot system consists of a continuously moving, horizontal rotating single lateral supported by wheeled towers and anchored at a fixed pivot point at the centre of the field. This system irrigates a circular field unless end guns and swing lines are cycled in corner areas to irrigate more of a square field.	Centre pivot systems are suited to: ▪ Large flat fields. ▪ Soils with high infiltration rate. ▪ Crops that can be established under the high application rates that are typical at the outer end of a centre pivot lateral. ▪ Farms or regions in which water is the limiting factor rather than land, because typically centre pivots cannot irrigate the whole area of a square field.	▪ **Pillar 1:** Centre pivot systems can be easily automated and have relatively low labour requirements (typically one person can manage 8-10 pivots (up to 1 000 ha of irrigated land). ▪ **Pillar 1:** Centre pivot systems can improve irrigation uniformity and water productivity. ▪ **Pillar 2:** The volume of water can be varied and precise applications of both water and chemicals are possible. ▪ **Pillar 3:** Well managed centre pivots can improve productivity and reduce GHG emissions per unit of product.	▪ **Pillar 1:** Light, frequent irrigations help to minimize surface runoff and translocation of water applied. The trade-off is that this may increase non-beneficial evaporation losses. ▪ **Pillar 2:** Because centre pivot systems are relatively expensive compared with other irrigation systems, they are often designed to barely meet, or even fall short of meeting, peak daily crop water use. The risk is that they are relatively less adaptable than other sprinkler systems. ▪ **Pillar 3:** Centre pivot systems require pressurized water and typically use more energy for pumping than surface irrigation systems. ▪ **Pillar 3:** Irrigation uniformity and efficiencies may be low when wind velocities and evaporation rates are high. This can result in additional pumping costs and energy usage.
Low energy precision application (LEPA) systems	LEPA is a low energy precision water application system that supplies water at the point of use. This system combines a self-moving mechanical device (centre pivot or linear move) along with water and soil management procedures that aim to retain and make efficient use of the water received as precipitation and irrigation. LEPA systems distribute water directly onto or very near the ground surface, using drop tubes fitted with low pressure application devices.	LEPA systems are suited to: ▪ Large flat fields. ▪ Regions that experience dry windy conditions. ▪ Crops and cropping systems that are associated with significant non-beneficial consumptive water uses (e.g. wind drift, canopy interception, etc.). ▪ Regions or crop seasons in which precipitation meets a significant part of crop water requirements. ▪ Soils with high infiltration rate. ▪ Crops that can be established under the high application rates that occur at the laterals positioned at the outer end of a centre pivot.	▪ **Pillar 1:** LEPA systems have the ability to improve irrigation uniformity, irrigation efficiency and water productivity for a range of field crops. ▪ **Pillar 2:** LEPA systems have the ability to make frequent small applications of water and fertilizer, in some cases to supplement precipitation. As a consequence, LEPA systems are more resilient than many others because they require less energy and less water. ▪ **Pillar 3:** Because system operating pressures are low, the energy needed to pump and pressurize water is relatively low. ▪ **Pillar 3:** The emphasis on 1) Making effective use of harvested rainfall, and 2) Using drop tubes to minimize non-beneficial consumptive water use also reduces the energy needed to pump and pressurize water.	▪ **Pillar 1:** LEPA systems are relatively expensive and require regular management and maintenance even though they can be automated. ▪ **Pillar 1:** For precision application of irrigation water using LEPA systems, circular rows must be used with centre pivots and straight rows with linear systems. Application devices should distribute and confine the water to the furrow area without eroding furrow dikes or crop beds. To optimize water placement, planting should be done to match the travel pattern and location of the drop tube applicators. ▪ **Pillar 2:** In terms of CSI adaptation, LEPA systems have a comparative advantage over centre pivots or micro-irrigation for some crops, cropping systems and agroclimates, but not for others. ▪ **Pillar 3:** The mitigation benefits of LEPA systems are more likely to be realized by a largish mechanized farm that has sufficient funds to meet the necessary capital and recurrent costs.

Travelling gun systems	The travelling gun (also called traveller, gun or big gun) is a high-capacity, single-nozzle sprinkler fed with water from a flexible hose that is either dragged on the soil surface or wound on a reel. The gun is mounted on wheels and travels along a straight line while operating. The unit is equipped with a winch – powered by a water piston or turbine – that reels in an anchored cable or hose. Some units have a small auxiliary gasoline engine to power the reel.	Travelling gun systems are suited to: ▪ Fields of an irregular shape. ▪ Fields that have not been levelled. ▪ Sandy and other soils that have a relatively high infiltration rate and that are not prone to puddling. ▪ Irrigation of several different fields that are part of a crop rotation. ▪ Regions or crop seasons in which precipitation meets a significant part of crop water requirements, and seasonal net irrigation requirements are small. ▪ Tall field crops and other field crops that are unlikely to be damaged by relatively large droplet sizes. ▪ Crops that can be established under high application rates. ▪ Regions that do not regularly experience dry, windy conditions.	▪ **Pillar 1:** Travelling gun systems are relatively inexpensive in terms of cost and well suited to providing supplemental irrigation at critical stages of crop development, thereby, increasing crop yields or salvaging crops that are suffering moisture stress. ▪ **Pillar 2:** Travelling guns are relatively flexible and adaptable to different cropping systems. In many cases, they are used for supplemental irrigation. This can effectively reduce the demand for groundwater and improve the resilience of irrigation systems in water scarce areas. ▪ **Pillar 3:** When used for supplemental irrigation, travelling gun systems can achieve a relatively low GHG emission intensity per unit of product despite their generally very high energy usage, because irrigation is applied only at targeted critical crop development stages.	▪ **Pillar 1:** Travelling gun systems do not deliver good irrigation uniformity during windy conditions. Also, the high application rate and droplet size can cause puddling and/or localized waterlogging on susceptible soils and on fields that have not been levelled. ▪ **Pillar 2:** While travelling gun systems do not require manual labour during sprinkling, they do need labour to move the guns before each pass, often several times a day. This can disrupt other farm operations and/or be a burden for small farms with limited labour. ▪ **Pillar 3:** Large gun type sprinklers require the highest pressures of any sprinkler system, and therefore use a large amount of energy for pumping and pressurizing water.

After: Stewart and Nielsen, 1990; USDA, 1997; Brouwer et al., 1989; Savva and Franken, 2001; Bjorneberg, 2013

TABLE 10: Typical advantages and limitations of localized irrigation relative to the CSI pillars

Type	Description	Suitability	Typical advantages relative to CSI pillars	Typical limitations relative to CSI pillars
Localized irrigation systems	Localized irrigation is the broad classification of frequent, low volume, low pressure application of water on or beneath the soil surface by drippers, drip emitters, spaghetti tube, subsurface or surface drip tube, basin bubblers, and spray or mini sprinkler systems. Localized irrigation is also referred to as drip and trickle irrigation.	▪ Localized irrigation is most suitable for row crops (vegetables, soft fruit), tree and vine crops where one or more emitters can be provided for each plant. Generally only high value crops are considered, because of the high capital costs of installing a drip system. ▪ Localized irrigation is adaptable to any farmable slope. Normally the crop is planted along contour lines and the water supply pipes (laterals) are also laid along the contour. This is done to minimize changes in emitter discharge as a result of land elevation changes. ▪ Localized irrigation is suitable for most soils. On clay soils, water must be applied slowly to avoid surface water ponding and runoff. On sandy soils, higher emitter discharge rates will be needed to ensure adequate lateral wetting of the soil.	▪ **Pillar 1:** If well managed, these systems reduce non-beneficial consumptive water use and achieve high levels of irrigation efficiency and water productivity. ▪ **Pillar 1:** Systems are relatively easy to automate and irrigation scheduling can be based on, for example, soil moisture sensors. The net result is that scheduling can maintain soil moisture conditions and produce high yields and good quality outputs. ▪ **Pillar 2:** The design and management of localized irrigation systems can be matched and adapted to farmer preferences and a wide range of crops and agroclimatic conditions. ▪ **Pillar 2:** Localized irrigation can be adapted to use poor quality (e.g saline) water. However, careful management is needed to ensure that salts are leached continuously from the root zone. ▪ **Pillar 3:** Fertilizer and other chemicals can be added to irrigation water and applied precisely in small quantities directly to the crop root zone. With proper management, this can reduce fertilizer-related GHG emissions and the risk of pollution. ▪ **Pillar 3:** While localized irrigation requires pressurized water, the pressures needed are relatively lower than those required for sprinkler irrigation systems. Note that the high level of irrigation uniformity that is normally achieved also reduces the energy requirements of localized irrigation systems.	▪ **Pillar 1:** Localized irrigation systems are relatively expensive, partly because water needs to be filtered before it enters the systems. Clogging is a major problem with most localized irrigation systems. Emitter outlets are typically very small, and can be easily clogged with chemical precipitates, soil particles or organic materials. Localized irrigation systems are also susceptible to damage by rodents, ant and in-field operations. ▪ **Pillar 1:** Localized irrigation systems require a higher level of management, maintenance and know-how than surface or sprinkler systems. There is a significant risk of failure if farmers manage localized irrigation in the same way as surface or sprinkler systems. ▪ **Pillar 2:** Localized irrigation is not suitable for most full-cover crops, e.g. alfalfa, cereals, grass, etc. ▪ **Pillar 3:** Farmers who are new to localized irrigation tend to over-irrigate. This can create waterlogging and increased GHG emissions. ▪ **Pillar 3:** High evaporation losses can occur with localized irrigation systems, either before a crop canopy has closed or if driplines or emitters are located in the centre of inter-rows in full sunshine. If they are not mitigated, these non-beneficial consumptive water uses also represent unnecessary use of energy.

After: Stewart and Nielsen, 1990; USDA, 1997; Brouwer et al., 1989; Savva and Franken, 2001; Bjorneberg, 2013

Efficiency and productivity of irrigation systems

Localized irrigation enables farmers to achieve high irrigation uniformity and apply fertilizer as and when needed via the irrigation water application (i.e. fertigation) (EIP-AGRI, 2016). However, localized irrigation requires water on demand; energy to pressurize the water; and, in the case of drip irrigation, filtration of water to avoid clogging of emitters. Localized irrigation is commonly used in greenhouses and with permanent horticultural crops such as vines and fruit trees. Localized irrigation can be used to exert a high level of automated control on conditions in the root zone and to minimize non-beneficial consumptive water use, for example in the form of evaporation from bare soil. If localized irrigation systems are well designed, well maintained and well managed, consumptive water use can be reduced for some crops and cropping systems (e.g. row crops, see **PHOTO 3**). Typically, however, localized irrigation systems use more energy than surface irrigation systems, though less energy than sprinkler irrigation systems.

The efficiency of localized irrigation systems depends partly on the design of the systems, and how well these are matched to cropping systems. It is also important to note that there are many types of localized irrigation (e.g. drip, mini-sprinklers, bubbler and tapes), each of which come with different advantages and disadvantages. In the case of drip irrigation,

PHOTO 3: Localized and mini-sprinkler irrigation systems in a semi-arid area of Rajasthan, India

Left: For row crops, localized drip irrigation is often the preferred option for reasons that include relatively high efficiency and productivity of water use, good irrigation uniformity, and the possibility of using fertigation.

Right: For field crops in semi-arid and arid areas, mini-sprinklers are not an ideal irrigation method due to the high non-beneficial consumptive water use as a result of wind drift and crop canopy interception. However, they can be a good option, for example, for germinating seedlings, irrigating specific crops in greenhouses and irrigating tree crops such as citrus beneath the canopy.

Photo credit: Charles Batchelor

important decisions need to be made, for example relating to the type of filtration system, control valves and emitters, the emitter discharge rates, the spacing between emitters, the spacing between driplines, and so on. More details on the planning, design, operation and maintenance of localized irrigation systems can be found in Savva and Franken (2002a).

Subsurface irrigation is a drip irrigation system that has driplines buried in the root zone of a row crop. The aim is to reduce evaporation from the soil surface and lower the risk of driplines being damaged by in-field operations. However, system management may be impaired by hard-to-detect problems such as blocked emitters. Note that for some crops and irrigation scheduling practices, roots will grow into and block emitters unless root inhibitors are applied through the irrigation system.

Precision irrigation aided by real-time data acquisition (e.g. from satellite, planes, drones and sensors in machinery) adjusts irrigation management to spatial variation in land capability, soil type and/or crop growth. Field crop variability can be identified and quantified from aerial images. However, prescriptions for taking irrigation decisions are not always clear. For example, if the crop in zone A is growing poorly, should it receive less or more water? Furthermore, precision irrigation requires an irrigation system that allows different amounts of water to be applied in different zones within the plot (**Variable Rate Irrigation (VRI)**). This technology is available for central pivots, but it is expensive (EIP-AGRI, 2016).

When water supplies are limited, the farmer's goal should be to maximize net income per unit of water used, rather than per land unit. For a range of crops and cropping systems, it has been shown that water productivity and farmer profits increase under **deficit irrigation**, relative to their value under full irrigation (Fereres and Soriano, 2007). As stated above, deficit irrigation (or regulated deficit irritation) is essentially a form of irrigation scheduling that creates and/or maintains a soil moisture deficit in the root zone for part or all of a crop season. It is not an irrigation method or system per se.

Sprinkler systems include periodic move systems, solid set systems, centre pivot systems, low-energy precision-application systems and travelling rain gun systems. Irrigation uniformity depends largely on the system’s characteristics. And high irrigation uniformity is generally possible, except with wind and in hilly terrain. This method is widely used because it is easy to install, maintain and manage. It is also flexible in terms of being moveable to different fields of a landholding, as long as submains are in place to provide pressurized water to fields that are to be irrigated. Irrigation scheduling is possible if water is available on demand. However, sprinkler systems can be relatively expensive, and non-beneficial consumptive water use in the form of evaporation from bare soil, evaporation from crop canopies and wind-drift can influence irrigation uniformity and water productivity (see **PHOTO 3**). The latter can be particularly high in arid and semi-arid areas when irrigation takes place on windy days during daytime. Sprinkler irrigation requires energy for pressurizing water and, in some conditions, it may result in higher risk of fungus attacks and soil erosion (EIP-AGRI, 2016). More details on the planning, design, operation and maintenance of sprinkler irrigation systems can be found in Savva and Franken (2001).

Surface irrigation is still by far the most common and popular method of irrigation globally. It is used mostly on flatlands and/or land that has been levelled or terraced. Reviled by many because of the large amounts of applied water and environmental risks (water contamination), it has regained attention due to its low energy consumption and costs compared with other systems (EIP-AGRI, 2016). There is also increasing recognition that: 1) The consumptive water use of surface irrigated crops is often much less than the water applied, since much of the water applied is recovered and reused locally or downstream, and 2) When well implemented and managed, the consumptive water use of surface irrigated full-stand crops is similar to that of the same crops when irrigated using sprinkler or localized irrigation systems.

On large surface irrigation systems, farmer controlled irrigation scheduling is not possible, because water is not available on demand. However, farmer controlled surface irrigation is feasible with many small surface irrigation

PHOTO 4: Surface irrigation system in India

Surface irrigation is still the most widespread – and for many crops and socio-economic and agro-ecological contexts the most suitable – irrigation practice. This type of ridge and furrow irrigation improves irrigation uniformity on fields that have not been levelled.

Photo credit: Charles Batchelor

systems that use water sources such as springs, small diversion or wells.

In saline soils, part of the excess water applied by surface irrigation leaches salts out of the rooting zone and, thus, increases the yield potential of soils. **Furrow irrigation** improves the distribution uniformity of flood irrigation (even more with intermediate dykes), but this often remains below the level obtained with sprinkler or drip systems (see **PHOTO 4**). On the other hand, furrow irrigation consumes less energy than these two systems (EIP-AGRI, 2016). **Laser levelling** is the best operation to improve distribution uniformity in flood and furrow irrigation systems, reducing the water application rate, percolation losses and nutrient leaching. It is expensive, but the levelling effect can last several years. More details on the planning, design, operation and maintenance of surface irrigation systems can be found in Savva and Franken (2002b).

In conclusion, irrigation efficiency is generally higher with sprinkler and localized irrigation than with surface irrigation, so these methods are preferred when water is in short supply (Brouwer *et al.*, 1989). However, it must be remembered that:

- Irrigation efficiency is just as much a function of the farmer as of the irrigation method used (Brouwer *et al.*, 1989).
- When farmers have access to unlimited water resources (e.g. access to a high-yielding well or a canal near to the offtake), improving irrigation efficiency is often very low on their list of priorities.
- Published figures for irrigation efficiency of different methods can be very misleading for reasons that include: 1) Many different formula are used to calculate irrigation efficiency; 2) Irrigation efficiency is influenced by many factors; 3) Irrigation efficiency is scale dependent (i.e. it will be different when calculated for a field and a large irrigation scheme; 4) In reality, irrigation efficiency varies in space and time (i.e. a single figure is a poor representation

of actual irrigation efficiency in space and time).

Options for improving irrigation efficiency, crop productivity and/or water availability

Irrigation efficiency can be improved for a specified domain by: 1) Reducing the volume or depth of water that is lost as non-beneficial consumptive water use; and/or 2) Increasing the volume or depth of non-consumptive water use or return flow that is reused. Water productivity can be improved for a specified domain by: 1) Increasing crop yields; and 2) Reducing the volume or depth of consumptive water use. Practical options for improving irrigation efficiency, crop productivity and/or water availability include:

Effective weed control in crops and orchards prevents the consumptive use of water by competing plants. Crop roots will also be able to explore more soil. Weed control requires attentive management and should consider the full crop rotation. Usually, an integrated approach of combined methods is more effective and environmentally safer than fully relying on herbicides.

Early crop establishment for ground cover during rainy seasons reduces non-beneficial soil evaporation and improves water infiltration; additionally, it reduces soil erosion and nutrient leaching. Early crop establishment can be achieved by, for example, seed priming (pre-soaking seeds to enhance germination).

Matching the cropping season to the rainfall season – growing annual crops when the evaporative demand is lower (e.g. during the rainfall season); growing annual crops in areas or regions with longer rainy seasons and/or relatively low evaporative demand (Wallace and Batchelor, 1997).

Selecting cultivars that improve yields and/or water productivity and are well matched to agroclimatic conditions, preferred cropping systems and value chains.

Planting along contours to increase infiltration and reduce runoff (and erosion).

Plastic mulch reduces soil evaporation and, when black plastics are used, improves weed control. Easy to install and manage, it is mostly used in horticultural crops, due to cost. A major problem is that the use of plastic increases the carbon footprint of crop production and risk of pollution when disposing of used or damaged plastic sheeting.

Organic mulches can also be used to reduce soil evaporation, for example, if crop residues are available that are not needed as fodder. Some care is needed when using organic mulches because they can be a source of, or provide ideal conditions for some weeds, pests and diseases.

Soil capacity to store water depends greatly on soil texture and structure. The texture is fixed, but the structure can be improved by **increasing soil organic matter,** or by reducing soil compaction.

Conservation agriculture is a farming system based on three principles: minimum soil disturbance, permanent organic soil cover, and species diversification. By applying organic mulches and no-tillage it provides both enhanced soil moisture conservation through reduced evaporation and enhanced water retention through increased soil organic matter. Moreover, it improves water infiltration into the soil and protects the soil from erosion by wind and water. Another option for organic soil cover would be cover crops. However, these should only be used where water resources are not a limiting factor, as they add to the total consumptive water use of a cropping system (FAO, 2014b; Richards *et al.*, 2014).

Improved crop husbandry that includes timeliness of operations, effective pest and disease control and effective plant nutrition. In many cases, extension services and other institutions (e.g. Farmer Field Schools) are needed to improve farmer know-how and to provide impartial advice regarding the adoption of new practices.

Whatever irrigation method is chosen, its purpose is always to attain a better crop and a higher yield. Therefore proper design, construction and irrigation practice are of utmost importance. Regular **maintenance** of system components is a vital part of system management that is often neglected (Brouwer *et al.*, 1989).

Irrigation systems should be **designed** to improve efficiency, productivity and water availability, rather than to minimize capital and current costs. In many cases, this involves additional expenditure on automation that facilitates good management of systems and timely scheduling of irrigation.

Factors influencing decisions to use water more efficiently and productively

A powerful narrative associating low efficiency in irrigation systems with the low level of water charges has widely promoted the idea that raising charges would lead to major improvements in irrigation efficiency and water productivity. This narrative draws on evidence from the water supply and energy sectors, but can be highly misleading when extended to the case of large-scale gravity irrigation schemes for reasons that include the following (Molle and Berkhoff, 2007; Molle, 2011):

i. Even if average scheme efficiencies suggest otherwise, water is not always wasted, because non-consumptive water uses (e.g. deep percolation and drainage) return to the water cycle and are reused locally or downstream.

ii. Even when some water is 'wasted' in the form of non-beneficial consumptive and/or non-recoverable non-consumptive water use, the causes often lie largely beyond the control of the end-users (the farmers) for reasons that include: 1) Farmers can do little to prevent water 'wastage' at the system level, and 2) System 'wastage' is often largely due to unpredictable supply to the scheme, improper internal management, and/or poor design rather than farmer behaviour. Unlike in urban piped systems, where users may normally access water at will, farmers often only use water when (and if) it is delivered to them.

iii. Even when water is 'wasted' at farm level, raising water prices generally has no impact on irrigation efficiency. This is mainly because few irrigation schemes use volumetric management, and even those that do use it often do not charge users volumetrically. Moreover, in the rare cases where water is charged according to volume, prices are almost invariably too low to induce a change in behaviour. This is all the more true because modern schemes with volumetric management are often pressurized and associated with high value crops, which means that: (a) water costs are negligible in the crop budget; (b) efficiency is already high; and (c) the costs of achieving higher efficiency would normally offset any gains from a lower water bill (Molle, 2011).

More positively, experience has shown that some factors influence the adoption of irrigation technologies and practices that can lead to more efficient and productive water use. The most prominent is water scarcity, which is created: by competition over limited water resources, unsustainable consumptive use of water resources, drought, climate change, and government policy. In the latter case, governments can create water scarcity by using direct controls (e.g. allocations, quotas, management rules etc.). A more radical measure than reducing allocations and entitlements in times of drought is the temporary 'retirement' of irrigated land, which can either be cultivated under rainfed conditions or left fallow (Molle and Closas, 2017). It seems likely that, in areas experiencing a severe decline in rainfall, planned full 'retirement' of irrigated land may prove a better option politically and socially than unplanned *ad hoc* failure of irrigated production systems and value chains – especially, if the planned retirement of irrigation systems is supported by an appropriate compensation scheme.

3.2.5 Key messages

- Typically, the CSI policies and practices focus initially on improving the performance, productivity and profitability of irrigation schemes because this generates stakeholder interest and buy-in. It is also notable that irrigation schemes that are performing well tend to be more resilient to climate change and other shocks than irrigation schemes that are performing poorly.
- There is a significant risk that investment in CSI adaptation and/or mitigation will be wasted if current irrigation policies and practices are substandard.
- Irrigation hardware (i.e. infrastructure) that is well designed, constructed, operated and

maintained) is an important and **necessary** component of CSI strategies and practices aimed at increasing water productivity of irrigation schemes and cropping systems, and the incomes of farmers, without having a negative impact on the environment. Similarly, irrigation hardware is often a **necessary** part of successful climate change adaptation and mitigation. However, good irrigation hardware alone is rarely **sufficient** to achieve desired outcomes, i.e. **irrigation software** is also needed.

- In general, there are significant gaps between *actual crop yields* that are achieved by farmers and *attainable crop yields* or *potential crop yields*. One of the aims of CSI policies and practices is to **close this gap**.
- There is a widely held belief that improvement in **water productivity** is an important objective of farmers. The reality is that farmers in both rainfed and irrigated settings must address a complex set of issues pertaining to risk, uncertainty, prices, and opportunity costs.
- Another challenge for CSI is that many farmers have **little or no interest** in using water more efficiently or productively. For example, farmers may be located in a water scarce region or zone, but do not experience scarcity because their landholdings are located near a canal offtake (rather than at the tail end), or because they have access to a high-yielding well.
- Attempts to increase productivity and farmer incomes are often based on **engineering and/or institutional quick fixes**. In both cases, iterative adaptive approaches that have a high level of stakeholder engagement are more likely to succeed.
- There are fundamental differences between public and privately managed irrigation schemes, low-input and intensive irrigated cropping systems, and, irrigated cropping systems in the humid tropics and arid areas (CA, 2007). In the latter case, it is important to recognize that irrigation plays different roles in different climatic contexts by fully or partially meeting crop water requirements.
- A major challenge for CSI is that improvements in water productivity at field scale often translate into **net increases in total consumptive water use** at irrigation system or river basin scales. This is on the rational economic basis that the more productive and profitable an activity is, the more a farmer wants to upscale it.
- As the consumptive water of areas equipped for irrigation increases, and as competition for water resources grows and the demand for good quality water outstrips supply, regulating and managing demand for water becomes increasingly important.
- **Lack of drainage** can be a serious impediment to increased agricultural productivity.
- When selecting an irrigation method and/or designing an irrigation system, a farmer should have a good knowledge of the comparative advantages, limitations and suitability of the different irrigation methods.
- Irrigation efficiency and/or water productivity is just as much a **function of the farmer** and the irrigation scheduling procedures as the method of irrigation used.
- A powerful narrative associating low efficiency in irrigation systems with the low level of water charges has widely promoted the idea that raising charges would lead to major improvements in irrigation efficiency and water productivity. This narrative draws on evidence from the water supply and energy sectors, but can be highly misleading when extended to irrigated agriculture**.**
- Another popular narrative is that improvements in irrigation efficiency save and free up water for other uses and users. The evidence from research and field measurements shows that this is not always the case.
- Water accounting should be used to better understand the benefits and possible unintended consequences (or trade-offs) that can result from the implementation of improved policies and practices.

3.3 CS1 Pillar 2: Irrigation related adaptation

3.3.1 Introduction and overview

CSI adaptation rationale

Climate change is happening. Even if global emission reductions and mitigation efforts over the next decades prove to be successful, a significant amount of human induced climate change has become inevitable. In addition to efforts to mitigate climate change by reducing greenhouse gas emissions, adaptation strategies are needed to enable the irrigation sector to cope with the immediate and expected future impacts of climate change.

The CSI rationale to climate change adaption is based on the understanding that:

- **Climate change vulnerability** is determined by both potential climate change impacts and adaptive capacity (see **FIGURE 18**). CSI's adaptation strategies aim to address both these facets of vulnerability.
- Climate change can be conceptualized as a **cascade of risks** from direct or indirect impacts (e.g. on water sources, irrigation related infrastructure, and irrigated cropping systems) through to socio-economic and environmental impacts (e.g. on value chains, livelihoods and environmental flows). Understanding this cascade of risks, as well as the vulnerabilities to them, is fundamental to effective climate change adaptation (FAO, 2016c).
- Effective adaptation is as much about **irrigation software** as it is about **irrigation hardware**, i.e. adaptation based on technical quick fixes is unlikely to produce desired outcomes.
- Effective adaptation involves **building on good irrigation practice**. The first step in an adaptation process at local level is to ensure that: 1) Irrigation schemes and practices in a specified area are productive, sustainable and non-polluting; 2) Farmers are competent, capacitated and financially secure; and that 3) Safeguards have been adopted that respect the environment (e.g. environmental flows), poor and marginal social groups (e.g. equitable access to water for multiple uses) and gender (e.g. women's rights and active participation in WUAs).
- **Consumptive water use in many regions is unsustainable** (e.g. groundwater levels are falling and river flows are declining). In other regions, there is a risk that adaptation activities may have the unintended consequence of increasing consumptive water use to the point that it outstrips sustainable supply.

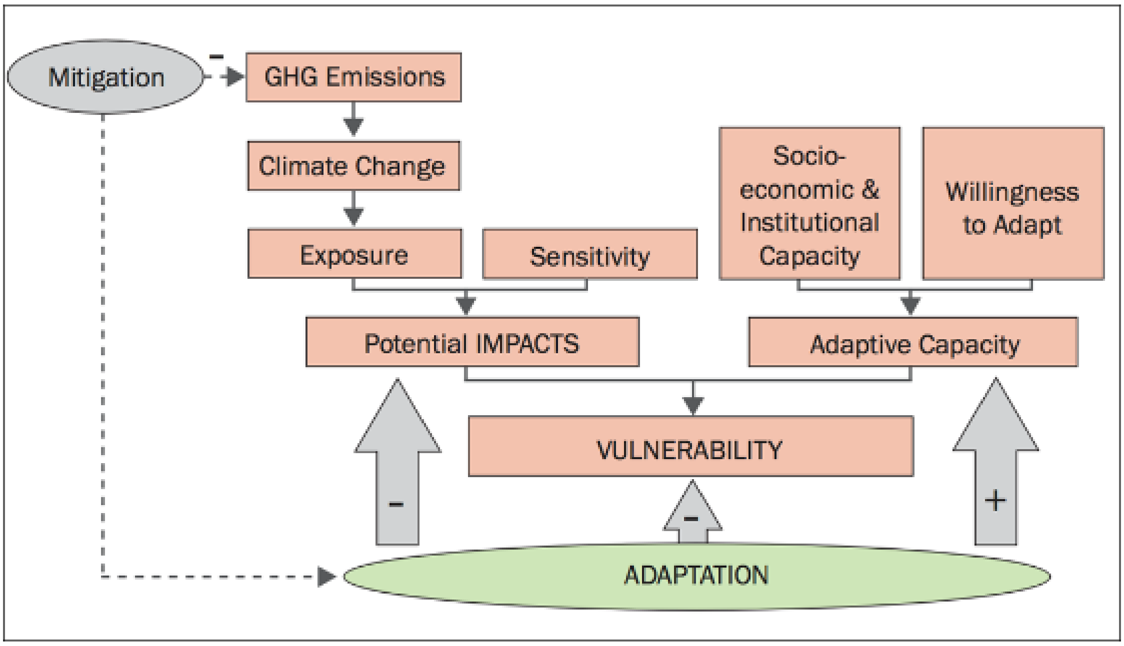

FIGURE 18: Conceptual diagram showing interrelationships between potential climate change impacts, vulnerability and adaptation

Source: Swart et al., 2009

- Adaptation activities should take place at various levels and **involve dialogue between stakeholders**, horizontally at each level and vertically between levels. In many cases, it makes sense for adaptation of irrigation related policy and practices to be based on a combination of top-down and bottom-up approaches (see **FIGURE 19**). More information on bottom-up approaches to climate change adaptation can be found in Ray and Brown (2015).
- Development of adaptation strategies should be **evidence informed** and account for differences between consumptive and non-consumptive water use in space and time (Batchelor *et al.*, 2017).
- CSI adaptation involves changes or reforms that may prompt stern **resistance** from some stakeholders who feel threatened by these. This can be pre-empted to some extent by addressing the following questions. Who are likely to be the **'winners' and 'losers'** from particular reforms? Are there any key reform champions within the sector? Who is likely to resist reforms and why? Are there 'second best' reforms that might overcome this opposition? It is also advisable as part of a CSI adaptation process to develop and continuously update a multilevel theory of change (Valters, 2015).

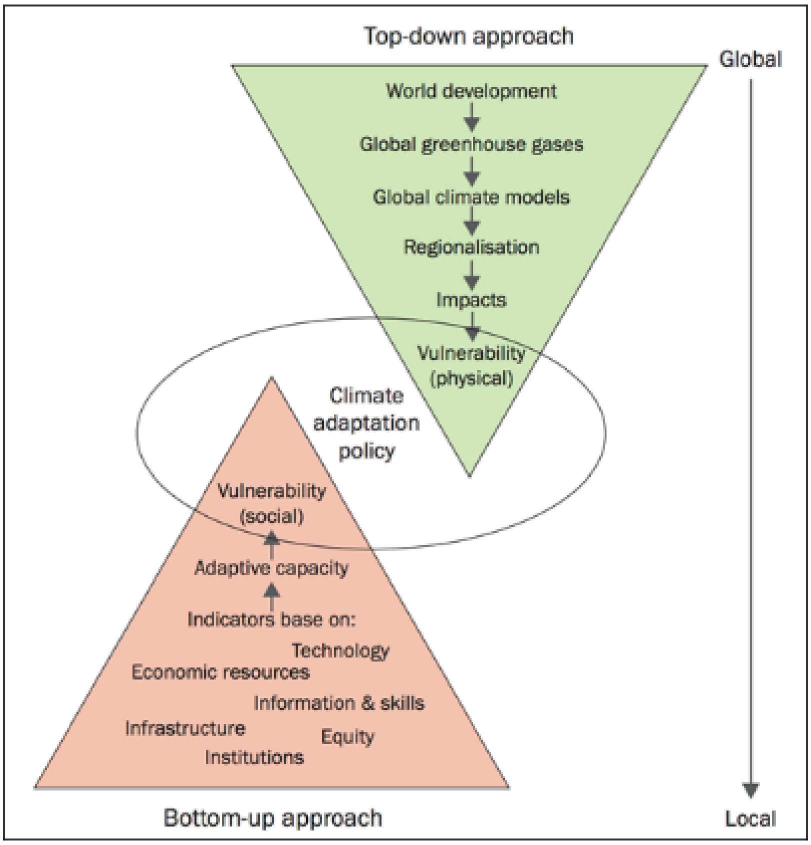

FIGURE 19: Top-down and bottom-up approaches to climate change adaptation

Source: Swart et al., 2009

The Paris Climate Agreement

CSI's rationale takes specific account of the Paris Agreement. For example, the agreement includes the global goal of enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change, with a view to contributing to sustainable development (FAO, 2016a). While adoption of CSI has the potential to enhance adaptive capacity, strengthen resilience and reduce vulnerability to climate change, sustainability is an issue. More specifically, consumptive water use by irrigation is already unsustainable in many regions of the world (e.g. southern India), and there is the risk that increases in the area under irrigation or in the intensification of irrigation will further increase and exacerbate unsustainable consumptive water use (e.g. resulting in falling groundwater levels and reduced river flows).

Planning and implementing CSI adaptation strategies

While broad regional and national patterns of climate change can be predicted with some certainty using climate models, making accurate predictions of the dimensions and character of changes at local level is problematic (FAO, 2016c). The **uncertainties associated with projections of climate change** at local level, coupled with uncertainties in political, social, economic and other responses to change, make it difficult for decision-makers, key stakeholders and others to decide which adaptation actions would be most appropriate and cost effective. In such circumstances it makes sense to:

TABLE 11: Options for climate change adaptation in the agricultural sectors

Altering exposure	Reducing sensitivity	Increasing adaptive capacity
▪ Assess impacts and map hazard zones ▪ Conduct proper land and water use planning ▪ Protect watersheds and establish flood retention zones ▪ Resettle humans and restructure agriculture ▪ Change cropping patterns	▪ Develop or adopt suitable crop, plant and animal varieties ▪ Improve irrigation and drainage systems ▪ Enhance soil nutrition and on-farm water management ▪ Diversify cropping and agricultural activities ▪ Adopt disaster prevention construction standards	▪ Develop adaptive strategies and action plans ▪ Diversify sources of household income ▪ Improve water and other infrastructure systems ▪ Establish disaster and crop insurance schemes ▪ Promote technical transfer and capacity-building

Source: Medeiros DuBois et al. (2012)

- Select and implement ***no- or low-regrets*** measures that have the potential to deliver benefits regardless of future climate trends, but also have the potential to be resilient to different climate change impacts across a range of short-, medium- and long-term climate scenarios.[18]
- Adopt an **adaptive management approach** that updates or refines irrigation related strategies, plans or practices as lessons are learned and/or more information becomes available (e.g. related to speed, direction and impacts of climate change).
- Recognize that climate change is **not the only source of uncertainty** and risk that might impact negatively on irrigation systems and value chains. If more immediate and/or more threatening sources of risk and uncertainty are identified in any given domain of interest, these should be given priority over climate change when, for example, developing adaptation strategies.
- Make sure that irrigation related adaptation strategies are either part of or well aligned with the adaptation strategies of other sectors and **national adaptation strategies**.
- Recognize that climate change adaptation can be enhanced by **altering exposure, reducing sensitivity and increasing adaptive capacity**. Also recognize that many CSI adaptation options are relevant to the agricultural sector in general, and vice versa. **TABLE 11** illustrates some options in each category.
- Recognize, as a general rule, that CSI adaptation strategies need to be **location and context specific, flexible and well integrated** (or aligned) with other sectors that use water and/or influence the availability of water resources in space and time (After Medeiros DuBois *et al.*, 2012). Change is nothing new. But the people, communities and societies who cope best with change of any kind are those who are resilient and able to adapt. The more resilient they are, the more they are able to manage climatic variability, diversify their livelihoods, and reduce risk (McCornick *et al.*, 2013). Building resilience now will bring benefits regardless of specifically how and when climate change plays out in space and time.

The smoothing of short-term impacts of climate variability provided by irrigation is threatened by changes in weather patterns and the increasing frequency and severity of extreme events (e.g. floods, droughts, hurricanes, cyclones). One consequence of warming is an increase in the variability of precipitation, which together with the loss of mountain snowpacks, has the potential to reduce the security provided by irrigation in some regions. Another consequence is the increasing risk of extreme weather events damaging irrigated crops and destroying infrastructure. Climate change will increasingly be entwined with **complex**

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[18] In general, within climate change adaptation a distinction can be made between CSI measures that adapt irrigated cropping systems to specific anticipated changes in climate to either moderate harm or exploit beneficial opportunities, and measures that increase the resilience of existing systems to current and possible future climate conditions. While the former bear the risk of maladaptation when based on uncertain projections that prove wrong, the latter may prove insufficient for coping with new extremes.

choices and trade-offs, in particular between food security, more resilient infrastructure and ecosystem health (After Turral *et al.*, 2011).

CSI adaptation takes place at farm, irrigation scheme and basin levels. These adaptations can be private or public, planned or autonomous. Trade-offs, constraints and incentives at irrigation scheme and basin levels often determine what farmers can achieve. However, in the absence of planned and public strategies, farmers may find themselves in the familiar position of having to fend for themselves. Most wealthy country governments clearly take the view that coordinated and planned responses are required. Poorer countries are likely to do the same, but have much weaker economic foundations supporting them (e.g. by subsidizing no- or low-regrets expenditure) (After Turral *et al.*, 2011).

Autonomous adaptation actions are defined as responses that will be implemented by individual farmers, rural communities and farmers' organizations, depending on perceived or real climate change in the coming decades, and without intervention or coordination by regional and national governments and international agreements (Tubiello and van der Welde, 2011).

While bottom-up irrigation related initiatives are to be commended, there is significant risk of maladaptation if these initiatives are not well coordinated and part of a broader intersectoral planning process that considers the potential trade-offs or externalities. For example, construction of a multipurpose reservoir may improve the resilience of a small-scale irrigation scheme, but the trade-off may be less water available for downstream water users and uses.

Ecosystem services and functions should no longer be treated as residual water uses (FAO, 2016a). Environmental flow analysis and integrated landscape or ecosystem-based approaches can be used to better quantify the benefits of functional ecosystems, and to develop adaptive strategies for restoring and maintaining ecosystems. This said, it is important to recognize that ecosystems are consumptive users of water and, in the context of irrigation schemes, are the beneficiaries of return flows that result from over-irrigation. Water accounting can and should be used to: 1) Investigate the extent to which aquatic ecosystems are competing for water with and/or benefiting from irrigation schemes (in space and time), and 2) Provide information or evidence for a specified domain that informs decisions relating to, for example, water allocation to ecosystems, and the potential negative impact on aquatic ecosystems that may result from improving the efficiency and productivity of irrigation schemes.

Irrigation related adaptation strategies should recognize the increased risk of **environmental pollution** that may result, particularly in areas of increasing water scarcity. The cost of not addressing pollution is high, and some impacts may be irreversible (e.g. contamination of groundwater) and have severe consequences for human health (FAO, 2016a). Water pollution from agricultural crop production can be reduced at both point and non-point sources through integrated pest and plant nutrition management, and pollution control (e.g. stringent monitoring, regulation and enforcement).

There is increasing recognition that significant volumes of water are used along **value chains** (e.g. as part of food processing). However this is primarily a non-consumptive water use that returns to surface or groundwater, albeit with reduced quality. In contrast, considerable amounts of food are wasted along value chains (often due to poor storage, handling and/or transport). This represents a loss of water that is equivalent to the total consumptive water use accrued in the production of this food. In some cases, this can represent a large volume of irrigation water that could have been used more productively in terms of improving food security.

CSI diversification

When developing irrigation related adaptation strategies, it is important to explore options for less water intensive and more climate resilient production (e.g. different cropping patterns, climate-resilient crops, improved irrigation scheduling); synergistic resource use in integrated systems (e.g. integrated food-energy systems that use agricultural residues or algae for biofuel production); and, income generation other than food production (e.g. solar energy as a crop). Incentives (e.g. subsidies, provision of extension services and/or payments for environmental services) or disincentives (e.g. quotas, fines and pricing) should be considered to support the most productive and sustainable allocation of resources (FAO, 2016a). Finding ways to combine diversity rich strategies with the production demands of the future is one of the major challenges, and the improved maintenance and use of genetic resources for food and agriculture will lie at the heart of meeting it (FAO, 2016c).

CSI adaptation policies and institutions

From a policy and institutional perspective, effective adaptation to climate change in agriculture and food systems for food security and nutrition requires investments, policies and institutions that are well matched and adapted to the societal context and broader political economy of the specific domain of interest (After FAO, 2016c). Ideally, CSI adaptation strategies should be gender sensitive, multiscalar and align with adaptation strategies of other sectors or be part of the National Adaptation Plan (NAP). They should be formulated with active engagement of key stakeholders and consider the different dimensions (social, economic, environmental) of the related issues, as well as the different time scales over which the changes will need to be implemented and supported. They should be based on assessments of risks and vulnerabilities, build on lessons learned, and be regularly monitored, evaluated and updated. It is likely that middle- and high-income countries will have necessary monitoring systems in place, but this may not be the case in other countries.

Policies that aim to reward improvements in irrigation, either through market mechanisms or increased regulations and improved governance, are an important tool for enhancing adaptation capacity at regional scale. However, unintended consequences may be increased consumptive water use upstream, resulting in downstream users being deprived of water that would otherwise have re-entered the stream as return flow (Moss *et al.*, 2008; Tubiello and van der Welde, 2011).

PHOTO 5: Dry irrigation canal in Iran

Poorly managed canal networks and irrigation schemes lead to inequitable access to water, especially at the tail end of canals.

Photo credit: Charles Batchelor

Planned adaptation solutions should focus on developing new infrastructure, policies and institutions, including addressing climate change in development programmes; increasing investment in irrigation infrastructure and precision water use technologies; ensuring appropriate transport and storage infrastructure; revising land tenure arrangements (including attention to well defined property rights); and establishing accessible, efficiently functioning markets for products and inputs (including water pricing schemes) and for financial services (including insurance) (Tubiello and van der Welde, 2011).

The **effectiveness of CSI adaptation strategies** and actions is determined by both internal and external factors. Typically, internal factors are those that come under the control of key stakeholders. In contrast, key stakeholders have little or no control over external factors. Notably, internal and external factors can act as constraints or enablers depending upon the context and type of adaptation planned (After Young, 2014).

Internal factors that influence CSI adaptive actions include:

- **Available resources** e.g. irrigation related skills, know-how, expertise, public and private finance.
- **Current strategic directions and planning** e.g. relating to irrigation, water management/allocation, domestic and urban water supplies, agriculture, economic development, environmental protection.
- **Geographical context** e.g. state of development of water resources, agroclimatic conditions and variability.
- **Infrastructure** e.g. capacity and condition of existing pumps, bulk water transfer systems (see **PHOTO 5**), reservoirs, drainage systems, water treatment plants.
- **Operational and institutional frameworks** e.g. roles and responsibilities of government, private sector, non-governmental organizations (NGOs), community-based organizations (CBOs).

External factors that influence adaptive actions include:

- **Politics and political economy factors:** e.g. relevant policies and legislation, importance given to climate change, food security, water security, gender issues.
- **Regulatory environment** e.g. relating to environmental sustainability, pollution, environmental flows.
- **Markets and value chains** e.g. prices, market forces, transport, storage facilities.
- **Cooperation between ministries** e.g. intersectoral alignment of adaptation plans, sharing of data.

Adaptation of CSI related policies and institutions should be based on **mutually supportive water accounting and auditing** that includes political economy analysis (PEA). PEA seeks to identify and evaluate the roles, interests and likely responses of key stakeholders and institutions to policy change. The goals of this analysis are threefold. First, it guides the design and evaluation of technical solutions, which have to be informed by a realistic appraisal of the political, economic and social context for which they are being designed. Second, it helps to identify both key stakeholders, including the poor and politically voiceless, who must be consulted and engaged, as well as the vital substantive issues and interests that need to be addressed in the decision-making process to ensure outcomes that are both workable and legitimate. Third, it provides political and social parameters for institutional adaptation and development (FAO, 2017b).

CSI adaptation research

Innovative and sustainable water management practices and technologies derived from applied research, combined with appropriate policies and strategies, will help in the mitigation of and adaptation to, climate change. In many cases these practices and technologies will be refinements of current practices and technologies (i.e. more of the same but better adapted). It is clear that CSI requires technological innovation and investment in research and development (R&D). Investment is also needed to implement and support new organizational forms of R&D that are closer to farmers' needs, as highlighted for instance through the experiences of Farmer Field Schools (FAO and INRA, 2016). For example, there is scope for citizen scientists and private sector organizations to work closely with

Farmer Field Schools, albeit taking advice from specialists as and when appropriate (see case study Citizen Science in Andean Agro-forestry systems, **Section 4.5**).

Given the trends in agricultural demand for water – as driven by population, income growth and changing diets – a recurring challenge for agricultural water management is how to do more with less (Turral *et al.*, 2011). Competition for bulk water is already driving this autonomous adaptation, but climate change is expected to sharpen the points of competition. This gives added impetus to water management adaptation, to reduce demand and improve the productivity of water use at all scales by **better managing consumptive and non-consumptive water uses.** The aim is, where possible, to take opportunities for using water non-consumptively several times before it is used consumptively.

To safeguard food security, measures for climate change adaptation need to be applied not only to crop production, but also to complete **'field to fork' value chains**. However, to date there has been limited research into the impacts of climate change on food processing, packaging, transport, storage and trade. Adaptation initiatives need to engage multiple sectors and consider a broad range of systemic and transformational options (Porter *et al*., 2014).

There may be merit in increased research on adaptation strategies that involve land use changes that **take advantage of modified agroclimatic conditions**. A few simulation studies show the importance of irrigation as an adaptation technique to reduce the impact of climate change. In general, however, projections suggest that the greatest relative benefit of adaptation is to be gained under conditions of low-to-moderate warming. Indeed, adaptation practices that involve increased irrigation water use will probably place additional stress on water and environmental resources as warming and evaporative demand increase (Moss *et al.*, 2008; Tubiello and van der Welde, 2011).

Seasonal climate forecasting has improved substantially in recent decades (Klemm and McPherson, 2017). Thanks to a better understanding of atmospheric processes, advances in computing, and improved prediction models, seasonal forecasts of temperature and precipitation are now standard products that are available in the USA and many other countries around the world. From a climate change adaptation perspective, the challenge now is to ensure that these forecast products are tailored to the needs of potential users at national, river basin, irrigation scheme and farm levels. The challenge is also to take full advantage of advances in cyber-technologies and informatics when designing and operationalizing forecasting systems.

Trade and CSI adaptation strategies

In many countries, food security will increasingly depend on food trade based on irrigated crop production. The highly political and complex international issue of agricultural trade needs urgent attention due to its crucial linkages with water security. This would require a collective effort at international level to address the trade–food–water nexus, and to draw benefits from virtual water (FAO, 2016a).

While trade is expected to play an increasingly important role under climate change, the negative impacts of climate change on infrastructure and transport links, as well as on economic performance of countries with a high agricultural share in the economy, raise questions on how well trade will actually be able to fulfil its role in adaptation (see **PHOTO 6**). Ultimately, global markets will only be accessible to the poorest countries and the poorest sections of these societies if they have sufficient purchasing power (FAO, 2016c).

CSI adaptation and vulnerabilities resulting from gender bias

"Vulnerability is often determined by socio-economic factors, livelihoods, and people's capacity and access to knowledge, information, services and support. Vulnerability and adaptation to climate change depend on opportunities governed by the complex interplay of social relationships, institutions, organizations and policies. Vulnerability assessments, which focus on climate and environment variables and macro-level data on poverty and economic activities, are often conducted nationally or regionally. At that level, analyses risk overlooking some of the most vulnerable people and groups and missing the

PHOTO 6: Sophisticated and well organized value chains help to ensure that post-harvest crop losses and virtual water losses are minimized

Photo credit: Charles Batchelor

underlying causes of their vulnerability" (FAO, 2016c).

Women and men possess and have access to different amounts and combinations of livelihood assets (human, social, financial and natural). For example, family farmers and smallholders everywhere face constraints in accessing credit, but in most countries the share of female smallholders who can access credit is five to ten percent lower than their male colleagues (FAO, 2011b). In the case of irrigation, men and women tend to participate in different activities with varying levels of decision-making power, each of which influences their vulnerability to climate change. For example, WUA membership is limited to landowners, frequently excluding those who farm the land but do not own it, often including women, but also tenants or sharecroppers. Evidence also shows that women are often inadequately represented in water users' groups and farmers' organizations, and if they are represented, their effective participation is very low (FAO, 2012b).

It is also important to note that not all men and women are equally vulnerable to climate change. Women are not necessarily victims of climate change, but can be crucial actors in finding solutions for how to cope with it (FAO, 2016c). A nuanced understanding of vulnerabilities to climate variability and change for different types of men and women is therefore necessary (World Bank, FAO and IFAD, 2012).

Specific opportunities for gender-sensitive strategies to respond to climate change include (McCornick *et al.*, 2013):

- Mainstreaming gender perspectives into national policies, action plans, and other measures on sustainable development and climate change.
- Carrying out systematic gender analysis, collecting and using sex disaggregated data, establishing gender-sensitive indicators and benchmarks.
- Developing practical tools to support increased attention to gender perspectives.
- Ensuring consultation with and participation of women in climate change initiatives.

- Strengthening women's groups and networks.

Mainstreaming CSI adaptation within pro-poor development strategies

Combating climate change goes hand in hand with alleviating poverty, which requires mainstreaming climate responses within pro-poor development strategies. Consequently, there is increasing support for mainstreaming climate change responses within human development and poverty alleviation, rather than pursuing separate climate and poverty tracks and risking potentially negative outcomes for one or the other of these goals. In the case of CSI, mainstreaming includes policies and programmes that, for example, seek to improve the livelihoods of poor and marginal farmers by improving their access to water for irrigation. Mainstreaming involves the integration of information, policies and measures to address climate change in ongoing development planning and decision-making. Mainstreaming should create 'no-regrets' opportunities for achieving development objectives that are resilient to current and future climate impacts for the most vulnerable groups, and avoid potential trade-offs between adaptation and development strategies, which can result in maladaptation (FAO, 2016c).

3.3.2 River basin scale (National institutional level)

Integrated CSI adaptation

There is general agreement that an intersectoral approach should be taken when building resilience of irrigated agriculture and food systems to climate change at river basin and national scales and levels. Such an approach requires the elaboration of an **integrated strategy** that encompasses agriculture and food security policies, strategies and plans, as well as those related to water, land and natural resource management, and economic development among others (FAO, 2016c). The integrated strategy should also be part of, or well aligned with National Adaptation Strategies (NASs) and National Adaptation Plans (NAPs).

Iterative risk management is a useful framework for decision-making in complex situations that are characterized by large potential consequences, persistent uncertainties, long time frames, potential for learning, and multiple climatic and non-climatic influences changing over time (IPCC, 2014; **FIGURE 20**). In the case of CSI, the intended outcome is irrigated cropping systems and value chains that are well adapted or tailored to a biophysical and societal context that is changing over time as a result of climate change and external factors, many of which are unknowable. Reliable monitoring systems and active stakeholder dialogue are central to this type of cyclical learning and adaptation.

The **Water-Energy-Food nexus** approach[19] (Hoff *et al.*, 2011) and FAO's Global Framework for Action to Cope with Water Scarcity in Agriculture in the Context of Climate Change (GFA) lend themselves very well to CSI adaptation. The GFA is based on the premise that a sustainable pathway to food security in the context of water scarcity lies in maximizing benefits that cut across multiple dimensions of

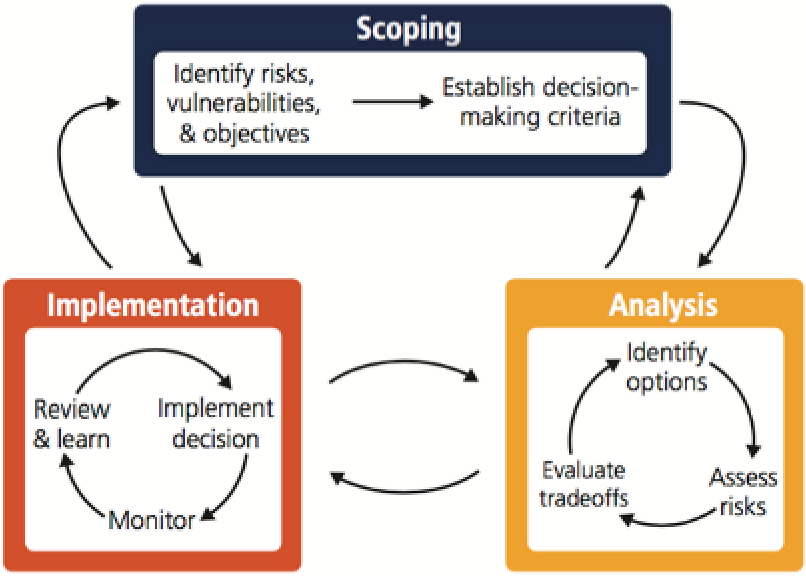

FIGURE 20: Climate change adaptation as an iterative risk management process with multiple feedbacks

People and knowledge shape the process and its outcomes.

Source: IPCC, 2014

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[19] The Water-Energy-Food nexus approach is discussed in more detail in **Section 'Integrated CSI mitigation'**.

the **food–water–climate nexus**, enabling sustainable agricultural production while reducing vulnerability to increasing water scarcity and optimizing the climate change adaptation and mitigation benefits (FAO, 2016a).

Disaster risk planning is a possible entry point for climate change adaptation and resilience building, as many disasters are increasingly related to climate change (e.g. floods, droughts and storm surges). It is therefore important to create opportunities for climate financing at national level, which establish strong linkages between disaster risk planning, climate change adaptation and resilience programming. The need for this integration is underpinned by estimates that emergency aid after a disaster exceeds investments in disaster prevention by almost 7 700 percent (ODI, 2016). **Synergies between CSI adaptation strategies and disaster risk planning** exist in part because in many countries, there has been huge investment in irrigated agriculture infrastructure (e.g. for storing water, bulk transfer of water, drainage of excess water). It makes good sense that CSI adaptation strategies aimed at improving the resilience of this infrastructure consider opportunities for mitigating a wide range of risks of disasters relating to water uses and users other than irrigated agriculture.

Adapting water management to climatic variability is **not something that can be done in isolation**. Water underpins sustainable development. There is broad consensus that adapting to climate change is best addressed in the context of sustainable development. Depending on local contexts, needs and interests, there are opportunities for improving water management that promote adaptation to climatic and other change, and simultaneously advance development. These opportunities usually integrate and apply the best and most promising approaches, tools and technologies to help vulnerable rural communities build resilience and develop sustainably (McCornick *et al.*, 2013).

Initiatives aimed at sustainable improvement of agricultural water productivity **cut across all agricultural subsectors**, from irrigated agriculture to livestock production, aquaculture and agroforestry. In this context, agricultural productivity should not only be looked at in terms of land, but in terms of water productivity, maximizing the return on water from a diverse range of activities (FAO, 2016c).

Future proofing

Many recommendations related to **future proofing** and the adaptation of water management to potential future changes in climate apply equally well to CSI (**FIGURE 21**). These recommendations highlight the need to (After McCornick *et al.*, 2013):

- Improve awareness and understanding of the potential impacts of climate change on the variability of rainfall, runoff, groundwater recharge and other water balance components.[20]
- Rethink water storage, emphasizing underground opportunities to minimize the impacts of variability and utilize the storage continuum.
- Improve understanding of the role of natural ecosystems in variability.
- Improve understanding of how humans influence variability.
- Develop and manage water resources fairly – share water, land and food in a cooperative manner, and in a way that does not leave vulnerable groups disproportionately burdened by the impacts of variability.

CSI adaptation assessment and analysis

River basin scale assessments should be complemented by a bottom-up approach in which the local community is fully engaged, and where local men and women farmers and other rural dwellers discuss and agree on the best adaptation interventions that they would be

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[20] Water storage can be conceptualized as a continuum, ranging from water stored in underground aquifers, through the soil profile to that stored in large reservoirs. In any specific situation, each of these types of storage has its own niche in terms of technical feasibility, socio-economic sustainability, institutional requirements and impact on public health and the environment (McCartney et al., 2013).

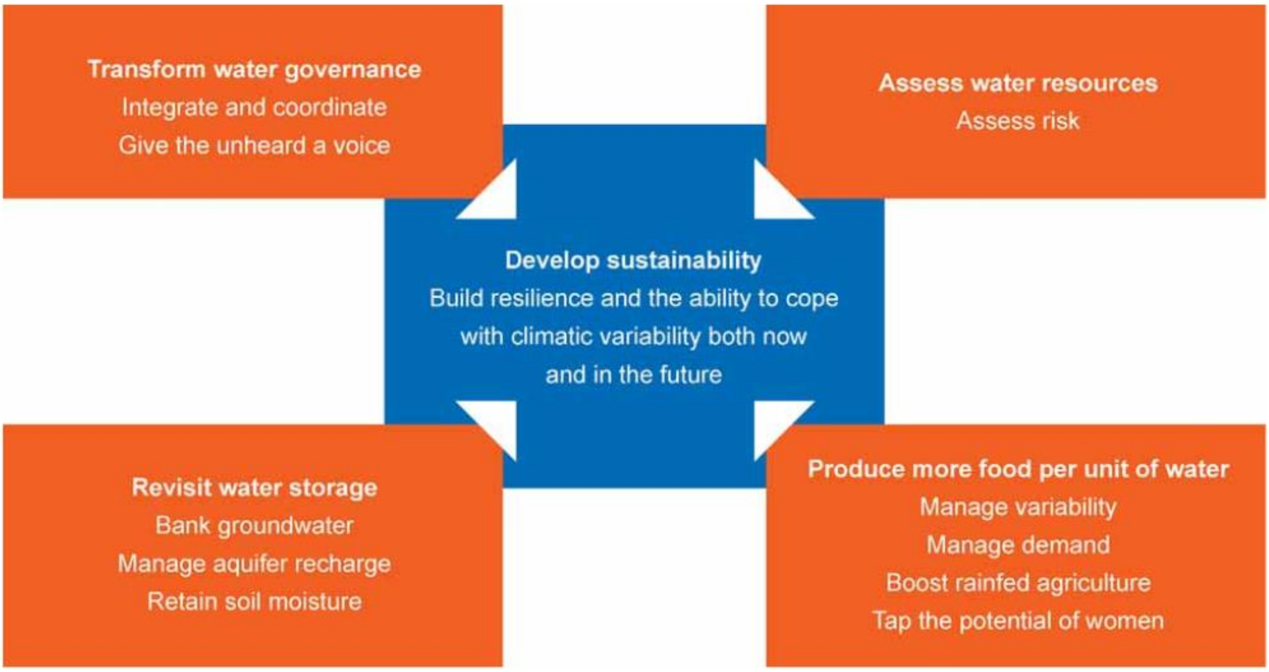

FIGURE 21: Adapting water management to climate change

Source: McCornick et al., 2013

willing to adopt, given the local climatic, socio-economic and environmental conditions (community-based adaptation). This provides an opportunity to link local traditional knowledge with scientific knowledge. In addition, it gives the affected populations an opportunity to identify possible unintended consequences of interventions and discuss how to resolve them. When the comparative advantage of different adaptation options is not clear, an assessment of the costs and benefits of adaptation measures can be carried out using economic analysis or non-economic evaluation methods. In either way, some metrics of costs and benefits need to be estimated (FAO, 2016c).

Assessments should be based on the **best available scientific information** (methodologies, tools, models and data), making use of model-based methodologies as well as participatory, perceptions-based methodologies. In order to ensure accountability, replicability and transparency, established and robust methodologies should be selected, while allowing for uniqueness inherent to each context (FAO, 2016c). Water accounting and auditing provides a good framework for adaptation and analysis, especially when used alongside models that have been selected on the basis of their **relevance, utility, credibility and usability** in a given biophysical and societal context (Batchelor *et al.*, 2017). Note that there is a large number of models that may be useful for climate impact assessment and adaptation planning (FAO, 2016c).

The boundaries of river basins transcend administrative and national boundaries. Worldwide, water management at all scales increasingly considers water resources in basins and watersheds according to natural boundaries. Yet management decisions and implementation of interventions are more often than not through national administrative arrangements. **Tensions between managing water within natural boundaries and managing water within national borders proliferate.** Competing interests – political and economic – between countries, while widely deliberated, are challenging to resolve. A key aspect of adapting to climate change is that countries in transnational basins plan and work together much more than they have done in the past (Turral *et al.*, 2011).

Decisions related to transboundary water resources management are shaped by a range of considerations, from traditional economic factors and physical constraints to political considerations such as the need to manage political support within a single state, or to navigate complex international relationships between riparian countries. In this regard, exploring political economy realities can reveal opportunities and institutional arrangements that have already contributed to successful negotiations and agreements in the past (World Bank, 2017).

While transboundary water management is widely advocated to be best implemented at a basin scale, solutions to certain water issues (e.g. dam operation, flood prevention, pollution control, conservation works) may be addressed more effectively at scales other than the full basin. While this approach may not be ideal, because developments in a particular sub-basin may affect downstream areas, the reality is that good progress and outcomes in one part of a basin may prompt positive changes throughout the basin (IWMI, 2015).

Strategic CSI adaptation

Planning investments also needs to take climate change into account. Investments can range from large dams and irrigation schemes, inter- and intra-basin transfer, or reforestation, to water pricing systems and water management infrastructure. New infrastructure or technologies may bring benefits, but these may be significantly less compared with those that would accrue in the absence of climate change. Introducing technologies or building new infrastructure may affect ecosystems or increase the risk of water related diseases. Failing to introduce technologies or build new infrastructure, however, may also have significant implications. Rigorous analysis of proposed infrastructure or technologies helps decision-makers to invest wisely and avoid unintended consequences (Turral *et al.*, 2011).

Before looking at adaptation options in more detail, it is useful to summarize the broad choices that exist at strategic, system and farm levels. In physical terms, the river basin is the logical strategic planning level that integrates hydrology, farming systems and infrastructure. However, markets, politics and public administration are rarely defined at basin scale, and national perspectives and imperatives will usually transcend those apparent there. Thus, the physical focus of **strategic adaptation** policy may often be on the basin scale, although much analysis and policy development will be at national scale and will concentrate on:

- Choices between expansion of irrigated or rainfed area;
- Intensification of agriculture;
- Supporting policies and incentives;
- (Agricultural) research priorities and management;
- Development of infrastructure, especially large-scale surface and underground water storage;
- Accompanying water accounting and allocation policy; and
- Inclusion of crop storage and trade strategy.

In certain conditions, the strategic choices available may be limited: for example, where crop productivity (yield and water use efficiency) is already high (e.g. California), one of the costs of maintaining high levels of yield under more hostile climatic conditions is likely to be a substantial loss in water use efficiency. Higher overall water productivity (and production) might however be achieved by expanding area and sharing water supplies sub-optimally across old and new areas. In this example, expansion might be preferable to intensification, subject to the other externality impacts of expanding irrigated area (Turral *et al.*, 2011).

In order to prioritize adaptation options, there are many factors that need to be evaluated and assessed, and that are specific to the given biophysical and societal contexts. The decision should take into account the following considerations (World Bank, 2010d):

- How effective are different adaptation options in reducing vulnerability to increasing climate variability (i.e. more unpredictable weather, shift in rainfall patterns towards fewer and more intense storms, increased frequency and duration of consecutive dry days)?
- To what extent do they help to reduce impacts of extreme events (i.e. floods and droughts)?
- How effective are they under different future climate scenarios?

- What are their economic costs and benefits (see World Bank (2010e) on economic analysis)?
- Are there secondary or cross-sectoral impacts, externalities or co-benefits?
- To what extent are they 'owned' by local communities, so that project performance risks are reduced (see World Bank (2010a)?
- To what extent do they address short-, medium- and/or long-term climate change impacts?
- Are there important limiting factors for implementation and sustainability, such as lacking legal, financial, technical and institutional resources (see World Bank (2010b) and World Bank (2010c) for more information on institutional capacity for adaptation and enabling an institutional environment)?

3.3.3 Irrigation scheme scale (District or intermediate institutional level)

CSI adaptation planning and governance at the irrigation scheme scale

CSI adaptation at the irrigation scheme and local and intermediate institutional levels or scales should: 1) Be both bottom-up and top-down in nature and have a high level of active stakeholder engagement; 2) Inform and be informed by CSI planning at the other scales and institutional levels; 3) Take place within the context of river basin and national CSI adaptation plans; 4) Take account of and build on landholding and community scale CSI adaptation plans; and 5) Align with or integrate well with other relevant sectoral or intersectoral CC adaptation plans.

In terms of CSI adaptation, the irrigation scheme and local and intermediate institutions are the scales and levels at which: 1) Scheme managers, irrigation services providers and farmers interact, and 2) Many government policies and programmes are administered and implemented (After Moriarty *et al.*, 2007). Many decisions at river basin scale and national level are strategic, and to some extent conceptual. In contrast, decisions at irrigation scheme scale and intermediate institutional level tend to be more practical and tactical. Many of these decisions relate to, for example, the allocation or reallocation of water resources and are politically charged, particularly in water scarce areas. More specifically, it is often necessary to balance competing demands and to decide: who is entitled to certain levels of irrigation service, how are services provided, and who pays and what happens in the case of reduced water allocation, for example, as a result of declining rainfall and or prolonged drought? Decisions also have to be made with regard to allocation of water to urban areas and domestic users, and to ensure the protection of aquatic ecosystems. From the perspective of CSI adaptation, the nature of intermediate level **governance systems** is often as important as the decisions taken, because these systems determine the ways in which decisions are made and authority is exercised and/or mediated. It is also notable that these systems usually reflect **political realities** that, for example, may or may not be supportive of no-regrets expenditure on irrigation.

Watershed management approach

CSI recommends the **watershed management approach** be employed as a basis for: 1) Planning and implementing integrated land and water resource management across the community, landscape, irrigation scheme and intermediate scales and levels; 2) Identifying and planning alternative management practices that may enable land users to better cope with increasing weather variability and climate change; and 3) Other components of spatial planning, such as planning for infrastructural and other rural development activities. The watershed management approach also provides a good basis for understanding vulnerability and identifying where resilience could reside within a watershed, or when and how resilience has/can be lost or gained (see **FIGURE 22**).

Watershed management is the **integrated use and management of land, vegetation and water resources** in a geographically discrete catchment or drainage area through people-centred approaches with all stakeholders, for the benefit of residents and wider society, through enhancing productivity and livelihoods and maintaining the range of ecosystem services, in particular the hydrological services that the watershed provides, and reducing or avoiding negative downstream or groundwater

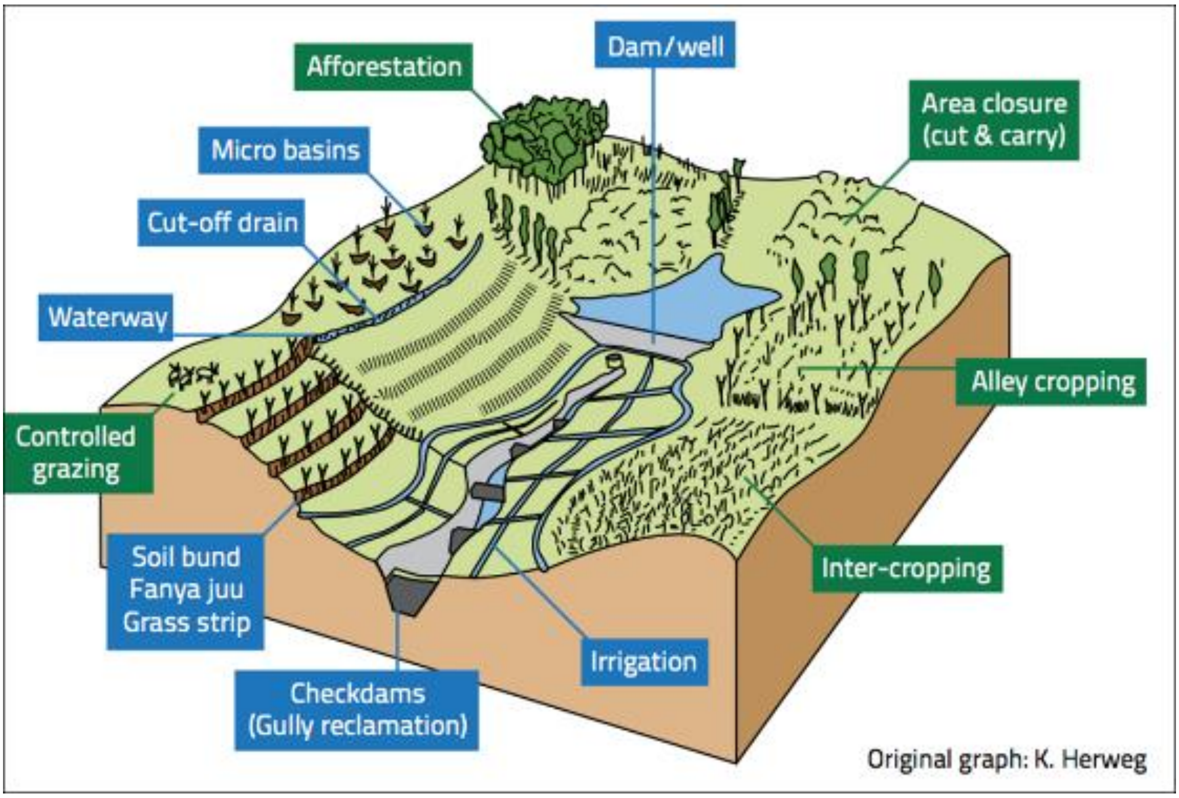

FIGURE 22: Watershed management approaches consider potential interrelationships and combined effects of different policies and practices

Source: FAO, 2014c

impacts. Key principles for successful watershed management include (FAO, 2006b):

- Treat underlying causes (not just symptoms);
- Generate scientific evidence (soil health, water quality, biodiversity effects, climate effects and resilience);
- Adopt an integrated approach (multisector and multistakeholder);
- Ensure holistic planning and implementation (watershed plan);
- Look for co-financing and low-cost interventions (wider adoption);
- Ensure institutional arrangements at all levels (local to national);
- Plan for capacity development at all levels;
- Combine bottom-up (local empowerment) and top-down (policy) processes;
- Ensure gender balance in decision-making and actions that lead to better gender equality;
- Design support and incentive measures to adopt sustainable land management (SLM), access to finance, investment;
- Make monitoring and evaluation an integrative part of the process (demonstrate multiple benefits and impacts including climate resilience);
- Plan for flexible, adaptive, long-term programme /partnership.

Logical framework for CSI adaptation planning and plan implementation

Similar to the river basin level, vulnerability at the watershed, irrigation scheme and intermediate scales and levels is understood as being related not only to the actual changes in weather and climate, but also to the degree of exposure, the sensitivity of people’s livelihoods and their adaptive capacity. Adaptive capacity is understood as ”*the ability of individuals and communities to anticipate, deal with and respond to change – both changing climate and development pressures – while maintaining (or improving) their wellbeing*” (ODI, 2011). In the case of irrigation schemes, adaptive capacity refers to the ability or capacity of farmers, irrigation scheme managers and mechanics and

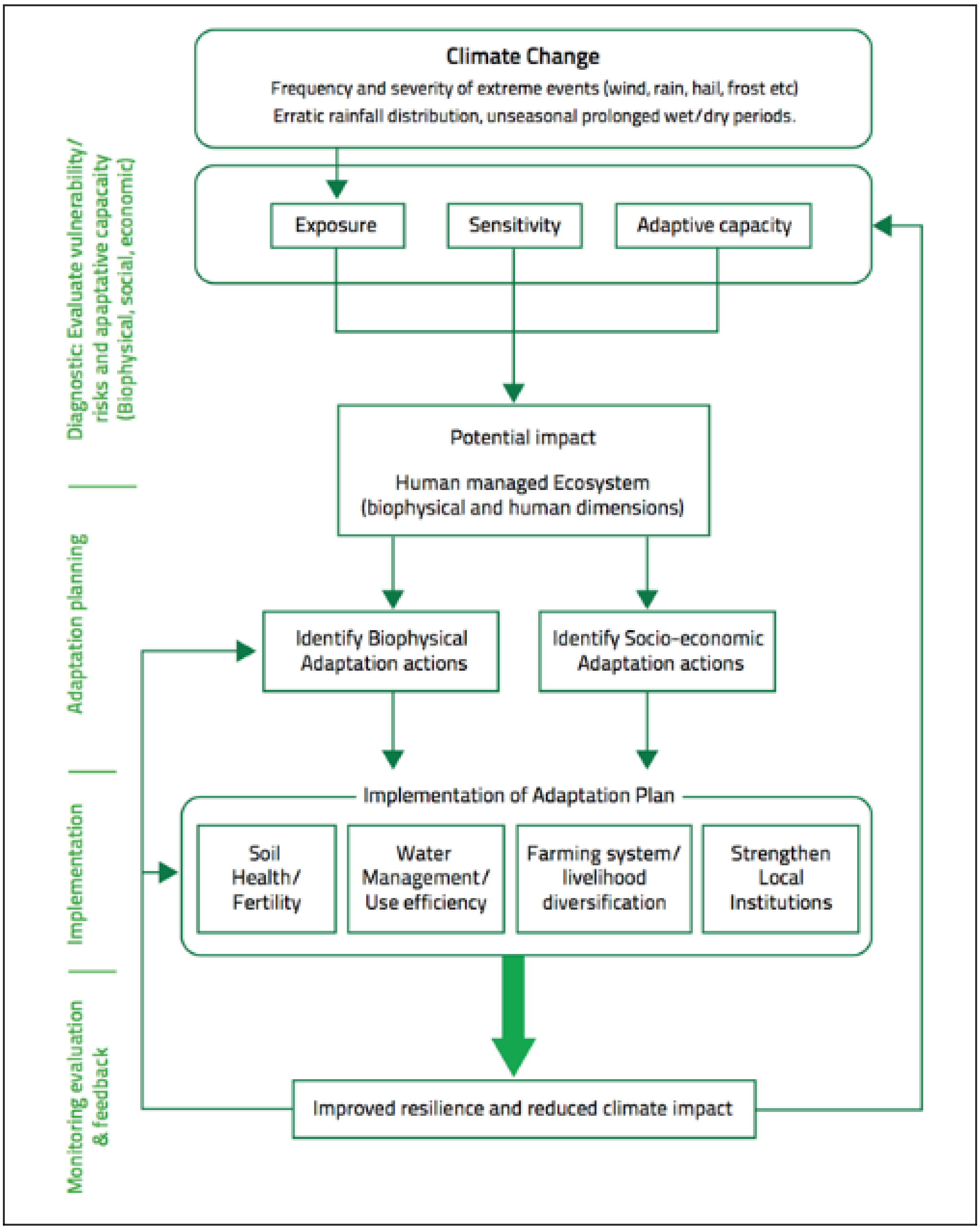

FIGURE 23: Logical framework used for adaptation planning and implementation

Source: FAO, 2014b

others to modify or change their behaviour or actions so as to cope better with existing or anticipated changes in climate conditions. **FIGURE 23** presents a logical framework that clearly indicates the key elements that contribute to the impacts of climate change on rural populations, and therefore the different points of entry for action.

It is also notable that CSI adaptation follows the core principles of FAO-Adapt (FAO, 2011c). These include mainstreaming climate change into local and community development, support to country driven processes, and design and implementation of **location specific adaption activities**. Increase in resilience to climate change can be achieved through adoption of technologies and activities that improve soil health and fertility and facilitate water conservation, through better diversification of sources of livelihood and income, and the creation of strong institutional networks. FAO-Adapt takes the view that adaptation should be perceived as a **continuum of approaches**, ranging from activities that aim to address the drivers of vulnerability, through to measures explicitly targeting climate change impacts, and efforts to promote farm level and wider

catchment or watershed adaptation to climate change.

Assessments and monitoring

In terms of CSI adaptation, the irrigation scheme and local and intermediate institutions scales and levels are important when assessing the performance of irrigation schemes (or irrigation districts) and potential negative (or positive) trade-offs or externalities. For example, assessment and monitoring at this scale and institutional levels can focus on:

- Monitoring trends in irrigation services (in space and time).
- Monitoring trends in the consumptive and non-consumptive water use of irrigation schemes of all types and sizes within a specified domain.
- Monitoring trends in land use, rainfed and irrigated cropping systems, crop yields and water productivity.
- Monitoring the functionality and performance of WUAs, irrigation service providers, value chains, etc.
- Providing early warning for drought and managing drought cycles, for example through improved management of reservoirs and bulk-water transfer systems.
- Managing secondary impacts of irrigation that includes salinity and drainage, flood management – warning and protection – and safeguarding natural ecosystems.

A key point here is that irrigation modernization (hardware and software) is often a central component of NASs and CSI. When NASs and CSI are implemented, monitoring systems should be in place to: 1) Monitor the performance and assess the outcomes of irrigation modernization, and 2) Provide information and evidence that informs decisions related to iterative improvements of adaptations. Note that MASSCOTE and WA&A provide a sound basis for monitoring and assessing irrigation modernization.

3.3.4 Field or farm scale (Local institutional level)

CSI adaptation overview

The reality is that actual irrigation practices at farm level often fall short of good practice in some or many respects.[21] As a consequence, a necessary first step in implementation of CSI is often to tackle the root causes of current poor irrigation practices and performance. The rationale is that climate-smart investment (e.g. aimed at improving resilience and reducing GHG emissions) will be of limited value if irrigation schemes are performing badly. The reasons for poor irrigation practices and performance are often complicated and beyond the control of farmers (e.g. poor irrigation services, unreliable electricity supply, low farm gate prices).

As stated earlier in this compendium, effective CSI adaptation at field, farm, community and local scales and institutional levels involves:

- **Building on good irrigation practice**. The first step in an adaptation process at local level is to ensure that: 1) Irrigation schemes and practices in a specified area are productive, sustainable and non-polluting; 2) Farmers are competent, capacitated and financially secure; and 3) Safeguards have been adopted that respect the environment (e.g. environmental flows), poor and marginal social groups (e.g. equitable access to water for multiple uses) and gender (e.g. women's rights and active participation in WUAs).
- **Innovative and sustainable water management practices and technologies** derived from applied research, combined with appropriate policies and strategies, will help in the mitigation of and adaptation to, climate change. In many cases, these practices and technologies will be refinements of current practices and technologies (i.e. more of the same, but adapted).
- **Active engagement of a broad set of actors** and not just specialists in processes

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[21] It should be noted that the exact nature and scale of the gap between actual irrigation and good irrigation practices is open for debate given that farmers, traders, consumers, politicians, environmental activists and others have different views on what constitutes good irrigation practice. However, there is a general consensus that, based on a range of indicators, there is scope for improving irrigation practices in most countries and regions.

that 1) Identify and solve specific problems rather than deliver generic best practice solutions; 2) Move forward via short iterative cycles of learning and adaptation; and 3) Adopt principles of good enough governance (Grindle, 2007), getting the basics right, for example by ensuring that activities are planned, properly sequenced and completed on time (EC, 2008), and of reform processes that aim to build on existing institutions.

There are strong relationships between system and farm level responses. System level activities intended to meet strategic targets may require support and incentives to farmers to enable them to adapt in harmony (Turral *et al.*, 2011). However, farmer innovation is more likely to lead rather than lag behind system level initiatives, and will require that system management be in harmony with effective and replicable on-farm adaptations. Service provision is still a fairly sketchy idea for many irrigation system managers, but understanding service requirements will increasingly require an open and inquiring mindset, with a commitment to observe and learn from farmers and work much more closely with them than in the past. Farm size and energy use, the cost and availability of well adapted crops, and the existing level of water resources development will all influence the trajectory of system and on-farm adaptations. Further fragmentation, or conversely, consolidation of landholdings creates constraints and opportunities for technology choice, acceptable capital and recurrent investment, and labour needs. The evolution of farm size is proceeding in greatly different directions, and in different contexts (for example consolidation in rural China versus increasing fragmentation in much of India and Africa) (Turral *et al.*, 2011).

Planning and implementing CSI adaptation strategies

Despite the existence of a considerable '**bag of tricks'** already available to farmers, successful implementation of adaptation responses in coming decades requires: 1) From the farmer's side, and somewhat autonomously, the ability to implement new or previously known practices and technologies in real time, i.e. as the climate changes; 2) From the policy-maker's side, in a planned and forward-looking fashion, the ability to enable farmers to make changes when needed, through, for example, the development of economic incentives, improved governance and CSI planning at irrigation scheme and river basin scales, and practical measures for regulating excessive consumptive water use; 3) From the public and private sectors' side, the ability to put in place monitoring and WA&A systems capable of informing and supporting decision-making for both autonomous and planned CSI adaptation (After Tubiello and Rosenzweig, 2008).

Malcolm (2000) observes that: "*a glance through history suggests that in the most important ways, the fundamental elements of managing a farm have altered little*." Successful farm management in a commercial context will continue to depend on timely decisions relating to, for example: purchasing machinery and irrigation equipment, hiring labour, land preparation, planting crops, applications of agrochemicals, harvesting and various post-harvest tasks. For subsistence farmers, the same is basically true, save perhaps the question of machinery and irrigation equipment, though in an increasingly large number of African and Asian countries, this is also a consideration. Much can be made of the differences between commercial and subsistence farming in terms of scale, technology and capital deployment, but the fundamental decision and management processes of how to produce more, and more reliably for the inputs made, are remarkably similar (Turral *et al.*, 2011).

The effectiveness of adaptation varies by context. Specific social and environmental conditions will influence smallholders' choice of adaptation measures. It is important to note that current adaptation measures to improve yields may have different impacts as the climate changes. For example, the application of mineral fertilizer may generate higher yields under average climatic conditions, but may bring lower yields when rainfall is highly variable or delayed. Similarly, crop rotation may produce lower yields under average climatic conditions, but produce higher yields when there is high rainfall variability (Arslan *et al.*, 2015).

Many adaptation strategies aim to maximize water availability to meet crop water requirements at field scale due to the close link between water consumed beneficially and biomass produced (EIP-AGRI, 2016). However, other strategies focus on improving water productivity and resilience at farm or landholding scales.

In semi-arid areas, rainfall often provides an important fraction of the water consumed by irrigated crops that are grown during rainy seasons. For some crops and cropping systems, *in situ* rainwater harvesting strategies can be used to increase the effective use of rainfall and the fraction of crop water requirements met by rainfall rather than surface or groundwater.

Financing and size of landholding

Farm size and access to capital set the limits for the scope and extent of adaptation and change at farm level. Larger farms have more scope for changing and adapting the enterprise mix: where conditions allow, the balance of irrigated and rainfed production can be changed on an annual basis, as in the irrigation areas of New South Wales in Australia (Turral *et al.*, 2011). Larger farms can concentrate their water allocations on smaller areas, and (providing the supply is assured) move to higher value production, such as horticulture. In contrast to smallholders and subsistence farmers, large-scale farmers, such as commercial producers of irrigated crops in South Africa, can afford capital equipment for timely operations, and can insure their crops against failure (Turral *et al.*, 2011).

Smallholder subsistence farmers are uniquely vulnerable to climate change. As described in the case study Creating foundations for resilient agriculture development in Kavre, Nepal (**Section 4.2**), the pace of environmental change in some areas of Nepal is much faster than farmers' capacity to adapt. To make things worse, farmers have limited ability to try out new practices due to their constrained resources and options. There is also the risk that their vulnerability would increase multiple times, if, having invested time and resources into new practices, those practices should fail.

A crucial point to consider in building resilient farm livelihoods is the costs involved in undertaking actions, and in particular the implications for financial flows at household level, since this is a key determinant of whether or not households can adopt such measures, and whether or not they can contribute to poverty reduction and food security (FAO, 2016c). For example, for many sustainable land management techniques that are part of CSI, an increase in labour is required, and this may not be adequately offset by benefits obtained. In some cases, the issue is that the costs are experienced at the initial stages of making a change, while the benefits can be considerably delayed. Restoration of degraded ecosystems can involve even longer periods before positive returns are gained, and involve very significant opportunity costs in the form of foregone income from the ecosystem during restoration.

Some strategies profit from spatial differences within the farm to increase resilience under water scarcity. Large farms have more scope for zone diversification and timely operations, and can afford their own equipment and labour. Crop diversification within a farm and within the plot reduces the impact of failure of one crop and reduces the risk of failure when rainfall is too erratic. The best soils within the farm can be allocated to the most productive crops, while the most drought adapted crops or natural water retention measures can be allocated to the poorer areas (EIP-AGRI, 2016).

CSI adaption opportunities and options

Many CSI adaptation options at field, farm or local scales or levels are variants of well proven climate risk management or irrigation related policies and practices. These include (After Tubiello and van der Welde, 2011; EIP-AGRI, 2016):

- Modernizing irrigation systems to improve irrigation efficiency and uniformity.
- Adopting improved irrigation scheduling technologies and practices.
- Altering inputs, crop varieties and cultivars to reduce yield gaps and improve resilience to heat shocks, drought, flooding and salinization.
- Altering cropping systems with a view to reducing non-consumptive water uses, thereby improving water productivity.
- Adopting conservation agriculture practices aimed at, for example, increasing soil organic matter and reducing soil compaction.

- Altering fertilizer rates to maintain and/or improve grain or fruit quality.
- Altering the timing or location of cropping activities and systems to, for example, reduce consumptive water use and make more effective use of rainfall.
- Diversifying towards rotation systems, including adding cover crops and shelter belts for improved soil-water retention and reduced erosion.
- Making wider use of integrated pest and pathogen management, developing and using varieties and cultivars resistant to pests and diseases.
- Increasing use of real-time and seasonal weather forecasting to reduce production risks and improve irrigation efficiency and crop productivity.
- Developing integrated food-energy systems (IFES).
- Building resilience of irrigated cropping systems based on seasonal climate forecasting.
- Increasing on-farm water storage and/or groundwater recharge through, for example, construction of farm ponds, reservoirs or percolation tanks.
- Constructing or enlarging flood relief or protection measures, e.g. enlarging reservoir spillways or drainage canals.
- Adopting supplemental irrigation that includes *in situ* soil and water conservation practice.
- Using surface and groundwater conjunctively to improve the resilience of water supplies to irrigation schemes.
- Applying irrigation deliberately for cooling and frost protection to mitigate the impacts of more severe weather extremes.
- Reducing post-harvest crop losses, for example by investing, in relevant machinery or storage facilities.
- Adoption of non-structural measures to better cope with floods and droughts, e.g. setting up flood warning and drought monitoring systems, improving flood plain management and improving reservoir operating rules.

As stated above, there are many generic CSI adaptation options many of which fall under the heading 'more of the same but better adapted.' However, in order to be effective, adaptation options should be matched to specific biophysical and societal contexts and/or challenges, and adapted iteratively over time on the basis of lessons learned and evidence gathered by appropriate monitoring systems. Typically, matching and selecting adaptation options and identification of adaptation opportunities has been based on a combination of historical knowledge, experience, common perception and beliefs (After Meinke *et al.*, 2009). This is far from ideal given that such an approach can easily result in maladaptation. In contrast, a CSI approach should be forward looking, evidence informed and give consideration to both irrigation hardware and software. Efforts should be directed to identifying best ways to adapt to future climatic conditions given the uncertainty associated with climate projections, e.g. through identification of irrigated cropping systems and technologies that are well proven across a wide range of agroclimatic and socio-economic conditions (After Dessai *et al.*, 2009). Consideration should also be given to CSI adaption strategies at other institutional levels, and the multilevel adaptation strategies of other sectors.

Given the inherent complexities and uncertainties in effective CSI adaptation, it is important to know how decisions are taken, how they may evolve over time, how different actors are involved in such decisions, and how these decisions can be supported (After Varela-Ortega *et al.*, 2016). In this context, a well-structured conceptual framework can support proactive decision- and policy-making. **FIGURE 24** is a good example of a conceptual framework for climate change adaptation that was developed as part of an applied research project in the Guadiana Basin (Spain and Portugal), which promoted regular dialogue between scientists and stakeholders.

Managing change

CSI adaptation involves reforms to policies and changes to current practices. These reforms and changes may be welcomed by some stakeholders and resisted by others, and the responses of stakeholders may also change over time. CSI adaptation is a process that, to

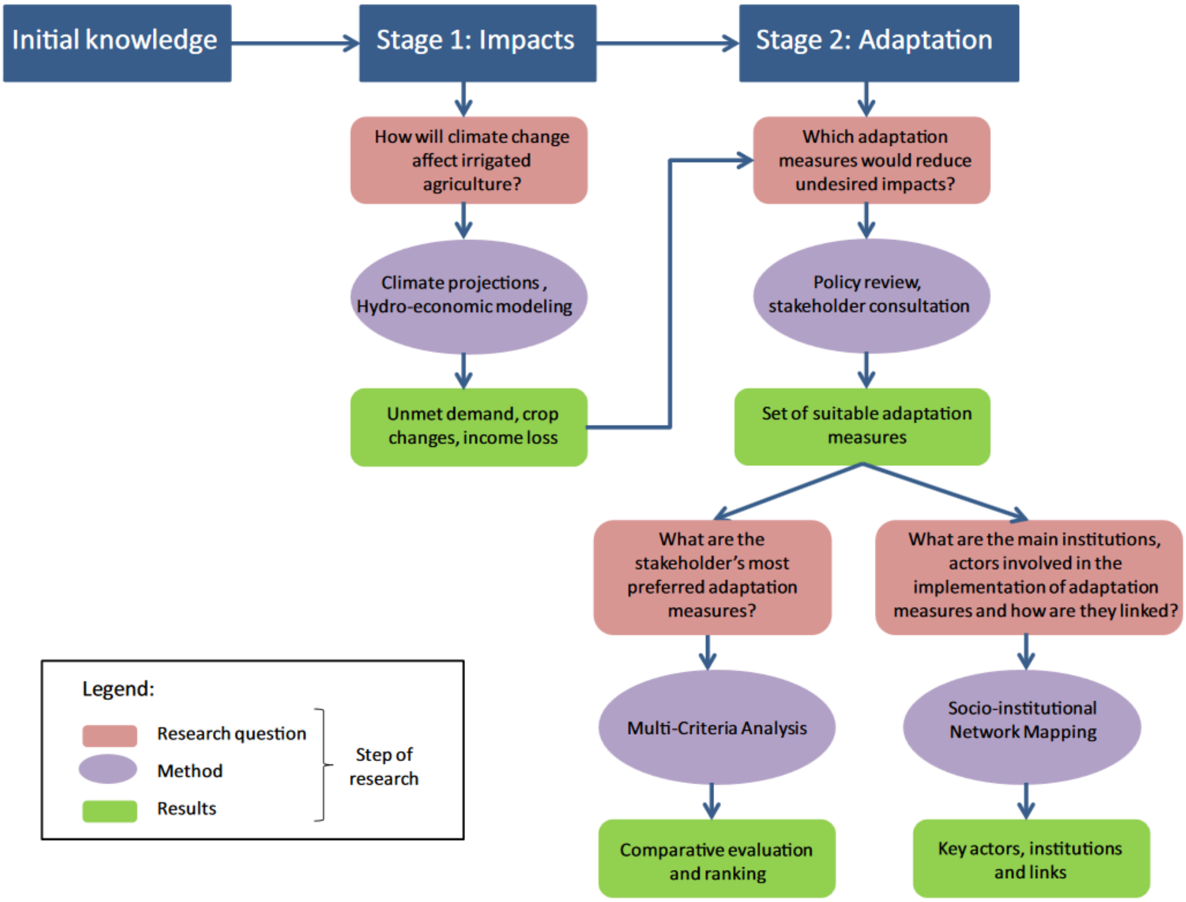

FIGURE 24: Application of the diagnostic framework to analyse climate change adaptation for water and agriculture in the Guadiana Basin

Source: Varela-Ortega et al., 2016

be effective, has to recognize and manage the responses of individuals and organizations to reforms and change (Young, 2014). A key point is that individuals and organizations reject information that could do them harm or could put them on the other side of an argument from more powerful individuals or groups. Also, individuals and organizations tend to reject facts and evidence because (After Batchelor *et al.*, 2017):

- It does not conform to their cultural values, accepted wisdom or social identity.
- It does not conform to a prevailing sanctioned discourse.
- It may embarrass them in the eyes of their peers and/or make them look weak.
- It may devalue the work that has been a source of considerable pride over a long period.
- It could harm their future employment prospects in some material way.
- It could close down opportunities for rent seeking or other dubious practices.

Given that CSI adaptation is already taking place and will be needed into the foreseeable future, adaptation and innovation should be considered in the context of long-term continuous change, which comprises a number of discrete adaptations and/or innovations, rather than a process with a well defined beginning and end. It requires thinking about short-, medium- and long-term visions of where stakeholders in a specified domain want to be in the future, and modifying or refining visions as priorities change and/or lessons are learned (After Young, 2014). Ideally, adaptations and innovations are planned on the basis of scenario analysis, with the aim of achieving visions on time. One reason is that succession of reactive and unplanned adaptations and innovations can waste limited resources and result in change fatigue and maladaptive outcomes. Another is that it is important to identify and manage resistance to change (After Young, 2014).

Irrigation modernization is frequently selected as a CSI adaptation option or opportunity. While this is often justified, irrigation modernization is a not a panacea and often the outcomes of modernization fail to meet expectations. To put it another way, the actual performance of, for example, pressurized drip irrigation systems, in terms of irrigation efficiency, crop productivity and distribution uniformity, is often quite different from that achieved in experimental stations (Benouniche *et al.*, 2014). One reason is that farmers do not necessarily target a high level of system performance as might be expected and desired by engineers or funding agencies. On the contrary, the following set of circumstances may prevail (After Benouniche *et al.*, 2014): 1) Farmers often have other agro-economic motivations, or want to improve their social status, and for them, irrigation performance is at best an intermediate objective. 2) Irrigation performance is not static, but highly variable in both space and time and influenced by the farmers' aspirations and willingness to put time and effort into managing and maintaining their irrigation system. 3) If extension services or social networks are lacking, farmers may not have access to necessary information and know-how related to drip irrigation (i.e. they may manage their modernized irrigation system in the way they managed their old irrigation system). 4) There may only be limited social or regulatory pressure to irrigate carefully, increase crop productivity and/or reduce consumptive water use at field or landholding scales.

Governance, institutions and capacity-building

At local level, effective adaptation depends to a large extent on the institutions – formal and informal, local and intermediate level – which plan and manage individual and collective action on water resources. These institutions channel funds, information and technologies into rural areas and facilitate or impede action. The power relations within them determine who can participate, who can make decisions, and who ultimately benefits (Turral *et al.*, 2011). Adaptation policies and strategies approved at national level may not be put into practice at lower levels, or may be put into practice, but not in the way intended. Water management institutions are often not tailored to handle dispersed smallholder water management arrangements. Small-scale private irrigation, for example, tends to neither come under the remit of irrigation departments, which generally deal with large-scale canal irrigation, nor under agricultural departments, which are concerned with rainfed farming (Turral *et al.*, 2011).

Social networks are important components of local governance that can initiate and implement effective responses to climate change. Traditional forms of reciprocal and mutual work (e.g. in soil and water conservation, repairs to irrigation canals) have been partially or totally abandoned in many areas due to social and economic changes (FAO, 2013b). Encouraging the perpetuation or reactivation of these arrangements, where appropriate, may be beneficial for conservation and repair work. Encouraging informal social networks for sharing information and experience on adaptation options may also help to build social resilience to climate change. In addition, such networks can play a key role in the establishment of surveillance, monitoring and early warning systems (FAO, 2016c).

The active participation of farmers in networks, including WUAs, has the potential to improve access to knowledge and irrigation services (EIP-AGRI, 2016). WUAs are fairly common in large publicly funded irrigation schemes and traditional irrigated areas, but the level of functionality varies. Similarly, Farmer Field Schools can play a central role in sharing knowledge, training, skills development, awareness-raising and planning CSI adaptation.

3.3.5 Key messages

- Typically, CSI **adaptation** measures aim to: 1) Adapt irrigated cropping systems in ways that reduce potential negative impacts of anticipated changes in climate, and/or take advantage of beneficial opportunities; and 2) Increase the **resilience** of existing irrigated cropping systems to current and potential future climate conditions. Given the high level of uncertainty of climate change projections, especially at local scale, no- and low-regret measures are often selected that have the potential to increase resilience across a wide range of possible climate scenarios and adaptation strategies.

- **Climate change vulnerability** is determined by both exposure and sensitivity to potential climate change impacts and adaptive capacity. CSI's adaptation strategies aim to address both these facets of vulnerability.
- Climate change can be conceptualized as a **cascade of risks**, from direct or indirect impacts (e.g. to water sources, irrigation related infrastructure, and irrigated cropping systems) through to socio-economic and environmental impacts (e.g. to value chains, livelihoods and environmental flows). Understanding this cascade, as well as the vulnerabilities to these risks, is fundamental to effective climate change adaptation.
- Effective adaptation is as much about **irrigation (software**) as it is about **irrigation (hardware)**, i.e. adaptation based on technical quick fixes is unlikely to produce desired outcomes.
- Effective adaptation involves **building on good irrigation practice**. The first step in an adaptation process at local level is to ensure that: 1) Irrigation schemes and practices in a specified area are productive, sustainable and non-polluting; 2) Farmers are competent, capacitated and financially secure; and 3) Safeguards have been adopted that respect the environment (e.g. environmental flows), poor and marginal social groups (e.g. equitable access to water for multiple uses) and gender (e.g. women's rights and active participation in WUAs).
- Development of adaptation strategies should be **evidence informed** and account for differences between consumptive and non-consumptive water use (in space and time).
- CSI adaptation involves changes or reforms that may prompt stern resistance from some stakeholders, who feel threatened by them. This can be pre-empted to some extent by addressing the following questions. Who are likely to be the **'winners' and 'losers'** as a result of particular reforms?
- As a general rule, CSI adaptation strategies need to be **location and context specific, flexible and well integrated** (or aligned) with other sectors that use water and/or influence the availability of water resources in space and time.
- CSI adaptation takes place at farm, irrigation scheme and basin levels. In practice, adaptation can be private or public, planned or autonomous. It is notable, however, that adaptation at river basin and irrigation scheme levels can **constrain or incentivize** attempts by farmers to adapt to climate change.
- Irrigation related adaptation strategies should recognize the increased risk of **environmental pollution** that may result, particularly in areas of increasing water scarcity.
- There is increasing recognition that significant volumes of water are used along the **value chains** (e.g. as part of food processing). However, this tends to be non-consumptive water use that returns to surface or groundwater, albeit with reduced quality.
- CSI adaptation should be perceived as a **continuum of approaches**, ranging from activities that aim to address the drivers of vulnerability, through to measures explicitly targeting climate change impacts, and efforts to promote farm level and wider **catchment or watershed adaptation** to climate change.
- Some CSI adaptation strategies aim to **increase surface and groundwater availability** for irrigation when and where it is needed. Other CSI strategies aim to increase the fraction of rainfall consumed beneficially by irrigated cropping systems. Still other CSI strategies focus on improving **water productivity** and the **resilience** of irrigated cropping systems and value chains.
- Given that CSI adaptation is already taking place and will be needed into the foreseeable future, adaptation and innovation needs to be considered in the context of **long-term continuous change**, which comprises a number of discrete adaptations and/or innovations, rather than a process with a well defined beginning and end.

3.4 CSI Pillar 3: Irrigation related mitigation

3.4.1 Introduction and overview

CSI mitigation rationale

The aim of CSI mitigation is to reduce greenhouse gas emissions for each calorie or kilo of food, fibre or fuel that is produced and supplied to an end user, i.e. to reduce the GHG emission intensity (cf. Smith *et al.*, 2014). Typically, CSI mitigation targets policies and practices to achieve: 1) Reductions in the use of non-renewable energy, for example used to pump, distribute and apply irrigation water; 2) Usage of organic and inorganic fertilizers in ways that minimize GHG emissions; 3) Management of soils, cropping systems and irrigation regimes in ways that maximize the potential of soils to act as carbon sinks; and 4) Recognition that, at the basin scale, intensification of irrigated cropping may be justified and offset by reductions in rates of land use change, for example, from forestry or rangeland to rainfed or irrigated cropping. Therefore, at the basin scale the aim should be to reduce the GHG emission intensity of products, as well as the overall GHG emissions of AFOLU sectors.

At its simplest, an irrigation system comprises: a source of water (e.g. a spring, well or stream), a means of getting water from the source to the field (e.g. some pipes), and the farming know-how and inputs needed to grow a crop (e.g. tools, seeds, etc.). While simple irrigation systems are commonplace, most are much more complicated in terms of irrigation software and hardware. It is also notable that: 1) GHG emissions occur at all stages, from the source of irrigation water through to the cultivation of crops and along the value chain (see **FIGURE 25**), and 2) GHG emissions are often enhanced as a result of, for example, unsustainable water resource use, poor farming practices and post-harvest losses up to and beyond the farm gate (see **TABLE 12**).

Dominant GHG emissions from an irrigated

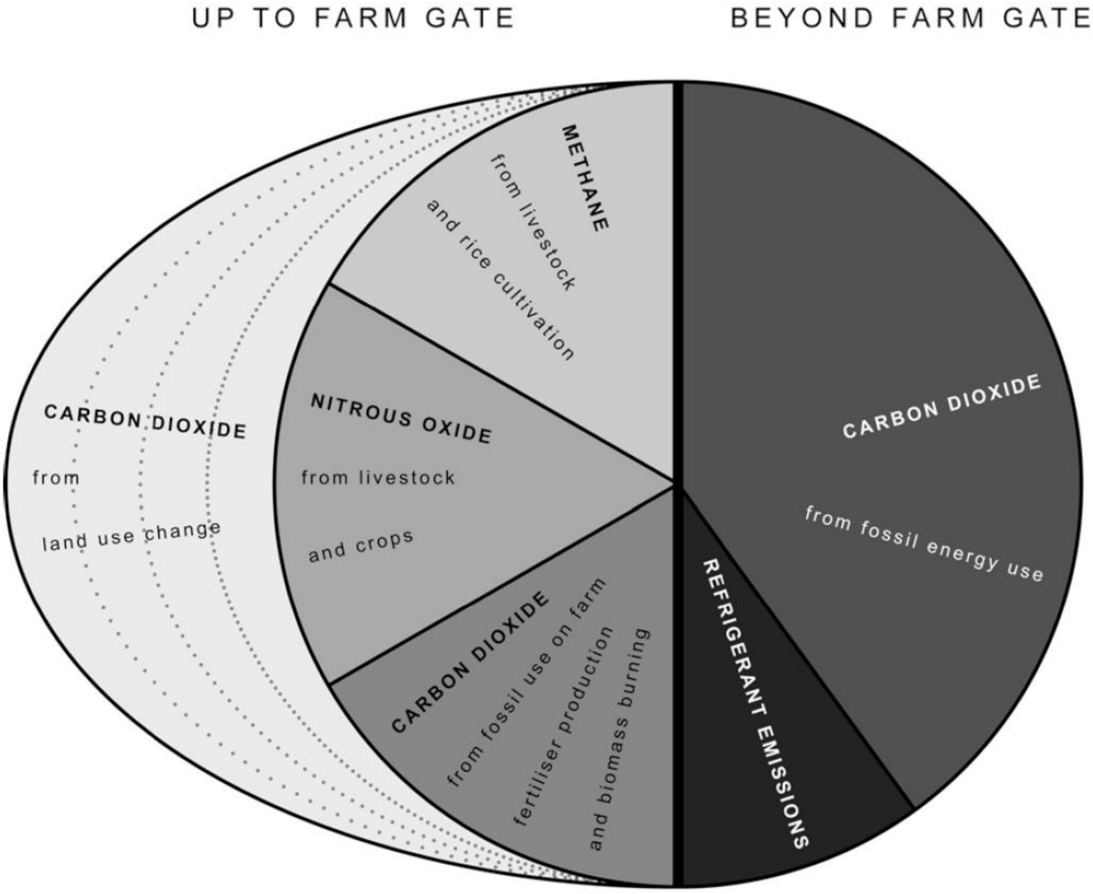

FIGURE 25: GHG emissions up to and beyond the farm gate. Note: proportions are for illustrative purposes only

Source: Garnett, 2011

production system up to and beyond the farm gate include (Garnett, 2011; see **FIGURE 25**):

- Carbon dioxide (CO_2) emissions resulting from land use change or land levelling.
- CO_2 emissions that result from the use of non-renewable energy 1) To pump and pressurize water and power machinery used during in-field operations, and 2) To transport goods and labour to, from and around a farm or irrigation system.
- Nitrous oxide (N_2O) emissions from applications of organic and inorganic nitrogen fertilizers.
- Methane (CH_4) from paddy rice cultivation (see **PHOTO 7**) and anaerobic soils.
- CO_2 from the burning of crop residues.
- CO_2 emissions that result from the use of non-renewable energy 1) To transport products from the farm gate to processing and packaging factories and on to distributors, wholesalers and end users, and 2) To process, pack and store products.
- Refrigerant gases that may leak from cold stores.

To summarize the above, agriculture and, more specifically, irrigated agriculture, has an important role to play in climate change mitigation by adopting 'whole system' policies and practices aimed at the following (After Medeiros DuBois *et al.*, 2012):

- Reducing emissions through better and/or more efficient management of **carbon and nitrogen flows**.
- Reducing GHG emissions by improving energy use efficiency or replacing **fossil fuel energy** with clean energy.
- Removing emissions by enhancing **soil carbon sequestration** above and below ground, and by increasing the land area under conservation agriculture, permanent pasture, agroforestry and/or forestry.

PHOTO 7: Cultivation of paddy rice during the dry season, India

This is relatively common in semi-arid areas of southern India, despite the fact that water is scarce. One reason is that individual farmers with high-yielding boreholes do not experience water scarcity or other pressures to use water frugally.

Photo credit: Charles Batchelor

TABLE 12: Issues and challenges relative to typical elements of an irrigated production system and their consequences for GHG emissions and mitigation potential

Elements of irrigated production system	Typical issues & challenges (generic and climate change related)	Consequences for GHG emissions and mitigation potential
Reliable sources of water	▪ Land use change, land degradation and soil erosion in upper watersheds and elsewhere. ▪ Adaptation activities that increase competition for water. ▪ Groundwater overdraft leading to falling water tables. ▪ Increasing pollution and water quality issues.	▪ Risk of increased CO_2 emissions resulting from energy used to: 1) Desilt reservoirs, farm ponds, check dams, etc.; 2) Pump water from lowered water tables and more distant sources; and 3) Treat or filter water. ▪ Risk of lower carbon sequestration in upper watersheds and elsewhere as a result of reduced biomass production. ▪ Risk of reduced water availability for the generation of renewable energy from hydro-electric power (HEP) plants.
Infrastructure to extract and convey water	▪ Poor design, shoddy implementation, poor O&M, etc. ▪ Leaking system, illegal connections, etc. ▪ Poor management, inequitable allocation of water, etc. ▪ Unreliable and unpredictable irrigation and energy services. ▪ Poor irrigation scheme performance (as per MASSCOTE indicators).	▪ Risk of increased CO_2 emissions resulting from energy used to: 1) Pump additional water to compensate for leaks, and 2) Operate poorly selected or poorly maintained and, hence, inefficient pumps. ▪ Risk of reduced yields per unit of CO_2 and N_2O emissions, i.e. high emission intensity, as a result of poor management, poor irrigation services, poor irrigation scheme performance, etc.
External inputs (representing indirect GHG emissions)	▪ Demand for inorganic fertilizers, other agrochemicals. ▪ Demand for plastic piping and fittings. ▪ Demand for seeds, tools, general farm supplies. ▪ Demand for machinery and fuel/energy. ▪ Demand for vehicles for moving labour and scheme operators around.	▪ Risk of increased CO_2 emissions resulting from energy used to: 1) Produce and deliver fertilizers and other agrochemicals; 2) Produce and deliver plastic piping and fittings; 3) Manufacture machinery and deliver fuel; and 4) Move labour around, transport produce, etc.
In-field infrastructure	▪ Poor design, shoddy implementation, poor O&M etc. ▪ Poor irrigation uniformity. ▪ Short life span of driplines and other parts. ▪ Lack of control devices for effective irrigation scheduling. ▪ Lack of irrigation scheduling know-how.	▪ Risk of increased CO_2 emissions resulting from energy used to: 1) Pump and additional water to account for poor irrigation uniformity, lack of control devices and lack of irrigation scheduling know-how, and 2) Constantly replace pipes and fittings that have a short life span.
Drainage infrastructure and management	▪ Poor design, shoddy implementation, poor O&M, etc.; ▪ Water-logging and salinization of soils; ▪ Environmental pollution;	▪ Risk of increased CO_2 emissions resulting from energy used to 1) Leach salts from saline soils, and 2) Treat polluted drainage water. ▪ Risk of CH_4 emissions from waterlogged areas, blocked drainage ditches, etc.

Agricultural operations	▪ Poor crop husbandry and selection of cropping systems. ▪ Poor soil management. ▪ Excessive, inappropriate or untimely application of irrigation or fertilizers. ▪ Poor harvesting and post-harvest practices. ▪ Lack of extension and other support services.	▪ Risk of reduced yields per unit of CO_2 and N_2O emissions as a result of: 1) Poor crop husbandry; 2) Poor soil management; 3) Poor use of fertilizers; and 4) Lack of extension and advisory services. ▪ Risk of reduced soil carbon sequestration as a result of reduced biomass production and poor soil management.
Value chains	▪ High levels of product loss as a result of poor processing, handling and storage procedures. ▪ Requirement for refrigeration. ▪ Energy demands of processing, packaging, storage and transport of produce. ▪ Often long distances from the farmgate to the consumer.	▪ Product losses along the value chain from the farm gate to the consumer often significantly reduce product yields per unit of CO_2 and N_2O emissions, i.e. they increase the GHG emission intensity. ▪ In addition to the above, many processes along the value chain increase CO_2 emissions per unit of product. ▪ Risk of release of refrigerant GHG.

A key point here is that the causes and scale of GHG emissions need to be determined, quantified and mapped (in space and time) when developing appropriate CSI mitigation strategies. It follows that CSI greenhouse gas reduction measures differ according to regional characteristics and farming systems. Since there is great diversity in natural conditions and farming systems, the selection of the most appropriate mitigation practices varies according to context, and depends on specific agronomic, environmental and climatic conditions (Frelih-Larsen and Dooley, 2015). When identifying appropriate measures it is also important to identify and quantify potential trade-offs that may be associated with individual or combinations of CSI mitigation measures. For example, mitigation measures that increase consumptive water use (e.g. afforestation) may have the trade-off of reduced water availability downstream.

The CSI rationale to climate change mitigation is based on the understanding that:

- CSI mitigation strategies aim to **reduce GHG emissions** for each calorie or kilo of food, fibre and fuel that is produced and supplied at the farm gate and to end users.
- Many **mutually reinforcing** synergies exist between CSI mitigation and adaptation strategies (After Tubiello, 2012).
- CSI mitigation strategies that are truly climate-smart identify and respond to opportunities for **reducing GHG emissions at all stages**, from the source of irrigation water through to the cultivation of crops and along the value chain.
- Rapid advances are being made in the cost-effective generation and utilization of clean energy by the irrigation sector, not just for pumping water but also for powering tractors and other machinery. This is creating opportunities for replacing **fossil energy by clean energy at all stages along irrigated food, fibre and biofuel** value chains.
- CSI mitigation strategies recognize that, at the basin scale, well planned sustainable intensification of irrigated cropping may be justified and **offset by reductions in rates of land use change**, for example, from forestry to either rainfed or irrigated cropping.

  Farmers can accrue benefits from CSI mitigation strategies (e.g. improved yields and income as a result of improved irrigation practices; reduced energy costs). However, **additional incentives** may be needed for strategies that do not deliver direct benefits.
- Risks exist that successful implementation of mitigation strategies will have the unintended consequence of **unsustainable extraction or diversion of water resources**.
- Similar to CSI adaptation strategies, effective CSI mitigation strategies are as much about **irrigation (software**) as they are about **irrigation (hardware)**, i.e. mitigation based on technical quick fixes is unlikely to produce desired outcomes.
- Effective CSI mitigation also involves **building on good irrigation practice**. The first step in a CSI mitigation process at local level is to ensure that: 1) Irrigation systems, value chains and practices in a specified area are productive, sustainable and non-polluting; 2) Farmers are competent, capacitated and financially secure; and 3) Safeguards have been adopted that respect the environment (e.g. environmental flows), poor and marginal social groups (e.g. equitable access to water for multiple uses) and gender (e.g. women's rights and active participation in WUAs).
- CSI mitigation activities should take place at various levels and **involve active dialogue between stakeholders**, horizontally at each level and vertically between levels. In most cases it makes sense for CSI mitigation of irrigation systems, value chains and practices to be based on a combination of top-down and bottom-up approaches.
- Food losses and waste represent a considerable waste of water, energy and agricultural inputs, and the unnecessary cause of the emission of millions of tonnes of GHGs.

- The development of CSI mitigation strategies should be **informed by evidence** that is acquired using appropriate procedures for systematically quantifying and mapping GHG fluxes (e.g. Tubiello *et al.*, 2015; Bockel *et al.*, 2017) and consumptive and non-consumptive water use, in space and time (e.g. Batchelor *et al.*, 2017).

The Paris Agreement

The Paris Agreement, concluded in 2015 by the member parties of the United Nations Framework Convention on Climate Change (UNFCCC), aims to strengthen the global response to the threats of climate change. A central goal is to keep long-term global warming well below 2 °C and, if at all possible, to limit it to 1.5 °C. To this end, the parties to the agreement "*aim to reach global peaking of GHG emissions as soon as possible, […] and to undertake rapid reductions thereafter*." The aim is to achieve a balance between immediate reductions in anthropogenic GHG emissions from sources and longer-term removals of GHGs from the atmosphere by sinks (Dombrowsky *et al.*, 2016).

Almost all IPCC scenarios where there is a high likelihood of limiting global warming to 2 °C rely heavily on technologies with negative emissions, that is, technologies that sequester atmospheric carbon dioxide (CO_2) in carbon sinks. Such sinks involve for example: 1) Reforestation and afforestation; 2) Carbon sequestration by soils; and 3) Use of bioenergy along with carbon capture and storage (BECCS). It is notable that BECCS involves growing biomass that is used to generate energy. While commendable in many respects, BECCS, reforestation/afforestation and carbon sequestration by soils can have significant trade-offs in terms of increased consumptive water use. This is likely to have a negative impact on water security in arid and semi-arid areas and other areas experiencing increasing water scarcity (Dombrowsky *et al.*, 2016).

Planning and implementing CSI mitigation strategies

There is a wide range of CSI mitigation measures that are both feasible and, in many cases, well proven. Some mitigation measures are essentially the **good irrigation practices** described in the last two sections on CSI pillars 1 and 2. Or to put it another way, many measures aimed at improving the water productivity and resilience of irrigation schemes and irrigated cropping systems will also have positive impacts in terms of CSI mitigation. Therefore these are **win-win options**. For example, improved crop husbandry has the potential to improve water productivity, farmer incomes and system resilience, and to reduce GHG emissions for each calorie or kilo of food, fibre and fuel that is produced. **FIGURE 26** highlights some potential additional synergies between mitigation, adaptation, and productivity (Underwood *et al.*, 2013).

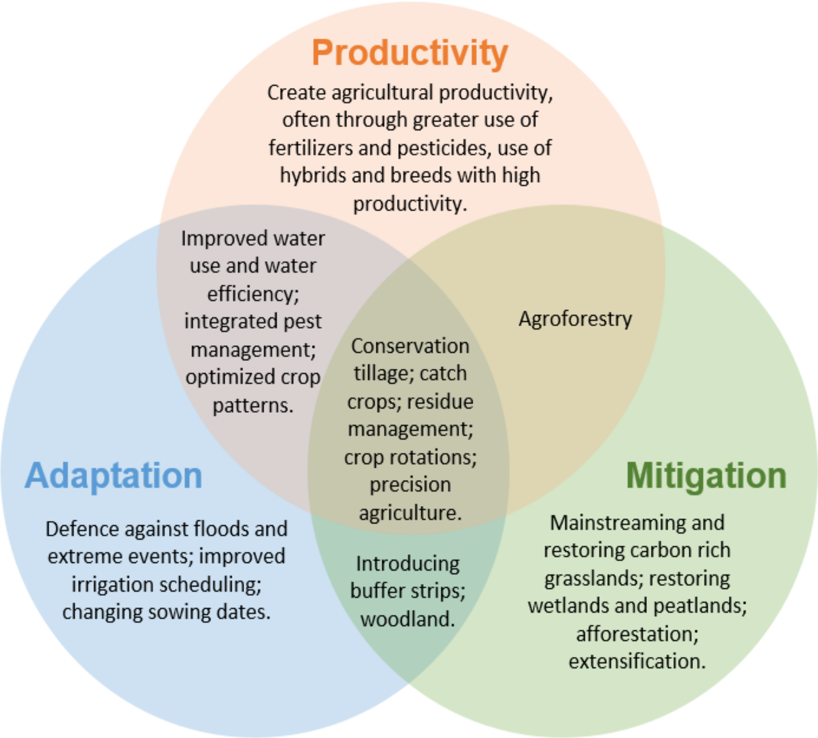

FIGURE 26: Potential synergies between climate change adaptation, mitigation and food production goals

Source: Underwood et al., 2013

However, some CSI mitigation practices can also have adverse effects on adaptation objectives (Frelih-Larsen and Dooley, 2015). For example, irrigated biofuel production is a practice that could lead to reduced GHG emissions. However, if this results in increases in net consumptive water use, the trade-off may be falling groundwater levels and reduced resilience for other farmers using irrigation. A key point is that the utility of **CSI mitigation measures varies across space and time**. The most appropriate solutions for CSI mitigation are often complex, as well as specific to the different irrigated cropping systems and agroclimatic conditions. The impact of management options also depends to a large extent on the farmers' skills and choices (for example, good irrigation scheduling and good choices of crop cultivars). Socio-economic considerations may also come into play. For instance, a relatively poor farmer may be growing crops primarily for home consumption, and unable or unwilling to invest in his or her irrigation system. In contrast, a richer farmer may be better placed to invest in CSI mitigation measures that deliver significant benefits in one form or another.

It is important to recognize that CSI strategy development and planning are unlikely to be carried out in isolation, particularly at river basin scale and national level. Most probably, in basin planning processes, consideration will be given to a wide range of land uses and mitigation options that are relevant to the whole agricultural sector, and not just to the irrigation sector. The objective is to ensure that the mitigation benefits are maximized at the basin scale, while achieving policy imperatives that include economic development, food security, water security and protection of environmental flows.

Claims are often made for the mitigation **potential of organic farming** and the viability of organic production systems. It is possible that large-scale organic farming may be an economic prospect in OECD countries, where land can be rotated and fallowed, and where mixed farming (livestock and cropping) may generate sufficient nutrient recycling to maintain productivity (Turral *et al.*, 2011). Similarly, well developed value chains exist in many OECD countries. While opportunities for developing viable organic farming systems and value chains in non-OECD countries exist, it is evident that any production system resulting in lower consumable or saleable production will be unattractive to small-scale farmers with limited land and water resources.

Precision agriculture is a mitigation strategy that attracts a great deal of attention, partly because it takes advantage of recent advances in cyber-technologies, remote sensing and various geographic information system (GIS) applications. For example, precision agriculture can be used to increase yields, and reduce GHG emissions by targeted timely application of fertilizer to different parts of fields, depending on factors such as soil type and yields achieved in previous years. Automated irrigation systems can also be designed and used to target different volumes of water to different parts of a field. However, precision agriculture requires additional hardware and software that may be expensive and difficult to operate. It may also require additional energy to power this machinery, and to make smaller and more frequent applications of fertilizer and/or water. Notwithstanding these potential drawbacks, it is likely that different adaptations of precision agriculture will become increasingly important components of CSI mitigation strategies in the future.

System of Rice Intensification (SRI) & Alternate Wetting and Drying (AWD). Paddy rice fields are a major source of agricultural GHG emissions due to the high activity of methane producing bacteria under anaerobic conditions. By alternating periods of aerobic and anaerobic conditions during the crop cycle, AWD considerably reduces the activity of these bacteria and hence CH_4 emissions. Although an increase in N_2O emissions under AWD is usually observed that corresponds to approximately 15 to 20 percent of the global warming potential of the avoided CH_4 emissions, AWD still has a net benefit for climate change mitigation (Adhya *et al.*, 2014; Richards and Sander, 2014). AWD is also used as an integral part of SRI (Styger and Uphoff, 2016). In addition, claims are made for AWD and SRI to reduce water use by 30 to 50 percent (Richards and Sander, 2014; Styger and Uphoff, 2016). However, quantified data is not available to support these claims (Turral *et* *al.*, 2011; Bouman, 2013). More specifically, a distinction is not drawn between consumptive and non-consumptive water use. In relation to AWD, Adhya et al (2014) state that "*all current estimates of water savings are at the field level and refer to the water applied by farmers. Evidence suggests that most or perhaps nearly all of the water savings will result from reduced percolation, which implies that some of the irrigation water saved by an individual field would have otherwise recharged groundwater or been used further downstream.*"

CSI mitigation policies

A core question facing global and national planners and policy-makers is whether today's agriculture and food systems are capable of meeting the needs of a global population that is projected to reach more than 9 billion by mid-century, and may peak at more than 11 billion by the end of the century (FA0, 2017c). As important, can we achieve the required production increases, even as the pressures on already scarce land and water resources and the negative impacts of climate change intensify? The consensus view is that current systems are probably capable of producing enough food, but to do so in an inclusive and sustainable manner will require major transformations (FAO, 2017b).

The above points raise further questions. Can agriculture meet unprecedented demand for food in ways that ensure that the use of water resources is sustainable, while containing greenhouse gas emissions and mitigating the impacts of climate change? This challenge comes at a time when large surface water irrigation systems and dispersed groundwater schemes are already struggling in some regions as a result of demand for water outstripping supply (e.g. in semi-arid areas of southern and western India). Furthermore, adopting mitigation measures would impose additional costs (at least in the short term), which would put upward pressure on output prices (Smith *et al.*, 2014).

Depending on the land and water availability and tenure, there is a risk that intensification of irrigated cropping will lead to an **expansion in the area equipped for irrigation**, ultimately resulting in higher water consumption and competition for water resources. In addition, mitigating climate change by, for example, mandating the use of biofuels in one region may prompt increased global GHG emissions from other areas as a result of land use change (e.g. forestry to agriculture), and/or intensification of existing irrigated cropping (e.g. a switch to double or triple cropping) (Lambin and Meyfroidt, 2011). It is also possible that increases in irrigation in areas producing biofuels will be unsustainable and have a negative impact on other water uses and users in the same area or downstream.

In general, most CSI adaptation measures have a positive impact on mitigation. However, there are some mitigation measures or practices that can **have a negative impact on CSI adaptation**. For example, higher prices for maize, as one example of a crop used for biofuel production, may incentivize farmers to change their crop rotation to include maize and, as a result, increase vulnerability to climate change if maize is produced in areas prone to drought. Therefore, the implications that mitigation measures or practices may present for adaptation need to be carefully considered (Frelih-Larsen and Dooley, 2015).

The **utility of CSI mitigation measures and practices** varies with context and the ability and willingness of farmers to adopt new practices. Socio-economic considerations may also come into play, for instance, if a farmer switches from surface irrigation to localized irrigation (and fertigation) as a means of improving yields, reducing fertilizer costs and reducing GHG emissions. While this switch to pressurized irrigation may deliver all these benefits, it may be more labour intensive, as a result of irrigation applications every day rather than, say, once a week. It may also require: 1) Increased capital and recurrent expenditure, and 2) Increased know-how, for example in irrigation scheduling that takes into account crop type, crop development stage and other factors. Depending on the public goods and wider benefits of shifting from surface to pressurized irrigation, subsidies may be made available to help with the investment costs, and Farmer Field Schools may be created to ensure that farmers gain and share the additional knowledge needed to operate and maintain pressurized irrigation systems.

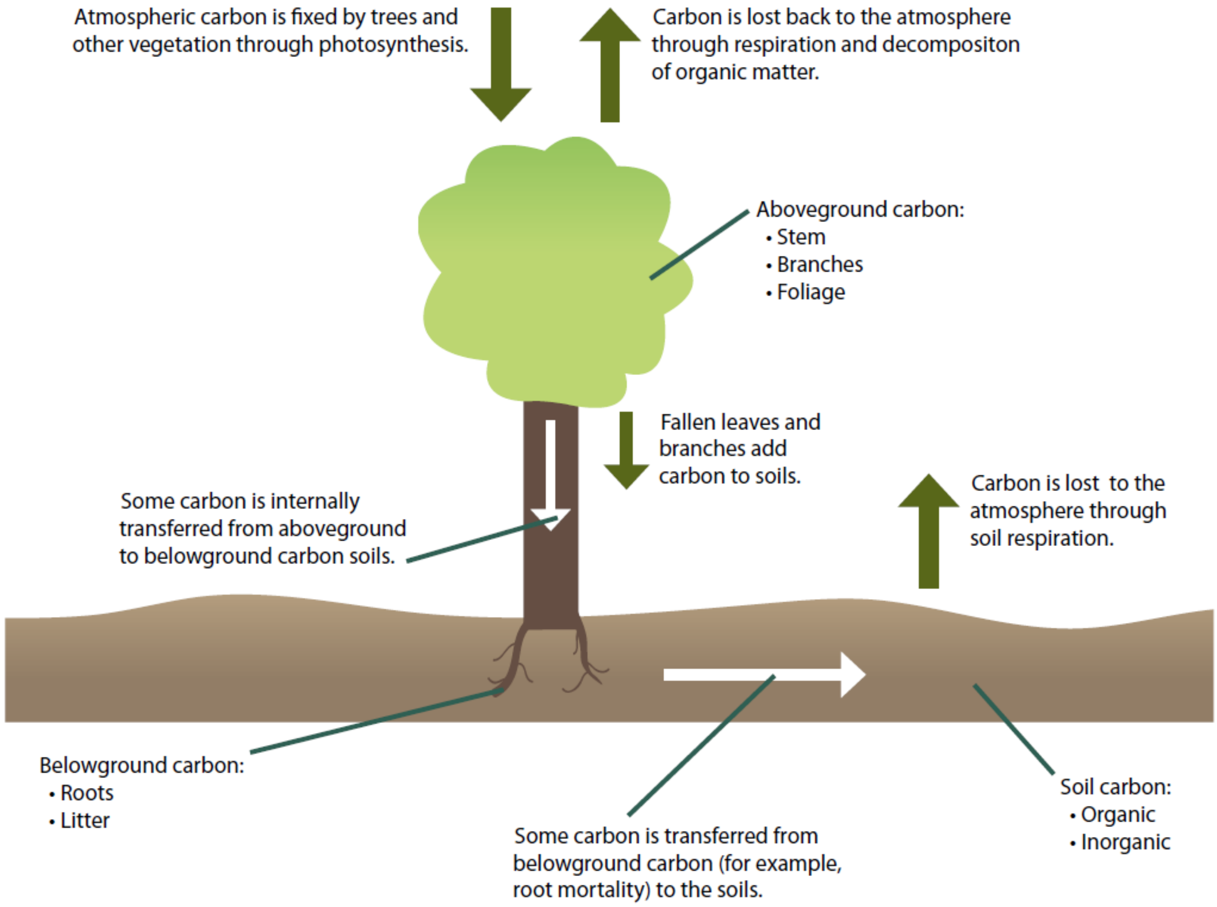

FIGURE 27: Carbon pools in forestry and agriculture

Source: Schahczenski and Hill, 2009

Carbon sequestration

Carbon sequestration in the agriculture sector refers to the capacity of agricultural lands to remove carbon dioxide from the atmosphere. Carbon dioxide is absorbed by trees, plants and crops through photosynthesis and stored as carbon in biomass in tree trunks, branches, foliage and roots and soils (See **FIGURE 27**) (Schahczenski and Hill, 2009). Forests and stable grasslands are referred to as carbon sinks because they can store large amounts of carbon in their vegetation and root systems for long periods of time. The ability of agricultural lands to store or sequester carbon depends on several factors that include climate, soil type, type of crop or vegetation cover, management practices, and whether or not the crop is irrigated. The amount of carbon stored in soil organic matter is influenced by the addition of carbon from dead plant material and carbon losses from respiration, the decomposition process and both natural and human disturbance of the soil. By employing farming practices that involve minimal disturbance of the soil and encourage carbon sequestration, farmers may be able to slow or even reverse the loss of carbon from their fields.

Soils in arable areas have the potential to store large amounts of carbon, perhaps as much as one-third of current global emissions (Turral *et al.*, 2011). However, there has been a worldwide trend of declining soil organic matter, with resultant acidification of soils and loss of fertility. This trend has to be reversed and then enhanced for soil carbon sequestration to become a reality. The potential for soil carbon sequestration can be mapped using existing soil databases. However, in many countries soil maps are coarse and contain limited data on their physical characteristics. While the potential for soil carbon storage in arid lands is considered to be low, **irrigation can improve carbon sequestration** in water limited arid and semi-arid climates (ICF, 2013). However, there is evidence that **irrigation can also reduce soil carbon storage** by stimulating the decomposition of organic matter through enhanced microbial activity (Denef *et al.*, 2011).

CSI mitigation related efficiencies

As a major user of fossil energy and a major consumptive user of water and fertilizers, it is only natural that the agriculture sector, and more specifically the irrigation sector, should be under pressure to use fossil energy, water and other resources more efficiently. The overall aim is to: 1) **Reduce emission per unit of product** at the farm gate and/or at the end of the value chain, and 2) Identify and mitigate potential negative trade-offs or externalities that might result from improving efficiencies in the use of fossil energy, water, fertilizers and other resources that are direct or indirect causes of GHG emissions. On the basis that '**we can't fix what we don't measure'**, the logical starting point for developing CSI mitigation strategies is to: 1) Use GHG accounting to identify and quantify sources of GHG emissions from all stages or elements of the whole irrigation system, and 2) **Target effort towards reducing the major sources of GHG emissions**. The aim is to base decisions on solid evidence rather than intuition when seeking to reduce emissions per unit of product and, more specifically, when developing and implementing CSI mitigation strategies (Braimoh, 2015).

Linked to the above, it is recommended that water accounting and auditing (e.g. Batchelor *et al.*, 2017) be used in parallel with GHG emission accounting (e.g. Bockel *et al.*, 2017). The objectives are to:

- Identify and quantify the potential trade-offs that may result in a given biophysical and societal context from CSI mitigation strategies or measures aimed at reducing emissions per unit of product from the whole irrigated production system.
- Identify and evaluate options for improving irrigation efficiency and water productivity in space and time at the same temporal scales as used when accounting and mapping GHG emissions, again for the whole irrigated crop production system.

CSI mitigation strategies and measures aimed at **improved nitrogen efficiency** (e.g. more precise application of fertilizers in terms of constituents, timing and amounts) or **improved energy efficiency** across the whole irrigation system, have the additional benefit of reducing costs incurred by farmers, traders and other intermediaries along value chains. Additional measures may be required to make measures that target improved efficiencies truly effective. Such additional measures, for example related to improving drainage and leaching salts from salt affected soils, may require additional expenditure, but still only be partially effective. In such cases, crop yields may be reduced and cropping systems may need to be modified. In addition, there is a risk that salinity levels in ground and drainage water may reach the point where it is no longer possible for farmers to continue cultivating preferred crops that deliver good returns.

There are often **barriers** that slow or impede the implementation of CSI mitigation strategies and measures. These include high cost and lack of awareness, know-how or availability of machinery or equipment for reduced tillage, direct drilling or precise application of fertilizers. Resistance to change or even to modifying current policies or practices may also be a factor.

Food losses and waste represent a considerable waste of water, energy and agricultural inputs, and the unnecessary emission of millions of tonnes of GHGs (FAO, 2017b). CSI strategies should include measures aimed at reducing food losses and waste and, in so doing, **reducing emission per unit of product** at the farm gate and/or at the end of the value chain. Food losses and waste often translate into **economic losses for farmers** and other stakeholders within the food value chain, and higher prices for consumers, both of which affect food security by making food less accessible to vulnerable or marginalized social groups.

CSI mitigation financing mechanisms

Private investment in agriculture and, more specifically, in irrigated agriculture is influenced by agricultural and food price policies (FAO, 2017b). Governments around the world provide incentives to farmers and agribusinesses in order to increase agricultural production, influence input costs, supplement farm incomes and achieve other social, economic and environmental objectives that include water conservation, poverty reduction, and climate change mitigation and adaptation (After FAO, 2017b). However, much of the existing production support worldwide involves subsidies for inputs, such as fertilizer and energy, particularly fossil fuels, or direct payments to farmers (i.e. subsidies to support expenditure on inputs that can cause or exacerbate GHG emissions).

More positively, there are many cost-effective CSI mitigation measures that have the potential to improve production systems, sequester carbon either above or below ground and reduce direct GHG emissions (Tubiello and van der Welde, 2012). The challenge is to devise and fund a range of CSI strategies that: 1) Take advantage of opportunities that exist in different biophysical and societal contexts and result in positive adaptation and mitigation synergies, and 2) Shape and improve domestic and international policies, trading patterns, resource use, regional planning and the welfare of rural people, especially in developing countries.

A major CSI challenge is to design financing mechanisms that remunerate management and protection of environmental services in smallholder agriculture. These should offer an incentive for providing and safeguarding ecosystem services such as watershed protection, carbon sequestration and biodiversity provision. For smallholders to be able to participate and benefit from financial rewards and adopt mitigation practices, mechanisms need to take account of upfront investment and recurrent costs. Proper monitoring, reporting and verification (MRV) models are also needed to monitor the impacts (positive or negative) of investments and financing mechanisms (Tubiello and van der Welde, 2012).

From the perspective of sustainable development, financial support measures may have unintended impacts on the environment. For example, input subsidies may induce inefficient use of synthetic fertilizers and pesticides and inadvertently increase the GHG emission intensity of production. Almost half of all agricultural subsidies provided by governments of OECD countries during the period 2010 to 2012 were classed as ‘potentially most harmful to the environment’ because they induced greater demand for chemical fertilizers and fossil energy. Such subsidies influence the magnitude and nature of investments in agricultural sectors and food systems. Making support conditional on the adoption of practices that lower emissions and conserve natural resources would be one way of aligning agricultural development and climate change goals. Policies in areas such as nutrition, food consumption, food price support, natural resources management, infrastructure development and energy, may similarly need to be reset (FAO, 2016b).

CSI mitigation research and innovation

Evidence informed CSI strategy development and implementation requires data and information on climate change impacts, local vulnerabilities and opportunities, and GHG emissions from different production and agro-ecosystems. However, the reality is that data and information are rarely available when needed at the temporal or spatial scales of most interest to decision-makers. Even when data and information are available the ‘owners’ are often reluctant to share it with other stakeholders. In addition, many organizations involved in CSI mitigation and adaptation prefer not to use evidence informed approaches to developing strategies. Instead, they prefer to promote and fund a smallish basket of CSI measures, regardless of the biophysical or societal context and/or lessons learned. With this in mind, CSI mitigation research and innovation is warranted in areas that include:

- Development and piloting of GHG emission accounting that: 1) Takes a whole system and/or value chain approach to identifying, quantifying and mapping sources and causes of GHG emissions; 2) Provides robust methodologies and procedures for collecting, interpreting and modelling necessary GHG emission data; and 3) Demonstrates that outputs from GHG emission accounting stand up to scrutiny.
- Development and piloting of mutually supportive approaches to GHG emission accounting and water accounting & auditing. The aim is to better identify trade-offs associated with CSI adaptation and mitigation strategies and measures.

- Development and piloting of improved methodologies for raising awareness and communicating evidence, information and data from GHG accounting and water accounting & auditing (e.g. by social media, smartphone applications and interactive visualizations or dashboards).

Technical advances and reductions in costs have made both wind and solar energy a viable option for use in the irrigation sector. Currently the focus is on using clean energy for pumping water for irrigation. This is to be commended, but more consideration could be given to the whole cropping system when developing and piloting the use of clean energy.

FAO, IWMI and a number of other national and international organizations have accumulated a wealth of know-how and lessons learned related to good irrigation practices. While this can be found in reports, training manuals, guidelines and sourcebooks, some of these documents are not easily accessible or well catalogued. A concern is that lessons are being relearned and, as important, mistakes are being repeated and resources wasted unnecessarily. Innovative approaches could be used for updating and repackaging this material in the form of, for example, multilingual online tutorials and massive open online courses (MOOCs).

3.4.2 River basin scale (National institutional level)

Integrated CSI mitigation

The **Water-Energy-Food (WEF) nexus** approach and FAO's **Global Framework for Action (GFA)** lend themselves particularly well to CSI mitigation. The GFA is based on the premise that a sustainable pathway to food security in the context of water scarcity lies in maximizing benefits that cut across multiple dimensions of the food–water–climate nexus. The aim is to achieve sustainable agricultural production while reducing vulnerability to increasing water scarcity and optimizing climate change adaptation and mitigation benefits (FAO, 2016a).

As demand grows, there is increasing competition over natural resources between the water, energy, agriculture, fisheries, mining and other sectors (Flammini *et al.*, 2014). For instance, large-scale water infrastructure projects may have synergetic impacts, producing hydropower and providing water

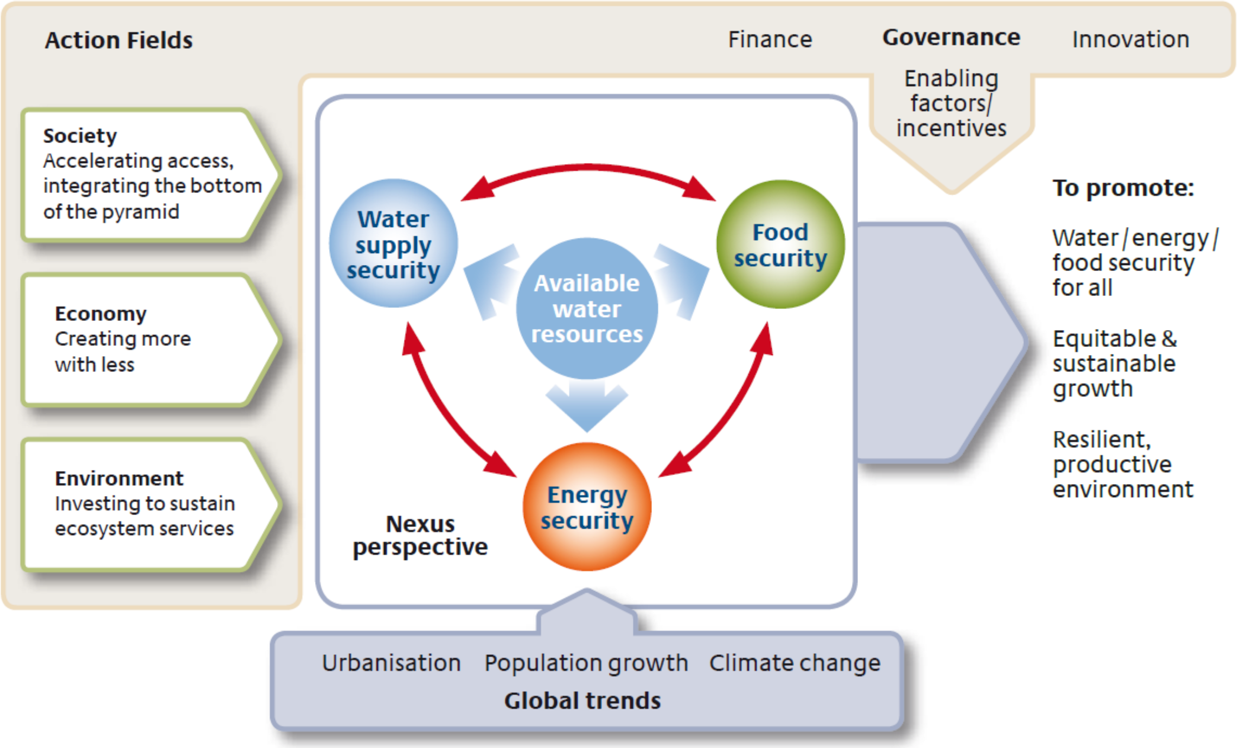

FIGURE 28: The water, energy and food security nexus

Source: Hoff, 2011

storage and regulated discharge for irrigation, but this may only be achieved at the expense of downstream ecosystems and food systems. Similarly, growing bioenergy crops on an irrigated agriculture scheme may improve energy supply, but this may be at the expense of increased water withdrawals and increased risks to food security.

Given the above, understanding the nature and scales of **synergies and trade-offs** becomes increasingly important as competition for natural resources increases. The WEF nexus approach recognizes that interdependencies between water, energy and food are often complex and inextricably entwined (see **FIGURE 28**). As important, the WEF nexus approach also recognizes that the policies and strategies of one part of the nexus can have a positive or negative impact on other parts. Adopting the WEF nexus in policy-making helps stakeholders to take an integrated approach to policy development and to reflect on a broad range of priorities, views and competing objectives.

During recent years, the WEF nexus approach has gained traction as an alternative or complementary approach to IWRM, for example in intersectoral strategy development and planning (Batchelor and Butterworth, 2014). A key difference between the two approaches is that IWRM always starts with water resources when considering interrelationships between water, land, food and energy, whereas the WEF nexus approach can start from different perspectives (e.g. water, energy or food). While the WEF nexus approach has significant merit, it has also attracted some criticism for being unnecessarily limiting and prescriptive, for example, by not explicitly highlighting interlinkages with land, climate change, poverty and economic development. In some respects, the WEF nexus approach is nothing new. Water managers and water users have long considered the energy implications of some of their actions, partly because energy costs can be a major component of their bottom lines

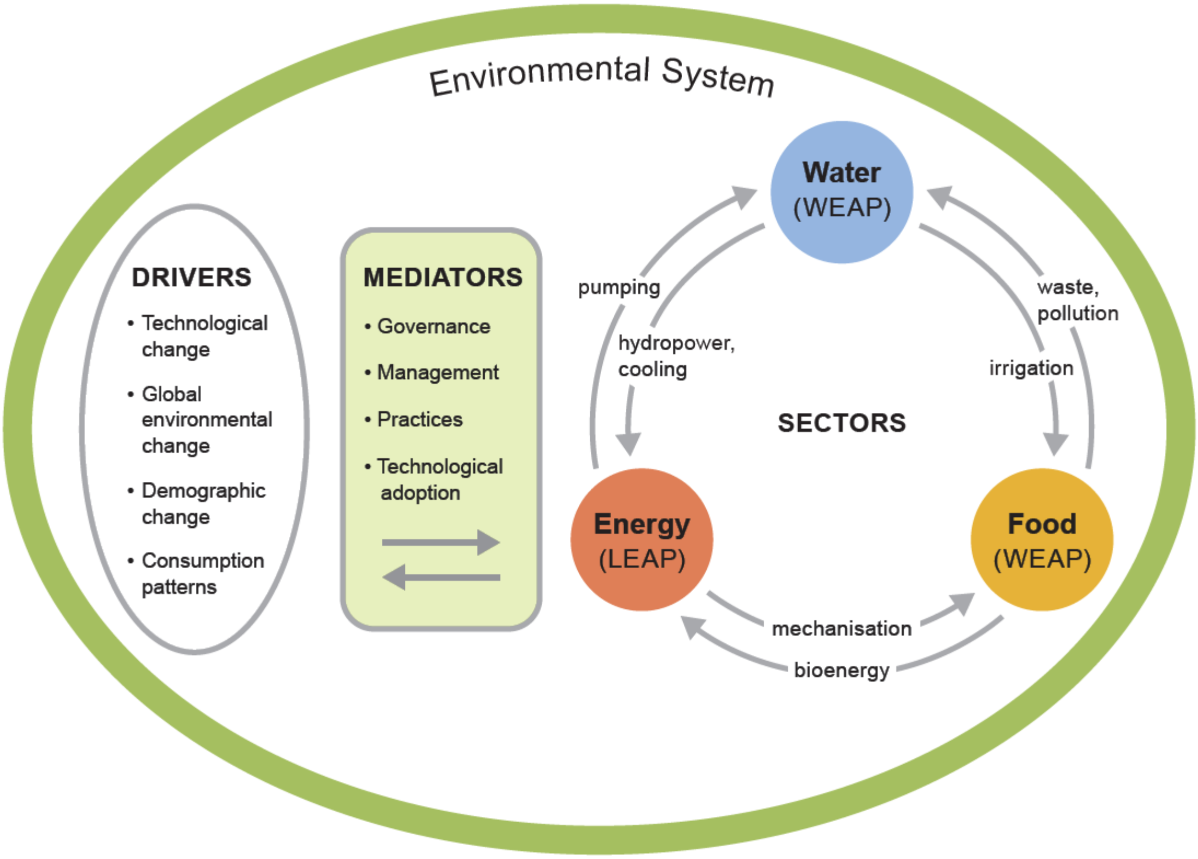

FIGURE 29: A preliminary conceptual model of the Water-Energy-Food (WEF) nexus
The model shows links between sectors and drivers and mediators of change. WEAP (Water Evaluation and Planning system) and LEAP (Long-range Energy Alternatives Planning system) are software tools developed by the Stockholm Environment Institute (SEI) that can be applied in the WEF nexus approach.

Source: SEI, 2015

(SEI, 2015). Energy managers must always consider where they will get the water they need to use along the energy production chain, from fuel extraction and processing to transforming fuel into energy. Food producers rely on both water and energy as inputs, and this reliance is strongest in irrigated, market-oriented food production systems (SEI, 2015).

However, where the WEF nexus approach differs – and it is here that its strength lies – is that it formalizes these links and explicitly considers them, taking human aspirations as the starting point and placing stakeholders at the centre of the process, rather than setting out from a traditional focus on allocation of natural resources (see **FIGURE 29**). The argument is that applying a nexus framework can improve the ways in which decisions are made, resources are managed and ecosystems and communities are supported (SEI, 2015).

Implementing the WEF nexus approach is not easy, because decisions about energy, water, food and ecosystems are often made in disconnected institutions that operate across different scales in response to different imperatives. This is a critical point, because nexus thinking asks resource managers, analysts and users to expand the scope of their engagement on the issues they confront. It must be clear to them that it is worth the effort in terms of generating outcomes that are meaningful to them, because inevitably stakeholder dialogue requires sustained effort and commitment.

From a CSI mitigation perspective, the WEF nexus approach is used for assessments to inform the development of CSI mitigation strategies, the selection of CSI mitigation measures and the identification of potential intersectoral synergies and trade-offs (in space and time). On the basis that the WEF assessment approach can highlight synergies between sector interventions, it promotes so-called 'win-win' solutions, helping stakeholders to develop insights into different options, which might not be apparent at first glance. Hence the objectives of applying the WEF nexus approach for assessments in CSI mitigation planning include (After Flammini *et al.*, 2014):

- Providing an overview of the current nexus status of the context in terms of natural resources and their uses to sustain society, through the identification and quantification of key nexus interlinkages.
- Applying specific tools to derive key indicators, if these are not readily available from existing datasets.
- Review and suggest how specific CSI mitigation strategies can be assessed and compare the performance of specific CSI mitigation strategies on the basis of the context status against WEF sustainability goals.
- Interpret the results of the nexus assessment, contextualize possible CSI mitigation measures and appropriate CSI mitigation response options.

CSI mitigation strategies and measures

There is an extensive list of potential measures that can be taken in agriculture and, more specifically, irrigated agriculture for mitigating emissions (see **TABLE 13**). Some mitigation options, which are **typically good management practices**, already lower farm emissions while also contributing to cost savings and thus increasing profitability and farmer incomes (Frelih-Larsen and Dooley, 2015). These are therefore win-win measures. Many options can be carried out at farm level, although some also require collective approaches involving multiple farmers and other stakeholders at irrigation scheme level. However, the uptake and effectiveness of these options often depend on the enabling environment, which includes having policies in place that, for example, provide incentives for adopting appropriate CSI mitigation measures and regulatory measures to prevent unsustainable levels of consumptive water use.

Mainstreaming of climate change considerations into agricultural and rural development activities largely depends on local awareness, political willingness, obligations within global climate change frameworks and technical and economic conditions. Hence **CSI adaptation and mitigation** interventions should be formulated and implemented in response to a country's specific demands and needs, and should be **in line with national and local climate change strategies and action plans**, especially National Adaptation Programmes of Action (NAPAs), National

TABLE 13: Some options for climate change mitigation in the agricultural sector

Reducing GHG emissions	Avoiding or displacing GHG emissions	Removing GHG emissions
▪ Increase feed use efficiency to reduce CH_4 emissions ▪ Increase fertilizer and water use efficiency ▪ Reduce emissions from deforestation and forest degradation (REDD) ▪ Decrease fishmeal use and reduce excess fishing capacity ▪ Lower post-harvest losses and increase waste recycling	▪ Replace fossil fuel energy with bioenergy from wood, agricultural feed stocks and residues ▪ Improve energy use efficiency in the agricultural sectors ▪ Undertake forestry conservation activities to help avoid emissions ▪ Substitute materials with wood products	▪ Practice afforestation, reforestation and forest restoration ▪ Engage in sustainable forest management (SFM) ▪ Improve cropland and grassland management ▪ Engage in agroforestry ▪ Restore degraded land

After: Medeiros DuBois et al., 2012

Adaptation Plans (NAPs), Nationally Appropriate Mitigation Actions (NAMAs) and Nationally Determined Contributions (NDCs) (after Medeiros DuBois *et al.*, 2012).

CSI strategy development and planning at the river basin scale and national level should also:

- Recognize and, where appropriate, **incentivize** the interlinked principles that underpin conservation agriculture. These are: 1) Continuous minimum mechanical soil disturbance; 2) Permanent organic soil cover; and 3) Diversification of crop types grown in rotation and/or companion crops. The premise is that this will enhance soil carbon sequestration and reduce nitrous dioxide emissions.
- Recognize that climate change is global, but its impacts are local. CSI mitigation strategies must be tailored to specific local conditions to ensure their relevance and effectiveness. Multistakeholder consultations are needed to jointly prioritize options and make decisions. It is therefore important to adopt demand driven, location specific approaches and participatory modalities that consider gender specific vulnerabilities, needs and capabilities, as well as the priorities of vulnerable, poor and marginal social groups.
- Create an enabling environment for scaling up the adoption of new technologies for generating clean energy that will displace the use of fossil fuel energy by the irrigation sector.

3.4.3 Irrigation scheme scale (District or intermediate institutional level)

CSI mitigation overview

Similar to CSI adaptation, CSI mitigation at the irrigation scheme and intermediate institution scales or levels should: 1) Be both bottom-up and top-down in nature and have a high level of active stakeholder engagement; 2) Inform and be informed by CSI mitigation planning at the other scales and institutional levels; 3) Take place within the context of river basin and national CSI adaptation plans; 4) Take account of and build on farmer and community scale CSI adaptation plans; and 5) Align with or integrate well with other relevant sectoral or intersectoral CC mitigation plans.

One of CSA's mantras is "*Wherever and whenever possible, CSA should help to reduce greenhouse gas (GHG) emissions*". While this is commendable in many respects, a more pragmatic cost-effective approach is to focus CSI mitigation strategies and measures on:

- Identifying and quantifying the main sources or causes of GHG emissions from the whole irrigation system, from the water source to the end of value chains.
- Prioritizing sources or causes of GHG emissions according to: 1) Their magnitude; 2) The availability of cost-effective mitigation options; and 3) Potential mitigation synergies or trade-offs.
- Identifying and taking advantage of possible offsetting opportunities that may result in

better net outcomes at the irrigation scheme scale (e.g. in terms of reducing GHG emissions per unit of product at the irrigation scheme level).

- Recognizing that GHG mitigation gains realized in one area may be lost in others. For example, gains from one CSI mitigation measure may be lost or reduced because more labour and vehicles are needed to implement the measure at scale.

CSI mitigation and irrigation modernization

CSI mitigation at irrigation scheme and intermediate scales is often as much about improving **water governance and management** as it is about, for example, upscaling the use of solar energy or conservation agriculture. Irrigation modernization is often included in CSI mitigation strategies and, increasingly, as much attention is being paid to irrigation software as to irrigation hardware. Typically, the aims of these strategies include: 1) Improving the sustainability of resource utilization; 2) Improving the level of services delivered to farmers; 3) Upgrading the technical and managerial aspects of irrigation schemes; 4) Improving the maintenance of both irrigation and drainage systems; and; 5) Making institutional reforms that include the establishment of WUAs or similar. Increasingly, attention is being paid to developing governance and management systems that are adaptive, and which make decisions that are informed by information acquired in real time, and over cropping seasons or longer periods of time. A key point here is that monitoring systems will need to be upgraded to assess the impacts and outcomes of CSI mitigation policies and measures (in space and time). In particular, innovative cost-effective monitoring systems are needed that track and monitor GHG emissions up to and beyond the farm gate and at irrigation scheme and intermediate scales, promoting the levels of confidence necessary to support decision-making.

Note that MASSCOTE, WA&A and EX-ACT provide a sound basis for contextualizing, modelling and analysing the impacts and outcomes of CSI mitigation policies and measures. However, these methods and frameworks require data for calibrating and validating the algorithms and models if they are to produce outputs that stand up to scrutiny.

CSI mitigation and social and economic development

CSI mitigation strategies can and should support social and economic development by addressing inequities in terms of access to water, for example, of relatively poor farmers with landholdings at the tail ends of irrigation canals, or who cannot afford to drill a borehole or purchase a solar pump. CSI strategies and measures can also address perennial problems of soil fertility, partly because irrigation can enhance carbon sequestration in arid and semi-arid areas and, in so doing, help to break the vicious cycle of depletion in soil organic matter, decline in crop yield and food security, and increase in soil and environmental degradation (Lal, 2004a).

3.4.4 Field or farm scale (Local institutional level)

CSI mitigation overview

Most of the farm-scale adaptation and productivity improvement practices described in the previous sections **will positively reinforce mitigation potential**. Better design, implementation and management of irrigation systems, use of crop rotations, more judicious use of fertilizers, increased farm diversity and improved crop husbandry contribute to irrigated cropping systems that: 1) Are more resilient to the impact of climate change and other shocks; 2) Improve water productivity and farmer incomes; 3) Increase carbon sequestration; and 4) Reduce greenhouse gas emissions for each calorie or kilo of food, fibre or fuel that is produced.

Over time, a new climate regime may alter the effectiveness of proposed **adaptation and mitigation strategies**. For example, increased rainfall in some areas may improve the availability of water for irrigation. Likewise, longer growing seasons may enable increased vegetative growth and thus carbon sequestration. On the other hand, warmer temperatures may have negative effects, for example, by increasing decomposition rates of soil organic matter; increased variability and higher frequency of extreme rainfall events will increase the risk of crop losses due to flooding and damage to irrigation related infrastructure.

Synergies and trade-offs between adaptation and mitigation

Consideration should be given to interactions between adaptation strategies, which will be implemented by farmers as the climate changes, and the **mitigation potential** of the adapted system. The risk is that, in areas of declining rainfall, farmers will adapt by increasing the amount of irrigation applied and, in so doing, increase the energy used (e.g. for pumping water) and the GHG emissions per unit of output. Poleward shifts in agricultural zones may lead to increased cultivation of previously marginal and currently undisturbed areas. While this may provide opportunities for economic development in those countries, the risk is that significant losses of above- and below-ground carbon will be caused as a result (After Tubiello and van der Welde, 2012).

Soil carbon sequestration

The amount of carbon stored in soil organic matter is influenced by the addition of carbon from dead plant material and carbon losses from respiration, the decomposition process and both natural and human disturbance of the soil (Schahczenski and Hill, 2009). By employing farming practices that involve minimal disturbance of the soil and encourage carbon sequestration, farmers may be able to slow or even reverse the loss of carbon from their soils. By increasing the ability of soils to retain soil moisture and to better withstand erosion, and by enriching ecosystem biodiversity through the establishment of diversified cropping systems, many mitigation techniques implemented locally for soil carbon sequestration will help cropping systems to better withstand droughts or floods, both of which are projected to increase in frequency and severity in future warmer climates (Tubiello and van der Welder, 2012).

It has been estimated that best practice and conservation tillage, if applied globally, over the next 20 years could store up to 1.5 billion tonnes of CO_2 annually in agricultural soils. **TABLE 14** compares traditional and recommended management practices in relation to soil carbon sequestration. Larger amounts can be sequestered via agroforestry practices, especially if established on marginal lands, or through cropland conversion and conservation programmes.

TABLE 14: Comparison between traditional and recommended management practices in relation to soil organic carbon sequestration

Traditional methods	Recommended management practices
1. Biomass burning and residue removal	1. Residue returned as surface mulch
2. Conventional tillage and clean cultivation	2. Conservation tillage, no till and mulch farming
3. Bare/idle fallow	3. Growing cover crops during the off-season
4. Continuous monoculture	4. Crop rotations with high diversity
5. Low input subsistence farming and soil fertility mining	5. Judicious use of off-farm inputs
6. Intensive use of chemical fertilizers	6. Integrated nutrient management with compost, biosolids and nutrient cycling, precision farming
7. Intensive cropping	7. Integrating trees and livestock with crop production
8. Surface flood irrigation	8. Modernized irrigation
9. Indiscriminate use of pesticides	9. Integrated pest management
10. Cultivating marginal soils	10. Conservation reserve programme, restoration of degraded soils through land use change

After: Lal, 2004b

An important caveat to the implementation of best practice and reduced tillage agriculture as a means to enhance carbon sequestration is that CO_2 emitted from the manufacture and use of additional agricultural inputs may negate all or part of the increased carbon sequestered in soils (Schlesinger, 1999). It is also important to note that the potential for soil organic carbon sequestration is finite in magnitude and duration. This is only a short-term strategy to mitigate anthropogenic enrichment of atmospheric CO_2. A long-term solution lies in developing alternatives to fossil fuel. Yet, soil organic carbon sequestration buys us time during which alternatives to fossil fuel may be developed and implemented. It is a bridge to the future. It also leads to improvement in soil quality.

Management of organic soils is central to limiting agricultural GHG emissions, since organic soils are the most carbon dense ecosystems of the terrestrial biosphere. Drained organic soils used for agricultural production are hotspots of GHG emissions, producing the highest emissions of all types of arable land (Frelih-Larsen and Dooley, 2015). Among non-livestock mitigation options in agriculture, avoiding drainage of organic soils, restoration of organic soils by re-establishing a higher water table, and land use change of arable land to grassland have the potential to deliver significant mitigation benefits. Similar to the addition of fertilizers and manure to a nutrient depleted soil, judicious application of irrigation water in a drought prone soil can enhance biomass production, increase the amount of above-ground and root biomass returned to the soil, and improve soil organic carbon (Lal, 2004b).

Nitrogen use efficiency

Improving fertilizer efficiency through practices such as precision farming using GPS tracking can reduce nitrous oxide emissions. Precision farming without GPS tracking will also improve nitrogen use efficiency, if it ensures that nitrogen applications are timely and uniform and well matched to requirements. Other strategies include the use of cover crops and manures (both green and animal manure), nitrogen-fixing crop rotations, composting, and integrated pest management. Reductions of GHG emissions that result from improved nitrogen efficiency use may partially be offset by a higher rate of N_2O emissions from relatively wetter soil profiles which, for example, result from a switch from rainfed to irrigated agriculture (Ruser *et al.*, 2006; Liu *et al.*, 2011).

For quite some time, precision agriculture was regarded as being irrelevant to small-scale farmers in developing countries. The rationale was that the variability in soil properties across small landholdings was not significant, and that poor farmers could not afford the technology. However, research in recent years has shown that significant benefits can accrue from microdosing of fertilizers using low-cost technologies (Richards *et al.*, 2015).

Energy efficiency of irrigation equipment

It should be noted that irrigation equipment is not the only direct or indirect user of energy on a typical irrigation system, particularly if a whole-system approach is taken to energy accounting. This said, irrigation equipment can use a great deal of energy (e.g. when pumping water from deep aquifers), and often the energy efficiencies are low for reasons that include (Morris and Lynne, 2006):

- **Lack of system maintenance**: Pump impellers that are out of adjustment, plugged screens, worn nozzles, engine drive units that need a tune-up, worn shaft sleeves, leaking gaskets and drains, and dried-out bearings and pump packing are just a few of the problems that can be avoided with regular maintenance.
- **Wrong pump for the system:** A pump that is oversized or undersized will not operate efficiently.
- **Pump wear from cavitation or abrasion:** Cavitation damages impellers, thereby reducing efficiency. If the water source contains large amounts of sediment, it is necessary to re-engineer the intake structure to allow sediment to settle before entering the suction line.
- **Improperly sized pipes and fittings:** Pressure losses occur as irrigation water passes through undersized pipes, valves or other fittings. This can also cause yield losses as a result of poor irrigation uniformity.

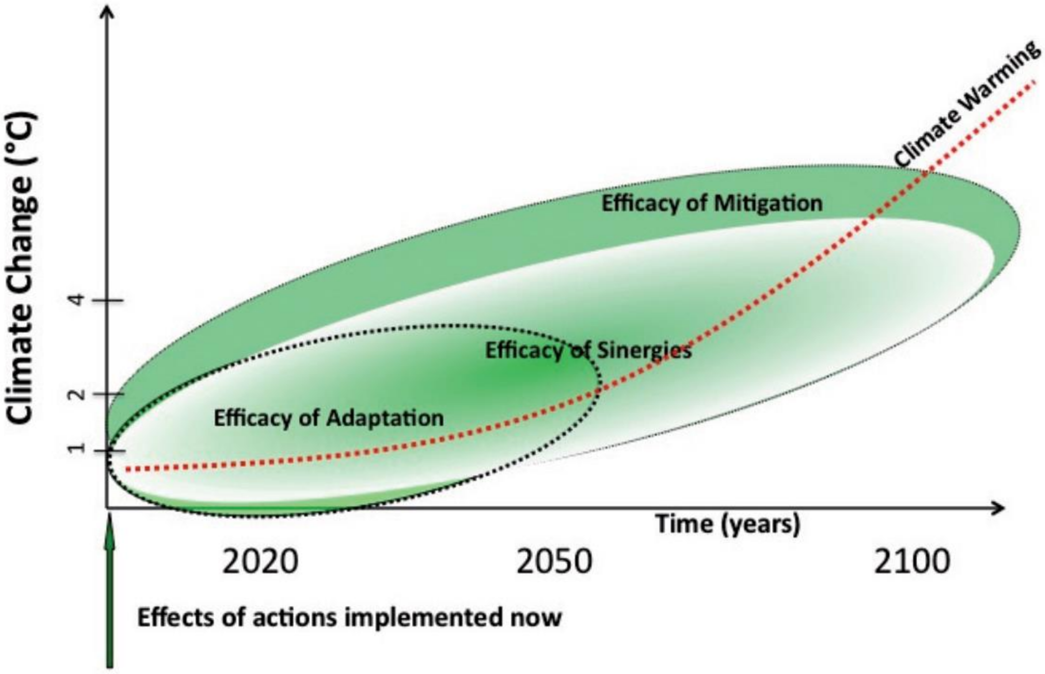

FIGURE 30: Adaptation and mitigation roles for land and water resources

Source: Tubiello and van der Welde, 2012

- **Unsustainable use of water resources:** If groundwater, streams and/or springs dry up, replacement or additional infrastructure may be needed, wells may need deepening, and it is likely that more energy will be required for pumping water.
- **Leaks or illegal connections:** Leaks or illegal pipe connections mean that more water has to be pumped or diverted to meet crop water requirements. Note also that leaks and illegal connections affect the hydraulic integrity of an irrigation system. This can reduce irrigation uniformity and the availability of water at the tail ends of the system.

Mitigation challenges facing farmers

Ultimately, farmers, traders and other intermediaries along value chains will be faced with challenges that include coping with and adapting to a changing climate, reducing GHG emissions, and generating a return on investments. **FIGURE 30** shows that, in general, well matched adaptation measures are likely to work effectively to limit damage from low to medium global warming (from now until mid-century), while well matched mitigation actions work on longer time scales, with benefits only materializing in the second half of the century.

Many mitigation measures are classified and promoted as win-win opportunities, but the reality may be different. For example, **TABLE 15** presents findings of an analysis from the USA showing that adoption of some typical field level mitigation measures may reduce yields. If farmers experience declines in yields, widespread adoption of these measures can only be expected if farmers are able to recover the associated implementation costs and foregone net income related to commodity production (ICF, 2013).

TABLE 15: Mitigation practices and modelled scenarios

Mitigation measure	Decrease in yield	No change in yield
Switching from conventional to reduced tillage	✓	
Switching from conventional to no-till	✓	
Switching from reduced till to no-till	✓	
10% reduction in N application rate	✓	
Inhibitor application alongside fertilizers		✓
Variable rate technology for fertilizer application		✓

Source: ICF, 2013

Barriers to the adoption of CSI mitigation measures include (After Underwood *et al.*, 2013):

- **Risk aversion:** Quite naturally, farmers are wary of changing from well proven irrigation practices that they have been using all their lives. In addition to losing income, they may be wary of losing face before their peers, especially should the new irrigated cropping system be a failure.
- **Conflicting messages in the media:** While there is increasing evidence that climate change is happening, there is still plenty of information in the mainstream and social media that questions the validity of this evidence.
- **Insufficient funding** for Farmer Field Schools or similar initiatives that provide opportunities for groups of farmers to evaluate, and, if relevant, adapt CSI mitigation measures to their own situations.
- **Competing uses of biomass:** Reduced availability of biomass for soil management (e.g. crop residue management or permanent soil cover) due to other uses such as fuel or fodder can be a problem, especially for poor farmers in degraded areas.
- **Availability of equipment/machinery:** For example, the availability of affordable equipment for solar-powered pumping of groundwater or affordable machinery for direct seeding.
- **Availability of long-term incentive programmes:** The full benefits may be slow to materialize, as soil physical and biological health takes time to develop. Governments may be unwilling to commit to long-term incentives for benefits that may not materialize during their time in office.

3.4.5 Key messages

- The aims of CSI mitigation policies and practices include: 1) **Reducing greenhouse gas emissions** for each calorie or kilo of food, fibre and fuel that is produced up to the farm gate and/or up to the end of irrigated crop production value chains; and, 2) Removing emissions from the atmosphere by enhancing **soil carbon sequestration** above and below ground, and by increasing the land area under conservation agriculture, permanent pasture, agroforestry and/or forestry.
- CSI mitigation strategies involve, for example: 1) Reducing the use of non-renewable energy used to pump, distribute and treat irrigation water; 2) Applying organic and inorganic fertilizers in ways that minimize GHG emissions; 3) Managing soils, cropping systems and irrigation regimes in ways that maximize the potential of soils to act as carbon sinks; and, 4) Recognizing that, at the basin scale, intensification of irrigated cropping may be justified and offset by, for example, reductions in rates of land use change, from forestry or rangeland to rainfed or irrigated cropping.
- GHG emissions occur **at all stages** of an irrigated crop production system, from the source of irrigation water through to the cultivation of crops and to the final phase of value chains. GHG emissions are often exacerbated by unsustainable water resource use, poor farming practices and post-harvest crop losses up to and beyond the farm gate.
- On the basis that '**We can't fix what we don't measure'**, the logical starting point for developing CSI mitigation strategies is to: 1) Use GHG accounting to identify and quantify sources of GHG emissions from all stages or elements of a functioning irrigation system, and 2) **Target efforts towards reducing the major sources of GHG emissions**. The key here is solid evidence rather than intuition when seeking to reduce emissions per unit of product and, more specifically, developing and implementing CSI mitigation strategies.
- The **causes and scale of GHG emissions need to be determined, quantified and mapped** (**in space and time**) when determining appropriate CSI mitigation strategies. In this regard, additional funds are needed for research into GHG emissions (e.g. using eddy covariance systems), as well as for monitoring systems to assess the utility and cost-effectiveness of CSI strategies in different contexts.
- Linked to the above, it is recommended that water accounting and auditing (e.g. Batchelor *et al.*, 2017) is used in parallel

with GHG emission accounting (e.g. Bockel *et al.*, 2017). The aims are to:

  - Identify and quantify the potential trade-offs that may result in a given biophysical and societal context from CSI mitigation strategies or measures aimed at reducing emissions per unit of product.
  - Identify and evaluate options for improving irrigation efficiency and water productivity in space and time in domains of interest.

- A wide range of CSI mitigation measures exist, which are both feasible and, in many cases, well proven. Some of these are essentially the **good irrigation practices** described in the sections on CSI productivity and CSI adaptation.
- A core question facing global and national planners and policy-makers is whether today's agriculture and food systems are capable of meeting the needs of a global population that is projected to reach more than 9 billion by mid-century, and may peak at more than 11 billion by the end of the century (FA0, 2017c). Just as important, can we achieve the required production increases, even as the pressures on already scarce land and water resources and the negative impacts of climate change intensify? The consensus view is that current systems are capable of producing enough food, but to do so in an inclusive and sustainable manner **will require major transformations**.
- This raises further questions. Can agriculture meet unprecedented demand for food in ways that ensure that the use of water resources is sustainable, while containing GHG emissions and mitigating the impacts of climate change? This is at a time when large surface water irrigation systems and dispersed groundwater schemes are already struggling as a result of demand for water outstripping supply (e.g. in semi-arid areas of southern and western India).
- CSI mitigation strategies and measures aimed at **improved nitrogen efficiency** (e.g. more precise application of fertilizers in terms of timing and amounts), or **improved energy efficiency** across the whole irrigation system, have the additional benefit of reducing costs incurred by farmers, traders and other intermediaries along value chains.
- Food losses and waste represent a considerable waste of water, energy and agricultural inputs, and cause the emission of millions of tonnes of GHGs (FAO, 2017b). CSI strategies should include measures aimed at reducing food losses and waste and, in so doing, **reduce emissions per unit of product** at the farm gate and/or at the end of the value chain.
- Similar to CSI adaptation, the **Water-Energy-Food nexus** approach and FAO's Global Framework for Action lend themselves particularly well to the planning and implementation of CSI mitigation strategies.

4. CASE STUDIES

4.1 “Misión Posible II”: improving water use in farming for conservation of *Las Tablas de Daimiel* wetlands[22]

The Misión Posible II project was undertaken throughout the irrigation seasons of 2016 and 2017. It was fully funded by the Coca-Cola Foundation and executed by WWF-Spain in collaboration with a group of consultants.

This project consolidated and extended the activities of a previous project, Misión Posible I, which ran from 2013 to 2015.

MISION POSIBLE
CONSERVAR EL AGUA DE LA MANCHA

The spatial scope of the project covered the overexploited aquifers in the Upper Guadiana basin, Central Spain. The main aim was to train farmers and technicians – principally drawn from cooperatives and irrigation communities – in using irrigation assessment tools for better use of water resources. This is expected to lead to an increase in productivity rates in terms of production per water abstracted, and to a reduction in the quantity of water used for irrigation, both important in promoting greater adaptation to more frequent and intensive droughts.

Why we decided to work in this region

Intensive use of water for irrigation in the Upper Guadiana basin (UGB) has had serious environmental impacts. Falling piezometric levels have led to a significant loss of groundwater dependent ecosystems; of the 25 000 ha of wetlands in the 1970s, only about 7 000 ha remain. Most of this area is included in the *Mancha Húmeda*, UNESCO’s Biosphere Reserve. *Las Tablas de Daimiel* National Park represents the most dramatic and best documented case of wetland degradation in the area. Due to pumping, the park experienced a strong decrease in flooded surface area, from approximately 2 000 ha under natural conditions to an almost completely dry state in particularly dry summers.

This wetland is situated just a few kilometres from the discharge area of the *Mancha Occidental* aquifer, known as *Ojos del Guadiana* (Guadiana´s Eyes). Almost all the freshwater flow coming from the UGB infiltrates into this aquifer. In addition groundwater flows from adjacent aquifers transfer to it. For this reason, the state of *Las Tablas de Daimiel* can be used to measure the 'health' of the UGB’S water system. Today, these hydrological flows are interrupted and the *Ojos del Guadiana* aquifer has turned from a water discharge into a recharge area. This shift has had several direct impacts besides water scarcity, causing the alteration of chemical characteristics of water and associated fauna and flora, as well as a modification in seasonal flooding patterns.

In 1987, the *Mancha Occidental* aquifer was the first to be declared overexploited in Spain, and continues to be designated as such. This is due to annual rates of water abstraction, through pumping, significantly exceeding the aquifer’s recharge rate, and has lead to diminished freshwater flows that no longer guarantee the conservation of ecological systems. An annual abstraction plan has been enforced since 1994, limiting the quantity of water that can be withdrawn by each farmer, dependent on the water rights owned. A ‘command and control’ strategy has been followed by the public administration since then, but this has proved to be only partly effective in an area where more than 30 000 farmers irrigate between 120 000 and 150 000 ha each year.

Policies alone are proving insufficient to protect and ensure the sustainability of the natural areas in the region. This is a complex issue and the support and empowerment of stakeholders is therefore key to finding viable solutions to the various challenges.

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[22] Case study prepared by Alberto Fernández-Lop, Rafael Seiz, Eva Hernández (WWF-Spain); Manuel Bea (I-CATALIST); and María Jiménez (Hidrosoph).

Tools for smarter irrigation

The project's main goal is to support farmers so that they can make better decisions in water use. The farming cooperatives and irrigation communities have been identified as the main actors and dissemination vectors to reach a broad number of farmers. In addition, project leaders believe that empowering these organizations will improve governance of water resources in the area, since traditionally, close collaboration between this kind of farmers' groups and the water authority has been lacking.

A number of tools and irrigation support services have been developed and tested as part of the Misión Posible project. The target during the 2016 and 2017 campaigns was to extend the application of these tools to a wide number of farmers, at no cost to them. The various tools used were ACUAS, SITAR and OPTIWINE.

ACUAS is a tailor made geographic information system tool that allows technicians in irrigation communities to support farmers in developing irrigation plans. These plans estimate the water consumption of irrigated crops so as to comply with the maximum volume allowed by the aquifer's annual abstraction plan.

The GIS tool takes data from the cadastral database, so that the farmer can define the farming area where irrigation is allowed. Updated aerial ortophotography is used as support (see **FIGURE 31**).

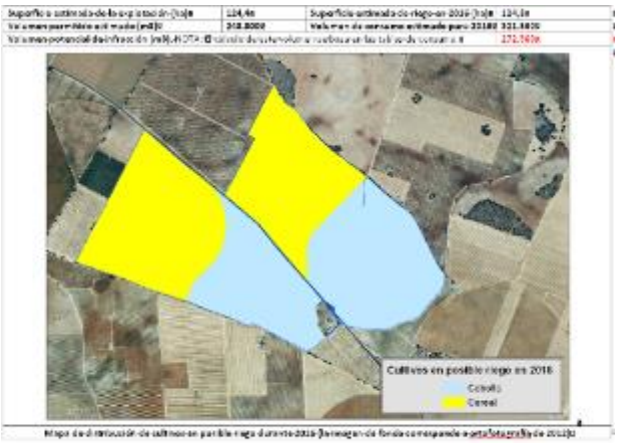

FIGURE 31: Example of graphical output of the ACUAS tool

The farmer provides indications of which crops and which area for each crop he or she is planning to irrigate, and these data are incorporated into the system. ACUAS is designed to guide the technician in adjusting this initial plan to the legal framework.

As a result, the farmer is provided with a graphical output that clearly shows the boundaries of the areas to be cultivated with each irrigated crop. Finally, remote sensing images are used to monitor whether the farmer complies with this irrigation plan. Remote sensing was also used to assess water abstraction in the participating farming areas before the introduction of this irrigation planning service. The analysis has shown that a significant number of farmers had not been complying with the water abstraction plan.

The **SITAR** tool sends farmers weekly irrigation recommendations via text message, based on their crops and soil type, and on information from the regional Irrigation Advisory System. The tool integrates agroclimatic data from the regional network of stations with crop development curves based on the crop coefficient (Kc), which have been adjusted to the characteristics of the climatology and irrigated crops in the region. The farmers provide other ancillary data that are taken into consideration in the calculation of weekly recommendations of irrigation volumes, including sowing date, soil type, extent of the cultivated area, type and performance of the irrigation system, and characteristics of the pumping system. Based on this information, the SITAR tool provides direct instructions on the recommended time period that the pumping system must work to provide the recommended weekly water volume per crop.

OPTIWINE is a decision support tool that calculates the exact amount of water to be applied in the irrigation of vineyards, so as to improve grape quality while also reducing water consumption. The tool integrates satellite data, e.g. a series of Normalized Difference Vegetation Index (NDVI) values correlated with the basal Kc coefficient, regional agroclimatic data, and data collected by weather, plant and soil moisture sensors installed on a number of sample plots.

The software behind the OPTIWINE system develops a water balance for each vineyard plot, based on reference climatic forecasting

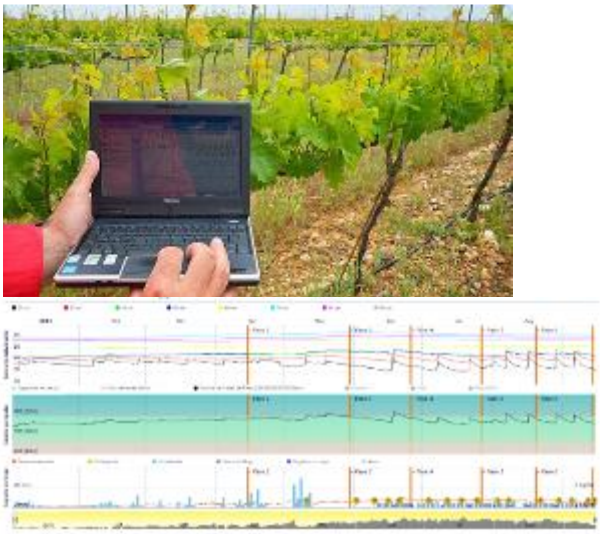

FIGURE 32: Vineyard plot with the corresponding graphical output of the OPTIWINE system

and parametrization of its soil characteristics, cultivated grape variety and irrigation system. Based on this water balance, a detailed irrigation schedule is drawn up (see **FIGURE 32**). The sensors are used to monitor the plan and make regular adjustments based on climatic forecasting, plant status and soil water reserve. The satellite data are used to extrapolate these recommendations to other vineyard plots in the same cooperative.

About the project results

Between 2016 and 2017, more than 200 farmers used the tools provided by the project with the support of cooperatives and irrigation communities.

The water savings obtained as a result have been calculated in two separate ways: as direct replenishment and additional benefits. The former addresses the direct reduction in consumption, while the latter relates to changes in the farmers' agronomical practices as a result of advice received from the project tools.

Although the data are not yet definitive, the total direct replenishment for the 2016 and 2017 irrigation seasons amounts to between 1.5 and 2 cubic hectometre (hm^3), whereas the additional benefit has been estimated at around 1.3 hm^3.

Farmers' improved planning capacity as a result of using the ACUAS tool, coupled with a reduction in water consumption through use of the other two tools, confirm the strategy's effectiveness as an adaptation measure against drought events.

In some plots targeted for irrigation advice, detailed monitoring was conducted using field sensors, alongside close collaboration with farmers. This has allowed the project team to obtain clear insights into the impact of the recommendations on agricultural outputs. In 2016, crop yields were slightly higher than average on these plots, despite the harsh agronomic conditions experienced that year (i.e. higher temperatures and low rainfall, especially in the second half of the crop cycle). This shows that an adjustment of irrigation to the real plant needs, both in terms of water volume and timing, can result in good production while consuming less water resources. This is expected to serve as a strong argument to convince farmers, although these kind of behavioural changes will probably take several years to become widely entrenched in the area, i.e. far beyond the project period.

These results aside, the project has strongly contributed to disseminating smart irrigation practices among farmers, raising awareness of the environmental and economic importance of making better irrigation decisions, and strengthening the role of farmers' organizations.

4.2 Creating foundations for resilient agricultural development in Kavre, Nepal[23]

Introduction

The Hindu Kush Himalaya (HKH), often referred to as the 'water tower of Asia', is the starting point of the world`s largest natural irrigation system located in the Indo-Gangetic plain (Rasul, 2014). As the source of Asia's ten largest rivers, the HKH provides water to more than 1.3 billion people living downstream – one-fifth of the world's population. Studies indicate that temperatures in the Himalaya are expected to increase faster than the global average, up to 1–2 °C on average by 2050, and even higher at greater elevations. The HKH region is also experiencing longer and more erratic monsoon seasons, with rainfall events becoming less frequent and more extreme. Changes in precipitation and temperature will have a substantial impact on climate dependent sectors, such as water, agriculture and the overall state of people's health and livelihoods (Shrestha *et al.*, 2015).

The tributaries of the Ganges River provide almost the entire population of Nepal with freshwater (Rasul, 2014). As Nepal's economy is primarily based on agriculture and forestry, it is highly dependent on access to water resources. However, in recent years Nepal has been exposed to changes in precipitation patterns that have resulted in increased prevalence of natural hazards, such as droughts and floods (Chamrakar, 2010). Kavre district, situated in the mid-hills of Nepal, has long been a place of significant agricultural production, with a large market for fresh vegetables in the capital city of Kathmandu. However, changing climatic conditions, increased use of hazardous pesticides, and resultant soil degradation are challenging the foundation of people's livelihoods (Bhatta *et al.*, 2015). Simultaneously, increasing outmigration, predominantly by young men, has substantially shifted the responsibilities of agriculture to women.

Since 2014, the Resilient Mountain Villages (RMV) approach, developed by the International Centre for Integrated Mountain Development (ICIMOD), has been piloted in eight villages in Kavre district, in cooperation with the Center for Environmental and Agricultural Policy Research, Extension and Development (CEAPRED). RMV draws elements from the Climate-Smart Agriculture and Climate-Smart Villages approaches of FAO and CGIAR. The approach aims to offer simple and affordable solutions for mountain farmers to adapt to ongoing environmental and socio-economic changes and prepare them better for future challenges. Based on vulnerability and risk assessment as well as participatory practices, the project focuses on three overarching goals: climate resilience, socio-economic resilience, and future resilience. Together these goals form a basis for an integrated approach to sustainable development and resilience building in mountain communities.

Resilient mountain villages

In the initial stage of the pilot project in Kavre, baseline studies were conducted in cooperation with district stakeholders and Village Development Committees (VDC) to map out the main concerns and vulnerabilities of communities in the district (see **FIGURE 33**). The assessment studies indicated that drought and storms, coupled with insect and pest attacks, were the main concerns. The study highlighted the fact that the pace of

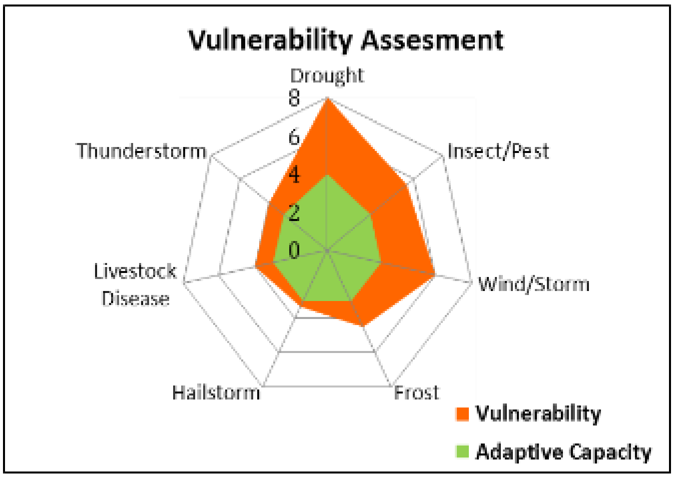

FIGURE 33: Key vulnerabilities identified by the communities in Kavre district

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[23] Case study contributed by Nand Kishor Agrawal, Laxmi Dutt Bhatta, Hanna Lønning Gjerdi (ICIMOD); and Keshab Datta Joshi (CEAPRED).

environmental change in the area was much faster than people's capacity to adapt. The communities also reported the high rate of outmigration as a major challenge: one-third of households had at least one male member migrating for work. This added to the workloads and responsibilities of women, as they were forced to take the lead in farming and household management. For this reason, it became necessary to strengthen and facilitate women's access to knowledge and resources for managing households and farms sustainably.

The pilot activities were developed in consultation with the community and district stakeholders. By applying a modular approach, the pilots used a combination of science and local knowledge to develop technologies and interventions that could be easily taken up by local farmers. Special attention was therefore paid to avoid activities that required large investments and substantial external support, thus reducing the dependence on outside agencies. As a result, the average investment per household for the first two years was less than USD 100.

To address the goals of climate resilience, practices on soil nutrition, cropping patterns, water scarcity and efficient irrigation were initiated. The aim was to reduce risk and increase the adaptive capacity, while at the same time promoting more climate-friendly practices. Farmers were encouraged to use crop rotation, intercropping and mixed cropping, as these have been shown to increase soil fertility and soil moisture. Mulching was also introduced to reduce evapotranspiration from crops during dry seasons. By combining local knowledge with scientific research, *jholmal*, a biopesticide and fertilizer, was further developed and applied to different crops. Before the introduction of *jholmal*, farmers used hazardous fertilizers and pesticides, neither of which was safe for humans or surrounding ecosystems. With the switch to *jholmal* farmers could enjoy both safe crops and an improvement in yield output (see **TABLE 16**).

TABLE 16: Interventions and outcomes related to water management and soil nutrients

Key area of vulnerability	**Key interventions**	**Results**
Water availability	- Water source protection - Household level conservation ponds - Community water storage - Waste water management - 410 plastic ponds at household level - 128 ponds (plastic and soil-cement) at community level. - 52 installations of drip irrigation - Conservation of 16 existing water sources	- Data shows 67.4% increase in cucumber/ bitter gourd output - Twenty-five hectares upland gained increased access to water for irrigation - All participating households manage their own kitchen garden with collection of wastewater at household level
Crop and cropping patterns	- Intercropping - Mixed cropping - Crop rotation - Promoting mulching practices - Varietal selection	- Introduction of direct seeded rice, and System of Rice Intensification (SRI), which requires less irrigation - Three ha of land applied mulching during (dry) summer season
Soil nutrients	- Promoting *Jholmal* - Improved compost management - Intercropping with leguminous crops - Green manure for rice planting	- Increased production output for rice (17.3%), wheat (25.5%), Tori (34.3%) and cauliflower (25%) with the use of *jholmal*, compared with farmers' previous practices
Pests and pathogens	- Irrigation management - *Jholmal* practices	- Production of pesticide free food crops (safe food production) - Reduction in health hazards - Reduced sale of chemical pesticides from the local shop - Increased sale of *jeevatu*, a microbe needed for *jholmal* preparation

In addition, local agro-veterinaries reported a significant decline in sales of chemical pesticides and fertilizers. *Jholmal* also proved more attractive to female participants as a home produced product, giving women both increased knowledge and skills. Local businesses now sell *jholmal*, which has a high take-up rate, not only at the pilot sites, but also in surrounding areas.To further reduce risk and promote good water management practices, the collection of wastewater in ponds lined with plastic or soil-cement was introduced as a means of improving water availability for irrigation. The practice encouraged collection and reuse of water from daily chores, either at household level (capacity: 1 000 to 2 000 litres), or at community level (40 000 litres). In total, 410 plastic-lined ponds were constructed for households, and 128 ponds (lined with plastic and soil-cement) for the communities. Assessment of the changes in water management proved that farmers were able to secure more stable access to water in the dry season and even establish home gardens. For example, during the dry spell of 2016, the use of lined ponds for wastewater collection and the production and application of *jholmal* resulted in substantial change in farmers' productivity, despite water scarcity. Most of the farmers who used water ponds also tested drip irrigation technology to make efficient use of water, which enabled them to grow tomatoes in the off-season.

Sita Neupane, a female farmer in Kavre: *"This year I made NPR 66 400 (USD 650) selling my cucumbers grown on a patch of 375 square meters. And I did it all without using chemicals just by producing and applying jholmal"*

To enhance socio-economic resilience, RMV worked on strengthening supply chains by bringing farmers together to find appropriate markets and providing up-to-date information on prices that would help them make more informed decisions. RMV worked closely with women to provide them with information on climatic changes and to develop their capacities in simple and low-cost sustainable practices. For sustainable institutional mechanisms, RMV also linked women's groups to local authorities to facilitate their engagement with village level planning. Future resilience was promoted through the use of digital services for disaster preparedness, with phone-based meteorological data, which allowed farmers to make more timely and informed decisions. Farmers could access advice on crop and market data through digital services, and linkages were made with insurance companies to further strengthen farmers' resilience.

One of the main challenges for implementation of RMV was smallholder farmers' high vulnerability and, therefore, limited ability to try out new practices due to their constrained resources and options – their risks and vulnerability would increase multiple times if the trials failed. It was therefore pivotal to ensure open dialogue and include the community and local government in the decision-making and planning process. Through these dialogues participating farmers were encouraged to try alternative approaches for safer and more sustainable farming. The exchanges have produced positive results. The activities were also deliberately kept simple and affordable, so as to guarantee that as many farmers as possible could adopt the different activities. As of 2017, 1 212 farmers (82 percent women) have participated in the pilot interventions.

In order to upscale these interventions, involving institutions at local and government level has been critical, and the project is supported by district line agencies and agro-veterinary centres in Nepal. Regular monitoring from high-level authorities, including Nepal's National Planning Commission, has also aided upscaling efforts. As a result, the Government of Nepal has already adopted and included the RMV in its development plan, and currently plans to pilot this approach in 14 districts.

Lessons learned

- Developing ownership of the approach and interventions among a wide range of stakeholders is key to further upscaling.
- Local practices, such as *jholmal* as a substitute for chemical-based fertilizers and pesticides and small ponds at household level to supplement water for irrigation, can prove highly beneficial without requiring large investment. There is a need to integrate people-centric climate resilient practices into long-term development planning, so as to enhance mountain people's resilience.

- New solutions should be affordable, simple and replicable, and they should directly address the communities' specific concerns.
- New practices should not add additional burdens or risks for women, but enable them to participate and play a central role in fostering change without the need of external assistance.
- Inclusion of communities in decision-making from the very start of the process creates stronger community ownership of projects, thereby increasing the likelihood of effective results and wider uptake.

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4.3 How climate-smart agriculture can help preserve the world's second largest hypersaline lake[24]

Introduction

Urmia Lake, situated in northwestern Iran (see **FIGURE 34**), is an important and internationally recognized natural area designated as both a Ramsar site and a UNESCO Biosphere Reserve (Eimanifar and Mohebbi, 2007). The lake is home to many species of reptiles, amphibians, birds and mammals, along with a unique brine shrimp species (Asem *et al.*, 2012). The Urmia Lake basin is also an important agricultural region with a population of around 6 million people. Urmia Basin supports a variety of agricultural production activities, including winter crops such as wheat and barley, summer crops such as sugar beet, perennials such as orchards and alfalfa, and livestock production (Hesami and Amini, 2016). The basin supports the livelihoods of approximately 6.4 million people (UNEP, 2012). It is located in a geopolitically sensitive region, bordering Iraq and Turkey, and is characterized by a linguistically and culturally diverse population with two ethnic

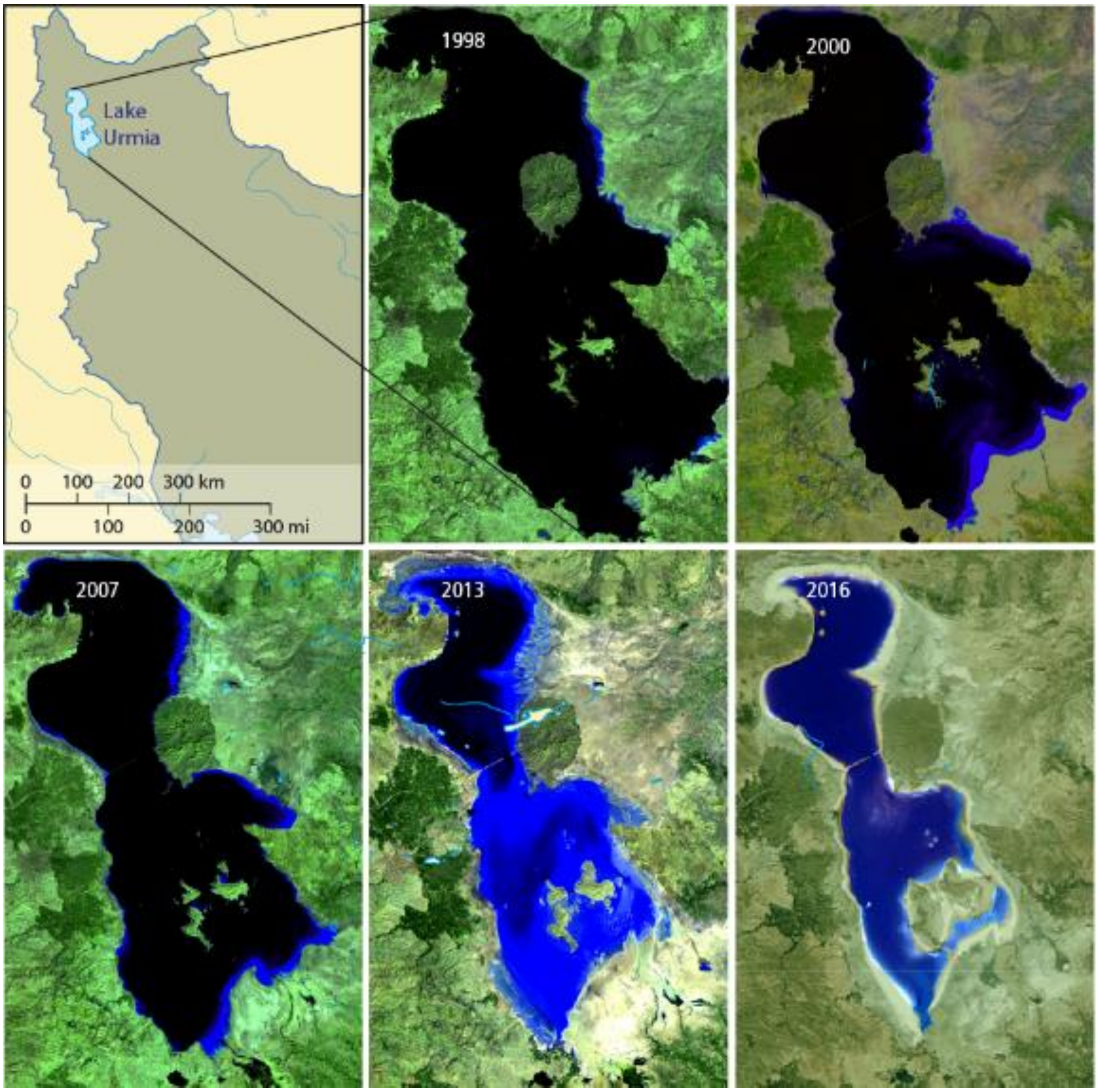

FIGURE 34: Urmia Lake location in Iran and the desiccation trend from 1998 to 2016

Source: USGS, 2016

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[24] Case study contributed by Somayeh Shadkam (IIASA, Wageningen University); Fulco Ludwig and Pieter van Oel (Wageningen University).

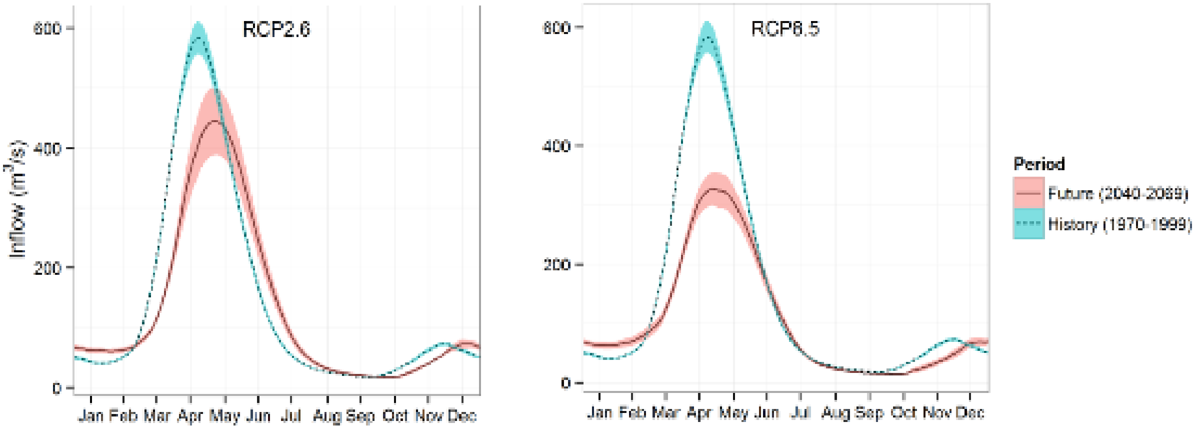

FIGURE 35: Mean annual cycle of projected 30-day moving average of inflow for five GCMs for control period (1971-2000) and future (2040-2069)

Left: low emission scenario (RCP2.6); right: high emission scenario (RCP8.5). The shadows represent the standard error of the mean for all five GCMs.

Source: Shadkam et al., 2016b

groups predominating, the Azeri Turks and the Kurds (Henareh *et al.*, 2014).

The surface area of Urmia Lake has declined dramatically, by 80 percent over the past 20 years (AghaKouchak *et al.*, 2015). As a result, the lake's salinity has increased sharply, which causes significant harm to its ecosystems, agriculture and livelihoods, public health and tourism. Several studies have already warned that the future of Urmia Lake may unfold similarly to that of the Aral Sea. The latter has dried up over several decades, producing windblown salt storms and severely affecting the surrounding population (Torabian, 2015). The population density around Urmia Lake, however, is much greater than that around the Aral Sea, resulting in higher risk (UNEP, 2012). Local reports have already indicated that thousands of people who were formerly living in the lake's vicinity have abandoned the area, either temporarily or permanently. It is believed that people living within a radius of 500 km of the lake – estimated to be approximately 76 million people, including those living in Armenia, Azerbaijan, Iraq, Syria and Turkey – are at risk of health and environmental consequences (Torabian, 2015). Urmia Lake's deteriorating conditions could thus exacerbate economic, political and ethnic tensions in this already volatile region (Henareh *et al.*, 2014). Previous studies have indicated that the lake desiccation is probably caused by a combination of human activities and climate change (AghaKouchak *et al.*, 2015; Fathian *et al.*, 2014; Hamzekhani *et al.*, 2015; Hassanzadeh, 2010; Jalili *et al.*, 2015).

The area of agricultural land has more than tripled over the past 40 years, supported by a considerable number of reservoirs and a large network of canals and pipelines (Iran Ministry of Energy, 2014a). Currently, there are about 510 000 ha of irrigated lands in the basin, with 33 modern and traditional irrigation networks. The reported irrigation efficiency is quite low: 37 percent for farming and 45 percent for gardening (Iran Ministry of Energy, 2014). Agriculture in the basin is highly dependent on irrigation due to the semi-arid climate. To support agricultural growth, the area under irrigation around the lake has increased more than seven times since 1970 (Iran Ministry of Energy, 2014), and 41 small and large reservoirs have been built in the basin since then (Iran Ministry of Energy, 2013).

Climate change and climate variability have also been among the key contributors to the lake's demise, causing about three-fifths of inflow reduction (Shadkam *et al.*, 2016a). The effects of climate change are likely to continue under both the lowest and highest emission scenarios. This is likely to further reduce basin water availability (see **FIGURE 35**) (Shadkam *et al.*, 2016b). Urgent actions are therefore needed to restore and preserve Urmia Lake, resulting in significant reductions in: 1) Consumptive water use of agriculture and other land uses, and 2) GHG emissions.

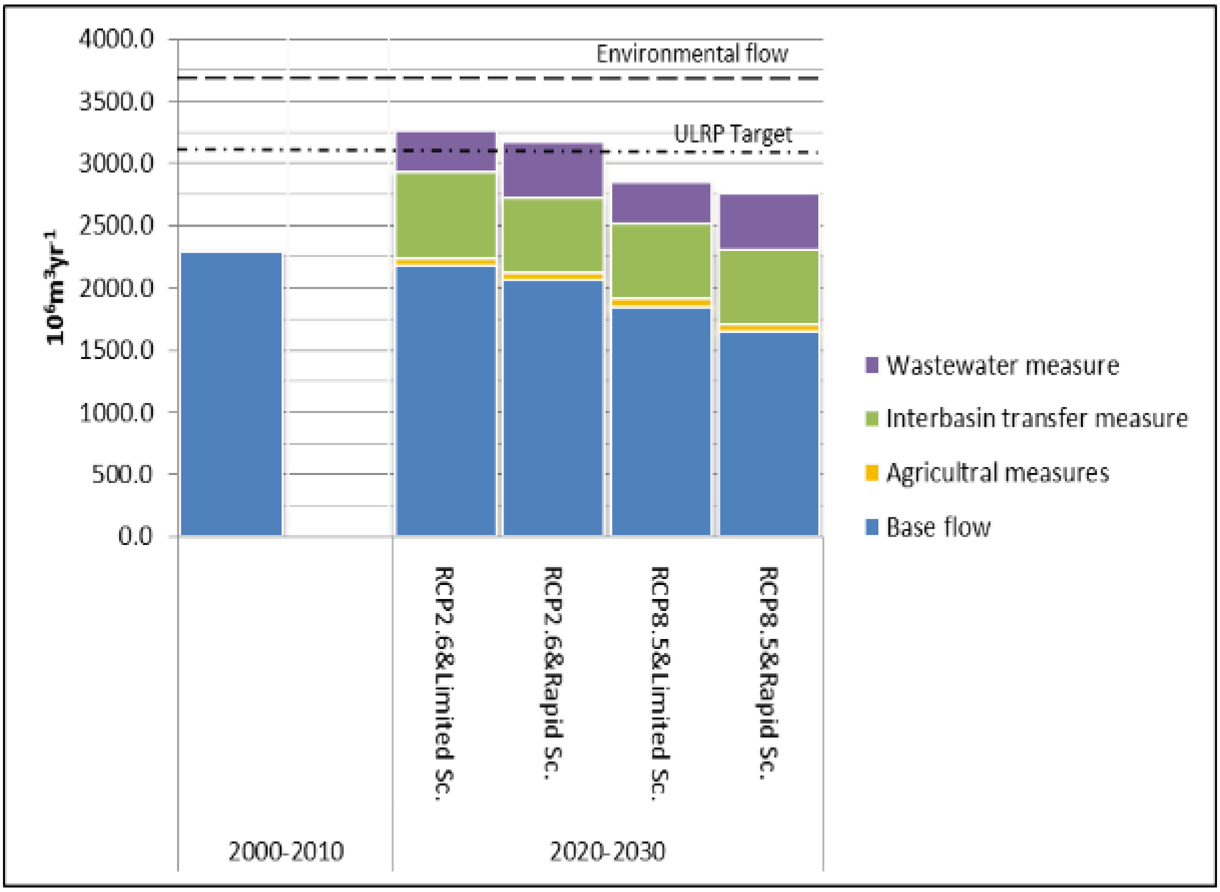

FIGURE 36: Historic inflow to Urmia Lake (2000-2010) and projected inflow under the Urmia Lake Restoration Plan (ULRP) for four different scenarios (2020-2030)

Projections are based on combinations of a low-emission (RCP2.6) and a high-emission (RCP8.5) climate change scenario, and a rapid and a limited socio-economic development scenario. The projections compare the effectiveness of the ULRP measures with the environmental flow of Urmia Lake and the ULRP target.

Source: Shadkam et al., 2016b

Climate-smart agriculture contribution in Urmia Lake Restoration Program

To address the lake's critical situation, the Government of Iran announced a national initiative, the Urmia Lake Restoration Program (ULRP) in July 2013. The Government later approved a budget of USD 5 billion for implementation (The Guardian, 2015). The programme's vision is to revive the life cycle of Urmia Lake and promote integrated water resource management and sustainable agricultural development in the basin. ULRP includes six approaches in terms of controlling, protecting, capacity development, engineering measures and supplying water from other sources, including interbasin transfer and routing wastewater to the lake. The plan pays particular attention to reducing water use by the agricultural sector, while maintaining food security and improving the resilience of farming systems (i.e. CSA pillars 1 and 2, see **Section 1.1.1**). Components of the plan include: deficit irrigation (mostly for wheat and barley), changing cropping patterns (mostly replacing barley with alfalfa), and using greenhouse cultivation for vegetables (ULRP, 2017). The plan also aims to increase irrigation efficiency and unformity by applying sprinkler and drip irrigation. Furthermore, ULRP aims to reduce tillage, improve rangeland management and restore degraded lands, all measures that can contribute to the mitigation of climate change (i.e. CSA pillar 3, see **Section 1.1.1**) (FAO, 2013).

Shadkam (2017) introduced a quantitative framework to assess the *ex ante* and *ex post* ULRP in the basin under different climate change and socio-economic development scenarios. The results showed that although the ULRP has the potential to increase the lake's inflow, it is unlikely that it will fully restore the water levels in the lake. Changes to cropping patterns, in particular, have the potential to reduce consumptive water use, while increased irrigation efficiency would lead to decreased return flows and consequently reduce inflow to the lake. Therefore, the current agricultural measures would probably not have a noticeable impact on the lake's restoration. In addtion, the plan does not take into acount the reduction in water availability. Additional sources of water, namely, interbasin transfer and wastwater, are the most effective measures likely to increase inflow (see **FIGURE 36**). However, these interventions bring with them trade-offs, associated with environmentally unsustainable outcomes. The results of this study also showed that the performance of the proposed interventions is more sensitive to changes in climate, compared with socio-economic changes, and that the ULRP can only help to preserve the lake if future climate change is very limited. Under a more rapid climate change scenario, the ULRP may not be able to reduce consumptive water use sufficiently to preserve the lake and, as a consequence, more drastic measures would be needed. In other words, future water management plans are not robust enough to achieve desired outcomes across a range of climate change scenarios. Therefore, any plan to restore the lake should recognize that mid-course corrections may be needed to account for uncertainty in the rate and severity of climate change.

Conclusion and recommendations

The ULRP focus in attempting to reduce consumptive water use in agriculture does not, as yet, take into account uncertainty in climate change. To prepare for the future, scenarios with reduced inflow into Urmia Lake, either due to climate change or even increased consumptive water use by agriculture, should also be considered. The plan should therefore be upgraded by considering whether it is sufficiently robust to achieve desired outcomes across a wide range of plausible scenarios. It is also recommended that explicit consideration be given to the vulnerability, sensitivity, adaptability and resilience of different agricultural systems in the basin (FAO, 2013), such as fruit trees and annual crops. In addition, the impact of relatively high rainfall on farming systems can vary with the type of system. For example, wheat yields can be much higher during wet than during dry years. This can compensate for the lost yield and income in dry years. Communication systems should be developed for farmers to inform them about seasonal forecasts and the current drought states of the basin. Mobile phone apps or a local radio channel could be developed to inform farmers how to optimize productivity, given the current drought status and seasonal forecasts. This should be accompanied by adaptive management of existing and future water infrastructure (Lim *et al.*, 2005).

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4.4 Improving on-farm water management through irrigation information for climate-smart agriculture in sub-Saharan Africa[25]

In sub-Saharan Africa (SSA), irrigation is promoted for intensified production and increased resilience to climate variability. In Ethiopia specifically, most agricultural land is under low input-low output rainfed cultivation and is highly susceptible to rainfall variability (Haileslassie *et al.*, 2016). Investment in sustainable water solutions has the potential to boost crop yields and household revenues and reduce risks associated with climate variability and change (Giordano *et al.*, 2012).

Sustainable development of irrigation requires sound use of natural resources at plot, scheme and watershed level. Timely and accurate water management can mitigate production and income risks associated with hydrologic variability, as well as soil and water degradation associated with inefficient water use both on-farm and downstream of irrigation hotspots (Gedfew *et al.*, 2017). This requires guiding farmers to more efficient on-farm water management – how much and when to irrigate – with tools that are robust in the field and easy for farmers to use.

The wetting front detector (WFD) and related tools were field tested with farmers in Ethiopia by the International Water Management Institute (IWMI) and partners between 2013 and 2017 to assess the effect of access to irrigation scheduling information on crop yields and income. The study included various scenarios of water lifting and irrigation technologies in different regions, agro-ecological zones and soil conditions, with more than 200 farmers irrigating cereals or vegetables. Measurements were taken on irrigation depth, and crop and water productivity (Schmitter *et al.*, 2016). Results were compared with a control group using well established irrigation methods.

Results from field testing are positive and show potential. The WFD is a feasible approach to supporting farmers in adapting to and mitigating climate variability. In most sites, use of the WFD reduced water consumption while improving or maintaining yield levels. In cases under manual water lifting and application, the WFD helped newly irrigating farmers to double their yields with just a 30 percent increase in irrigation (Tesema *et al.*, 2016). For smallholder farmers using motorized pumps or in a gravitational scheme, water use decreased and yields increased, depending on crop and soil. The average change in water use for farmers using the WFD as a source of information for irrigation, compared with the control group, is presented in **TABLE 17**.

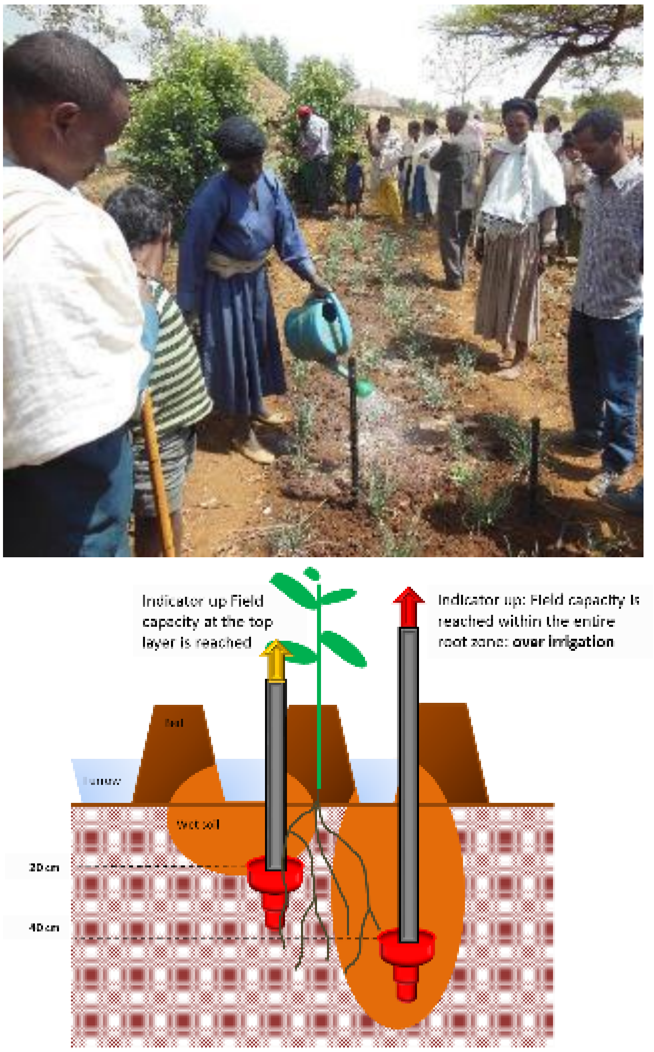

FIGURE 37: Top: Woman farmer in Ethiopia learning to use irrigation scheduling tools. Bottom: Diagram of the wetting front detector in use
Photo credit: IWMI

Source: Schmitter et al, 2017

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[25] Case study Petra Schmitter, Nicole Lefore, Jennie Barron and Meredith Giordano (IWMI).

The more efficient water use following the introduction of the WFD also led to yield increases in most crops, though these were highly dependent on agronomic practices and crops. Yield improvements observed for farmers using wetting front detectors as a source of information for irrigation, compared with the control group, are presented in **TABLE 17**. Moreover, 80 percent of farmers preferred the produce from the WFD plots because of improved quality.

TABLE 17: Decrease in water use and increase in yield obtained for farmers using motorized pumps or within an irrigation scheme

Farmers using irrigation scheduling information provided by the WFD were compared against a control group with no irrigation scheduling information (depicted in % difference).

Crop	Decrease in water use	Yield increase
Onion	16 – 26%	4 – 21%
Potato	19 – 43%	5 – 17%
Tomato	21%	14%
Pepper	22 – 28%	14 – 75%
Wheat	44%	-3%
Cabbage	5%	13%

With the WFD, farmer incomes improved as a result of yield gains coupled with a reduced number of irrigation events, which in turn reduced input costs for labour, fuel and fertilizer. **FIGURE 38** shows the trend in increased profit when smallholder farmers used the WFD as they irrigated less, translating directly to reduced irrigation costs and improved yields. **FIGURE 39** shows the variability in profit for three different irrigation information groups: Control (no information access), Time Domain Reflectometry (TDR for information on soil moisture), and WFD. The variability in profit is strongly correlated to the effect of the irrigation quantity on yield, and is proportional to the associated irrigation labour.

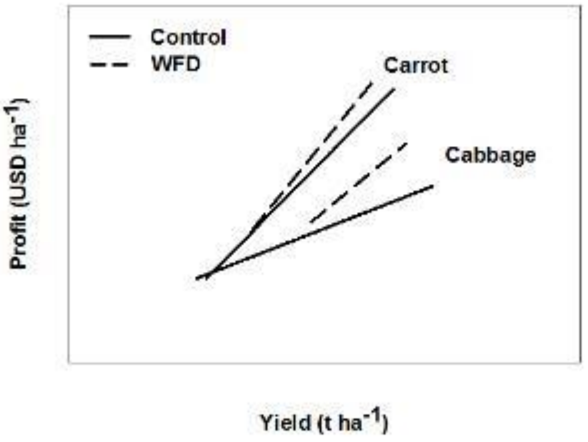

FIGURE 38: Trend in profit and yield for different levels of farmer information on irrigation on farms using manual water lifting technologies

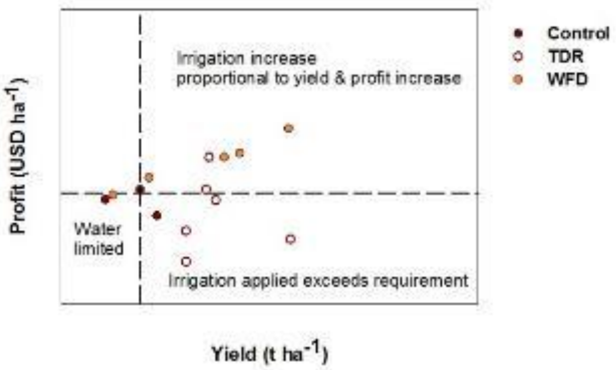

FIGURE 39: Variability in profit for different levels of farmer information on irrigation on farms using manual water lifting technologies

The study found that use of WFDs by water user associations in an irrigation scheme saved a volume of water sufficient to increase irrigated area by 33 percent in the case of onions, and 75 percent for potatoes – equivalent to 2 to 5 percent of the entire irrigated land and 1 to 5 percent of the designed command area in the scheme (Banteamlak *et al.*, 2017).

Farmers benefit from the improved productivity and incomes, as well as from strengthened information about water use. The tools complement and extend existing indigenous understanding about on-farm water management. The efficient use of irrigation water further improved in the second year, as farmers learned more about irrigation and using the tools. The improved access to information on crop water application and sharing of irrigation information within irrigation systems can improve water resources management at community level and larger scales. For these reasons, the tools can make a positive contribution to overall natural resources management – leading to more climate-smart and resilient agricultural systems.

Scaling use of simple tools for irrigation management could improve efficiency with substantial gains for economic and

environmental sustainability. Smallholder irrigation is developing quickly in sub-Saharan Africa, creating a need for increased water efficiency. Motorized pumps in SSA could benefit 185 million people, extend irrigated area to nearly 30 million ha and generate revenues of USD 22 billion a year (Xie *et al.*, 2014), but this will require climate-smart management of water in farmers' fields. The introduction of the WFD and similar tools could reduce fuel costs by USD 1.5 to 4.4 billion, and save 3 to 29 billion m^3 of water per year (Schmitter *et al.*, 2017).

The promotion of climate-smart agricultural techniques, such as water lifting and related agricultural water management technologies should include appropriate tools and technical advice on irrigation scheduling. The inclusion of on-farm water management support can help to better manage overall water demand and support sustainability of natural resources. Becoming more climate-smart and resilient requires targeting not only the technologies, but also the supporting management tools appropriate to the agro-ecological context. As this study suggests, the extent of benefits gained from irrigation scheduling tools depends on water availability, method of water lifting and application, crop and soil type, and land size. For larger scale impact, we will need to identify ways to link technologies to ICT/SMS services and bigger data apps to transfer knowledge, outreach and advice, so as to effectively scale resilience through climate-smart agriculture.

Acknowledgement

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4.5 Citizen science in Andean agroforestry systems[26]

Mollesnejta, a non-governmental, privately-run experimental farm for Andean agroforestry systems, is located in Cochabamba Valley in the Eastern Bolivian Andes on the slopes of the Tunari massive between 2 750 and 2 850 m above sea level (a.s.l.). The climate is semi-arid with about 500 mm of precipitation per year, mainly received in the months of January and February. There is usually no rainfall in the period from May to October.

The farm was established on former pastureland, degraded by overgrazing (see **FIGURE 40**). On an area of 16 ha, the farm maintains 39 agroforestry systems with different species combinations. These plant associations consist of 30 to 50 percent companion plants, i.e. endemic or other plants that provide benefits for the crop plants, such as nitrogen fixation (e.g. *Acacia visco*), control insect pests (e.g. *Zanthoxylum coco*), and improve nectar sources for pollinators and other beneficial insects (e.g. *Tipuana tipu*).

The main vegetation growth period, when water is most needed by the crops, occurs during the period 21 June to 21 December. At *Mollesnejta*, however, rainfall events that provide sufficient amounts of water for agricultural production only begin in January. It is therefore important to ensure sufficient water holding capacity of soils that can store and conserve rainwater until the next main vegetation growth period. For this purpose, a set of soil moisture conservation practices are being piloted and demonstrated on the farm:

- Mulching: Due to the high percentage of companion plants, the agroforestry systems must be pruned regularly to ensure that the fruit and annual crops receive sufficient light. The prunings are shredded, either with loppers or a chopper and spread on top of the soil around the base of trees and along the rows of companion crops. With a mulch layer of 5 cm thickness, a practical lesson learned is that irrigation water applied can be reduced by one-third compared with water applied to unmulched companion plants and agroforestry systems.
- Addition of organic material to topsoil and planting pits: Tree prunings are shredded (up to a maximum diameter of 7 cm) and added to the topsoil or planting pits, especially for fruit tree crops. The shredded wood improves infiltration rates and soil moisture storage. Under the semi-arid conditions at *Mollesnejta*, significant improvements can be achieved by adding a 10-litre bucket of shredded wood to every square meter of cropland, mixing it lightly into the upper five centimeters of the soil.
- The addition of activated charcoal[27] to topsoil and planting pits: Thicker prunings that cannot be handled by the shredder are

FIGURE 40: View of terrain on *Mollesnejta* experimental farm before establishment of agroforestry plots in 2000 (left) and after in 2006 (right)

Photo credit: Noemi Stadler-Kaulich

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[26] Case study contributed by Noemi Stadler-Kaulich (*Mollesnejta* Center of Andean Agroforestry)

[27] Charcoal *per se* improves the structure and water holding capacity of a soil. In order to achieve a positive effect on

transformed to charcoal in a charcoal kiln. Charcoal has a high water holding capacity and is added to the topsoil or to the substrate used in planting pits. Charcoal in itself is pH-neutral, but the traces of ash it contains make it slightly alkaline. This can benefit the soil by preventing acidic conditions caused by humic acids that form during decomposition of other organic material.

- Shading: The simplest measure for soil moisture conservation is shading of the cropped area with tree species that are tolerant to pruning, fast-growing and, in addition, positively impact the crop plants through leave fall, root growth, nitrogen fixation or insect control. In addition to their shading effect, some tree species, including native species such as Peruvian pepper (*Schinus molle*), were shown to produce significantly elevated soil moisture levels in their vicinity during the dry season (Bolaños *et al.*, 2014).

FIGURE 41: Unirrigated apple tree bearing fruit
Photo credit: Noemi Stadler-Kaulich

The combination of these measures has contributed to the establishment of a productive agro-ecosystem on previously sparsely vegetated land (see **FIGURE 40**) with limited irrigation. Due to the increased infiltration rate of the soil surface, the cooler microclimate and the enhanced retention of soil moisture, the amount of irrigation water applied to vegetables could be reduced by 30 to 50 percent, compared with unshaded plots without soil moisture conservation. Also, it was found that fruit tree crops only needed irrigation in the year of planting. Thereafter – in years of regular rainfall – fruiting was successful without further irrigation, as illustrated in **FIGURE 41**. Irrigation is predominantly carried out by hand with a bucket or watering can. While this is labour intensive, a positive benefit is that plants and trees are assessed regularly, and issues such as excessive competition by companion plants, plant health, and infestation by pest insects are detected and resolved.

Another benefit of the agroforestry system is its potential for climate change mitigation. Through the high density of trees and the incorporation of organic material in the soil, the plots store considerably more organic carbon than the surrounding degraded and sparsely vegetated hillsides of the valley.

While this agroforestry system evidently requires less direct input of irrigation water at farm level, and may also increase the groundwater recharge locally through increased infiltration of rainwater, it should be noted that no systematic measurements of the total consumptive water use of the system were taken. It is therefore not possible to assess its impact on the water balance at the scale of the watershed or river basin, and potential effects on downstream water availability if the practice is upscaled in the area. Such an assessment could be the subject of future research activities on the experimental station, which is currently trying to develop closer collaboration with research institutions.

Agricultural production in the area around *Mollesnejta* is not yet constrained by poor water availability, and the interest of local farmers in the agroforestry and moisture conservation practices is limited. The traditional tree and bush rows made up of native species surrounding fields are disappearing, as they hamper the use of tractors for ploughing. Also, fruit trees are usually not pruned. However, smallholder farmers from more water constrained areas in Bolivia and neighbouring countries are showing interest in the farming and agroforestry systems being piloted at *Mollesnejta*. Therefore, an assessment of its

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soil fertility, charcoal should be 'activated', i.e. charged with nutrients, through treatment with compost, manure or similar before application to the soil.

effects on the water balance at watershed scale would be an important next step.

A broader lesson learned from *Mollesnejta* is that privately funded citizen science can play an important role in piloting improved natural resource management practices (Buytaert *et al.*, 2014). This can be achieved in part through opportunities created by combining and integrating the experience and local knowledge of committed practitioners with outputs from formal publicly funded scientific research. Looking forward, close collaboration between research institutions and citizen scientists will help the latter to apply systematic approaches and formalize their knowledge and observations and, eventually, support the identification and testing of climate-smart practices for agriculture and natural resources management.

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4.6 IMA's experience in Llullucha: Gender and Integrated Water Resource Management (IWRM) to mitigate the impacts of climate change[28]

This case study depicts how indigenous women and men from the community of Llullucha in Cusco-Peru have adapted to a water shortage problem caused by climate change and changes of land use patterns. This community is located on the oriental Southern Andes of Peru, in a very steep valley of the watershed of Quencomayo, between 3 025 and 3 800 m a.s.l. and 1.5 km from Paucartambo (the main administrative and commercial centre). Up until the 1990s, people from Llullucha (who identify themselves as *comuneros*[29]) mainly worked with extensive livestock and rainfed agriculture (barley, potatoes and wheat), which was complemented by small areas of (gravity) irrigated crops. However, due to recurrent erratic rainfall – caused (in part) by the combined effect of the El Niño and La Niña phenomena[30] – the *comuneros* started to experience continuous water stress, which forced them to search for alternative solutions to assure their food production. Due to climate change, El Niño is becoming a frequent phenomenon in Peru, and has negative lasting impacts on local people's livelihoods, with the poor and women being the worst affected. Until 2010, and after a prolonged occurrence during 1982-83, El Niño made itself felt to a moderate degree in 1987, 1992, 2002-2003, and 2004-2005. During 1997-1998 and 2009-2010, it had devastating effects (Zanabria *et al.* 2012, SENAMHI 2014).

In 1990, IMA (*Instituto de Agua y Medio Ambiente*), a special programme of the Peruvian Government started to make a situational diagnosis of different communities in the watershed of Quencomayo. At first, IMA engineers identified soil erosion as a key obstacle to achieving improved crop production. Soil was degraded because of overgrazing, deforestation and sloping agriculture, and – coupled with intense erratic rainfalls – was highly susceptible to erosion, leading to the loss of topsoil, nutrients and vegetation. For this reason, engineers convinced local men *comuneros* to develop different soil conservation activities in an effort to improve the capacity of local soils to retain water from rainfall and recover its natural vegetation. In this way, the *comuneros* from Llullucha started to build infiltration trenches on steep surrounding hills and terraces on the farmland, which was complemented with forestry. The *comuneros* were not convinced by soil conservation methods, especially those developed on the surrounding hills, far from their farmland. They only began to implement them reluctantly, delaying the advance of planned activities.

Given IMA's requirement to show the project results to its funding agencies, in 1992 it added economic incentives, and paid *comuneros* who were willing to apply soil conservation practices on their land. In response, the *comuneros* started working immediately and finished their work in just three months – nine less than originally planned. After two years of work, the *comuneros* convinced the engineers to tackle their real problem, namely water scarcity. Two natural springs barely provided enough water to the community, and farmers were constantly fighting each other for water to irrigate their land. Due to the lack of water, very little agriculture was possible. The women had to walk considerable distances to fetch water for

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[28] Case study contributed by Juana Vera Delgado (Gender and Water Alliance); adapted from Vera-Delgado (2005)

[29] *Comuneros* are peasants registered in the official communal records and have the right to use communal assets (land, water, pasture, trees, etc.) to make their livelihoods possible. They are usually united by a sense of collective identity rooted in culture and elements of the surrounding natural environment. In Andean communities, water management, as any other local livelihood activity, is the result of a collective discussion and decision-making process, and women are usually granted rights to participate in this process. In most Andean communities, the community-based institutions are more relevant than state-centered institutions (see also Boelens, 2009).

[30] As it is well known, in Peru the 'El Niño' phenomenon causes drought conditions in the Andes (especially in the southern part) and abundant rainfall in the northern coastal region (see also Vaule, 2013), while 'La Niña' produces an inverted effect in comparison with 'El Niño'. The frequency of occurrence of 'El Niño', coupled with the increase of average temperature (see also Zanabria *et al.* 2012) has exacerbated the water availability problems of tropical Andes since the 1990s, not only due to erratic rainfall, but also because of the deglaciation phenomenon.

their daily household needs, as well as to water their livestock. Most men *comuneros* were forced to migrate to surrounding villages or cities looking for supplementary income, while women stayed behind to look after the family and livestock. Some girls also migrated to work as domestic servants in the cities.

By the end of 1992, acting on the *comuneros'* concerns, IMA decided to carry out a participatory diagnosis of the water problem in Llullucha. The IMA engineers were surprised by the results. They discovered that the *comuneros* were not convinced of the benefits of the soil conservation practices, as they still faced water scarcity problems. As a result, a participatory proposal was designed to increase the water availability by optimizing the water supply from nearby springs via construction of a reservoir. To maximize its use and efficiency, a sprinkler irrigation system was installed and water was piped to the fields. To implement this project, IMA established new incentives and urged the *comuneros* to continue with the soil conservation practices. Men in the community were very active during the process of consultations and discussions, and later during project implementation. Women were not invited to these 'participatory' discussions. Once construction began on the reservoir, and the pipes were laid to bring water to the fields, the women of Llullucha started to express their concern, because the project was preventing water from reaching the waterholes they customarily used for domestic purposes and for their animals. This conflict of interest between the project and women's needs for water required immediate attention, and had to be solved before the irrigation project could continue.

The women's observations forced the engineers to redefine their project design, which now included a watering place for cattle and a drinking water system installed close to the homesteads. Lessons learned from this experience encouraged IMA to change its policy in tackling climate change impacts in rural communities. Henceforth, water problems would be approached from an Integrated Water Resource Management (IWRM)[31] perspective, and gender would be taken into account. A gender-sensitive IWRM approach allows the different water needs of women and men to be addressed and accommodated: agriculture, livestock, consumption and the environment.

After five years of intervention, women and men in Llullucha started to notice the first effects of the soil conservation practices and new irrigation. Natural vegetation in the surrounding environment of the infiltration trenches started to recover, and water charge in the springs started to increase, making it possible to irrigate more land. The community saw the need to create a water user organization, not just to manage the increasing need for irrigation, but also to democratize participation. In addition, people were able to diversify their crops, as they started to grow maize, vegetables and forage, and raise poultry, guinea pigs and rabbits. This contributed to improving the quality of their nutrition, while also generating income. Women and men from Llullucha began to sell their agricultural products in the nearby market, something that they could not even have imagined five years earlier. This success was a source of pride for the *comuneros*, who now found themselves being invited as trainers by other communities. Therefore, participatory development of irrigation, soil conservation and mixed farming not only contributed to increasing the resilience and adaptive capacity of local women and men of Llullucha, it also helped to empower them and make them more knowledgeable.

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[31] IWRM is used here as a 'boundary term' rather than a 'nirvana term' (Mehta *et al.* 2016), indicating that implementation of the IWRM concept/idea is shaped by main stakeholders' (NGO and donors) discourse/agenda and local women's and men's *comuneros* needs, as well as customary local institutions. In Peru, IWRM was first appropriated and implemented by NGOs and later by State-led water professionals. This facilitated the translation and adoption of the IWRM concept into practice as a 'boundary term', in contrast with the experience of South African countries (van Koppen 2014), where IWRM was adopted by the State as a blueprint approach.

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GLOSSARY

Actual yield reflects the current state of soils and climate, average skills of farmers, and their typical use of technology.

Adaptation (to climate change): Adjustments to current or expected climate variability and changing average climate conditions. This can serve to moderate harm and exploit beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory and reactive adaptation, private and public adaptation, and autonomous and planned adaptation (FAO, 2013a).

Attainable crop yield is the best yield achieved through skilful use of the best available technology. Some studies use attainable yield as an approximation to either potential crop yield or water-limited crop yield (Hall *et al.*, 2013).

Bowen ratio is the ratio of the sensible heat flux to the latent heat flux. In meteorology and hydrology, the Bowen ratio is used to describe the type of heat transfer in the atmosphere. Sensible heat is related to changes in temperature of a gas or object with no change in phase. Latent heat is related to changes in phase between liquids, gases, and solids.

Climate forcing (also known as *radiative forcing*) results from imbalances in the Earth's energy budget resulting from: increases in greenhouse gases and particles in the atmosphere, and/or changes in the nature of the Earth's surface.

Climate-smart agriculture (CSA): Agriculture that sustainably increases productivity, resilience (adaptation), reduces/removes greenhouse gases (mitigation), and enhances the achievement of national food security and development goals (FAO, 2013a).

Conservation agriculture (CA) is an approach to managing agro-ecosystems for improved and sustained productivity, increased profits and food security, while preserving and enhancing the resource base and the environment. It is characterized by three linked principles, namely, continuous minimum mechanical soil disturbance; permanent organic soil cover; and diversification of crop species grown in sequences and/or associations (FAO, 2013a).

Data mining is the process of accessing and searching online databases for information that may be of value, for example, during a water accounting and auditing process (Batchelor *et al.*, 2017).

Emissions cap limits the maximum amount of greenhouse gas emissions a country or company is allowed to produce during a certain period of time.

Energy efficiency links the energy output to the energy input, meaning that a system, appliance or activity is more energy efficient than another system, appliance or activity if it delivers the same service for less energy input. Common examples for energy efficient devices are energy-saving light bulbs that produce the same amount of light as conventional light bulbs but use less energy.

Emissions trading or cap and trade is a government mandated, market-based approach to controlling pollution by providing economic incentives for achieving reductions in the emissions of pollutants. Various countries, states and groups of companies have adopted such trading systems, notably for mitigating climate change. Under the established system, the 'cap and trade system', an emissions cap limits the maximum amount of certain greenhouse gas emissions, measured in tonnes, that companies may emit during a certain period of time. Emissions trading systems can create incentives to reduce emissions.

Equity is the degree to which different individuals or groups within a community or society at large benefit from a good or service. Taking an equity-based approach means paying special attention to the specific needs of the most marginalized members of society who may otherwise be excluded from the benefits of a good or service. Note that equitable access to a good or service is not necessarily the same as equal access.

Food security is a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life (FAO, 2006a).

Gender relates to the different roles played by men and women, boys and girls. A gender-based approach means dealing explicitly with these differences. Often, it also implies an element of empowerment of women. Gender is often bundled with equity (see above), with which it is closely related.

Gender mainstreaming ensures that gender inequities are considered during stakeholder dialogue and decision-making processes.

Governance is defined as follows in the frequently cited: "The exercise of political, economic and administrative authority in the management of a country's affairs at all levels. Governance comprises the complex mechanisms, processes, and institutions through which citizens and groups articulate their interests, mediate their differences, and exercise their legal rights and obligations" (UNDP 1997).

Institutions include the rules, norms and conventions governing human interaction. Institutions may be formal in the sense of constitutional rules, codified laws and bureaucratic rulebooks, or informal in the sense of social and cultural norms.

Institutional level refers to the tiers of political and administrative decision-making on a scale that runs from local level to national and international levels. In administrative terms, local level is usually considered to be the level of small towns, villages and below, whereas intermediate level is considered to be district and governorate level.

Impacts: Effects on natural and human systems. Impacts generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system. Impacts are also referred to as consequences and outcomes. The impacts of climate change on geophysical systems, including floods, droughts and sea-level rise, are a subset of impacts called physical impacts.

Irrigation efficiency: Generically, 'water efficiency' is a dimensionless ratio that can be calculated at any scale and used for different classes of water supply and use (e.g. an interbasin transfer system, a town water supply network). In the agricultural sector, it is referred to as irrigation efficiency (IE) and is used to assess and monitor system losses that can be classified as non-beneficial water use fractions that may be non-recoverable (e.g. evaporation from a canal) or recoverable (e.g. seepage from unlined canals). In the CSI context, IE is defined as the ratio of the volume of water beneficially consumed (e.g. as evapotranspiration or possibly as leaching to prevent soil salinization) and the total water applied. However, it should be noted that other formulae can be used to calculate IE, and IE estimates are less comparable than sometimes implied because they are scale dependent, both in time and space – this hampers comparison of IE values, across scales, time frames and localities (Van Halsema and Vincent, 2012).

Irrigation hardware refers to the infrastructure for: pumping, diverting, storing, treating and conveying water to irrigation schemes; scheduling and applying water to crops; cultivating and harvesting crops; and a wide range of post-harvest "crop to shop" activities.

Irrigation software refers to policies, institutions, governance and management systems that are central to planning, operating, and managing irrigation hardware. Irrigation software also refers to a wide range of factors that influence the sustainability of water sources used for irrigation and the performance of irrigation systems and their value chains e.g. land and water tenure; farmer know-how; gender sensitivity; and, effective marketing and financial systems.

Maladaptation is the adverse outcome of adaptation efforts that inadvertently increases vulnerability to climate change. Action that undermines the future ability to adapt by removing opportunities and hampering flexibility is also maladaptive (modified from IPCC, 2012).

No or low-regret options are solutions to specific challenges that are valid whether climate change occurs as expected, or not. In the CSI context, they are aimed at increasing the resilience of irrigated cropping systems and value chains and reducing their vulnerability to climate change and other risks.

Potential crop yield is the yield of a crop cultivar "*when grown in environments to which* *it is adapted; with nutrients and water non limiting; and with pests, diseases, weeds, lodging, and other stresses effectively controlled*" (Evans and Fischer 1999).

Resilience: The ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner (FAO, 2013a).

Scenarios: An enabling tool that can combine both diverse knowledge and potential futures in a way that allows the evaluation and assessment of a number of possible options.

Service delivery approach: FAO recognizes that the primary goal of the operation of an irrigation system is ‶*to convey and deliver irrigation water to users according to an agreed level of service that is well adapted to their requirements for water use and cropping systems*″ (Renault *et al.*, 2007).

Threshold: The level of system change or impact that prompts or merits a changed response. In terms of management, jurisprudence, legislative requirement and performance, targets are often applied at critical control points within a system.

Trade-off, in economic terms, is what must be given up, and what is gained, when an economic decision is made. Although the terms trade-off and externality are often interchanged, the main difference is that a trade-off is an intended loss or negative impact, whereas an externality is unintended.

Water accounting is the systematic study of the current status and future trends in water supply, demand, accessibility and use within specified spatial and temporal domains. The concept of water accounting is based on the argument that knowledge of the current status of water resources and trends in demand and use is a precondition for successful water management.

Water auditing goes one step further than water accounting by placing trends in water supply, demand, accessibility and use in the broader context of governance, institutions, public and private expenditure, legislation and the wider political economy of water of specified domains.

Water governance, at its simplest, relates to ‘who gets what water, when and how’ (Tropp, 2005). The Global Water Partnership’s broad definition of water governance provides a similar, if less snappy definition: *“the range of political, social, economic and administrative systems that are in place to develop and manage water resources, and the delivery of water services, at different levels of society”* (Rogers and Hall, 2003).

Water management refers to planned development, allocations, distribution and use/reuse of water resources, in accordance with predetermined objectives, and with respect to both quantity and quality of the water resources.

Water-limited crop yield is similar to potential crop yield, except that yield is also limited by water supply, and hence influenced by soil type (water holding capacity and rooting depth) and field topography.

Water productivity is the ratio of net benefits and the volume of water consumed when producing these benefits. In the CSI context, water productivity is defined as the ratio of agricultural output to the volume of water consumed – ‶more crop per drop″ (e.g. kg of product per cubic metre of water), and economic water productivity is defined as the monetary value generated from each unit of water consumed – ‘more cash per splash’ (e.g. USD per cubic metre of water). It is important to note that other formulae can be used when calculating water productivity, and there are potential pitfalls or challenges associated with economic water productivity analysis (van Halsema and Vincent, 2012).

Water scarcity is defined here as an imbalance between supply and demand of freshwater in a specified domain (e.g. country, region, catchment, river basin, etc.) (FAO, 2012a).