Water-Smart Agriculture

A biophysical-focused introduction: addressing needs and opportunities in developing nations

UC DAVIS
GLOBAL ENGAGEMENT
College of Agricultural and Environmental Sciences

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Cover Photo: Protected sloping hill-land agriculture in Rwanda water-smart agriculture promotion Photo by: Kueneman 2016

Disclaimer

This paper does not necessarily reflect the opinions of the University of California, Davis or the Inter-American Institute for Agriculture, but draws on literature and the authors' opinions, based on decades of experience in international research and development on agriculture systems and food production.

ABBREVIATIONS AND ACRONYMS

ACIAR	Australian Centre for International Agricultural Research
Ag-GB	Agricultural Groundwater Banking
AIARD	Association for International Agriculture & Rural Development
ARS	Agronomy Research Station
BMGF	The Bill and Melinda Gates Foundation
BNF	Biological Nitrogen Fixation
BNS	Balanced Nutrient Systems
CA	Conservation Agriculture
CARE	Cooperative for Assistance and Relief Everywhere
CCAFS	CGIAR Research Program on Climate Change, Agriculture and Food Security
CGIAR	Consultative Group for International Agricultural Research
CI	Cropping Intensity
CIMIS	California Irrigation Management Information System
CIMMYT	International Maize and Wheat Improvement Center
CIRAD	French Agricultural Research Centre for International Development
CSA	Climate Smart Agriculture
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSISA	Cereal Systems Intensification South Asia
E	Evaporation
ECHO	Educational Concerns for Haiti Organization
EFMA	European Fertilizer Manufacturers' Association
EGP	Eastern Gangetic Plain
EMBPAPA	Brazilian Agricultural Research Corporation
EPA	United States Environmental Protection Agency
ET	Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
FBMP	Fertilizer Best Management Practices
FC	Field Capacity
FEW	Food-Water-Energy Nexus
FFS	Farmer Field Schools
FtF	USAID Feed the Future Program
GHG	Greenhouse Gas
g/l	Gram per liter
ICT	Information Communication Technologies (including social media)
IFA	International Fertilizer Association
IFAD	International Fund for Agricultural Development
IFDC	International Fertilizer Development Center
IFPRI	International Food Policy Research Institute
IGP	Indo-Gangetic Plain
IITA	International Institute of Tropical Agriculture
ILRI	International Livestock Research Institute
IPM	Integrated Pest Management
IPO	International Programs Office, University of California, Davis
IRRI	International Rice Research Institute
ITPS	Intergovernmental Technical Panel on Soils, FAO
IWMI	International Water Management Institute
LAC	Latin America and the Caribbean
LFTPT	Lay Flat Thin Wall Polythene Tubing

LGI	The Land Grant Institutions
LR	Leeching Requirement
MAS	Marker-assisted Selection
MDG	Millennium Development Goals
Mha	Million Hectares
NARES	National Agricultural Research and Extension System
NGO	Non-governmental Organization
NRCS	Natural Resource and Conservation Service, USA
OM	Organic matter
PGPR	Plant growth-promoting rhizobacteria
PUE	Precipitation Use Efficiency
QTL	Quantitative Trait Loci
RDI	Regulated Deficit Irrigation
SALT	Sloping Agriculture Land Technology
SDG	Sustainable Development Goals (United Nations)
SI	Sustainable Intensification
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SSA	Sub-Saharan Africa
T	Transpiration
TFP	Total Factor Productivity
UCD	University of California, Davis
UDP	Urea Deep Placement
UN	United Nations
USAID	United States Agency for International Development
VRI	Variable Rate Irrigation
WaSA	Water-Smart Agriculture
WASH	Water Sanitation and Hygiene
WP	Wilting Point
WLE	CGIAR Research Program on Water, Land and Ecosystems
WUE	Water Use Efficiency
WWW	World Wide Web
ZT	Zero Tillage

FOREWORD FROM IICA

The agriculture sector in the Americas is facing many water-related risks. For instance, major droughts in Chile and diminishing surface and ground water reserves in the United States and the Caribbean Islands, have negatively affected agricultural production. Floods in Paraguay have also caused extensive damage to the sector, while food production from rain fed agriculture in Central America suffers from increasingly unpredictable precipitation patterns. Unfortunately, the frequency and intensity of water-related extreme events, such as floods, droughts, and climate variability are projected to increase under future climate scenarios. Water resource quantity and quality are affected by changes in the patterns, intensity and volumes of precipitation, nutrient laden-runoff, river flows and soil water retention. Coupled with these changes, farmers in the Americas will face increasing competition for water from non-agricultural users due to increasing water demand for the energy and industry sectors, often linked to rising urban population density and growth. Such challenges underscore that managing interactions between climate change, water and agricultural risks for sustainable food production is complex and challenging, requiring locally contextualized solutions, especially at the farm level.

Without water, there would be no agriculture, and thus no food for the world´s burgeoning population. As water is the primary vehicle through which climate change impacts are transmitted to the agriculture sector, responses to this risk require a focus on hydrological resources. As the largest water user, responsible for approximately 70% of freshwater use globally, agriculture also affects water quality, via agricultural fertilizer runoff, pesticide use and livestock effluents. Together with the increasing impacts of climate change, this in turn undermines the productivity of rain-fed and irrigated agriculture, which then impacts markets, trade, and broader food and nutrition security issues. There is thus a need for urgent and strategic action on agricultural water management along the value chain, in combination with policy changes that consider the context of climate change. Such policies and actions should identify and prioritize adaptation strategies for agricultural water management, such water smart agriculture, as a prerequisite for building resilient farms and food systems.

It is within this context that IICA, through its programs that promote a more competitive, low carbon, sustainable and inclusive agriculture sector at the hemispheric level, has provided technical cooperation to its member countries to strengthen policies, plans and actions related to the management of climate change and natural resources in agriculture. These actions have focused on promoting and supporting water resource smart systems, technologies and innovations that facilitate the development of economically viable and sustainable agriculture. In this sense, IICA has served as an effective broker for advancing the dialogue among farmers, the private sector, and policy makers and community leaders who have interpreted improving water productivity differently - as “more crop for the drop”, “more dollars for the drop” or “more jobs for the drop”. Through this role, IICA has emphasized that the resilience of agricultural systems to climate change requires an inter-disciplinary approach that balances the needs and priorities of different actors and sectors.

This publication represents a continuation of IICA’s previous commitments and efforts to consolidate and strategically leverage its expertise and partnerships to improve water management in agriculture at multiple levels. Specifically, it represents an advancement from the policy-problem focus of previous series publications on water for agriculture (Water for Agriculture in the Americas, Water Smart Agriculture- Brief) to solution-based approaches at the field level. As this book emphasizes, water smart agriculture and soil management are critical pillars of climate smart agriculture, fundamental for addressing the negative impacts of climate change on smallholder and other farmers. All of us working in the agriculture sector have a great responsibility in using this precious resource efficiently so that we can continue to produce sufficient quantities of nutritious food to feed the world under a changing climate.

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Headquarters,
San José, Costa Rica July, 2020

FOREWORD

As the world's population continues to grow, with projections indicating that it will increase by an additional billion over the next 10-15 years, surpassing 9 billion by 2050, food demand is expected to increase disproportionally, as the global per capita income will demand more diverse diets, and particularly, more animal-based food. Business-as-usual projections suggest that this growth may double fresh-water needs, particularly in the fastest growing regions of the world. However, even today there is already a huge imbalance between water demand and availability, with almost half of the world's population suffering from water scarcity.

Water scarcity cuts across all three components of water security: water availability, water accessibility and water use. Specifically, about 20% of people today are affected by physical water scarcity, as withdrawals currently exceed sustainable limits. It is estimated that one quarter of the world lives in economic water scarcity conditions, because of limited access to water even when it is available. Moreover, in situations where water is available and accessible, unsustainable use that creates problems in water quality and human health may further diminish its ability to fulfill its main purpose. A UN report predicts that by 2025, 1.8 billion people will be living in countries with absolute water scarcity. Although society has struggled with the competing demands of a water-limited world for decades, continued population growth and the consequent increased need for nutritious food, coupled with a changing climate, will create even greater challenges for our society to find sustainable solutions. A World Bank report published in May 2016 suggests that water scarcity, exacerbated by climate change, could cost some regions up to 6% of their GDP, increasingly causing those most affected to flee and triggering regional conflicts. Therefore, additional investment in soil and water expertise and Water-smart Agriculture (WaSA) approaches is required to build sustainable water management systems for a secure world.

This paper focuses on WaSA practices for smallholder farmers in developing countries and reviews soil biophysical parameters and processes, given that these are often less understood. WaSA practices are closely linked to Climate Smart Agriculture (CSA), as efficient water management is among the key contributors to the CSA goals of productivity, adaptation and mitigation. These include the building of soil organic matter, reduction of soil erosion, use of efficient water and nutrient irrigation management practices, and the minimizing of water quality impacts. Effective long-term adaptation of agricultural innovation is challenging, and it is my strong belief that if soil and water concepts are made more available, the implementation of practices such as WaSA will become more widespread. Nevertheless, this will require that innovative training and extension activities be undertaken in parallel, and I am hoping that the content herein will prompt further consideration to be given to adopting this material for training workshops in-country.

Understandably, one must not focus solely on WaSA without considering all aspects of the food value chain. This was clearly articulated in the 2016 US Government Global Food Security Strategy[1] document, which defined its overarching goal as sustainably reduce global hunger, malnutrition and poverty. The report makes a strong case for integrated US interagency efforts towards the following three unifying and interdependent goals: (1) inclusive and sustainable agriculture-led economic growth; (2) strengthened resilience among people and systems; and (3) a well-nourished population, especially among women and children. WaSA is a cross-cutting component to the achievement of all these goals, as well as other relevant objectives such as increased gender equality and youth empowerment, increased public and private investment in food security, and more effective governance, policy and institutions. I must also refer to a recent IAIRD report[2], highlighting the pivotal role that agricultural development plays in achieving global food and nutrition security. The report speaks to five SMART

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1. USAID (United States Agency for International Development). 2016. U.S. Government Global Food Security Strategy FY 2017-2021 (online). Washington D.C. 113 p. Accessed 21 May 2018. Available at: https://www.usaid.gov/sites/default/files/documents/1867/USG-Global-Food-Security-Strategy-2016.pdf.

2. AIARD (Association for International Agriculture & Rural Development, United States of America). 2017. SMART Investments in International Agriculture and Rural Development: Recommendations to the New Administration and Congress (online). 62 p. Accessed on 21 May 2018. Available at: http://www.aiard.org/uploads/1/6/9/4/16941550/smart_investments_final_1.pdf.

US domestic and foreign investment area, namely: (1) **S**ecurity and stability; (2) **M**arkets and trade; (3) **A**daptation and conservation; (4) **R**esearch and innovation; and (5) **T**raining and education. Not surprisingly, investment in water resource availability, access and utilization is an integral aspect throughout the **SMART** domain.

As one of the top-ranked agricultural universities globally, UC Davis has many strength areas, including in matters related to WaSA, CSA and Healthy Soils, and many members of UCD's expert faculty, extension specialists and other research scientists are committed and ready to engage in international agricultural development. It is my hope that this report will assist those involved in agricultural development, training and extension for the benefit of farmers, especially those smallholder farmers in low-income and resource-poor regions of the world.

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December, 2019

1. INTRODUCTION

Water-smart agriculture (WaSA) is a flexible concept that was coined in 2013 by the Cooperative for Assistance and Relief Everywhere (CARE), under the Global Water Initiative — East Africa meetings. The WaSA concept was introduced to encourage smallholder farmers of Eastern African countries (Ethiopia, Tanzania and Uganda) to adopt improved crop, soil and water practices to mitigate yield losses due to the irregularity of rainfall (Nicol *et al.* 2015). Since then, the WaSA concept has been embraced globally as an integral component of climate smart agriculture (CSA). In this regard, the International Water Management Institute (IWMI) and CARE, supported by the Research Program on Water, Land, and Ecosystems (WLE) of the Consultative Group for International Agricultural Research (CGIAR), have been the main institutions promoting the concept of WaSA (Nicol *et al.* 2015).

WaSA, it can be argued, is a key concept for achieving a sustainable global future without hunger and poverty, since more than 75% of the world's poor depend heavily on agriculture for their direct subsistence food needs and income (WB 2013). In the same vein, agricultural development and the consequent increase in incomes could be considered as one of the most powerful ways to rise out of poverty and improve nutrition and health (WB 2013). This is particularly significant since ex-ante research forecasts that by 2050 global agricultural production must sustainably increase by 60% to meet the food, fiber and feed needs of an additional two billion people. Moreover, production must double in Sub-Saharan Africa to meet growing demands (Alexandratos and Bruinsma 2012). This increase must be realized under climate change conditions, without compromising the natural resource base on which our food, water, and air systems depend. In this context, WaSA can be used to sustainably increase agricultural productivity to facilitate enhanced agricultural development.

The African continent requires special attention, as it relates to increasing agricultural productivity, as this region is expected to account for approximately half of the world's population growth by 2030, while experiencing high levels of inequality, child mortality and poverty. Juxtaposed to the African continent is the Latin American and Caribbean region (LAC), which also merits closer attention. LAC contains more than a quarter of the globe's arable land and approximately a third of its water resources, making it a potential powerhouse for food production (Zeigler and Truitt Nakata 2014). Indeed, these abundant natural resources have great potential to help the world to achieve the UN's Sustainable Development Goals (SDGs) as it relates to food security. In addition to the region's wealth of natural resources, farmers in LAC have shown their ability to meet targets regarding capacity building and development. This was demonstrated by the region's success in exceeding the 2015 SDGs related to hunger, conservation and protected areas, and improve drinking water sources (MDG Monitor 2015). Despite these achievements, there are significant poverty pockets, especially in Central America, where adoption of WaSA approaches in hill-land agroecologies could help stabilize fragile ecosystems and improve livelihoods. WaSA can also play a significant role in addressing the challenge of sustainably feeding other regions like South Asia. As such, with appropriate technical support and financing mechanisms from international organizations, the implementation of concepts such as WaSA could potentially increase agricultural yields and reduce poverty and malnutrition on a regional and global level.

3. FAO, in collaboration with the CGIAR and other partners, published in 2013 an electronic CSA 'sourcebook' that is to be periodically updated. It is targeted at development managers and outlines CSA techniques and approaches.

- Global food security is at risk. An additional two billion people will inhabit the planet by 2050, even as climate change continue to exacerbate the challenges of food and nutrition security (UN, 2015[4]).
- Rising temperatures, extreme droughts, storms and floods are increasing in frequency and undernourished population is also increasing (UNICEF, 2019[5]).
- More productive and resilient agriculture requires a major shift in the way land, water, soil nutrients and genetic resources are managed to ensure their effective application (FAO, 2020[6]).
- Water-smart Agriculture (WaSA) is addressing this challenge from a 'water-first' perspective, as water is essential to all life processes related to agricultural production.
- In our collective pursuit to secure nutritious food for all, it is essential that we consider water-smart practices now, as approximately one third of the world's population is living under water scarce conditions.

WaSA involves assisting smallholder farmers primarily to identify and apply 'best-fit' water management regimes that improve water accessibility, storage and use in agroecological systems and socioeconomic environments (Nicol *et al.* 2015: xxiii). A core feature of WaSA is ensuring that the ultimate water delivery vehicle — the soil system — is continually enhanced and supported to nourish crops, support livestock, and cater for other domestic and broader societal needs (Nicol *et al.* 2015: xxiii). As such, WaSA considers soil and water management, crop and varietal choices, and water-use optimization from the field to the entire farm and/or watershed and across the food value chain.

Water-smart Agriculture includes adaptation practices that reduce vulnerability and increase resilience to changing weather patterns, such as droughts and excess rainfall. It also includes mitigation practices that help sequester carbon through smart soil management. Incorporated into WaSA are multiple layers of biophysical, socioeconomic, and political sciences that underpin the tapestry of action areas and stakeholders who make choices on water and land use. The multilayered and technical aspects of WaSA often result in complexity. However, much is gained by creating a shared vision among stakeholders to contextually define WaSA and institute practices that are supported by local policy and strategy.

Though the concept applies globally to production systems of all sizes, it is particularly applicable for smallholder family farming in the lesser-developed countries of the world, where scaling adoptions require new and well-focused societal partnerships and investment in enabling stakeholders.

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4. UN (United Nations) 2015. World population projected to reach 9.7 billion by 2050. Department of Economic and Social Affairs (online) Accessed 7 March 2018 Available at: https://www.un.org/en/development/desa/news/population/2015-report.html

5. UNICEF (United Nations Children's Fund) 2019. Food Security and Nutrition in the world. Accessed 7 March 2018. Available at: https://www.unicef.org/reports/state-of-food-security-and-nutrition-2019

6. FAO (Food and Agriculture Organization) 2020. Land and water management. Accessed 7 Mar 2018. Available at: http://www.fao.org/climate-smart-agriculture/knowledge/practices/land/en/

In this regard, there is a growing understanding that many of the changes needed in agricultural practices are knowledge intensive. Lasting changes in our thinking and the adaptation of water smart practices are approaches that are learned by doing. As such, there is need for a strong enabling environment that is guided by policies and is usually accompanied by knowledge-rich extension support services, appropriate technology (such as Information and Communication Technologies), hands-on training and continuous capacity building opportunities for extension agents, technicians and producers. This will often entail embracing opportunities afforded by partnerships and alliances with others who have a shared vision and willingness to invest in action-oriented programs that enhance agricultural development through productivity improvements.

For the purpose of this paper, the authors propose that WaSA be defined as: the convergence of good water use practices in concert with enhanced soil, crop and ecosystem management for resilient, sustainable, and where appropriate, intensified agriculture, toward the improvement of farmers' livelihoods. The objective of this publication is to provide students, trainers, and development partners with a comprehensive overview of water and soil management practices within the context of WaSA. The document also presents a review of WaSA in the context of agricultural systems that are prevalent in resource-challenged developing countries. Given the complexity of the broader dimensions of WaSA, focus is placed on soil biophysical processes, as these are most often not sufficiently understood. Hence, the emphasis is specific and does not fully address the companion needs for upscaling, support for value chains, sustainable financing, policy development, planning, and other factors that should be considered for the adoption of WaSA. Moreover, this publication acknowledges that livestock is an integral part of the production systems and livelihood strategies of smallholder farmers. However, the focus is on water optimization in cropping systems and strategic land use, even while recognizing the importance of integrated crop-livestock production systems. This publication is aligned with the WaSA brief prepared for policy makers and funding partners (Appendix 1 & 2).

2. CLIMATE AND WATER-SMART AGRICULTURE

Smallholder farmers in developing countries are the major providers of global food production. However, these more than 500 million farmers are affected or at risk of being affected by climatic changes (FAO 2017). These climatic changes affect the availability and accessibility of basic food production inputs, such as water and soil, and the quality and sustained use of these inputs. As such, food security and rural livelihoods are intrinsically linked to sustainable and efficient use of water. Increasing water efficiency should be a critical element of any comprehensive strategy for achieving the sustainable development goals, such as the elimination of hunger. It is also important in sustainable intensification (SI) agricultural systems, which are designed to increase production while decreasing the negative impact on the environment and enhancing ecosystem services (CIMMYT, 2016). Resource use must be optimized and the natural resource base, for example, soil, water, air, biodiversity, etc., must be protected and enhanced. Therefore, as a function of increased total factor productivity (TFP) (GHI 2017), WaSA, through its focus on effective and efficient use of water, is an essential component of SI. In most cases, enhancing water productivity through improved land management, agronomic practices and genetic resources is the single most important way to increase and sustain yields (UNESCO 2015). Additionally, this optimization translates into a reduction in the contribution of agriculture to water and carbon "footprints."

Thus, it is important to focus not only on water management but also to recognize the critical importance of water management interactions within complex agricultural socio-ecosystems. For example, smallholders often have limited access to sufficient clean water resources and innovative practices such as SI or WaSA. This highlights the need for governments to strengthen extension systems, by providing information and hands-on practical learning experiences, and to implement relevant policies to scale up adoption of WaSA practices. The roles of the private sector and civil society must be clear and supported by investment strategies, which will be instrumental in creating an enabling environment for implementation and promoting sustainable water management and practices.

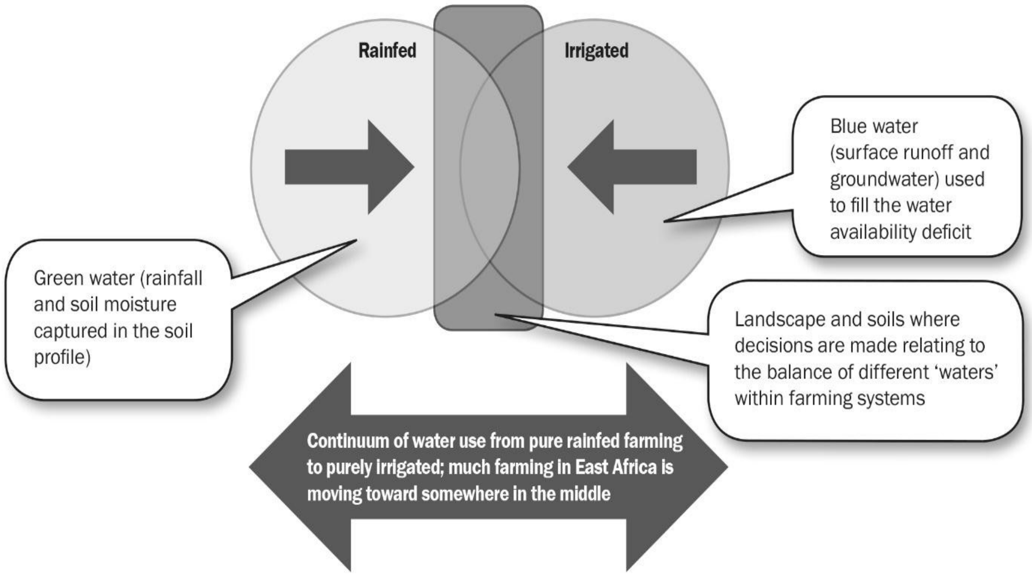
2.1. WaSA, a "water-first" perspective for climate smart agriculture

About 80% of global agriculture is rain-fed (without irrigation), representing 60% of total agricultural production (FAO 2016c). In Latin America, rain-fed agriculture accounts for about 90% of agricultural production and in Sub-Saharan Africa for approximately 95% (IWMI 2010). Although there are high levels of rain-fed agricultural production, groundwater extraction for irrigation accounts for approximately 70% of total abstraction. As groundwater is becoming increasingly scarce, and given the diverse demands by other sectors, it is imperative that water be used more thoughtfully. Whether rain-fed or irrigated, optimization of rainfall and stored water for sustainable and resilient agricultural production underpins WaSA (Figure 1). Efficient water management is particularly relevant, since almost half of the world's regions are subject to water scarcity (economic or physical) and better management is central to the broader goals of climate smart agriculture (CSA).

The concept of CSA was introduced in 2010 at the FAO Hague Conference on Agriculture, Food Security and Climate Change (FAO 2010). The urgent need for CSA is based on three pillars, which are to:

1. sustainably increase agricultural productivity and incomes;
2. adapt and build resilience to climate change; and
3. mitigate by reducing and/or removing greenhouse gas emissions, where possible.

Figure 1. Water-smart Agriculture



Source: Nicol et al. (2015)

As a major component of CSA, WaSA contributes to all three pillars. As it relates to mitigation, conservation agriculture increases soil carbon sequestration, thereby reducing atmospheric $C0_2$. Moreover, alternately wetting and drying soils in flooded rice fields, reduces nitrous oxides and methane emissions. WaSA and CSA are companion concepts that have similar objectives, with WaSA focusing primarily on water and soil management and addressing climate change from a 'water first' perspective. WaSA is based on the notion that it is rational and pragmatic to emphasize water first because water is essential to all life processes, including agricultural productivity. It focuses less on non-water climate-related issues than CSA, and slightly more on sustainable productivity and income gains for smallholders. In many cases, WaSA may be the most common approach to achieving CSA goals, as evidenced by the fact that most case studies advocate for WaSA investments (FAO 2014)**.** Most of these studies identify WaSA components as the means of achieving CSA goals. These studies correctly highlight the importance of investments using integrated approaches along with strategic partnerships and the identification of policy barriers to adoption. Steenwerth *et al.* (2014) present an excellent review of the CSA global research agenda, including the significant contributions of WaSA. Addressing the constraints and opportunities involved in operationalizing WaSA and CSA goals, which includes both environmental and socio-economic dimensions, will require the engagement of multiple partners and institutions. Undoubtedly, the examination, development and alignment of policy action has major implications for water-use, which in turn has implications for broader agricultural policies and development strategies. However, details for specific policies are beyond the scope of this document. As such, from the perspective of policy, concepts and actions, WaSA and CSA are essentially different sides of the same coin, with WaSA according priority to water issues.

3. HYDROLOGIC CYCLE AND WATER MANAGEMENT

3.1. Hydrologic cycles, categorized as shades of water (Green, Blue and Grey water)

A fundamental conceptual framework of WaSA is derived from hydrology, which is the scientific study of the occurrence, distribution, movement and properties of the Earth's waters and their relationship to the environment[7]. As it relates to agriculture and the environment, the pictorial terminology (Figure 2) for the various components of the hydrologic cycle are clearly articulated by Rockström et al. (2009) and by Sposito (2013), in his landmark paper on "green water"**.** Green water is defined as water in soil that remains potentially available to plant roots and to the soil biota, after precipitation losses from runoff and deep percolation. It accounts for approximately 65% of all water within the hydrologic cycle (Rost et al., 2008; Schneider 2013) and consists of two main parts: 1) transpiration, which is the productive component that produces biomass; and 2) soil evaporation, the non-productive component that vaporizes into the atmosphere without supporting photosynthesis and plant growth (Falkenmark and Rockström 2006; Mulligan et al. 2011). Nearly 80% of the water consumed by croplands worldwide is green water, mainly through rainfed agriculture (Falkenmark and Rockström 2006; Mulligan et al. 2011). However, Rost et al., (2008) noted that non-agricultural ecosystems currently consume about three-fourths of the global green water flow, with the remaining one-fourth apportioned equally between croplands and pastureland. For this reason, Sposito (2013) makes a compelling case that the greatest opportunity to meet future agricultural production needs will come from more efficient use of green water, since it is essential for plant growth. The primary opportunity to augment green water and its positive effects is by enhancing the ability of soil organic matter to serve as a sponge.

"Green water" refers to water in soil that remains potentially available to plant roots and to the soil biota after precipitation losses to runoff and deep percolation have occurred (Rockström et al., 2009a).

Green water supplies enable rain-fed agriculture, which provides about 60% of all agricultural output on 80% of global agricultural lands.

The global flow of green water by transpiration alone is approximately equivalent to water from all the rivers in the world flowing to the oceans (Oki and Kenae, 2006; Bengough, 2012).

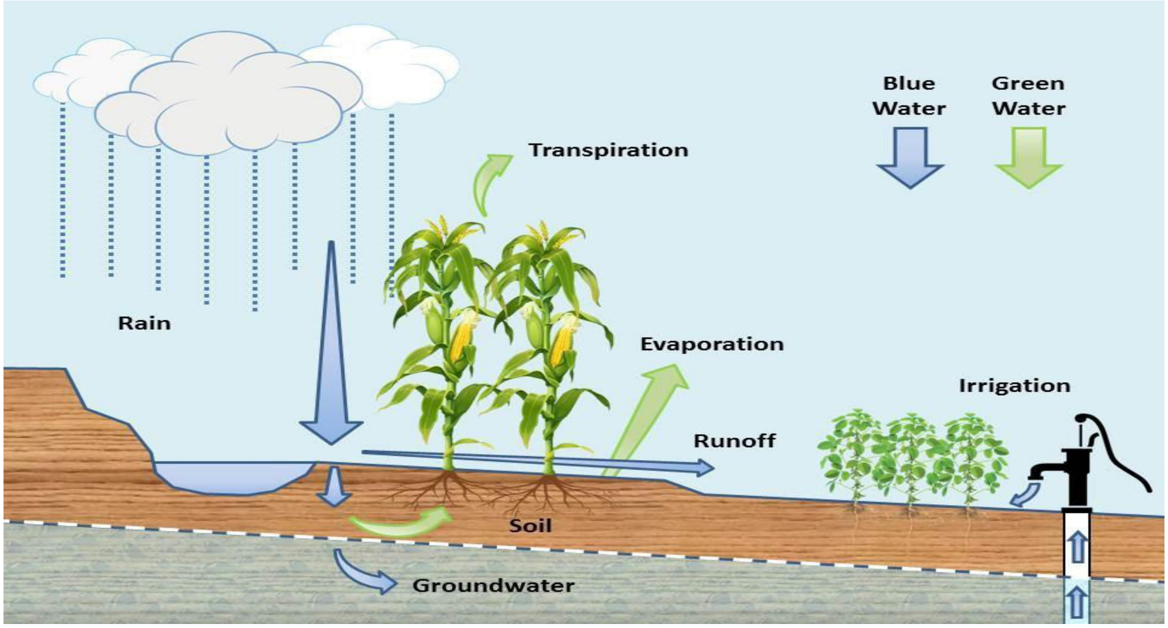
In contrast, "**blue water"** refers to rainfall that flows into streams and rivers and is stored in lakes and reservoirs or is pumped from aquifers (Rockström et al., 2009) (Figure 2)**.** It accounts for only 35% of all water within the hydrologic cycle and is the main source of water for industrial, domestic and irrigation purposes. The agricultural sector accounts for 70-90% of global consumption, which is known as the 'blue water footprint' (Sposito 2013). Although this represents a relatively level of consumption, only 20% of the water that crops use comes from blue water (irrigation), which in turn translates into nearly 40% of the global food supply (FAO 2016c). These statistics emphasize the fact that enhancing the efficiency of blue water usage through efficient irrigated agriculture is the most logical path to address water scarcity in food production. However, determining how much blue water should be allocated to agriculture remains a huge

7. USGS (U.S. Geological Survey). 2016. What is hydrology and what do hydrologists do? (online). Accessed May 17,2020. Available at https://water.usgs.gov/edu/hydrology.html

dilemma, as its extraction affects our aquatic ecosystems and groundwater resources. Blue water is used extensively in Asia where tube well irrigation, use of small reservoirs and aquaculture are commonly included in production systems. However, blue water use is much less developed in Africa and Latin America, where small reservoirs use between 4% and 20%, respectively, of total blue water resources (FAO 2016c). Tube well use is also less developed in these two regions.

Figure 2. Two principal water resources that feed production agriculture.

[“Green” water enters the soil through precipitation, and directly provides water for plant root uptake and for the biological processes of “healthy” soils. Precipitation also feeds lakes, streams, reservoirs, ponds and aquifer groundwater resources. This collective body of water is known as “blue” water. Better agronomic practices enable better output per unit of both green and blue waters — “more crop per drop.” Adapted from Rockstrom and Falkenmarck (2015).]



Effective and efficient use of blue water is concerned not only with the volume of water used but also with the quality. Unfortunately, when water is used by humans its quality is typically reduced, posing problems for downstream users. Given the challenge of adequately balancing the rates of withdrawal and replenishment of blue water, the agriculture sector in most countries can no longer afford the luxury of using water only <u>once</u>. For sustainable development purposes and to conserve water, water quality must be considered so it can be recovered for other uses. In this way, sustainable water can be recovered from wastewater. Recycled or “grey water” provides for an opportunity to prolong the lifespan of water used for irrigation or household water purposes.

Grey water, which is of growing importance, particularly in water-stressed regions/countries, such as the Middle East and countries like Israel, refers to previously used water, which may contain impurities (Schneider 2013). The use of grey water usually involves a recovery mechanism consisting of filtration/separation, microbial digestion and purification before it is used for agricultural, domestic or industrial purposes. Although it is not easy to clearly conceive of grey water (a product of human use) as a differentiated part of the hydrologic cycle, it does provide tremendous prospects to supplement green and blue water. Schneider (2013) reported that the US Environmental Protection Agency (EPA) estimates that by 2025, the volume of grey water produced by an increasing population (52 trillion gallons per day) could hypothetically provide enough green water for 20 million acres of land. One of the key messages of grey water use is that it does not have to be treated to a pristine level for reuse in agriculture and industry. In fact, grey water provides the benefit of nutrient recycling since it may contain a substantial concentration of plant important nutrients. Recycling those nutrients not only helps improve crop yields but provides alternative or divergent paths for nutrient-laden wastewater that might otherwise be discharged into surface or underground water sources, potentially negatively impacting water quality. For these reasons, countries such as Israel and Spain are already recovering ≈85% and ≈20%, respectively, of wastewater for agricultural irrigation and other purposes (Brenner 2012; Brixio et al. 2006). The stigma of using wastewater for crop irrigation has limited its use in many other countries or regions.

"Grey water" or recycled water refers to previously used water that may contain impurities. It is wastewater that is usually treated, discharged, and used by cities, households, and industries (Schneider 2013).

Israel reuses 85% of recovered wastewater for agricultural irrigation and for other purposes (Brenner 2012).

The relatively high energy consumption and cost of desalination technologies limit the use of **desalinated water** for agricultural irrigation in many countries.

Assouline et al. (2015) stressed that one must be careful in using recycled water for irrigation purposes for various reasons. They provided a critical analysis on the use of marginal water and management approaches to map out potential risks. Long-term application of treated effluent for irrigation has been shown to impact soil salinity and infiltration and may introduce health risks, due to persistent exposure of soil biota to anthropogenic compounds (e.g., pharmaceuticals). In addition, health risks involving contamination of fresh fruits and vegetables irrigated with water containing microbiological organisms, such as *E. coli* and *Listeria monocytogenes*, is a major concern for all irrigation water sources, and especially when using grey water. Desalinated water has been a more psychologically acceptable alternative source for irrigation. However, in many countries, the cost of using desalinated water for agricultural irrigation is still prohibitive.

A watershed (drainage basin or catchment) is an area of land that drains all the streams and rainfall into a common outlet such as the outflow of a reservoir, mouth of a bay, or any point along a stream channel. Ridges and hills that separate two watersheds are called the drainage divide. The watershed consists of surface water: lakes, streams, reservoirs, and wetlands and all the underlying groundwater. Large watersheds contain many smaller watersheds. Watersheds are important because the stream flow and water quality of a river are affected by activities, whether human-induced or otherwise, in the land area "above" the river-outflow point.

3.2. Water management for floods and droughts

WaSA must address both the extremes—drought and floods—and all conditions in-between. Often, these conditions occur in the same geographic regions, and are expected to increase in frequency and severity due to climate change. As such, improved soil and crop management practices, as part of WaSA, will mitigate both flood and drought conditions in the field and farm and the level of the watershed (also see Chapter 6).

3.2.1 Storm-driven soil erosion and flooding

WaSA practices for excess water conditions must include soil management practices that maintain protective soil coverage. This is necessary to protect soil from erosion and excessive runoff and to improve water infiltration. In agricultural soils, this often includes use of crop residue, mulch and cover crops. In tropical hill-lands, severe storms often have devastating effects on crops and homesteads. If erosive, susceptible soils are not protected with plant cover, erosion will remove the most fertile topsoil, causing gullies in eroded landscape, frequently leading to disastrous consequences. The impact of high intensity rainfall is soil erosion, which is particularly destructive for soil that is left bare. Unfortunately, preventative measures to avoid this damage are too often not undertaken. WaSA practices, including terracing, bunding, live mulching, agroforestry, and other techniques, discussed in Chapter 6, could be applied.

Managing flooded, waterlogged soils can also be a major challenge, especially for smallholders. Where flooding is predicable, such as in rice-based systems in Asia, community approaches have evolved. For example, in South Asia, flood-tolerant rice is sown during the monsoon followed by wheat in the dry season. However, erratic unpredictable floods are generally devastating, and flood insurance for smallholders in developing countries is nearly nonexistent. Smallholders dealing with erratic flooding must consider water diversion approaches as well as recovery strategies and may even need to change to less susceptible crops and other enterprises, such as aquaculture.

3.2.2. Droughts

Spatial and temporal variations in precipitation can be critical constraints for both rain-fed and irrigated agriculture. Short-term moisture deficit is a frequent risk in rain-fed systems. Periods of drought are still not acurately forecasted, although there are mechanisms in specific regions to help communities prepare for water scarcity. Such mechanisms include the Famine Early Warning System Network (FEWS NET), NOAA's **Drought** Task Force (DTF) and the Caribbean Drought Bulletin, all of which are regularly updated. In any case, appropriate soil management practices will also reduce moisture-deficit mediated risks of crop losses and will generally result in improved productivity.

Strategic irrigation can significantly assist in addressing droughts. In many parts of LAC, and especially in Sub-Saharan Africa (SSA), surface water resources are generally not effectively harnessed for agriculture. Where sustainable ground and surface water resources exist, investment in irrigation development to harness these water resources merits serious consideration. Often, even when resources are developed, farmers may not be given access when they need it. Surface or groundwater could be available, but often water accessibility, not physical lack of water, limits water use for irrigation (Ringler 2013 and 2017).

Managing agricultural water for drought mitigation has many dimensions, ranging from optimization of green water through the soil organic matter (SOM) 'sponge'; harnessing of water from watersheds by way of rivers and streams, diverting it directly to storage reservoirs and/or irrigation canals, and finally to judicious solar-powered pumping of groundwater. WaSA practices should consider both upstream water availability and downstream impacts after water use, as smallholder fields are typically only a small area of a much larger distributed irrigation network. WaSA practices at the small field scale may have little benefit if they are not coordinated with users of all sizes. Irrigated WaSA practices and management options generally should be coordinated within their drainage area or watershed. Expansion of the use of solar-powered pumps provides an opportunity to scale up smallholder irrigation in water-deficit regions. However, over-extraction of groundwater is a real risk in many locales, particularly in times of drought, and should be monitored.

3.3. Water productivity and water use efficiency

Productivity growth, a measure of output per unit of input, allows more to be produced while optimizing the use and impact of scarce resources. As it applies to WaSA, productivity growth lowers the cost per unit of output and can be achieved through the adoption of innovation, sustainable intensification and irrigation, and by increasing efficiencies to improve total factor productivity (TFP) – the ratio of total outputs to inputs (GHI 2017). Specifically, this can be achieved by reducing soil evaporation, thereby significantly increasing green water use efficiency. TFP can also be attained by introducing conservation agricultural practices (Chapter 5) or through simple techniques such as narrowing rows, and early sowing. The application of innovation, best practices, and enhanced crop genetics on small and medium-sized farms offer great potential to enhance yields.

"At current the yields produced in African, about two-thirds of soil moisture is lost via soil evaporation, leaving only one-third of the captured rainfall available for plant transpiration. But when cereal yields rise from one to three t ha−1, the crop canopy closes and the balance flips over: only about a third is lost through soil evaporation, and two-thirds is funneled through the plants as transpiration." (Sánchez 2010: 300)

Estimates indicate that global TFP growth must increase at an average rate of 1.75% annually, to double agricultural output through productivity gains by 2050. TFP growth has been stagnating, particularly in low-income countries, where it needs to be approximately 2% for smallholder farmers (Global Harvest Initiative 2016). WaSA and water-factor productivity are the essence of the appeal for More Crop per Drop —a theme of the UN's International Year of Fresh Water (FAO 2003).

A significant portion of water loss through soil evaporation and surface runoff can be reduced by improved soil and agronomic practices (Rockström *et al.* 2007). These practices will generally increase the area of soil covered by plants, thus reducing nonproductive soil evaporation (E) losses in favor of productive plant transpiration (T). Plant growth and associate crop yield is dependent on adequate soil moisture availability. Crop physiology comes into play and as soil moisture is depleted, plants can become water-stressed and respond by closing leaf stomata. As a result, transpiration is reduced, which is a plant's response to mitigate long-term water stress. However, for most crops, reduced transpiration equates with a reduction in crop yield, because the gas exchange for photosynthesis also "grinds to a crawl" with stomata closure. To quantify crop water use, one defines water use efficiency (WUE) as the amount of crop biomass or crop yield produced per unit of water transpired by the crop. Hence, to alleviate water scarcity, one may resort to crop breeding and other genetic approaches to select crop traits that are more tolerant to water stress, and that therefore have greater WUE values (more crop per drop). Root morphology, including growing depth, is a component of crop and varietal differences in determining drought tolerance.

In rain-fed agriculture, WUE is equated with precipitation use efficiency (PUE), in other words, crop yield per unit of rainfall. The two terms are often used interchangeably in the agronomy of rain-fed systems. However, one should be careful in doing so, as soil management practices may likely affect the partitioning of precipitation between soil water storage, leaching and runoff, soil evaporation and crop transpiration. Typically, the term WUE includes water losses through soil evaporation, with crop water use representing total soil evaporation and crop transpiration, generally referred to as evapotranspiration (ET, sum of E and T). Mulched cover crops and crop residue that cover the soil between cropping cycles can reduce evaporation, thereby improving WUE.

Clearly, soil tillage is a major determinant of soil compaction, soil structure, soil organic matter, ultimately determining soil health and associated productivity and WUE. Many short-term agronomic experiments have been conducted to evaluate the impact of soil management on WUE. Crop yield on any field, in any given year, is the outcome of many factors. Consequently, WUE or PUE, is difficult to strongly correlate to any given management practice. Year to year variability in WUE is also large. In addition, it can take years of no-till agriculture to raise soil organic matter (SOM) levels enough to sufficiently increase water storage capacity to produce improved WUE (Hatfield *et al.* 2001). Enhancing plant nutrition is often an essential component to increase biomass production for SOM acquisition and soil regeneration. Consequently, much of WaSA is based on improved soil, water, and crop management practices that increase WUE, which, as defined, includes soil evaporation.

3.4 Hydrologic modeling

Improved water management practices can be assessed through the application of hydrological models that simulate relevant hydrology across fields and watersheds, such as water balance components of rainfall/irrigation, evapotranspiration, soil water storage, runoff, and groundwater, and may also include water quality and soil erosion modeling, as it relates to water flows. The hydrologic component of these models varies from simple field water balances to sophisticated and numerically intensive river and groundwater models.

Some models have fully integrated both hydrological and economic components into a single program, whereas others have separate, loosely coupled models. Economic components of such models include optimization (what is best?), simulation (what if?), cost-benefit analyses and water value assessment (Kirby and Ahmad 2014). Economic modeling is common in water resource management. However, the specific requirements of the developing world have not yet been well described. For developing countries, holistic policy considerations should place greater emphasis on food security, poverty alleviation, economic development and equitable allocation, while paying attention to in equal measure to issues such as the environment, markets and social equity.

4. SOIL HEALTH AND BIOPHYSICAL PROPERTIES

WaSA practices largely contribute to improving soil health, which is a major focus of good agricultural practices. As such, biophysical factors related to WaSA, CSA and soil health are intertwined and have implications for climate change adaptation and mitigation at the farm and at the global level. In this context, the World Resources Institute reported that about 30% of the world's croplands are already degraded, that is, soils are less "healthy" and productive than before. However, through proper management, soils can and do recover. Programs such as Payment for Ecosystem Services, which encourage sustainable land stewardship can improve soil health and water systems. These programs, where landowners are paid to protect the natural resources of their lands, have yielded positive results in places such as Costa Rica. Brazil and Panama have also progressed significantly in revitalizing degraded lands, through government incentives to improve soil conditions, protect watersheds and promote green infrastructure (Weber and Buckingham 2016).

Soil health speaks to the importance of managing soils, so they are sustainable for future generations and refers to the continued capacity of the soil to function as a vital living ecosystem that efficiently absorbs, stores and releases green water for crop growth. If managed with care, soils are resilient and self-regenerating.

Soil health (in the past referred to as soil quality) refers to the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans. As health implies "living," much of the soil health concept relates to soil as a living ecosystem that includes, invertebrates (eukaryotes), bacteria, fungi and other microbes. In addition to soil biology, healthy soils have specific functional properties that are related to the soil's ability to sustain plant and animal life; to control water flow over and through the soil by infiltration and by soil water retention; to assist with filtering water by buffering potential contaminants; to store, transform and cycle plant nutrients such as carbon, nitrogen and phosphorus; and to provide physical support for plant roots. In this light, inherent soil properties such as soil texture, mineralogy and inert organic matter determine the soil's potential water- and nutrient-holding capacity and ultimately influence soil health.

Soil health is difficult to measure, since it is determined by soil biological, chemical and physical properties. Many of these properties can be altered through appropriate soil management practices. It is measured by indicators that provide information about the soil's ability to function. A main indicator of soil health is total organic matter or carbon content in the soil, which serve as a food source for plants and microbes. Soil organic matter content also affects water and nutrient retention, as well as soil structure, stability and erodibility. Physical parameters of soil, including bulk density and porosity, water holding capacity, water permeability and infiltration, also affect soil health. At the same time, soil chemical properties related to soil health and productivity include electrical conductivity, pH, nutrient concentration and cation exchange capacity (CEC). Minimum Soil Disturbance (MSD) maintains soil structure and function and the use of cover crops and residue management are excellent practices for improving soil health, as they protect the soil from erosion while introducing soil nutrients and carbon.

"Soil management must be geared toward passing a habitable, albeit highly altered landscape to the generations that follow—one where our exploitation of, and impacts on, soil resources is adjusted to the pace of our planet's renewal. These strategies should focus on regaining a balance in (i) organic C inputs and losses, (ii) soil erosion and production, and (iii) release and loss of nutrients. Soil sustainability—based on quantitative principles and measurements of soil erosion and production, soil nutrient loss and release, and soil carbon loss and return—must be the ultimate goal for managing the global soil resource" (Amundson et al. 2015: 1261071-5).

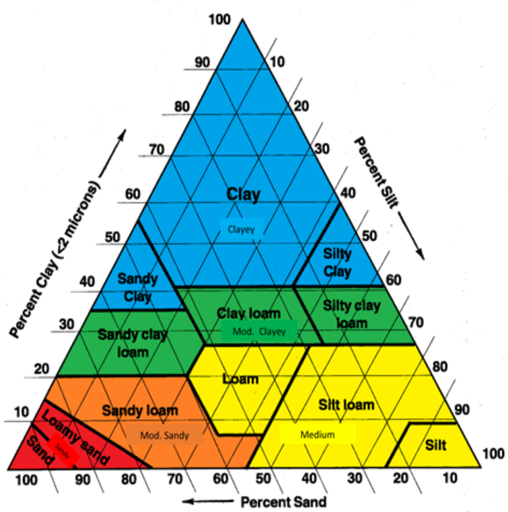
4.1. Soil biology

The biological properties of soil strongly affect its ability to perform core functions and ecosystem services, which include nutrient and water cycling, flood mitigation, waste recycling and filtering of contaminants (Dominati *et al.* 2010). As such, soil biology is a major discipline informing WaSA practices since the abundance and diversity of soil organisms (invertebrates and microorganisms) are affected by land management practices and climatic factors. For example, highly productive soils generally have a great diversity and abundance of microorganisms. This is particularly so since soil microorganisms—an estimated 10 billion per gram of soil—are important for decomposing organic matter, cycling nutrients and producing humus – compounds that improve soil aggregation and structure. As such, changes in soil microbial and earthworm populations and activity often precede detectable changes in soil physical and chemical properties, thereby providing early warning signs of soil degradation or improvement (Kennedy et al.1995; Pankhurst et al. 1995; Yuan and Chen 2012). Thus, soil biological properties have been found to be excellent indicators of soil health to illustrate cause and effects links of land management decisions that affect plant productivity and environmental health. However, although useful, these biological properties, particularly those related to microbiota, present some measurement and interpretation challenges, which often limit their widespread use in soil health analysis, particularly at the farm-level. These challenges are further compounded by: (i) an almost limitless diversity of species that inhabit different soil types under agricultural production and (ii) our lack of understanding about the roles of most of these microorganisms as they relate to soil health and the adoption of WaSA. Advances in molecular genetics, including community genetics approaches and high throughput biological informatics hold promise for accurately measuring diversity and understanding the roles and relationships of microbes as they interact with each other and the environment (Giller *et al.* 2015, Brussaard *et al.* 2007). Land managers, who are the ultimate stewards of soil quality, must endeavor to understand indicators of soil health.

"The challenge for the future is to develop sustainable management systems which are the vanguard of soil health; soil quality indicators are merely a means towards this end" (Doran and Zeiss 2000: 3).

"Soil organism and biotic parameters (e.g. abundance, diversity, food web structure, or community stability) **meet most of the five criteria for useful indicators of soil quality.** Soil organisms respond sensitively to land management practices and climate. They are well correlated with beneficial soil and ecosystem functions including water storage, decomposition and nutrient cycling, detoxification of toxicants, and suppression of noxious and pathogenic organisms." (Doran and Zeiss 2000: 3).

Figure 3. USDA-NRCS Soil texture triangle.



Source: USDA-NRCS (2020)

4.2. Physical properties of soil

While crop growth and surface mulch can help protect the soil surface, stable and well-aggregated soil structure resists surface sealing, thereby enabling continued water infiltration during intense rainfall events. In turn, this decreases the potential for erosion and downstream flooding. Soil physical properties will be discussed below as they relate to WaSA and best practices to improve productivity:

4.2.1 Soil texture

The texture of a given soil is largely determined by the relative proportions of sand, silt, and clay particles. Many of soil properties and functions can be assessed by knowledge of soil texture. Coarser textured soils (sands and loamy sands) typically have a low capacity to hold soil water and plant nutrients; have high water permeability and infiltration capacity and little structure; and are more erosive than finer-textured soils (clays). The most productive soils are loamy soils. Typically, soils have a mixture of coarse and fine-textured soil particles and are classified according to the USDA soil texture triangle (Figure 3).

4.2.2 Soil porosity

Pore space is that part of soil bulk volume not occupied by either mineral or organic matter. This open space is occupied by either air or water. Ideally, total pore space should be about 50% of soil volume. Pore space of unsaturated soils is partly filled with air, allowing for gaseous exchange required for plant root and soil respiration, while simultaneously having water and water-soluble nutrients available for root water uptake. Most importantly, soil pore space provides for water and nutrient storage, as well as movement of water and dissolved nutrients in the soil. When soil is saturated, its pores are completely filled with water. Any additional water beyond this point, results in oversaturation, flooding, runoff, and soil aeration issues.

4.2.3 Soil bulk density (SBD)

SBD is a measurement of soil mass per unit volume and is inversely correlated to soil porosity. More dense and compacted soils have lower porosity, and management of crops and soils that increase SOM also generally increase porosity and often reduce compaction.

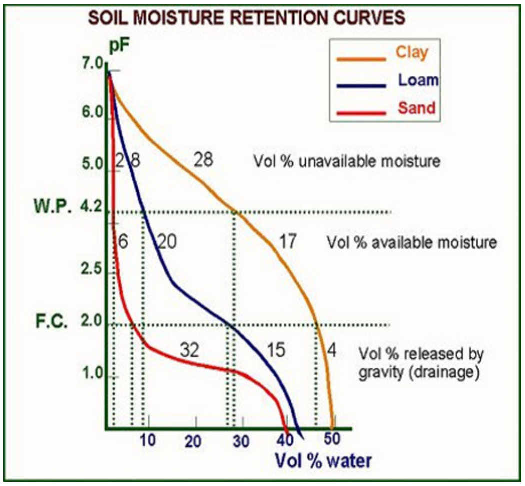
4.2.4 Soil moisture

Soil moisture content refers to the water volume fraction, in other words, the ratio of water volume to total soil volume. As soil moisture decreases beyond a threshold point (wilting point), plants become water-stressed, and soil pores will need to be refilled by rainfall or irrigation. Soil texture and associated pore size distribution influences the rate of soil moisture depletion (by soil evaporation and soil drainage), as well the ability of soil to retain water, also defined as soil moisture retention.

4.2.5 Soil moisture retention

Unsaturated water flow is largely controlled by the physical arrangement of soil particles in relation to the water and air phases within the soil's pore space, which is determined by pore size distribution and the soil's water content. The soil moisture retention or pF curve shows the relationship between wa-

Figure 4. Soil moisture retention curves as a function of soil type.



Source: FAO (2018).

ter content and water potential (Figure 4). Changes in soil water potential of the soil rooting zone determine the tendency of water to move by gravity and matrix or suction forces through capillary and adsorptive action (FAO 2018). The pF value increases as the size of the water-filled pores decrease, as may occur from drainage, water uptake by plant roots or evaporation. Since pF at a specific water content is controlled by the soil's pore size distribution, the soil water retention curve is very soil informative. It provides an estimate of a soil's capacity to hold water after free drainage (field capacity or FC); minimum soil water content available to the plant (permanent wilting point, or WP) and available soil water for plants or soil water holding capacity. As indicated in Figure 4, available soil moisture is highest in loamy soil (20%), and lowest in sandy soil (6%) (FAO 2018). Generally, at FC, clay soils can hold about 2 to 5 times more water than a loam soil; and at FC, loamy soils retain almost 4 times as much water as sandy soils. Moreover, at permanent wilting point (WP), clay soils still hold almost 30% water, but the suction forces on clay particles are so high that this water is not available for most plants.

4.2.6 Soil permeability

Water moves through soil due to the forces of gravity and capillarity. The rate of water movement at a specific soil moisture content is controlled by the permeability of the soil. Soil permeability determines the rate of water infiltration into soil and its drainage further downward into the deep soil and groundwater. The permeability of coarse-textured soils is much higher than for loamy and fine-textured clay soils. Rates of water infiltration are greatly enhanced by most soil covers (see Chapter 5 - Cover Crops and Conservation Agriculture). In soil literature, permeability is also referred to as soil hydraulic conductivity, and depends strongly and nonlinearly on soil moisture content, the size and tortuosity of the pores, as well as the viscosity of soil water.

4.2.7 Soil structure

The main determinates of soil structure are the size, shape, and arrangement of soil particles. Soil structure controls the presence of secondary porosity as created by the large-sized pores or macro-pores between the larger soil aggregates. In many instances, aggregation is achieved by soil organic matter (SOM), with binding forces that maintain soil aggregates by polysaccharides produced by soil microbes feeding on SOM. Soil structure is key to preventing erosion. Sanchez (1976) states that: "For tropical crops, except for paddy rice, good structure is that which maintains aggregate stability upon changes of moisture." Soil aggregation can be demolished by physical forces, such as high intensity rainfall and soil tillage practices, thereby soils become more vulnerable to erosion (from both wind and water) (Figure 5).

4.2.8 Soil erodibility

In addition to dust storms and land degradation, soil erosion removes the most fertile soil components, including SOM and nutrients (Figure 6). Consequently, soils become less productive and the landscape becomes increasingly prone to further erosion. Eroded soil material causes sedimentation of waterways, negatively impacting stream water quality due to turbidity and eutrophication. Erosion from wind affects air quality, thereby becoming a health hazard. In addition, soil erosion is accelerated by soil crusting, thus creating a thin and highly impermeable soil surface layer that hampers seedling emergence, reduces infiltration and leads to increased runoff and erosion. Vulnerability to soil crusting also largely depends on soil texture and aggregate stability. Soils with a high silt content and low SOM are most vulnerable to crusting, often due to high intensity rainfall that destroys soil aggregates and results in much smaller soil particles. Soil crusting/capping problems generally disappear in conservation agriculture where seeds are sown into unplowed mulched soils.

Figure 5. Destruction of soil aggregation and soil structure by disc plowing (Malawi).

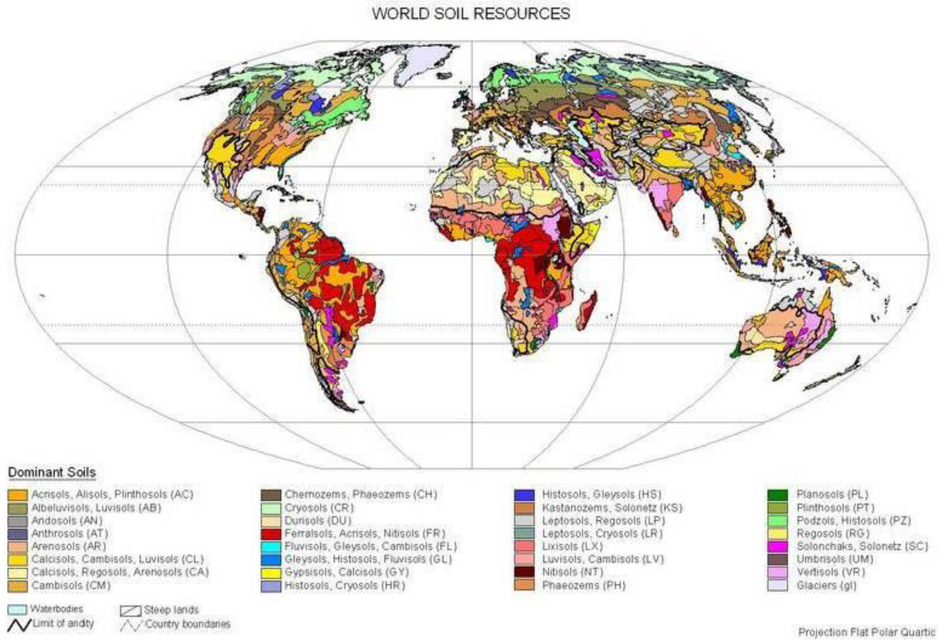
Source: Kueneman (2013)

Figure 6. Eroded hillside in Nicaragua - leaving exposed Rocks but still farmed.

Source: Kueneman (2013)

Soil types and their general characteristics can be viewed from soil maps that include mapping units, as determined from soil surveys rendering classifications (FAO 2018). Soil classification refers to grouping of soils with similar properties (chemical, physical and biological) into units that can be georeferenced and mapped. For example, in California, soil maps can be downloaded from the (USDA, 2018), whereas FAO provides the world's soil map (Figure 7), and country-specific soil maps.

Figure 7. World soil map.



Source: FAO 2018.

In summary, choosing WaSA practices will depend on many factors, including soil properties. WaSA requires farming practices that protect soils from physical, chemical, and biological degradation. The need to reduce erosion is much more relevant for finer-textured soils, with low infiltration rates, being much more vulnerable to erosion. For coarse-textured soils, WaSA practices that increase available soil water, for example, by increasing SOM, are particularly relevant. Generally, soil coverage will minimize soil crusting, erosion, and runoff. Various parameters of the physical properties of soil can be found at the California Soil Resource Lab. The site includes many fact sheets and videos presenting detailed information on specific soil measurements.

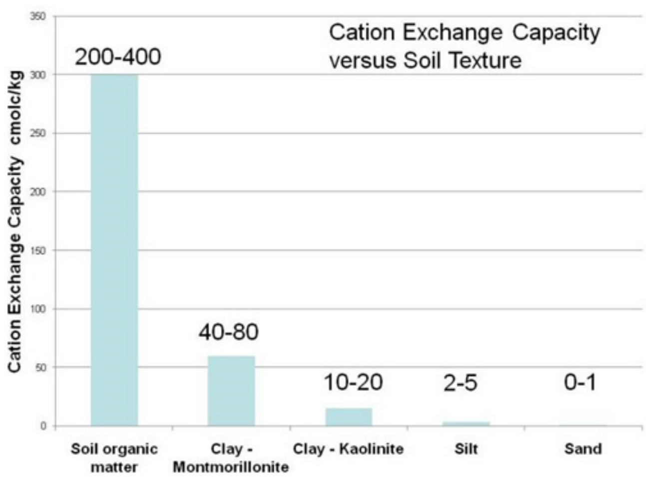
4.3. Chemical properties of soil

Many of the chemical properties of soil are closely related to soil texture, mineralogy, weathering intensity, and SOM content. Rather than providing a comprehensive review of soil chemistry, we present key chemical properties of soil such as cation exchange capacity (CEC), pH, SOM and electrical conductivity (EC), all of which influence plant nutrition. In this context, the focus of WaSA practices is to enhance the availability of plant nutrients and reduce soil salinity buildup and greenhouse gas emissions that, in turn, are affected by soil moisture dynamics. Biological and chemical reactions in soil are highly controlled by soil moisture, with chemistry-reducing soil conditions occurring when soil is saturated for long periods of time**.** This can result in greenhouse gas (GHG) emissions of methane and nitrous oxide, which is a serious issue emerging especially from flooded rice production systems.

4.3.1 Soil cation exchange capacity (CEC)

CEC, or soil cation exchange capacity, is the ability of the soil to retain cations (positively charged nutrients: Ca, Mg, Mn, Fe, Cu, Zn, NH_4^+). It is defined as the number of positive charges (cations) that a representative sample of soil can hold and is described as the number of hydrogen ions (H^+) necessary to fill the soil cation holding sites per 100 grams of dry soil. CEC is strongly related to soil texture and soil organic matter content (Figure 8). The typical CEC of soil textural components in decreasing order is Soil organic matter > Clay > Silt > Sand. In some soils, CEC will increase as pH rises. Using soil texture and OM, one can estimate soil CEC (CEC Calculator). Some tropical soils are prone to acidity accompanied by toxic levels of aluminum ions on the CEC. Adjusting soil acidity with the application of lime in combination with gypsum is common, as is done in the savannahs of Brazil. Often heavy applications of lime are repeated over several years to reach a target pH of above 5.5 with low Al saturation.

Figure 8. Cation exchange capacity vs. soil texture.



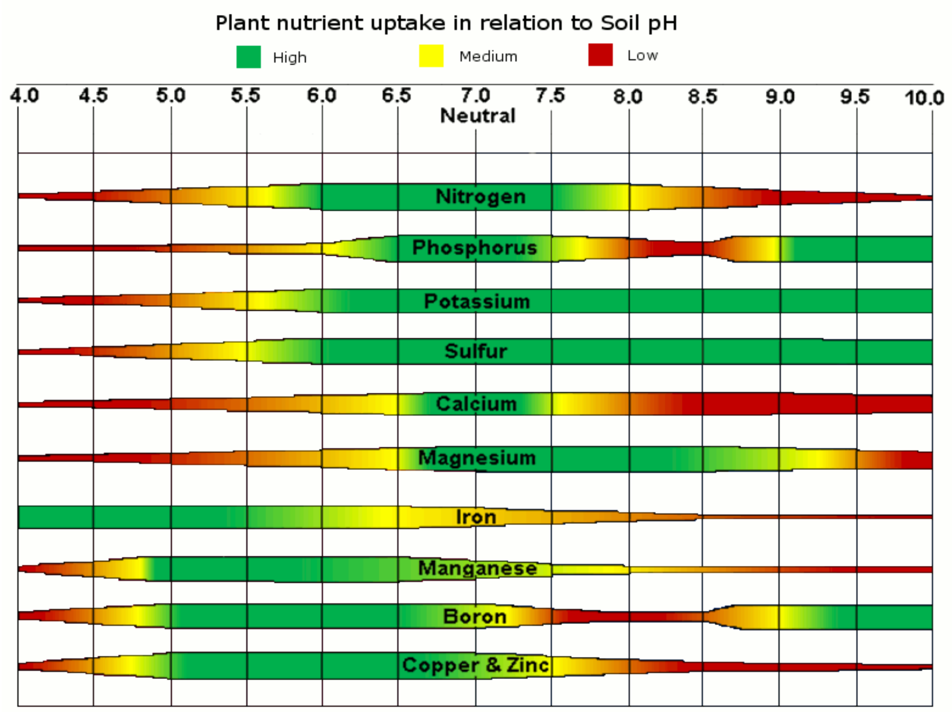
Source: ILaco (1985)

Soils with increasing SOM content generally have higher CEC values and higher nutrient concentrations, such as calcium, magnesium and potassium. Highly weathered, low SOM tropical soils have low CEC, often along with low pH values. Therefore, WaSA practices in the tropics must consider elevating SOM, generally by reducing tillage and optimizing plant biomass production and its retention.

4.3.2 Soil pH

Soil pH is an indication of the acidity or alkalinity of soil and is measured in pH units. Soil pH is defined as the negative logarithm of the hydrogen ion concentration. The pH scale ranges from 0 to 14 with pH 7 as the neutral point. As the amount of hydrogen ions increases, soil pH decreases and becomes more acidic. From pH 7 downward, soil becomes increasingly more acidic, and as soil pH increases from 7 upward, soil is increasingly more alkaline or basic. Low soil pH negatively affects plant availability of some major nutrients (Figure 9), soil microbial activity and soil structure. Soils tend to become acidic as a result of: (1) leaching of basic cations; (2) the dissolving of carbon dioxide in soil water (This forms weak organic acids, such as what occurs in organic matter decomposition and root respiration. Then too, root exudates are often rich in diverse organic acids) and (3) formation of acids from oxidation of ammonium and sulfur fertilizers. Soil pH is easily measured using a soil pH meter, which is typically part of a soil test kit. In tropical soils, acidity is frequently associated with Al toxicity, resulting in reduced root growth and stunted plants. Several key micronutrients, e.g. Fe, Mn, and Zn, become poorly available when soil pH reaches 8 (Figure 9).

Figure 9. Plant nutrient uptake in relation to soil pH.



Source: Fast Grow Fertilizers (2019)

4.3.3 Soil organic matter (SOM)

SOM is the fraction of soil that consists of plant or animal tissue in various stages of decomposition. Organic matter can be grouped into three major types: (1) plant residues and living microbial biomass; (2) active soil organic matter, also referred to as detritus and (3) stable soil organic matter, often referred to as humus. The first two types of organic matter contribute to soil fertility because their breakdown through mineralization provides for essential plant nutrients such as nitrogen and phosphorus. The humus fraction is the final product of decomposition and contributes to soil structure and CEC. Highly productive soils have a SOM content of between 3% and 6%. SOM benefits the soil's physical, chemical and biological properties (Greenland 1980).

The SOC reservoir is not static but is constantly cycling between different global carbon pools in various molecular forms. While CO2 (carbon dioxide) and CH4 (methane) are the main carbon-based atmospheric gases, autotrophic organisms (mainly plants), as well as photo- and chemo-autotrophic microbes, synthesize atmospheric CO2 into organic material. Dead organic material (mainly in the form of plant residues and exudates) is incorporated into soil by soil fauna, leading to carbon inputs in the soil through organic material transformation by heterotrophic microorganisms. CO2 is emitted back into the atmosphere when soil organic matter is decomposed (or mineralized) by microorganisms. Soil tillage accelerates CO2 emissions and decreases SOM.

WaSA practices should focus on increasing SOM by mulching and/or the use of cover crops, including perennial grasses and legumes. For vegetable gardens, incorporating plant residues and manures into the soil, as is practiced by many organic farmers, can help increase SOM. As SOM contains roughly 55–60 percent carbon per mass, it is the largest terrestrial carbon stock on earth. Therefore, soils are a major reservoir of global carbon, providing many opportunities to further sequester carbon from the atmosphere. Consequently, WaSA practices that raise SOM increase crop productivity, make soils more climate resilient through increasing water and nutrient availability, and mitigate greenhouse gas emission through soil carbon sequestration. Finally, soil carbon is the lifeblood of most of our biosphere (Franzluebbers 2010).

4.3.4 Soil salinity

Soil salinity is measured as the concentration of salt in the soil in terms of mg/l or electric conductivity (EC) in dS/m (with 680 mg/L equivalent to about 1.0 dS/m). For example, seawater has a salt concentration of 30 g/l, which is equivalent to an EC of 45 dS/m. Soil salinity is often determined from a saturated paste extract of the soil, denoted by its EC_e. Accumulation of salts in agricultural soils typically arises from irrigation, with salts remaining in the soil after crop root water uptake and soil water evaporation. This "secondary salinization" typically results from shallow groundwater tables, when upward capillary flow to the plant roots brings additional salts into the soil rooting zone, and from waterlogging that causes elevated salt concentration by excess soil evaporation.

Salts in soil solutions create osmotic forces to soil water, thereby decreasing the ability of plants to extract water by root uptake. This results in salinity stress, similar to soil water stress, by increasing soil suction forces as the soil dries. Soils are considered saline and severely saline for EC_e values larger than 4 dS/m, and 16 dS/m, respectively, and are defined as sodic when the Na concentration as part of the soil CEC is larger than 15% (Ghassemi *et al.* 1995). Especially in dry climates soil salinity issues are likely to arise, leading to reduced crop yield as many crops are sensitive to salts. In such cases, crop water requirements and irrigation water volumes will need to be reduced, otherwise this will lead to over-irrigation and the lowering of the WUE, thereby triggering ponding, flooding and soil erosion. Crop salt tolerance information is available for most crops (Grattan 2016). High Na concentration causes soils to swell and disperse when wetted. Subsequently, soils become impermeable, causing flooding and erosion, rather than the infiltration of irrigation water. For sodic soils, WaSA management includes leaching of Na ions and soil reclamation by replacing exchangeable Na with Ca ions, by application of chemical amendments such as gypsum (CaSO4). Ghassemi *et al.* (1995) provides an excellent review on soil salinization.

4.3.5. Nutrient availability

Soil nutrient availability is affected by soil chemical and physical properties, such as SOM, soil minerals and texture, water holding capacity and drainage (Benton 2012). The three macronutrients essential for plant growth are Nitrogen (N), Phosphorus (P), Potassium (K); secondary nutrients include Calcium (Ca), Magnesium (Mg), and Sulfur (S). Seven micronutrients are essential for plant growth including Boron (B), Copper (Cu), Chloride (Cl), Iron (Fe), Manganese (Mn), Molybdenum (Mo) and Zinc (Zn) and sometimes Nickel (Ni). Since plants extract nutrients from the soil solution, any restriction to plant root growth, such as soil compaction and the lack of moisture, will affect nutrient uptake. Soil nutrient availability is also largely dependent on soil pH (Fernández and Hoeft 2009). Specifically, most plant nutrients are optimally available to plants within the range of 6.5-7.5 pH (Figure 9).

Nitrogen, Potassium and Sulfur appear to be less affected directly by soil pH compared to other major plant nutrients. Phosphorus, however, is more directly affected by soil pH. Most micronutrients tend to be less available when soil pH is above 7.5 and are optimally available at slightly acidic levels. Nitrogen and Phosphorus are the most commonly deficient macro-nutrients. Potassium is also increasingly deficient, especially in heavily cropped areas. Some crops, such as cassava, generally respond well to supplemental potassium applications. Plant visual symptoms (generally crop specific) are indicators of possible nutrient deficiency or excess. Although field kits for nutrient testing are available, many tests are quite complicated, so it is preferable to send soil and plant tissue samples to a laboratory for testing.

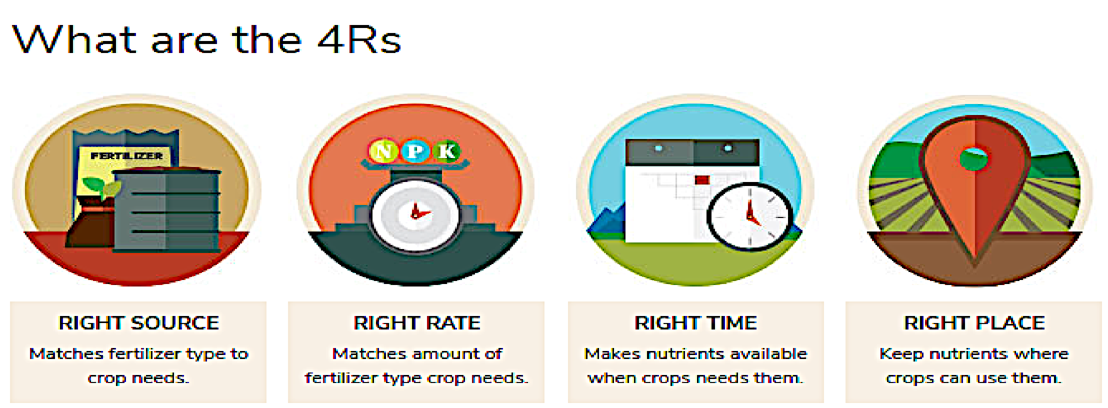
4.3.6. Soil fertility

Soil fertility refers to the capacity of soil to provide plant essential macro-and micronutrients in forms that roots can uptake. In totality, it reflects the soil's ability to support and sustain plant growth. Soil fertility is facilitated by (i) nutrient storage in SOM; (ii) nutrient recycling from organic to plant-available mineral forms; and (iii) physical and chemical processes that control nutrient absorption, availability, displacement and eventual losses to the atmosphere and water. Overall, the fertility and functioning of soils depend on interactions among the soil mineral matrix, plants and microbes. These interactions are responsible for both building and decomposing SOM, and therefore, for the preservation, cycling, and availability of nutrients in soils. **WaSA practices strive to ensure a balanced plant nutrition system (BNS), and to maintain SOM, ensuring that all required plant nutrients are present in balanced amounts and are not limiting plant productivity.** The literature on nutrient management for crops and cropping systems is extensive. However, a recommended text, *Plant nutrition for food security: a guide for integrated nutrient management* by Roy et al. (2016) provides an excellent review.

4.3.7. Fertilizer-use efficiency

Fertilizer-use efficiency is an important component of WaSA and has direct implications for productivity and reduction of greenhouse gas (GHG) emissions. The International Fertilizer Association (IFA) has proposed tools and technologies to assist farmers to correctly apply plant nutrients. These include use of soil testing, field mapping, tools for monitoring crop nutrient status, slow- or controlled-release fertilizers, and micro-dosing. IFA further advocates for Fertilizer Best Management Practices (FBMP) using the 4R approach, that is, using the Right nutrient source, at the Right rate, at the Right time, and in the Right place (Figure 10) (IFA, WFO & GACSA 2016).

Figure 10. The 4 R's of increasing fertilizer use efficiency



Source: IFA (2016)

5. WASA PRACTICES

In this chapter, we provide examples of key management practices that contribute to WaSA implementation. Many of the action areas presented focus on farm-level interventions and build on the concepts presented in the previous chapters. Wider scale adaptation requires policy enabling environments and decision-making, as evidenced by a recent paper by Mwamakamba et al. (2017) for selected irrigations schemes in SSA. We highlight the need for convergence of better practices with the creation of a shared vision by key stakeholders and enabling policies in subsequent chapters. Readers should be mindful that research and development of these practices, even when done in the local context, will often not be widely adopted without enabling support from the public and private sectors as well as from not-for-profit organizations. Investments and policies for an enabling environment and in farmer-learning processes are generally essential for meaningful scaling. We first address practices that optimize "green water"—soil water in the range of plant roots—followed by attention to blue water utilization/optimization at farm and farm community levels, such as micro reservoirs and the use of tube wells.

5.1 Agronomic practices to optimize water use

Agronomy is the science and technology of producing plants for food, fiber, fuel, medicinal use and land care. Good agronomic management practices are based on science aimed at optimizing the production of plants for food, feed, fiber and fuel, while protecting the environment. Thus, soil, water, pest, crops and the interactions among these factors are to be managed effectively and sustainably. Elements of productivity-resilience and risk-management also affect choices regarding WaSA practices. Good practices include the conservation of natural resources and protection of the environment from the field to the level of the watershed. Increasingly, water quality issues and water-use efficiency are becoming important considerations and are dependent upon adoption of better agronomic practices.

"The use of improved varieties, adequate production practices for irrigation, soil preservation, direct seeding, or zero or low tillage and water management are some of the most important practices aimed at counteracting the impact of climate change on agriculture." (IICA and Fundación Colegio de Postgraduados en Ciencias Agrícolas 2017: 122)

Basic agronomic principles, such as crop rotation, remain relevant for increasing resilience to biotic and abiotic stresses by enhancing nutrient cycling and reducing plant diseases, while serving as a strategy to mitigate against drought. Incorporation of nitrogen (N) fixing legumes in the cropping system as cover crops, for example, in rotation with cereal crops, is another important agronomic practice. Specifically, cereal crops generally have large N requirements, and legumes can largely complement these needs, while reducing fertilizer costs and providing nutritional value to human diets, as declared by the UN, in declaring 2016 as the International Year of Pulses (FAO 2016). This section provides examples of the kinds of agronomic practices that contribute to better production systems, building on WaSA.

5.1.1 Conservation agriculture

Conservation Agriculture (CA) is an approach to managing agro-ecosystems for improved and sustained productivity, which is aimed at increasing profits and food security while preserving and enhancing the resource base and the environment (FAO 2015, Kassam et al. 2018). The enhanced soil health from CA optimizes soil moisture toward remunerative sustainable intensification. CA is characterized by three interconnected pillars:

1. Continuous minimum mechanical soil disturbance (minimal soil tillage)
2. Permanent organic soil cover, with crop residues or cover crops,
3. Diversification of crop species grown in sequences and/or associations (crop rotations).

FAO emphasizes that conservation agriculture, CA, enhances biodiversity and natural biological processes above and below the ground. Soil amendments, including agrochemicals and plant nutrients, are to be applied optimally in ways that do not interfere with biological processes. CA facilitates timely operations and generally improves overall land husbandry for both rain-fed and irrigated production. CA is an important basis for sustainable intensification, as CA-adopting farmers generally incorporate integrated pest management (IPM), as well as nutrient and water management. Opportunities for inclusion of integrated crop and livestock systems are also increased as cover crops can also be used as feed or as pasture crops. Trees, including fodder trees, can often be included in CA-based farming systems. A thorough analysis of the pros and cons of CA in SSA Africa was done by CCAFS, showing the benefits of mulching, crop rotation and no-till agriculture (Corbeels *et al.* 2014).

The three pillars of CA are strongly interactive and synergies among the pillars are normally evident:

1) Minimum soil disturbance. Minimizing soil disturbance serves to maintain overall soil structure, including aggregate stability and porosity, both of which promote the exchange of water and gases and provide habitat to diverse populations of soil biota. Specifically, less soil disturbance improves water infiltration, builds SOM, and reduces soil erosion. In some farming systems, reduced tillage has been widely adopted by shallow-tilling a narrow strip of the planting/seeding row only. In these “strip tillage” approaches, a shallow soil cultivator is often placed on a tool bar just in front of the seed and fertilizer disc. Herbicides are generally used to control weeds in most no-till or reduced-till approaches. Relatively small no-till planters exist (Figure 11) and are employed increasingly by smallholders in South Asia, pulled by small 4-wheel or 2-wheel tractors. No-till hand-jab planters have been developed, but adoption has been modest. Especially in Eastern India and Bangladesh, progressive farmers are being trained and given incentives to purchase smallholder no-till planters. They often become service providers, by renting their planting services to other farmers after completing their own field operations.

2) Maintaining permanent soil cover. In CA systems, prior to planting, non-harvested crop residues from the previous crop (e.g. straw) are left on the soil to decompose *in situ*. This protects the soil surface from water or wind erosion and runoff, increasing soil organic matter and enhancing water infiltration into soils. In addition, crop residues may reduce soil evaporation losses, improve soil nutrition and support weed control. Increasing crop residues in the form of mulch has produced positive impacts in agricultural systems, although there are clear trade-offs related to energy use and livestock feed (Ranaivoson *et al.* 2017). Surface cover also favors enhanced levels of biological activity, by providing food for soil microbes, especially in tropical and sub-tropical areas. Using cover crops in rotation and in relay cropping, when practical, increases soil organic matter, even when combined with modest tillage (FAO 2015; Jat et al. 2020). Excessive plant residues on the soil surface may make planting with conventional equipment more difficult. In such cases, tractor-mounted knife rollers may be used to cut the plant material into smaller pieces. Crop residues should not be burned, as this creates significant air pollution and dramatically increases mineralization rates, leading to the rapid depletion of soil organic matter and nutrients from the soil. Preventing dry season fires from moving into no-till fields with residues is a serious problem for would-be CA adopters in Africa, and even in parts of Asia.

Inclusion of nitrogen-fixing legumes as cover crops contributes to soil nitrogen, thereby reducing the need for N fertilizers. Some cover crops such as velvet bean (*Mucuna puriens),* can crowd out pernicious weeds such as cogon grass (*Imperata cylindrica)* and sedges. Nevertheless, most smallholder farmers are often reluctant to invest in planting a cover crop as they have limited direct nutritional or monetary value. Therefore, the adoption of cover crops may be enhanced when the cover crop can be used for animal feed or has economic value. For example, in southern Africa, pigeon pea is seeded into a maize as a relay crop, thereby maintaining soil coverage after maize harvest. There is also a strong market for pulses such as pigeon pea in India.

As crop residues and cover crops are valuable feed sources for ruminant livestock, smallholders will consider trade-offs between removing residues to feed their animals and leaving them as soil cover. Sometimes, both functions may apply by grazing livestock on the field after harvesting of the main crop with the residues or cover crops. However, keeping animals out of the neighbors’ fields may require fencing. Living fences such as trees can introduce additional economic benefits (ICRAF 1994).

Figure 11. No-till planters are being increasingly manufactured widely; as an example, the picture shows a no-till grain drill built in Iran.

Source: Kueneman (2016b)

In Africa, smallholders have cattle and goats that open-graze crop residues for livestock feed (Gregorich *et al.* 2001). However, care must be taken not to overstock these fields, as this can negate the positive effects of residues and cover crops. A thorough meta-analysis of crops by Corbeels *et al*. (2014) concluded that reduced or no-tillage CA practices would only reliably increase grain yields, when combined with crop residue mulches or cover crop rotation. CA practices can often improve profitability even when yields are not improved significantly.

3) Regular crop rotations. Well-balanced crop rotations can neutralize many of the pest and disease problems, including those associated with reduced soil tilling, thereby also benefiting other specific WaSA practices. Rotation enables beneficial species of insects and microbes to multiply, helping keep pest and disease problems in check. Rotating crops also interrupts the life cycle of many weeds, resulting in a reduction in overall weed growth. These benefits translate typically into yield increases of about 10 percent of crops grown in rotation, compared to those grown in single crop monocultures. For example, including a nitrogen-fixing legume crop such as soybean, cowpea, pigeon pea, lentil and chickpea can enhance N in the farming system, while the reducing the N fertilizer needed for cereal crops.

Incorporating legumes in African farming systems is mixed. In the highlands of Eastern and Southern Africa. Phaseolus beans are grown alone and in association with maize, potatoes and other upland, cool-season crops, often on stakes. These same regions in Africa also grow pigeon peas at lower elevations for attractive export markets to India, which is a driver for maize-pigeon pea intercropping. The recent expansion of soybean in Africa as a cereal rotation crop merits attention, as the opportunities for continued local and regional markets are huge. Due to the processed poultry feed concentrates and vegetable oil demands, soybean has a distinct market advantage compared with most other food legumes. Crop rotation is a recommended agricultural practice. However, its benefits may be greater when combined with reduced tillage-based conservation agriculture. No-till soybean can be considered for smallholders. India is the fifth largest producer globally —nearly all by smallholders.

5.1.1.1 CA adoption

Historically, training smallholder farmers and Service Providers to adopt conservation agriculture approaches has been slow. Yet, the efforts of national training programs, such as the Indo-Gangetic Plains (IGP) initiative with India, Nepal and Bangladesh has been successful. These efforts are being scaled up with technical guidance by CGIAR, especially by CIMMYT, IRRI and IFPRI (Erenstein 2009). The water management practices associated with CA efforts has been of central focus in the IGP, which allowed expansion to double and triple cropping in many regions, through on-farm tube wells and pump sets. This has only been possible due to an investment in a national program that supports applied research, extension and policy. Additionally, donors such as USAID Feed the Future, BMGF and ACIAR were essential to its success, especially to support the CGIAR in a sustained engagement. Moreover, CA was built on two previous decades of support by the Rice-Wheat Consortium. Adoption of Conservation Agriculture-based Sustainable Intensification (CASI) approaches in Asia is expanding, especially in the establishment of wheat crops in South Asia. Such sustained and focused research for CA development and adoption by smallholders is rarely seen in Africa, nor in Latin America, except for countries in the Southern Cone including, Brazil, Argentina, Paraguay, Uruguay, the Bolivian lowlands and to some extent, Chile. The NGO, Conservation Farming Unit (CFU) based in Zambia is another important example; it has gradually garnered hundreds of thousands of smallholder adopters through persistent efforts in facilitation and partnership-development in four counties in southeast Africa (see: https://conservationagriculture.org).

That being said, Latin America is recognized as a leader in no-till farming practices in the tropics and sub-tropics, and nearly half of the farmland that is classified as no-till is located in Latin American countries (Derpsch et al. 2010, oo et al. 2019,) though adoption by smallholders is still limited.

While some smallholder adoption of CA has taken root in Zambia, Malawi, Mozambique and Tanzania, adoption generally lags behind in Sub-Saharan Africa. Medium and relatively large holding mechanized farmers in South Africa are adopting more readily (Thierfelder et al. 2018). As CA is knowledge-intensive, investment in proper training and empowerment for smallholder farmers is required for them to adopt CA practices. Public/private sector partnerships for investment in system changes, including for appropriate mechanization, are often limiting. The CFU, mentioned above, is catalyzing adoption through enabling of trainers and service providers in southern Africa, but a similar facility has not yet taken a strong rooting in West Africa, though more recently in Ghana the Buffet Foundation is beginning to foster smallholder farmer CA-enabling (https://centrefornotill.org/#home).

Adoption is widespread, with about 180 million ha under CA globally. Approximately 12.5% of all agriculture is now under CA systems (Kassam *et al.* 2009, 2018), which is substantial growth, considering that CA was only practiced in about 25 million ha in 1990. Medium- and large-holder farmers are the primary CA adopt-

Expanding the Service Economy for Sustaining Impact: Through its partners, the USAID-supported Cereal Systems Initiative for South Asia (CSISA) facilitated the **emergence of an additional 740 zero-tillage (ZT) service providers for wheat, reflecting an annual growth rate of 34%.** Aided by the project's efforts, **more than 47,000 smallholder households implemented ZT** for wheat in Bihar and Eastern UP India in 2015-16. (MacDonald 2017).

ers in Latin America. The agricultural land area with smallholder CA in Asia is estimated at 13 million ha and is growing, while estimates indicate that there are only 2.7 million ha of land under CA in all of Africa.

5.1.1.2 Other benefits of CA

Besides the reduced air pollution from crop residue burning that is avoided in CA systems, reduced tillage lowers the need for fossil fuel to run machinery, thereby decreasing greenhouse gas (GHG) emissions. Further, the increased levels of soil organic matter (SOM) and plant-available nitrogen typically found in CA soils reduces the need for synthetic fertilizers, many of which require significant fossil fuel energy to produce. Franzluebbers (2010) has reported on several solid cases where nutrient runoff has been reduced by CA practices. Brazil has presented a unique case study, where the Brazilian "Cerrados," once a land area unsuitable for agricultural production, have been transformed into some of the most fertile croplands on earth through CA adoption that has increased soil organic carbon (SOC). CA adoption in Brazil reduced soil erosion and consequent severe silting of rivers and reservoirs that resulted from heavy disc plowing of the Cerrados soils in the 70s and 80s, as documented by Sanderman *et al.* (2017).

CA adoption often enables farmers to sow rainfed crops several weeks before farmers practicing conventional tillage, who have to engage in several land preparation practices which can be delayed by the lack of rain and/or waiting for fields to dry enough for the next soil preparation activity. For example, there are thousands of smallholders who adopt sowing (reduced tillage) wheat into rice stubble in the Eastern Gangetic Plains (Eastern India and Bangladesh). By not plowing the rice stubble, they gain time. *See boxes below.* The earlier sown wheat crop matures before the extreme temperatures develop, prior to the next monsoon rice planting. Early sown wheat yields are generally greater, and production costs are lower because of reduced tillage costs and lower irrigation costs.

The United States and Canada are major adopters of CASI approaches, especially in the rainfed systems (primarily maize, soybean and wheat) in central USA. Supplemental overhead irrigation is increasingly part of the package, reducing risks of drought. Adoption of CASI approaches in furrow irrigated lands of the northwestern USA remains modest, though rapid and major expansion of no-till perennial crops (nuts and grapes) under drip irrigation is a form of CASI (Mitchell et al. 2019).

5.1.2. Soil erosion control practices

Agriculture runoff is considered a primary source of contamination of rivers, lakes and estuaries. Soil, pesticides, organic matter and fertilizers are washed from agriculture fields into streams across watersheds, creating wide-ranging ecological problems. WaSA must consider these strong negative effects and use practices that reduce runoff and erosion in general. Approaches such as adoption of conservation agriculture have been helpful in many areas, especially in Brazil. Far more care is required to reduce the "over-use" of inputs that result in environmental contamination through runoffs. An excellent review of theory and solutions to runoff issues is presented by Durán Zuazo *et al.* (2009).

Soil erosion is most often associated with surface runoff, leading to loss of fertile topsoil washing into surface water systems, creating water quality issues. Runoff and improper fertilizer application lead to water pollution and are major contributors to surface water eutrophication via nitrogen and phosphorus pollution. Therefore, most Northwestern European countries now monitor nitrogen applications, and farmers are penalized for excess application. Similarly, California is developing statewide policies to reduce groundwater contamination by field-applied fertilizers (European Fertilizer Manufacturers' Association – EFMA 2000). Without question, WaSA includes management of crop inputs in type, amounts, timing, and application methods that minimize water contamination. Also, practices such as rotating crops with N-fixing legumes (e.g., soybean, cowpea, chickpea, lentil or alfalfa) and reducing runoff through reduced tillage approaches, are effective in reducing fertilizer-caused pollution.

Similarly, many pesticides are washed into ecosystems and into potable water sources. The World Health Organization and FAO work in concert to enable global discussion and regulations. FAO hosts the Codex Alimentarius, the International Plant Protection Convention and the Rotterdam Convention, toward regulation of toxins in agriculture. WaSA embraces integrated pest management and judicious use of agriculture protectives, with special exclusion of use of Category[8] I Pesticides.

Arsenic and cadmium are common (non-input-derived) contaminates in agricultural waters. Arsenic is an increasing local concern in rice grown under irrigation in South Asia, especially in a few districts in Bangladesh, where arsenic-laden bedrock is the main source of groundwater arsenic. Areas of extreme toxicity are spatially complex, difficult to monitor, and greatly affected by location-specific tube well irrigation in the dry season. Events of low monsoon rainfall can increase arsenic concentrations in well water.

Erosion by surface runoff will eventually lead to excessive sedimentation downstream, overwhelming aquatic ecosystems, smothering freshwater breeding substrates and, in extreme conditions, degrading coastal and marine ecosystems, including coral reef ecosystems. Pathogens and pharmaceuticals from livestock and poultry operations are emerging as another cause of water quality issues. With continuing concentration trends in animal agriculture, concerns about the potential for impairment of water resources by livestock-based agricultural practices have increased. The US Environmental Protection Agency (EPA) highlights the steps to reduce farm-derived pollution and makes the following recommendations (EPA 2017):

- **Watershed efforts:** Collaborating with people and organizations, often across an entire watershed, is vital in order to reduce nutrient pollution. State governments, farm organizations, conservation groups, educational institutions, non-profit organizations, and community groups all play a part in successful efforts to improve water quality.
- **Nutrient management:** Applying fertilizers in the proper amount, at the right time of year and according to the right method can significantly reduce the potential for pollution.
- **Cover crops:** Planting certain grasses, grains or clovers can help keep nutrients out of the water by recycling excess nitrogen and reducing soil erosion.
- **Buffers:** Planting trees, shrubs and grass around fields, especially those that border water bodies, can help by absorbing or filtering out nutrients before they reach a water body.
- **Conservation tillage:** Reducing how often fields are tilled lessens erosion and soil compaction, builds soil organic matter, and reduces runoff.
- **Managing livestock waste:** Keeping animals and their waste out of streams, rivers and lakes keeps nitrogen and phosphorus out of the water and restores stream banks.
- **Drainage water management:** Reducing nutrient loadings that drain from agricultural fields helps prevent degradation of the water in local streams and lakes.

Though this set of recommendations was developed for US conditions, many of these practices also apply to landscapes with smallholder farmers, but application will require a collaborative approach through local governments and cooperatives.

Soil management practices that are relevant to WaSA focus primarily on soil erosion mitigation and soil

8. CFR 156.64: Toxicity Category (PDF). Code of Federal Regulations. Office of the Federal Register. Retrieved 2009-04-30.

conservation. On sloping lands, such techniques are employed to reduce soil erosion from heavy rains, especially problematic on freshly plowed, exposed soils. Such approaches are well presented by the so-called Sloping Agricultural Land Technologies (SALT) approach (Mindinao Baptist Rural Life Center 2012).

Conservation agriculture has proven to be an important practice to reduce soil erosion. So have other soil conservation practices including land preparation along contours, inclusion of raised soil contour bunds and other terracing, soil trenching to capture water, and building of grazed waterways. Potential recharging of ground water and water collection in local reservoirs and ponds are also major benefits of CA practices. Farming steep hill lands generally requires sustained soil erosion management practices, such as those promoted in SALT, and/or reinvestment in establishing and managing terraces, as was done in the highlands of Rwanda and Uganda (Figure 12).

Figure 12. Farming on steep hill lands in the highlands of Rwanda using terracing and other sustainable soil erosion management practices,

Source: Kueneman (2013)

5.1.3. Soil water management practices

In addition to those WaSA practices already listed, other soil water management practices may be applied by smallholder farmers, especially those relevant for semi-arid environments, to optimize water capture and storage and to complement existing irrigation options.

Ridging, Tied Ridges and Raised Beds: Such common practices include the building of soil ridges that may have broad tops (raised beds) or "pointed" ridges (ridging), in which seeds are planted, allowing rain and/or irrigation water to flow through and/or accumulate. By closing (tying) selected furrows, water is stored for infiltration and soil water storage or groundwater recharge.

In CA on permanent raised beds, the beds are reshaped every season prior to planting. Soil disturbance on beds is minimized. Beds alternating with furrows can facilitate furrow irrigation. More recently, this bed shaping is done simultaneously with the planting operation. Research on raised-bed wheat in The Punjab, India, has been very encouraging, both in terms of facilitating early planting to avoid heat stress during wheat maturation and to reduce irrigation costs. This method has been strongly promoted by CIMMYT's scientists.

Zaï/Chololo planting pits: This soil water management technique is intended to collect and direct rainfall into planting basins. It is widely applied in Sahelian countries, such as Mali, Burkina Faso, and Niger, and promoted as a WaSA practice in rain-fed agricultural systems in Eastern Africa (Nicol et al. 2015).

Such small-scale water harvesting methods can be very meaningful to smallholders of low population zones of the semi-arid. They are very labor intensive but can be applied for high-value perennial crops, such as banana or pistachio.

5.1.4. Other WaSA management practices

Other agronomic WaSA practices may include:

Integrated production systems: Until about a hundred years ago, most agricultural production systems were integrated systems that included livestock, pastures and/or fodder, sometimes with trees or fish culture (Asian rice systems). The subsequent widespread adoption of mechanization, and applications of herbicides and synthetic fertilizers eliminated the need for animal traction and manure application. However, the merits of integrated systems are being "re-discovered." For example, reduced tillage crop production has made it easy for farmers to alternate between row-crops and livestock pastures. One example has been adopted in the Brazil Cerrados, where some farmers make this shift as often as once every three years. These evolving systems are attractive from the perspective of increased biodiversity, but mostly appealing because of the economic benefits from more efficient use of inputs, including irrigation. Fuel costs for land preparation are also much reduced, as are the costs of farming equipment. Many farmers value diversifying risks by having part of their land in crops and part in managed pastures with livestock (ICRAF 2015).

Dr. Muhammad Aslam of ARS, reported that planting on raised beds in the Punjab reduces the amount of water needed for irrigation by 30% to 40% and, also improves crop yield by 15% to 25% (Nasrullah and Hussain 2014).

Also, tree integration into cropping systems has been shown to be economically and environmentally advantageous. Family farm Teak "Banks" are popular in smallholder systems in Benin. Households have 4 to 12 Teak trees around their homestead, which are cut and sold for income when needed by the family. *Faidherbia albida* is a legume tree integrated in cropping systems in the semi-arid Sahel and the dry savannas of southern and eastern Africa. Mature *Faidherbia* helps recover soil fertility, and because of its unusual reverse phenology, it does not compete with crops for sunlight. Its leaves are set in the dry season and fall in the rainy season. Eucalyptus strips are becoming increasingly common as part of the cropping systems of medium-holder farmers in the Brazilian Cerrados. Water use efficiency and nutrient cycling are central components of the enhanced integrated system.

***Weed management**:* Where water is adequate for crop production, weed control will become a critical component of integrated WaSA. With no herbicides available, a smallholder family farm generally cannot manage a field larger than 5 ha, constrained in area by the need to control weeds. Judicious, safe herbicide use by smallholders in Africa, especially in maize and cassava-based systems in Nigeria, is increasing. Training of weed control service providers on safe use of herbicides may be part of the weed control solution, which will enhance WUE. Mechanical cultivation with tractor or livestock-cultivators enables partial weed control, but usually at rather high fuel or labor expenses. In addition, yield reduction caused by weed competition for light, nutrient and water is enormous. Without herbicide use, there is no simple solution. Weed control in organic production systems that prohibits the use of herbicides, is problematic, especially where labor is either unavailable or expensive. However, research on the use of cover crops in organic agriculture is expanding and may prove effective in some situations. Without question, weed management is often a central determining factor in farming success or failure.

Planting pits are used as a precipitation harvesting method to prevent water runoff and to reduce erosion while conserving water for crop uptake. Basically, holes are dug 50-100 cm apart from each other with a depth of 5-15 cm. They are applicable for semi-arid areas with annual and perennial crops (such as sorghum, maize, sweet potato and bananas). These micro-catchments are best suited for medium permeability soils, with silts and clays, but use is also spreading in sandy soils in West Africa. To further increase crop production, organic matter (such as compost or manure) can be placed in the pits as a fertilizer (UNEP n.d.).

Multi-cropping: Practiced since the onset of agriculture, intercropping and relay cropping are generally practiced to optimize production and income per land unit. In intercropping, multiple crops occupy the same field at the same time. In relay cropping, two or more crops are overlapped during part of their growing seasons, with the first crop generally halfway to maturity before the second crop is sown in the same field. As the first crop matures, the second crop enters its exponential growth phase. These common practices by smallholders are effective ways to improve water-use efficiency, both for rain-fed and irrigated systems. For example, in Asia, legumes such as lentils, chickpeas or peas are grown with rice and wheat rotations, taking advantage of residual soil moisture from the cereal for legume germination and crop establishment, and then taking advantage of full sunlight after the cereal crop harvest. Without the need for additional investments, smallholders can relay crop with legume cover crops, including pigeon pea, into main crops such as maize. These cover crops can provide additional and much-needed biomass, protect soils, and contribute to nitrogen balance and water-use efficiency.

West Africa is the "center of origin" for cowpea *Vigna unguiculata*), where it is often seeded as an understory intercrop with sorghum and millet in the semi-arid zones. However, managing disease and pests of cowpea remains challenging in most of Africa. In Asia and Latin America, cowpea can be productive with minimum plant protection concerns, but markets are often limited. Peanut is an important smallholder crop that is often grown in rotation or by intercropping. In Africa, where groundnuts have been grown for hundreds of years, viral diseases and parasitic weeds such as striga (*Striga hermontfrica and Alectra vogelii*) are making low-input production challenging. Moreover, tightening regulations with respect to Aflatoxin contamination, resulting from plant infection by *Aspergillus spp*., has reduced groundnut international trade, especially to Europe.

Utilization of green manure/cover crops and fodder crops (GMCCs)**:** Cover crops are grown specifically to help maintain soil fertility and productivity. GMCCs increase soil organic matter (SOM) levels in at least one of two ways, by decreasing erosion and/or by adding fresh plant residue to the soil. Leguminous cover crops offer the added advantage of being able to fix nitrogen from the atmosphere and add it to the soil, thereby increasing the overall nitrogen availability for other crops. Cover crops are usually mowed, sprayed with chemical herbicides or otherwise killed before or during soil preparation for the next economic crop. A period of a week is generally recommended between the killing of the cover crop and the planting of a primary crop, to allow for some decomposition to occur, as well as to lessen the effects of nitrogen immobilization and allelopathic effects. However, in practice, crops are often sown into a cover-crop stubble soon after dry-down. Many cover crops are very valuable feed sources and a portion of the cover crop production is often used for ruminant livestock feed. In most situations, smallholder farmers need to think of the tradeoff between removing residues to feed their animals and leaving them in to feed the soil. A win-win situation would do both, and as yields and biomass increase over time, both become more feasible. Cover crops are often key to regeneration of soil biota, resulting in improved soil health and water-use efficiency (Schmidt et al, 2018)

***Integrated pest management*:** Integrated pest management (IPM) is defined as the tactical use of crop rotations and other beneficial plant associations, fostering conditions for beneficial insects, all in combination with judicious use of chemical pesticides, herbicides and fungicides, to control insect pest and disease problems. As in the case of CA, IPM adoption and application by smallholder farmers is very knowledge intensive. Combining CA and IPM, as linked farmer field school (FFS) curricula, could be a powerful approach toward WaSA adoption. Healthy plants reduce evaporation by shading soil and increasing transpiration, resulting in enhanced WUE – more crop per drop.

***Limiting of tractor traffic and utilization of biological plowing*:** Water infiltration into soils and its movement in the soil profile is compromised by soil compaction, including “plow pans” and by high soil bulk density. Use of tractors and other heavy equipment, and use of mechanical plows and discs, often contribute to detrimental soil compaction. The number of tractor passes over a given field is significantly reduced under CA, as compared to conventional tillage systems. However, increased soil bulk densities have been reported under CA. This can be corrected by limiting the use of heavy farm machinery when soils are wet and most prone to compaction, and/or by converting to a permanent raised-bed system. Often, in reduced tillage systems, occasional soil ripping or plowing may be needed. The inclusion of deep-rooted species, such as pigeon pea or vetches, in the crop rotation can also assist in reducing compaction. This practice of using crops like these for soil aeration is also called “biological plowing.” They can also increase root biomass and soil C, thereby contributing to improved soil structure, soil water infiltration and water retention.

***Precision fertilizer placement*:** Precision application of fertilizers has been practiced for many decades and is widely adopted by smallholders across the tropics. By increasing yield per unit of fertilizer, it also increases WUE. Several recent innovations in fertilizer coatings are enabling better placement for efficiencies and savings. The development of urea briquettes is an excellent example of this. The Urea Deep Placement (UDP) technique, developed by the International Rice Research Institute (IRRI) and the International Fertilizer Development Center (IFDC), is a good climate-smart solution for rice systems. Broadcast application is the usual technique for applying urea, the main nitrogen fertilizer for rice. This is a very inefficient practice, with loss of 60% to 70% of the nitrogen being applied and contributing to GHG emissions and water pollution. In the UDP technique, specially pelleted urea “briquettes” of 1 to 3 grams are placed at 7 to 10 cm soil depth after the paddy is transplanted. This technique decreases nitrogen losses by 40% and increases urea efficiency to 50%. UDP increases yields by 25%, with an average 25% decrease in urea use.

"UDP has been actively promoted by the Bangladesh Department of Agricultural Extension with IFDC assistance. The widespread adoption of the UDP technique in Bangladesh has had important impacts: farmers' incomes have increased thanks to both increased yields and reduced fertilizers' costs. Jobs have been created locally in small enterprises, often owned by women, to make the briquettes. There are now 2,500 briquette-making machines in Bangladesh. On-farm jobs have also been created, as the briquettes are placed by hand, which requires 6 to 8 days' labor per hectare. Higher yields and savings on fertilizer expenditures more than compensate for the additional field labor expenses. At the national level, imports of urea have been reduced, with savings in import costs estimated by IFDC at USD 22 million and in government subsidies of USD 14 million (2008), for an increase of production of 268,000 metric tons." (FAO 2014).

5.2. Irrigation water management

Globally, irrigation has expanded from about 40 Mha, at the end of the 19th century, when the population was under 1.5 billion. Currently, the area of irrigated land is over 320 Mha, and the global population exceeds 7 billion. About 70 percent of extracted water is used for irrigation and much of this is applied inefficiently. The rate of expansion is slowing, in part due to the negative side effects of water and land resource development. There are issues of rapid siltation of reservoirs, impacts on biodiversity, creation of conditions favorable for waterborne diseases, and decreases in water quality, due to highly inefficient fertilizer applications and misuse of herbicides and pesticides. Soil salinization is often a consequence of expansion of irrigation without adequate drainage facilities and strategies.

Being able to apply supplemental irrigation in predominately rain-fed agriculture can make huge differences in the resilience of crop production by reducing soil water stress. In such climates, at the onset of the rainy season, precipitation can be erratic, or altogether late. Especially for smallholders, planting a crop under such conditions is risky, and investments inputs can be frequently marginalized or entirely lost. In addition, plant nutrition and weed control may be jeopardized. Similarly, drought during crop flowering or grain-fill periods can have devastating effects. Having the option to save the crop by supplemental irrigation often makes the difference between a low yield or no crop, versus having a sustainable and reliable farm enterprise. For smallholder family farmers, tube wells and pump sets, and/or small ponds and reservoirs, can be a critical part of the WaSA menu of management options (Woodhouse et al. 2016).

Worldwide, over 351 million hectares are currently equipped for irrigation, of which 304 million hectares are equipped for full control irrigation. Yet, the distribution of irrigated land varies widely. Almost 40% of irrigated land is in East Asia and the Pacific region, and more than 30% is in South Asia. Only 5% of harvested land in SSA is irrigated (Ringler 2017).

On-farm monitoring of water stress or irrigation is complicated for most farmers in developing countries, as there is a lack of knowledge and availability of simple and cost-effective water measurement devices. In developed countries, irrigation management information systems have been developed and are integrated at the landscape level, to guide farmers. However, these require government-led investment and intervention. For example, California developed the California Irrigation Management Information System (CIMIS), which currently has about 6,000 registered users. Approaches like these are very helpful in guiding irrigation practices for large commercial farms but may not be as applicable for smallholders in developing countries, in general. However, the approach may eventually be considered in parts of India or Bangladesh, where many thousands of smallholders are irrigating the rabi (dry) season crops from tube wells. Many of these farmers now have cell phone connectivity and could request recommendations, based on their soil type and location.

Field irrigation water management practices are developed to optimize timing and control of irrigation water applications that will satisfy crop water requirements, while minimizing water losses, nutrients, and degrading the soil. Over the past few decades many texts and references have become available, for example, by FAO, introducing us to basic terminologies, irrigation systems, crop water requirements, and soil management options for reducing soil degradation, including by soil erosion and salinization. Efficient irrigation water management practices may also reduce the impact on offsite water quality. Most of these do not necessarily apply to irrigation practices for smallholder farmers, although principles still hold. Available technologies may need to be scaled down, simplified and made cost-effective. The Water Land and Ecosystem (WLE) program of the CGIAR concludes there are four key areas on which investments should focus in order to unlock the potential of small-scale irrigation: 1) increasing access to water resources, including sustainable groundwater, small reservoirs and rainwater harvesting; 2) catalyzing smallholder value chains, while removing information and marketing constraints; 3) creating policy synergies, such as aligned energy policies; and 4) taking a watershed perspective to reduce adverse environmental impacts (Ringler 2017).

Various development programs are emerging to encourage irrigation service providers to increase access to water for smallholder farmers, including in Sub-Saharan Africa. These programs have great potential, especially to support peri-urban horticulture, where many smallholders are growing in close proximity. IWMI is providing technical guidance and encouragement as part of its AG-WATER Solutions program. The urgent need for appropriate irrigation in Sub-Saharan Africa is of the highest priority, but public and private sector investment is lacking (Woodhouse et al. 2016). The Asian model of farmer-owned tube wells and pumps could be an option for Africa if the energy costs for pumping can be reduced. Solar powered pumps may be help reduce water extraction costs.

As irrigation is expanded for smallholder farmers, WaSA also must address water-borne food contamination issues. Specifically, waterborne organisms such as Listeria, *E. coli* and other human pathogens often enter food systems through the use of unsanitary water from irrigation and washing of produce that is not adequately cooked for sterilization. The World Health Organization (WHO), FAO and UNICEF have major programs on Water Sanitation and Hygiene (WASH) to support both rural and urban health, which emphasize the separation of waste, and especially microbial contaminates of food and drinking water systems. Hygiene has a fundamental role in WaSA, especially for crops whose products are not cooked, as is the case with many fruits and vegetables. Sprouts (e.g. from soybean, mungbean, alfalfa, etc.) require special hygiene, as the conditions for sprouting seeds are ideal for multiplication of microbial contaminants. Irrigation water should not contain human pathogens, especially if water is sprayed on to plants. Wash water used on harvested fruits and vegetables must be free of human pathogens and toxins. Use of untreated wastewater can also put farm families and workers at risk. WaSA and WASH dovetail in addressing food security, food safety and preventive medicine approaches to better health.

As the world's growing population requires increased agricultural production, there is a need for expansion of more efficient and sustainable irrigation water management practices. Ringler's policy brief (2017) highlights the drastic need for serious, but appropriate farmer-centric, irrigation expansion in Sub-Saharan Africa, and adds that: "If water resources are to be used both productively and efficiently, irrigation expansion must be coupled with investments in efficiency enhancement. Efficiency can be increased by adopting

Safe water is essential for safe fruits and vegetables consumed raw. **Washing can decrease but not eliminate contamination,** especially if the water is contaminated with chemicals and pathogens. Similarly, **a single event of irrigating the edible crop with pathogen-contaminated water can lead to severe disease outbreaks.** This is especially relevant in developing countries with limited accessibility to high-quality irrigation water in and around peri-uban areas where horticulture produce is often grown.

high-efficiency irrigation technologies or by improving water management. For example, through upgrading water-delivery infrastructure and strengthening institutional mechanisms such as groundwater governance, farmer-led irrigation management, and water-user associations.” (Ringler 2017: 1).

Table 1 Total harvested area (million ha) by region in 2010 and projected area in 2030.

	2010		2030	
Region	Irrigated	Rainfed	Irrigated	Rainfed
East Asia and the Pacific	136	139	145	151
South Asia	114	114	131	106
Former Soviet Union	13	94	14	99
Africa south of the Sahara	9	185	13	224
Middle East and North Africa	23	44	26	48
Latin America and the Caribbean	20	123	23	148
Developing countries	315	709	354	786
Developed countries	36	206	40	211
World total	351	915	394	997

Adapted from (Nelson et al. 2017).

Timing of irrigation depends on many factors, including irrigation type, crop water use (ET, see chapter 3.3), soil water holding capacity (see section 4.2) and crop rooting depth. Traditional irrigation systems are gravity-driven, i.e. they rely on gravity to distribute water across the field, using ditches and pipes. Typically, because of uneven water delivery, these gravity systems flood the field, applying water when crops already show signs of waterlogging stress and leading to reduced crop yields. Also, gravity-driven systems, such as border and furrow irrigation, are inefficient, especially for smallholder farmer fields and may cause soil erosion and downstream water salinity by surface and drainage runoff water (tail water). As a result of water application inefficiencies, applied irrigation water often exceeds the soil water holding capacity, leading to rising water tables nearing the crop rooting zone and increased soil salinity from upward soil water movement from shallow water tables. Mitigation of waterlogging and high soil salinity often require installation of drainage systems through ditches or subsurface drains. In such cases, field-scale water use efficiencies can be increased by reusing drainage and tail waters; however, drainage water reuse is likely to increase soil salinity levels in the long-term.

The fraction of water that drains beyond the root zone relative to the amount of applied irrigation water is defined as the **leaching fraction (LF).**
The leaching requirement (LR) has been defined as the minimum LF that is required over a growing season for a particular quality of water to achieve maximum yield of a given crop.

Worldwide, more efficient pressurized irrigation systems, such as sprinkler and drip, are increasingly implemented; however, these systems require individual farmer control of irrigation timing so water can be applied more frequently and efficiently as needed. Therefore, these pressurized irrigation systems often rely on groundwater pumping. Also, pressured irrigation systems are appropriate for supplemental irrigation in rain-fed systems, providing water in periods of low rainfall and droughts. However, gravity and pressurized irrigation systems are prone to generate soil salinity buildup, as irrigation water contains soluble salts that will ultimately salinize the field. This is so because most crops only take up "pure" water through their root systems, hence the salts remain behind in the crop root zone. Therefore, irrigated fields must occasionally be leached by excess water application, moving the accumulated salts back downward to avoid toxicity reducing crop yields.

Substantial research has been conducted to assess crop salt tolerance levels to determine the recommended leaching requirements. This has been summarized for many crops [see FAO publication by Ayers and Westcott (1985), and by Hanson *et al.* (2008)]. The latter publication shows model simulation results, demonstrating the need for excess irrigation water application for drip irrigation systems. A practical review with soil salinity drainage guidelines is provided in a publication by California's Division of Agriculture and Natural Resources.

The USAID Feed the Future (FtF) Innovation Lab for Small-Scale Irrigation provides a list of successful small scale irrigation projects at http://ilssi.tamu.edu/ and http://horticulture.ucdavis.edu/main/projects/irrigation_uganda.html. Selected irrigation systems that may uniquely apply to smallholder farmers are listed below (Figure 13).

Figure 13. Cambodian woman raising vegetables on drip irrigated raised beds with mulch

Source: Dr. Manuel Reyes, Kansas State University

5.2.1 Drip irrigation

In addition to large-scale and intensive irrigation systems in developed countries such as in California, USA and Israel, drip irrigation is becoming especially suitable for high-value horticulture crops, including for smallholder farmers. Drip irrigation can be applied through both surface and subsurface drip lines. The latter system allows for farming operations during the crop year and has proven to be functional for up to 10 years. Both systems allow for controlled water and fertilizer application through fertigation, thereby largely improving water and nutrient application efficiencies.

Fertigation has tremendous potential for **maximizing yields, while minimizing environmental pollution** that could help turn vast areas of arid and semi-arid land in many parts of the world into farmland, as well as preventing water from being wasted in conventional irrigation systems. Efforts to enable and **empower smallholder vegetable farmers to benefit from these drip fertigation technologies are underway.**

Increased use of drip irrigation combined with fertigation is expected, including in developing countries. The USAID Feed the Future Horticulture Innovation Laboratory is testing CA on permanent beds with drip lines in Guatemala, Cambodia, Nepal and Uganda, with considerable local partner interest in scaling up adoption. Dr. Manuel Reyes (2017) reported that water use efficiencies (WUE) in Nepal was enhanced by about 30% in combination with CA, by planting into mulched permanent beds. Simple drip emitters can work well for many smallholders, if properly trained, and if pump sets for tube wells are improved to filter debris to eliminate emitter blockage. Drip irrigation kits for smallholder farmers to use in concert with water tanks are available but will need to be upscaled to enable application in a larger range of field sizes. A significant challenge for drip irrigation systems is having clean water to minimize plugging of nozzles. There are several kinds of water filters used, but in all cases having relatively clean water (free of debris) is extremely important.

5.2.2 Tube wells, pumps and collapsible irrigation pipes

In regions with relatively shallow water tables, tube wells in combination with pumps are increasingly used by smallholders for second and third crops in a year, often with rice as the first (monsoon) crop. Similarly, tube well irrigation can be sustainable when adequate winter water from snow or rainfall is captured and returned to the groundwater. However, in many of the world's regions, there are examples in which this irrigation is practiced unsustainably (e.g., in much of North Africa and Central Asia), resulting in groundwater overdraft. This unsustainable water use results in declining groundwater levels that are too deep to make pumping economical, while yielding deep water with unacceptable contamination levels. Occasional pumping of groundwater may be quite effective for supplemental irrigation to ensure crop establishment or for use during dry spells in the growing season, such as in the Cerrados of Brazil. The use of wells may be productive for selected savanna lands in Sub-Saharan Africa, but will require investment, as electrical power is typically cost prohibitive. However, with the recent development of low-cost solar pumps, such as those developed by iDE, the energy constraint may be largely eliminated. However, security issues (theft of high-value solar pumps and batteries) in isolated rural lands will remain a challenge in much of the developing world, especially in Africa. In India, programs are now in place to sell energy from solar pump systems that is not used for irrigation back to the grid, which has been shown to encourage judicious pumping of water (IWMI 2012). Farmers with solar powered pumps become energy providers.

In tropical zones, solar radiation is often limiting crop productivity in the rainy (monsoon) seasons due to cloud cover. Consequently, yields are often better in the dry season under irrigation. For example, production of groundwater irrigated, dry-season rice in Bangladesh has more than doubled since 1990 when the government facilitated the importation of efficient and reliable pumps, as part of the Boro rice promotion, thus increasing production by 6 million tons (Hossain 2010). The Bangladeshi story is important, as it is a good example of an effective government policy.

One of the best, most widespread and least acknowledged water saving technologies is the low-cost, collapsible flat pipe [plastic water delivery hose pipes that move water from pumps across large distances (up to hundreds of meters), thus significantly reducing water loss, when compared to conventional flood irrigation. The lay flat pipe technology spread via the private sector (Justice 2017). On short runs of 60 meters, CSISA observed up to 30% savings in water loss (Justice *et al.* 2017).

5.2.3 Overhead irrigation sprinklers

Modern overhead irrigation systems are capable of Variable Rate Irrigation (VRI) and other water saving technologies. However, their general application for smallholders is very limited, though they may have merit if farmers are organized into sharing water users, such as through cooperatives. The administration and maintenance of large systems is generally complex. Most of these new approaches require major investments and are generally way beyond the financial access of smallholder farmers. However, small-scale systems may be applicable for smallholders as well, using low-cost generators coupled with a pump for a smaller number of sprinklers.

5.2.4 Small reservoirs

An additional option for making irrigation water available in times of water shortage is the building of small reservoirs, which temporally hold runoff water upstream from the cropped field, allowing the smallholder farmer access to water through gravity flow and/or axial-flow pumping for supplementary irrigation. In Asia, many such ponds are used for aquaculture, as well as for supplemental irrigation. Smallholder farmers with access to water sources like these are less vulnerable to irregular rainfall and can plant early, and late, to take advantage of better offseason prices. The change from the use of large dams and large reservoirs to community-based small dams demonstrates progress in the integrated management of water resources. This change has occurred due to three main factors: a) the design and construction of large damns is costly and can be structurally challenging; b) small farmers are unable to repay large investments for the larger dams; and c) the social benefits and profits of larger dams have not been proven (IICA 2015). To overcome these challenges, the government of Nicaragua and CATIE started a project to build 1,200 community-based reservoirs to benefit smallholder family farmers, including female farmers, who are farming on less than 3.5 hectares of land (IICA 2015). WaSA not only promotes the creation of small catchments for crop and livestock production purposes, but also ensures that water systems do not become contaminated with agro-chemicals or by soil erosion. While there is no significant data on the number and size of small reservoirs for irrigation in Central America and the Caribbean, the use of larger reservoirs is extremely important for irrigation in South America. In the northern region of South America, large reservoirs are commonly used for irrigation, including 68 reservoirs with a capacity of more than 2721 km^2 (IICA 2015).

5.2.5 Land leveling

Water savings for irrigation often requires proper land preparation, including land leveling for smallholder irrigation. These management practices affect water-use efficiency, directly and indirectly. In irrigated systems, especially in furrow- and field-flooding approaches, land leveling enhances the distribution of water during irrigation and reduces the time for field irrigation. Adequate irrigation water coverage is needed to achieve water application uniformity, thereby reducing water losses by leaching and runoff and optimizing water availability across the farmer's field. Either the excess or shortage of applied irrigation water leads to inadequate seed emergence, reduced crop yields and large soil evaporation losses. Laser-assisted land leveling (LLL) using heavy planks or graders to move soil has greatly assisted in the precision of land leveling. For example, smallholder farmers in the northern states of India have used medium size tractors and local service providers to level field plots as small as one hectare (Figure 14). Their adoption will depend on investment in training and in some cases equipment access facilitation. The linked factsheet by CIMMYT provides an example. Specifically, the governments of India and Bangladesh provide diverse subsidies that support the adoption of LLL.

Figure 14. Smallholder use of laser land leveler in rice/wheat rotations in Eastern India.

Source: Kueneman (2013)

5.2.6 Aquifer recharge

Recent satellite data indicates that one-third of Earth's major aquifers are unsustainably depleted and seriously at risk. As these groundwater levels drop, the entire system becomes unsustainable [Stockholm International Water Institute (SIWI)].

Using groundwater aquifers to irrigate crops is a widely used practice, especially in regions where available surface water flows are inadequate, or in times of drought. Yet, in many cases, farmers start to depend on this deep storage reservoir, resulting in severe groundwater overdrafts. This is a global phenomenon – from North and South America to Southern Europe, to the Arabian Peninsula and North and Sub-Saharan Africa, to Asia and Australia – virtually everywhere. As these groundwater levels drop, the system becomes unsustainable. As lands subside, groundwater quality is reduced, energy costs for pumping become limiting and people lose their water supply. Groundwater overexploitation is a major environmental global concern. In some cases, aquifer depletion can be managed through conjunctive use of groundwater and surface water. This option is under study in California, by restoring depleted ground water and aquifers by winter flooding of croplands when rain and snowfall are abundant (Harter and Dahlke 2014). In practice, existing streams and water conveyance systems are releasing excess surface water in periods of high availability and redirecting it to dormant agricultural fields that serve as infiltration basins. If successful, the banked groundwater can be used to satisfy agricultural and urban water demand during the dry years, leaving surface water available for critical environmental flows that maintain aquatic ecosystems.

5.3 Closing

Application of WaSA approaches are critical, given the urgency to sustainably meet the needs of humanity in this critical time of environmental instability, coupled with population expansion and urbanization. Expansion of sustainable irrigation, including supplemental irrigation in rainfed systems, will be essential, especially in Africa, where the greatest population pressures are mounting rapidly, and financial resources are so limited. Much of this irrigation for sustainable intensification will depend on responsible use of groundwater-based water extraction. Enforcement of policies on sustainable water use will also be essential towards adoption of WaSA. Good practices and good policies go hand in hand.

6. BIOLOGICAL APPROACHES

In light of population and climate change pressures (droughts, floods, storms and temperature increases), abiotic stress tolerance breeding is expanding as an imperative to address these challenges. This section will briefly summarize varietal development targeting tolerance to abiotic stresses (drought, waterlogging and salt tolerance) and use of biologicals, generally through probiotics[9], as strategies to address these stresses in the context of WaSA.

6.1. Breeding

The development of crop varieties with tolerance to drought, salt, and waterlogging is often a major goal in plant-breeding. For the last 50 years, conventional public and private sector breeding programs have selected for stress tolerance, with some success. One of the main challenges for breeders has been to combine abiotic stress tolerance with agronomic characteristics that maintain production levels. Generally, stress tolerance traits are multi-genic, adding to the complexity and inefficiency of reliably recovering the desired phenotypes following genetic recombination. The relatively recent use of molecular marker technologies and Quantitative Trait Loci (QTLs) show great promise for making breeding for stress tolerance more efficient, even without employing GMO approaches. This is because these technologies can be used to identify genotypes in segregating breeding populations carrying desired genes for recombination. Moreover, recent understanding and manipulations through precise gene editing approaches, such as "CRSPR-Cas9," "TILLING," "TALENS" and "Zinc Fingers," have opened doors for precision genetic modifications (DNA editing) in some countries, particularly those that may pass the regulatory gauntlet currently targeting GMO applications (Georges and Ray 2017). However, as science-regulation with respect to gene editing is still in its infancy, it is difficult, or too early, to predict how quickly these new tools will be widely applied to address genetic control of abiotic stresses in crops. For example, adoption of non-GMO status in the USA for varieties derived through gene editing may not be accepted in the EU, where the politics on genetic applications in food systems is extremely complex.

Currently, there is a disconnect between "academic" research on abiotic stress response and their adoption by commercial breeding companies (Gilliham *et al.* 2017). Moreover, links between public sector research on abiotic stress and the private sector's varietal development are often not connected. Consequently, the speed of application is slow. Nevertheless, for major cereal crops, such as rice, wheat and maize, effective breeding progress has been realized for specific abiotic stresses, including addressing the needs of developing countries. The CGIAR centers (e.g., CIMMYT, ICARDA, and ICRISAT) and strong NARS, such as EMBRAPA, ACIAR, ICAR, JICA, and the Chinese Academy of Sciences, along with several key donors, have invested in abiotic tolerance breeding, targeting food crops of importance to the needs of developing countries.

6.1.1. Drought tolerance breeding

Various plant traits are considered relevant for drought tolerance such as rooting depth, stomatal closure, leaf orientation, cellular turgor maintenance and resilience. Some varieties escape drought stress by maturing early. In some cases, short duration varieties survive and are productive in short rainfall periods. Within each crop maturity group, breeders/physiologists frequently observe varietal differences for drought stress and select those that exhibit increased drought tolerance. However, negative selection procedures are common. That is, breeding lines that have erratic productivity and larger-than-expected yield declines under drought stress may be discarded, even if they perform well under non-stress conditions. Also, drought and heat stress are especially problematic during pollination periods, as pollen viability is often compromised by abiotic stresses, such as heat and drought.

9. The term "biologicals" refers to microorganisms selected, multiplied and deployed for a desired outcome, such as nitrogen fixation, pest tolerance, and drought tolerance.

In the early 80s, there were efforts to breed against stomatal closure responses to drought, under the belief that genotypes capable of higher stomatal conductance under stress were advantaged, in that photosynthesis would continue. This approach was largely abandoned, probably because the overall drought tolerance response is generally due to a combination of factors. Moreover, stomatal resistance appears to be associated with plant survival under severe drought. Breeding sorghum for drought tolerance led to the selection of plants with delayed leaf senescence. The "stay-green" trait was associated with leaf longevity and its continued photosynthesis under drought during grain filling. The stay-green trait is often associated with reduced tillers, enlarged lower leaves, and decreased upper leaf size (Borrell *et al.* 2000) – three traits, which by themselves may contribute to drought tolerance.

As a side issue, there is an interest in taking advantage of positive varietal responses to "regulated deficit irrigation" (RDI), whereby drought stress at critical periods results in changes in secondary plant metabolites that contribute to fruit quality, especially observed in some tomato and grape varieties (Davies *et al.* 2002).

Employment of induced mutation-based breeding for abiotic stresses, including drought tolerance, has been practiced for several decades, with mixed results. The more recent coupling mutation breeding to TILLING (target-induced local lesions in genome) appears to help reduce deleterious mutations throughout the genome. Furthermore, it enables less costly, more precise genotypic screening by identification of polymorphisms within genes that can be associated with desired phenotypic variation (Taheri *et al.* 2017). However, in general, the polygenic nature of drought tolerance inheritance has been discouraging. In many breeding studies, no major specific genes have been identified that underpin water-use efficiency that can be used for genomic selection (Parent *et al.* 2015). New enthusiasm is emerging with the refinement of marker-assisted selection and associated use of quantitative trait loci (QTLs), which enable a selection based on genotypic as opposed to phenotypic expression (Kumar *et al.* 2015). A recent general review describes the breadth of research on drought tolerance breeding (Lou et al. 2019).

6.1.2. Salt tolerance breeding

Salinity constraints are often linked to irrigation practices, where salts, such as sodium salts from irrigation water, accumulate in the upper soil surfaces as soil water concentrates resulting from crop evapotranspiration (ET). Many of the above-mentioned approaches for drought tolerance breeding also apply to selection for salt tolerance. However, compared to drought tolerance, there are multiple examples of major gene-mediated tolerance expression. For example, Munns *et al.* (2003), identified a major Na transporter gene affecting salt tolerance in wheat. A "high-affinity" potassium transporter gene (HKT) has been identified in various cereal crops. This family of genes limits Na uptake associated with salt toxicity by selectively and preferentially pumping K ions across membranes, excluding Na. The HKT1-5 gene/allele, found in *Triticale monococcum,* has been integrated into many durum wheat varieties, and a major gene (GmSALT3) mediates levels of salt tolerance in soybean (Guan *et al.* 2014).

Seedling sensitivity tests have proven to be generally reliable for identifying progeny with tolerance to salt. IRRI, CIMMYT and national programs, for example, in India and Bangladesh, have released many rice and wheat varieties with relative tolerance. Kumar *et al.* (2015) described the use of marker assisted selection (MAS) approaches for salt tolerant rice breeding. Application of MAS for salt tolerance and other abiotic stresses is the "wave" in breeding methodologies, especially for polygenic inheritance, and where phenotypic selection is expensive or lacking in precision.

One recent insight is that a number of processes that improve stress tolerance occur in a limited number of cell types, making it difficult to assay at the molecular level without addressing cell specificity. For example, xylem parenchyma cells appear to be "gatekeeper" cells for salt exclusion (Henderson and Gilliham 2015).

To date, most genotypes with salt tolerance genes, inserted through backcrossing, have not suffered losses of yield potential when grown under non-salt-stress ecologies, compared to their respective iso-lines without the salt tolerance gene.

6. 1. 3. Flood tolerance breeding

The rice/wheat rotation is one of the most important production systems globally. For example, it covers about 14 million hectares in the Indo-Gangetic Plains of South Asia. Wheat follows monsoon rice in much of South Asia, where fields are often waterlogged at the onset of wheat planting. CIMMYT and NARS partners include parents with relative tolerance to waterlogging in crossing programs and discard progenies with high sensitivity (Setter and Waters 2003). High sensitivity to seedling waterlogging stress is highly heritable and can be avoided by attentive breeders.

While the efforts to breed for short-term flood tolerance have been much lower, when compared to drought or even salt tolerance breeding, there have been interesting examples of flood tolerance research in rice, wheat, maize and soybean. Some root crops, such as taro and even cassava, can thrive in hydromorphic soil environments, but this is due to natural genetic variation/tolerance. Efforts to breed waterlogging tolerance in root crops has been minimal.

Xu *et al.* (2006) elucidated a gene with an apparent ethylene-response factor conferring submergence tolerance in rice. Rice with this tolerance allele can survive for a week or more totally covered with water. The Sub-1 gene has been successfully incorporated into breeding programs in Asia (Septiningsih *et al.* 2009). Such varieties are now beginning to be deployed in the flood-prone zones in the Delta biome in Bangladesh and the Mekong Delta in Vietnam.

Soybean is often subject to short-term field flooding with very deleterious outcomes. Varietal differences in tolerance were identified in Vietnam and later appraised in Ohio, where a molecular marker (SAT_064) was associated with a QTL conferring a useful level of flood tolerance (Vantoai *et al.* 2001).

Recent attention to waterlogging tolerance in maize is driven by expanding markets for maize as a feed crop in parts of Asia, including as an in-year rotation crop with rice. Current estimates are for 1.5 million ha of rice/maize rotation in South Asia alone (Zaidi *et al.* 2015). In many lowland zones, late rains in the rice cycle result in waterlogging conditions for maize production during seedling stages. CIMMYT, in concert with the NARs in Eastern India and Bangladesh, are making progress in selection against high sensitivity to low soil oxygen conditions (hypoxia) in maize and wheat. Mano and Omori (2007) proposed three primary physiological mechanisms conditioning water logging tolerance: 1) the ability to grow adventitious/brace roots at the soil surface during flooding conditions; 2) the capacity to form root aerenchyma and (3) tolerance to toxins (e.g., Fe^{2+}, H_2S) under reduced soil conditions. Efforts to develop useful molecular markers to facilitate selection for components of tolerance are promising (Mano and Omori 2007). The markers will be even more critical in combining the diverse main traits associated with waterlogging tolerance.

6.2 Biologicals/plant probiotics

Probiotics are beneficial microorganisms that provide health benefits. However, it has been shown that plants can benefit from microbes residing in their habitat. Specifically, plant growth-promoting rhizobacteria (PGPR) do not only stimulate plant growth but may also protect plants from diseases and stresses (Kaur and Gosal 2017). In recent years, a number of companies, including many global agro-industrial giants such as Bayer, Syngenta, Monsanto, and BASF, are investing in identification of microorganisms that stimulate plant responses favorable to crop productivity and abiotic stresses. Soon we can expect an expanding diversity of marketed biological products that, under certain conditions, will enhance WUE, drought and waterlogging tolerance. If this approach succeeds, there may well be a need for special technologies to keep stored microorganisms viable in remote rural agro-ecologies. Rural refrigeration is often lacking or unreliable in many developing countries. Even after many years, in most of Africa the reliable marketing of high quality rhizobial inoculants for legumes is still a challenge without rural electricity for refrigeration to keep biologicals viable and effective until planting. Thus, inoculant longevity without refrigeration will be a future factor in WaSA, although solar-powered refrigeration may provide solutions.

Aflatoxin is particularly relevant in ecologies where plants are under moisture stress. Apparently, drought stressed plants are more susceptible to Aspergillus. Aflatoxin is also problematic in humid zones, when grain is not properly dried, and the fungus grows in the grain during storage. Groundnuts, maize and sorghum are often contaminated. "Aflasafe" is an exciting innovation that reduces the toxin/carcinogen aflatoxin in food systems, by saturating soil biospheres with strains of Aspergillus (fungus) that are very competitive, but do not produce the toxin. Aflasafe can be applied to the soil along with the seed at planting.

Dr. David Johnson, adjunct professor at California State University Chico and a molecular microbiologist at the University of New Mexico is documenting exciting, albeit preliminary observations suggesting cocktails of microbial inoculants—primarily of fungal species—when applied to desert soils in low volume compost, can jump-start soil functionality and significantly increase WUE. https://www.csuchico.edu/regenerativeagriculture/bioreactor/david-johnson.shtml. While it is too early to comprehend the full relevance of plant probiotics, levels of investment and examples of rhizobial inoculants and microbial plant growth stimulants abound. It is more than likely that probiotic markets will become increasingly important, including for smallholder farmers. Again, enhancing productivity, including through use of biologicals/probiotics, will enhance WUE in some circumstances. This industry will grow and will most likely contribute to restorative regenerative agriculture. Unfortunately, however, there is great scope for unscrupulous marking of pseudo-solutions as well. Farmers in developing countries can benefit from the science but may also be harmed by charlatans. We are entering a new world of applied biology in agriculture.

7. WASA POLICY

International agricultural development policies and their implementation are often marginalized by political tensions. Historically, conflicts arise from trans-boundary water-sharing, such as from cross-border river basins. Over 200 of the world's river basins are shared by one or more countries (Ghassemi *et al.* 1995). The policy and political dimensions that relate to WaSA are becoming "front-page" concerns. Historically, sectoral policies were common, addressing water needs and resources within individual sectors. Presently, it is important to incorporate water policies in overarching multi-sectoral, national and regional policies, requiring a change in traditional management practices (IICA 2015). While the agriculture sector is of utmost importance, being responsible for the food security of the planet, agriculture is at the same time the largest water-user globally and a major source of water pollution.

The unsustainable use of ground and surface water is an extremely serious issue in most North African countries[10]. Most notable is the case of South Asia, where about 1.2 billion people depend heavily on groundwater-based agriculture. To allow increased groundwater use, the Indian government subsidized solar-powered pumps, which led to enormous groundwater drawdown in some areas. This situation was so important that in 2016 a regional conference brought the governments and their development partners together to identify sustainable solutions. The governments formed a South Asia Groundwater Forum as a first step to enhancing cooperation, and water-smart policy solutions are ongoing. For example, in the case of India, farmers with solar-powered pumps will be able to sell excess electricity back to the national electric grid, so there will be a disincentive for inefficient power use in irrigation.

Enhanced water policy is critical in the Near East and North Africa zone (NENA), where per capita renewable water availability has decreased by two-thirds over the last five decades and is now only about 10% of the world average. Sustainably improving agricultural water productivity will be an important driver for enhanced production systems and growing populations. WaSA policies and strategies need urgent implementation to reduce political instabilities for the 400 million people in the NENA region.

As in CSA, WaSA brings together water management practices, policies and institutional engagement that are integrated and used in the context of adapting to—and mitigating the effects of—climatic change. The multiple challenges faced by agriculture and food systems are addressed simultaneously and holistically, which also helps countries to avoid counter-productive policies, legislation and/or financing.

Much can be learned from experiences in linking policy to technology development for sustainable intensification in the Indo-Gangetic Plain (IGP), where livelihoods are at stake for over a billion people who farm more than 250 million hectares. CIMMYT, IRRI, IFPRI and ILRI, as well as their national partners, have invested heavily in applied research for sustainable intensification of the IGP, in conjunction with key funding from donors such as USAID, ACIAR, BMGF and the Asian Development Bank. This has resulted in significant progress in appropriate mechanization and WaSA practices.

The IGP provides a useful example of landscape hydrology and policy considerations. The main water policy goals in the IGP are designed to address the challenges of about one billion people, including by providing adequate and safe drinking water, providing food security, developing hydropower for economic growth, mitigating floods and minimizing flood damage, maintaining water quality and enhancing the environment. Policies to support these goals include: conservation of both surface water and groundwater resources; increased efficiency of use (particularly in agriculture); development of more water storage; water treatment and reuse; various water institutional reforms; as well as continued efforts to further trans-boundary cooperation on water resources and to resolve interprovincial wariness of water sharing. The challenges

10 There are occasional large, very deep aquifers that are sometime considered as "fossil water," and can rarely be tapped economically. The Nubian Aquifer under Egypt and Libya is an example.

and policy goals point to a clear need for better river and groundwater models of the Indus watershed. Current models do not adequately address several processes and issues, including rainfall runoff and snow/glacier melt, in addition to floods and salinization processes. This inadequacy limits the ability to address climate change issues coherently (Kirby and Ahmad 2014).

As natural forests can serve as additional income for smallholder farmers, land-use issues across the forest and arable land interface often occur. The sustainability of many agro-ecosystems depends on healthy upstream forested watersheds, where mountainous soils are protected from erosion by diverse forests. Therefore, policy makers must be vigilant to ensure that they maintain those forests, despite their agro-economic value. The case for forest stewardship could not be made clearer than by the example of forest over-harvest in Haiti, where mountain- and hill-lands have lost most of their soil, and consequently, crop production levels are very low. Colonial "masters" in the 1800s were drivers of this catastrophe, by harvesting tropical hardwoods and exporting lumber to Europe. As a result, soils on hillsides are very badly eroded. Today, similar exploitation of the forests of Mozambique and Malawi, including by Chinese lumber extraction, are threatening the landscape (WWF 2015). WaSA practices prioritize the sustainability of the agro-ecosystem while supporting smallholder livelihoods. These issues need to be built into both public and private sector policies and action plans (Hui 2016, WWF 2015).

Making stakeholders aware of the challenges that climate change is posing, including steps to be taken toward adaptation, costs of up-scaling and out-scaling adaptation options, coupled with the costs of not taking action, is critical to having a full understanding of the severity of the situation (IICA and Fundación Colegio de Postgraduados en Ciencias Agrícolas 2017).

It should be noted that national governments should align their WaSA policies with other policies, such as those related to trade, energy pricing, agricultural subsidies and poverty reduction, as their combined implementation impacts water supply and demand (UNESCO 2015). Ministries of agriculture, as well as ministries of water, environment and other public sector entities will need to formulate mechanisms to coordinate and cooperate with one another to avoid duplication of efforts and achieve common goals. This organization is not only necessary within ministries, but should also include municipal level partners, NGOS and community groups, who all have a stake in the natural resources of their community and a desire to maintain and preserve its health (IICA 2015). Additionally, there is a need to invest, not only in physical infrastructure that allows for efficient and appropriate use of water resources, but also to invest in capacity building of major water users, to increase knowledge surrounding new technologies and best practices in integrated management of water resources.

As farmers worldwide adapt to increasing water scarcity, they need to be better supported with appropriate policies and the right mix of public and private investments to access knowledge and resources on how to produce more with less water (FAO 2016a). The policy, institutional and regulatory elements associated with WaSA are many and complex, depending on the country or region and on the general sensitivity of the population to water issues. This complexity and specificity demand focus on overarching issues for action by federal governments and their partners, with lower level solutions varying widely because of differences in the regional context. These include[11]:

1. Farmer-friendly import and export tariffs and subsidies on cost-effective WaSA technologies.

2. Engagement in significant and critical investments in farmer "learning-by-doing" forms of extension, such as farmer visits to field demonstration sites with adoption of successful WaSA innovations. Fostering of farm family communication enhancement, through cell phone, radio and TV, on WaSA innovations.

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11. Many of the elements here are drawn from lists prepared by IFPRI in the context of South Asia (http://www.ifpri.org/topic/water-policy).

3. Pricing of rural electricity and investment in rural energy access, including to production fields. Promotion of use of solar irrigation pumps through initial subsidies, in appropriate zones with adequate water recharge.

4. Promotion of irrigation service providers, while protecting farmers from price gouging.

5. Support for family farm access to fair credit and risk insurance, including for droughts and floods.

6. Drought monitoring with data feeds to farmers, banks and insurance providers.

7. Investment in infrastructure for blue water use, when economics are clear and sustainable.

8. Implementation of policies and regulations that do not allow for food products that are unsafe, such as those containing arsenic or aflatoxin.

9. Fostering of the participation of farmer representatives, including women, at public hearings on policies, institutions and regulations.

10. Fostering and enabling of water-user associations, especially for blue water-based irrigation environments.

11. Enabling and encouragement of the private sector to invest in entrepreneurial activities that promote the adoption of WaSA practices.

12. Government long-term support for research for WaSA and CSA practices.

8. SYNTHESIS AND REFLECTION

The adoption of sustainable agricultural practices is key to finding food security solutions in developed and developing countries where climate change amplifies the urgency and complexity of addressing socio-economic and environmental challenges. WaSA is a water-centric approach to a holistic methodology that sustainably optimizes agricultural production systems, by embracing efficient and effective crop, soil, water, pest, and livestock management practices to improve productivity. Its goal is to sustainably improve productivity, while optimizing water availability, access, and utilization. WaSA provides a shared vision for farmers, production agronomists, the science community, donors and policymakers to support and advocate for water resources to be central to the food security discussion and to be integrated across the agricultural food system.

The focus of this paper is on WaSA practices for smallholder farmers in developing countries, and soil biophysical parameters and processes, as these are most often less well understood. This paper draws connections between WaSA practices and Climate Smart Agriculture, as efficient water management is among key contributors to CSA goals of addressing productivity, adaptation and mitigation. In a companion summary brief, we present the key messages of WaSA that include management practices that (1) increase soil water storage, (2) minimize soil water losses through soil evaporation, (3) build soil organic matter, (4) reduce soil erosion, and (5) minimize contamination of available water resources. It is recommended that government agencies expand the vision of water efficiency to include on-farm practices that focus on building soil health and holistic water management. For example, where rechargeable groundwater resources can be tapped sustainably, investments and support that empower smallholders to invest in farmer-owned and controlled tube wells can enable supplemental irrigation, thus reducing risks and meaningfully enhancing productivity. Similarly, promotion of on-farm ponds for water saving and efficient utilization often calls for supportive policies.

Institutional support for WaSA is extremely important. For example, quality extension advice on judicious water management options and strategies can make a significant difference in farm productivity and water availability for all users. Institutional regulatory decisions can determine if and when water reaches irrigation canals, or even if irrigation canals are built and maintained. Most decisions, at any point in the management pathway, have implications for all subsequent management choices. For example, if irrigation water is not available in the distribution canals, individual farmers cannot benefit from the option of early planting. Likewise, if upstream farmers do not apply soil management practices that minimize soil erosion, such as conservation tillage or cover crops, heavy rainstorms may have enormous negative impacts for downstream farmers, despite their being cognizant of the need for erosion control.

Flowing water does not recognize field boundaries and, therefore the environmental impact of WaSA can only be realized collectively and through coordination of smallholders, for example, through cooperatives or water districts. If upstream farmers do not adopt WaSA practices, the benefits for downstream water users may be limited. WaSA also considers larger development policy choices, such as the intergovernmental issues of sharing water systems across different governments. In addition to institutional buy-in for WaSA practices, it is also necessary to instill a sense of ownership over the health of natural resources at the community level to promote the collective responsibility of not only water resources, but of all natural resources.

Most components of WaSA are knowledge intensive, and therefore typically will not be adopted through field demonstrations only. Therefore, agricultural extension approaches need to be adjusted to this reality to adequately enable farmer learning and discovery. For smallholder farmers, farmer field schools (FFS) have proven to be quite effective in empowering farmers to understand and implement innovative practices, such as the adoption of micro-irrigation, conservation agriculture or integrated pest management (IPM). Very often coherent inputs from both the public and private sector are synergistic, facilitating farmer adoption of improved management practices and jointly investing to develop farmer service-provider training. In developing countries, where institutional cooperation is often difficult, it is recommended that district, state and federal development planners create strategic alliances with relevant private sector partners and non-governmental organizations (NGOs). This is necessary to create a shared vision and roadmap for effective long-term cooperative action in training and farmer adoption. Governments, at all levels, should plan and invest in appropriate WaSA approaches, enabling farmers to use water for sustainable intensification of crop and livestock production and to satisfy local and national food security needs.

Adequate investment in "innovation adoption," in combination with the necessary research support, is often lacking. Farmers need to understand their choices— and the implications of those choices—in the immediate and longer terms. Broad adoption of development innovations takes time and funding, and requires support of local ministries, technical staff and international donors. While donors are continually striving to be at the cutting edge of the development curve to justify their investments, often becoming mesmerized by short-duration buzzwords, it is necessary to focus on long-term outcomes. The concepts and principles of WaSA, as presented in this report, are among the core elements for sustainable agricultural development that will be required in the near future, in order to increase the availability of and access to nutritious food, without Overexploiting available water and land resources.

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10. APPENDICES

Appendix 1

UCDAVIS
COLLEGE of AGRICULTURAL AND ENVIRONMENTAL SCIENCES
International Programs

IICA

March, 2018

Water Smart Agriculture (WaSA)- Brief

Addressing needs and opportunities for small holder farming

Key Messages

1. Optimization of rainfall and stored soil water underpins WaSA contribution to the broader goals of Climate Smart Agriculture (CSA). Soils provide for a huge water storage reservoir - a fact that is generally underappreciated.

2. Minimizing water evaporation from soil and other non-plant surfaces is essential for improving WaSA efficiency (more crop per drop).

3. Conservation agriculture and other WaSA practices minimize soil disturbance, surface runoff, erosion and water pollution, and promotes use of cover crops and residues, as well as crop rotations.

4. Farm-scale adaption of WaSA requires policy enabling environments and coordinated decision-making. We highlight the need for convergence of practices through creation of a shared vision of the development pathway by key stakeholders: public, private, as well as civil society partners.

5. WaSA practices are context dependent. There is no single "silver bullet" innovation, nor a fixed recipe that applies everywhere. This demands that decision makers, primarily farm families, need to understand their choices in water use, soil and crop management, and appreciate their implications.

6. Crop and soil management practices that increase soil organic matter (SOM) generally improve water use efficiency. SOM improves soil stability thereby reducing erosion, increasing water infiltration. SOM also increases soil porosity, while increasing soil water storage and deep soil recharge.

7. Water smart agriculture demands that water quality —safe water— be a priority for producers and consumers.

BRIEF | WATER SMART AGRICULTURE
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