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Potential of soil and water conservation technologies for dryland agriculture and forestry

REVIEW PAPER

Riziki Mwadalu[1]*, Abdalla Kisiwa[1], Mohamed Elema[1] and Mary Gathara[1]
[1]Kenya Forestry Research Institute, P.O Box 20412-00200, Nairobi, Kenya
Corresponding author's contacts: zikiemwa@gmail.com, +254 727555260 (ORCID ID-0000-0002-3278-0502)

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ABSTRACT
Objective: Drylands cover 41% of the earth's terrestrial landmass while in Kenya; they cover 80% of the land surface with production in these areas often impeded by soil moisture limitation thereby necessitating soil moisture conservation. The study aimed at identifying feasible soil moisture conservation technologies for agriculture and forestry development.
Methodology and Results: The current metadata analysis evaluated 80 reference materials comprising of journal papers, book chapters and conference proceedings; 38.8% being research conducted in Kenya, 31.2% was research undertaken in other parts of Africa while 30.0% was research done in other parts of the globe. Available data shows that mulching enhanced infiltration by 81% reduced runoff by 54% and enhanced crop yield by 39%; terraces enhanced infiltration by 8% and reduced runoff by 30%. Micro-catchments enhanced moisture content by 45%, reduced runoff by 63% and enhanced crop yield by 17%. Further, the use of polymers enhanced crop yield by up to 45%. In Kenya, soil and water conservation technologies have been tested in Machakos, Embu, Kitui, Busia, Makueni and Tharaka Nthi counties. The main impediments to adoption of these technologies in Kenya and other parts of the globe include increased risk of pest and diseases incidences; high labour requirements; require large land sizes and increased cost of production resulting from labour requirements. The research gaps identified by different researchers concerning soil water conservation technologies are: lack of effective dissemination platforms to highlight efficiency of the different technologies; cost-benefit analysis of the different soil water conservation technologies and limited data on potential of various soil water conservation technologies for tree growing in ASALs.
Conclusion: This review has revealed that adequate information on soil and moisture conservation technologies is needed and tailored to specific farmers' needs to enhance level of adoption. In order to realize the full potential of soil and moisture conservation technologies, effective dissemination platforms such as use of demonstration plots and farmers' field schools are required.
Key words: soil moisture, technologies, conservation, adoption, ASALs

INTRODUCTION

Drylands cover 41 percent of the earth's terrestrial surface, are home to a third of the global population and have some of the highest levels of poverty (Montimore *et al.,* 2009). Approximately 80% of Kenya's total land surface is arid and semi-arid lands (ASALs) holding 25 percent of the human population (Njoka, 2016). These ecosystems are unique in nature and require special attention to strengthen the economic base of the inhabitants and the national economy in general. These ASALs have the utmost potential for enhancing tree cover through intensified afforestation. Dryland forestry has great socio-economic and ecological benefits in Sub-Saharan Africa. They have important roles in livelihood diversification, provision of fodder, wood, food security, herbal medicine and environmental conservation (KFS, 2014). Despite their benefits, dryland forests have undergone severe degradation as a result of human, natural, policy-related and socio-economic dynamics resulting to their total loss in some areas (Teketay, 2005). Persistent droughts are the major limiting factors that affect plant growth and productivity in drylands (Vijayalakshimi *et al.,* 2012). Soil productivity in ASALs is also often reduced by low and erratic precipitation, reduced soil moisture resulting from low water holding capacity and through infiltration losses affecting plants' water use efficiency (Spitalniak *et al.,* 2019). Studies have shown that in ASALs, inadequate soil moisture is a major limiting factor to crop and tree farming since about 5-10% of precipitation is lost as runoff, <45% is transpired by plants while <45% is lost through evaporation (Mwende, 2019). Soil water conservation thus plays a crucial role in enhancing productivity of these areas (Spitalniak *et al.,* 2019). Efficient utilization of soil and water resources necessitates the adoption of appropriate soil moisture conservation techniques (Sivapalan, 2001; Vijayalakshimi *et al.*, 2012; Cheruiyot *et al.,* 2018). Most studies have focused on agricultural crops and potted nursery experiments (Vijayalakshimi *et al.*, 2012; Patil *et al.*, 2013; Danjuma and Mohammed, 2015; Abobbata, 2018). Zai pit technology in particular has the potential to alleviate water stress and enhance soil fertility thus enhancing productivity (Danso-Abbeam *et al.,* 2019; Kimaru-Muchai *et al.,* 2020). Furthermore, despite the benefits accrued to the use of soil moisture conservation technologies as outlined by Hamado (2011) and Mutiso *et al*. (2018), Njenga *et al.* (2021) observed that several SWC technologies promoted in drylands have not been adopted because of inadequate knowledge on the benefits and proper use of these technologies. The study further revealed that adequate information is needed and tailored to specific farmers' needs to enhance adoption levels. This metadata analysis thus sought to identify feasible SWC technologies for agriculture and forestry, and evaluate their effectiveness for enhancing moisture storage and erosion control in ASALs. It further sought to identify impediments to adoption of soil water conservation technologies earlier promoted in the ASALs of Kenya.

MATERIALS AND METHODS

The literature review was undertaken through purposeful sampling of relevant journal papers, book chapters and conference proceedings. The literature review involved in depth analysis of 80 literature materials all addressing issues of soil and water conservation for agriculture and forestry. The literature materials comprised 70.0% of research conducted in Africa with studies undertaken in Kenya accounting for 38.8% while 30.0% of the reviewed studies were conducted in other parts of the globe.

RESULTS AND DISCUSSION

Advantages and disadvantages of soil moisture conservation technologies : Water stress in plants mainly resulting from loss of soil porosity leads to low agricultural productivity (Shaxson, 2003). Restoration of degraded soils to curb water stress challenges in ASALs calls for adoption of soil and water conservation technologies. Karuku (2018) categorized soil and water conservation measures practised in Kenya into: Agronomic measures such as plant/soil cover, conservation farming methods and contour farming; Vegetative methods such as vegetative strips, live fences and wind breaks; Structural methods such as fanya juu, terraces, bunds, cut-off drains and barriers, and management measures such as selective clearing and area closures. The Metadata shows that agronomic and structural measures are the commonly used technologies in drylands. Table 1 highlights the advantages and disadvantages of soil and water conservation technologies being promoted in Africa and other parts of the globe.

Table 1: Advantages and disadvantages of common soil and moisture conservation technologies

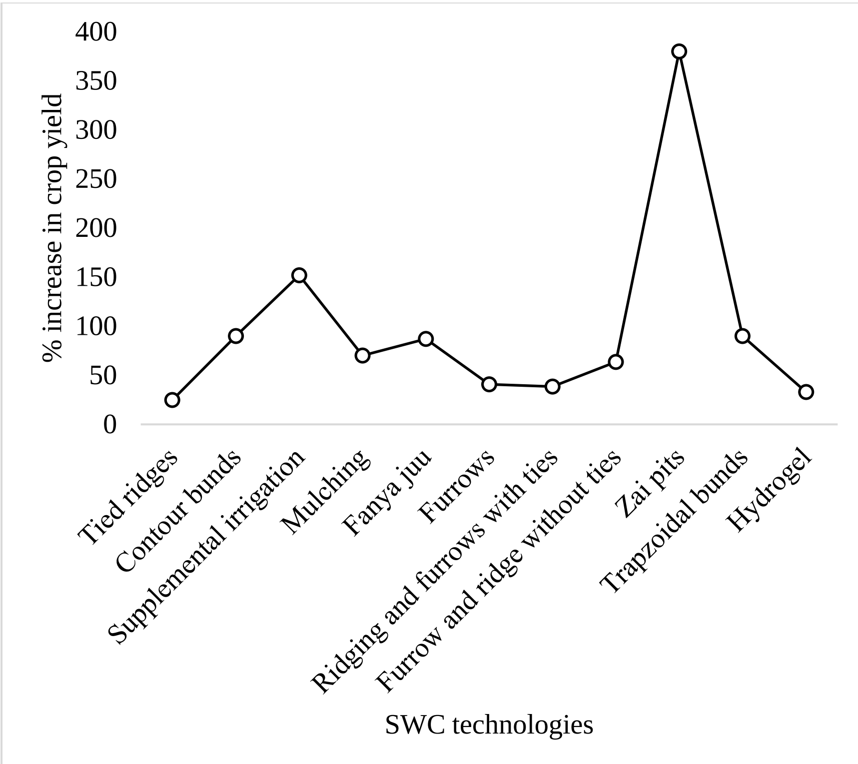
Category	SWC technologies	Advantages	Disadvantages
Agronomic	Conservation Agriculture	• Improves infiltration/Soil moisture content (*Karuku, 2018*) • Improves soil organic matter content (*Kathuli & Itibari, 2013; Karuku, 2018; Descheemaeker, 2020)* • Enhances soil structure (*Swaminathan et al., 2013; Karuku, 2018)* • Reduces labour needs (*Swaminathan et al., 2013*) • Enhances crop yields *(Kramer and Ceballos, 2017)* • Help in erosion control *(Swaminathan et al., 2013)* • Reduces cost of production through reduction of labour needs and reduced mechanization *(Swaminathan et al., 2013)*	• Increased risk of insect pest and diseases *(Kramer and Ceballos, 2017)* • Decomposition of crop residues may lead to temporary nitrogen immobilization *(Swaminathan et al., 2013)* • Increased weed pressure (*Descheemaeker, 2020)*
	Trash lines	• Decreases erosion and runoff (*Wakindiki et al., 2007,Karuku, 2018*) • Improves infiltration/Soil moisture content (*Wakindiki et al., 2007; Karuku, 2018*) • Improves soil organic matter content *(Wakindiki et al., 2007; Karuku, 2018)* • Improves soil structure *(Wakindiki et al., 2007; Karuku, 2018)*	• Require frequent maintenance *(Wakindiki et al, 2000)*
	Mulching	• Conserve soil moisture *(Kasirajan & Ngouajio, 2012; Ojha, 2018; Iqbal et al., 2020; Kuzucu, 2021)*	• Dry mulch materials increase risk of fire incidences *(Ojha,*

Category	SWC technologies	Advantages	Disadvantages
		• Organic mulch enhance soil nutrient status *(Ojha, 2018, Kasirajan & Ngouajio, 2012)* • Reduces weeds incidences by 92% *(Muttaleb, 2018; Iqbal et al., 2020)* • Reduce runoff by up to 43% using straw mulch *(Ojha, 2018; Iqbal et al., 2020)* • Reduces soil erosion by 86 - 97% *(Iqbal et al., 2020; Kuzucu,2021)* • Increases agricultural yields by 34.5- 47% *(Bharati et al., 2020; Iqbal et al., 2020)* • Reduces evaporation by 35 - 58% *(Iqbal et al., 2020; Kuzucu, 2021)* • Maintains good soil structure through organic matter addition (*Kasirajan & Ngouajio, 2012*) • Stone and gravel mulch enhanced tree growth by 70% *(Kuzucu, 2021)*	*2018; Iqbal et al., 2020; Kuzucu; 2021)* • Increase incidences of pests *(Ojha, 2018; Kuzucu; 2021)* • Woody mulch may lead to nitrogen immobilization during decomposition (*Kasirajan & Ngouajio, 2012*) • Labour intensive *(Ojha, 2018)* • Plastic mulch may increase cost of production *(Ojha, 2018)*
Vegetative	Legume intercropping	• Improves infiltration/Soil moisture content (*Bekele et al., 2021*) • High Land Equivalent Ratio *(Bekele et al., 2021)*	• High cost of buying legume seeds *(Descheemaeker, 2020)*
Structural	Pitting and micro-basins	• Decreases erosion and runoff (*Wiyo et al, 2000;Wakindiki et al, 2007; Kathuli & Itibari, 2013*) • Improves infiltration/Soil moisture content (*Wiyo et al, 2000; Wakindiki et al, 2007*) • Enhances crop yield *(Coulibaly, 2018; Danquah et al., 2019;Kimaru-Muchai et al., 2020)* • Improve soil fertility *(Danquah et al., 2019;Kimaru- Muchai et al., 2020)*	• Labour intensive *(Namirembe et al., 2015; Koome, 2017; Kimaru-Muchai et al., 2020)* • Difficult to maintain *(Koome, 2017; Kimaru-Muchai et al., 2020)* • Occupy larger portions of land *(Kimaru-Muchai et al., 2020)* • No immediate benefits *(Kimaru-Muchai et al., 2020)* • Water logging in clay soils *(Kimaru-Muchai et al., 2020)*
	Terraces	• Reduces runoff and sediments by up to 41.9% and 52% respectively *(Karuku, 2018; Ovalle et al., 2020; Deng et al., 2021)*	• High labour requirement (*Karuku, 2018; Doren and Rey, 2022*)

Category	SWC technologies	Advantages	Disadvantages
		• Improves infiltration *(Karuku, 2018; Wolka et al., 2018; Deng et al., 2021)* • Enhances soil moisture by 12.9% *(Deng et al., 2021)* • Improves soil organic matter content *(Karuku, 2018)* • Enhanced crop yields by up to 270% in Tanzania *(Deng et al., 2021)*	• High maintenance and construction costs (*Doren and Rey, 2022*) • Soil loss in poorly constructed terraces during rainy seasons *(Deng et al., 2021)*
	Earth bunds	• Decreases erosion and runoff *(Wakindiki et al, 2007; Kumawat et al., 2020)* • Improves infiltration/Soil moisture content *(Wakindiki et al, 2007)*	• Prone to damage by human beings *(Wakindiki et al, 2007;)*

Potential of soil and water conservation technologies in agriculture and forestry : Majority of the population in Sub-Saharan Africa are dependent on agriculture for its livelihood (FARMESA, 2003; Mwadalu and Mwangi, 2013) with smallholder agriculture accounting for 75% of agricultural production. Most smallholder farmers rely on rainfed agriculture, which is often hampered by constant drought, that leads to perennial crop failure. Arid and semi-arid lands (ASALs) account for 40% of the global landmass (Njoka, 2016) and 55% of land in Africa (Cussac, 2008). Climatic variation in ASALs has led to water scarcity on farmlands limiting agricultural production in these areas often leading to food insecurity (FARMESA, 2013; Wolka *et al.*, 2018). Enhancing soil water availability for crop production is often hampered by low and erratic rainfall in African drylands (Desta, 2016; Uwizeyimana *et al.*, 2018). There is thus need for feasible farming technologies that enhance soil moisture retention for increased agricultural productivity.

In Africa, soil water conservation technologies that have been promoted for improving agricultural production include: zai pits, tied ridges, mulching, furrows, improved fallows, cover crops, polymers, minimum tillage among others (Desta, 2016, Wolka *et al.*, 2018). These technologies have been observed to enhance soil water holding capacity, reduce nutrient losses through erosion control, improve soil structure through organic matter addition and enhanced soil fertility thereby increasing crop yields (Desta, 2016; Karuku, 2018; Mutiso *et al.*, 2018; Mwende, 2019). Figure 1 shows maize yield increase under different SWC technologies in ASALs. Over 80% of reviewed literature revealed enhanced crop yield emanating from adoption of appropriate SWC technologies.



Sources
Muthamilselvan et al., 2006
Adimassu & Mokennen, 2012
Kathuli & Itibari, 2013
Desta et al., 2016
Uwizeyimana et al., 2018
Wolka et al., 2018
Chimdessa et al., 2019
Kumar et al., 2020
Muchiri et al., 2020

Figure 1: Maize yield increase under selected SWC technologies

Data on the potential of soil and water conservation technologies for enhancing dryland forestry in Kenya is still outstanding. There is limited information on feasible soil and water conservation technologies for tree growing in the ASALs. This is despite the critical role played by dryland forestry for socio-economic development and ecological functioning (KFS, 2014). In Kenya where drylands account for over 80% of the landmass (Karuku, 2018; Njenga *et al.,* 2021) and harbour great potential for enhancing forestry development in the country (KFS, 2014); feasibility studies need to be done to identify soil and water conservation technologies for tree growing in the ASALs. A study by Hamado (2011) in Burkina Faso revealed that zai pits retained moisture by two to four folds and was efficient for growing woody vegetation.

Feasible soil and water conservation technologies for dryland agriculture and forestry in Kenya: Drylands consist of different ecosystems with patches of different vegetation types and variation in the limiting factors of soil moisture and nutrients (Flintan *et al.,* 2019). Dryland forests provide vital ecological services in terms of water storage, recharge of ground waters, water regulation, micro-climate regulation, reduced erosion and siltation, water purification and conservation of biodiversity (Karuku, 2018). Soil and water conservation efforts are therefore, paramount for improving the productivity of dry lands as well as improving the living standards of people living in these areas (Mutunga, 2001). Table 2 shows soil and water conservation technologies that are practiced by farmers in Kenya's dryland areas. The benefits of selected SWC technologies practised by farmers in Kenya is outlined in Table 3.

Table 2: Common soil and moisture conservation technologies practised in different parts of Kenya

SWC Technology	Areas technology is commonly practiced	References
Terraces	Machakos, Makueni, Kangundo, Matungulu, Masii, Mbiuni, Embu, Kitui, Tharaka	*FAO-AGL, 2000; Wakindiki, 2000; Mutunga., 2001; IGAD, 2007, Gachagu et al, 2018; Karuku., 2018*
Cover cropping	Machakos, Makueni, Kitui	*Lal, 1979; FAO-AGL, 2000; Karuku, 2014*
Agroforestry	Western Kenya region, lower Eastern region, Tharaka	*Lal, 1979; FAO-AGL, 2000; Karuku, 2014*
Buffer strips	Machakos, Makueni, Kangundo, Matungulu, Masii, Mbiuni, Embu, Kitui	*Mutunga., 2001; Danga et al., 2009; Karuku, 2018,*
Mulching	Machakos, Makueni, Kitui, Western Kenya region	*Lal, 1979; Gachene, 1999; Karuku., 2014,*
Contour farming	Machakos, Makueni, Kangundo, Matungulu, Masii, Mbiuni, Embu, Kitui	*Wakindiki, 2000; Mutunga, 2001; Karuku, 2018,*
Intercropping	Machakos, Makueni, Kitui	*Lal, 1979; FAO-AGL, 2000; Mutunga, 2001; Karuku, 2014*
Ridging	Machakos, Makueni, Kangundo, Matungulu, Masii, Mbiuni, Embu, Kitui	*FAO-AGL, 2000; Wakindiki, 2000; Mutunga, 2001; Karuku, 2018,*
Macro catchment systems (semi-circular bunds, trapezoidal bunds, retention ditches)	Machakos, Makueni, Kitui, Tharaka.	*FAO-AGL, 2000; Wakindiki et al., 2000; Mutunga., 2001*

Table 3: Benefits of selected SWC technologies promoted and practised by farmers in various parts of Kenya

Technology	Benefits
Terraces	Increases infiltration and base flow by 8%, reduces runoff by 30%, *(Gachagu et al., 2018)*
Mulching	Increases infiltration and reduces soil loss by 87% (Danga, 2009), Reduces runoff from surface placement by 54% and increases dry weight of wheat by 39% *(Danga, 2009)*
Micro-basins/Pits	Increases soil water content by about 45%, reduces runoff by about 63%, reduces sediment and nutrients yield by 96% and 86% respectively and increases maize yield by about 17% *(Sui et al., 2016)*
Contour farming	Reduces runoff by 12% and increases base flow by 6.5% *(Mwangi et al., 2015)*
Filter strips	Increases infiltration and reduces sediment yield by 75% *(Mwangi et al., 2015).*

Conservation agriculture	Reduces runoff by 50%, increases wheat yield by about 11% *(Araya et al., 2010).*
Trash lines	Increases maize grain yield by 0.32t/ha *(Okoba et al., 1998).*
Hydrogel	Increased *Melia volkensii* survival rate by 40% (*Eryau, 2017*)
Biochar	Enhanced Casuarina height by 20.2% and DBH by 30.2% (*Mwadalu et al., 2021) and maize yield by 32% in Western Kenya (Cernansky, 2015)*

Adoption levels of soil and water conservation technologies in Kenya: Despite the benefits accrued to the use of soil and water conservation technologies in the ASALs, their adoption levels have remained low. Inadequate knowledge of soil water conservation technologies among farmers has hindered their uptake (Njenga *et al.,* 2021). Studies have shown that farmers knowledge of a technology determines their level of adoption. The study by Njenga *et al.* (2021) also revealed that adoption of soil and water conservation technologies especially in Kenya has been hampered by inadequate knowledge on the benefits and proper use of the technologies. Low knowledge has been linked to farmers' poor access to timely and quality information (Atampuagre, 2011). Other studies further reported that technology adoption is a function of several factors such as age, education, land-use, family size, landholding size, access to labour, access to capital and perceived profitability of the technologies (Muriuki and Macharia, 2011; Njenga *et al.,* 2021). Knowledge on proper use and benefits of soil and water conservation technologies is crucial for increasing their uptake. Table 4 summarizes factors influencing adoption of soil and water conservation technologies. Reviewed literature revealed that education status of the household head significantly influenced adoption of SWC technologies at household level. Access to extension services and training was also positively correlated to adoption of SWC technologies. Further, net family income was identified as an important factor influencing the decisions of farmers to adopt SWC technologies. Only 1.4% of the reference materials indicated access to financial credit as a major impediment to adoption of SWC technologies in the ASALs.

Table 4: Factors influencing adoption of soil water conservation technologies

Factors influencing adoption	**Significant (+) Insignificant (-)**	**Reference sources**
Education status of household head	+	*Asafu-Adjaye, 2008; Asfaw and Neka, 2017; Kerse, 2018; Wordofa, 2020;Belachew et al., 2020; Nyirahabimana et al., 2021*
Access to extension services and training	+	*Asafu-Adjaye, 2008; Asfaw and Neka, 2017; Kerse, 2018; Wordofa, 2020; Belachew et al., 2020*
Size of farmlands and slope	-	*Asafu-Adjaye, 2008; Teshome et al., 2014; Kerse, 2018; Wordofa, 2020; Belachew et al., 2020*
Access to labour	+	*Kenduiwo, 2007; Asfaw and Neka, 2017*
Sex of household head	+	*Asafu-Adjaye, 2008; Kerse, 2018; Wordofa, 2020; Belachew et al., 2020*
Age of household head	-	*Asfaw and Neka, 2017; Kerse 2018*

Factors influencing adoption	**Significant (+) Insignificant (-)**	**Reference sources**
Distance of farmlands from homesteads	-	*Asfaw and Neka, 2017; Wordofa, 2020*
Access to credit	+	*Belachew et al., 2020*
Net family income	+	*Kenduiwo, 2007; Asafu-Adjaye, 2008; Karidjo et al., 2018*
Land ownership	+	*Danquah et al., 2019; Kimaru-Muchai et al., 2020*

Research gaps on soil and water conservation technologies for dryland agriculture and forestry: Over 60% of reviewed literature has highlighted the benefits accrued to soil and water conservation in agriculture landscapes especially in the ASALs (Adimassu & Mokennen, 2012; Kathuli & Itibari, 2013; Desta *et al.*, 2016; Uwizeyimana *et al.*, 2018). The benefits in terms of erosion control, soil fertility enhancement and increased soil moisture retention cannot be overemphasized (Wolka *et al.*, 2018; Chimdessa *et al.*, 2019; Kumar *et al.*, 2020). However, most literature focusses on the benefits of soil moisture technologies for crop yield improvement. Despite the benefits accrued to these technologies, existing research gaps need to be addressed to ensure their full potential is realized and adoption enhanced. Table 5 shows identified research gaps, which need to be addressed to enhance agriculture and forestry productivity.

Table 5: Research gaps on soil and moisture conservation technologies

Research gaps	**Reference sources**
Lack of suitable dissemination platforms for SWC technologies	*Muriuki and Macharia, 2011; Mlenga, 2019; Njenga et al., 2021*
Validation of selected SWC for tree growing in ASALs	*Data on potential of SWC for tree growing is limited (Researcher's own observation)*
Cost-benefit analysis of various SWC technologies being practised by farmers	*Coulibaly, 2018; Njenga et al., 2021*
Effect of biodegradable mulches on plant growth, soil biota, erosion control, soil fertility and yield	*Kasirajan & Ngouajio, 2012; Iqbal et al., 2020*
Lack of guidelines for extension service providers and smallholder farmers on proper use, effectiveness and efficiency of various SWC technologies	*Kimaru-Muchai et al., 2020, Swaminathan et al., 2021*
Factors leading to adoption lag of SWC technologies in ASALs	*Nyirahabimana et al., 2021*

CONCLUSION AND RECOMMENDATIONS

The metadata analysis shows that soil and water conservation technologies harbour great potential in enhancing dryland agriculture and forestry. This is due to their role in enhancing soil moisture storage, increasing infiltration, soil fertility improvement and soil erosion control. Recent studies also show that upcoming technologies such as the use of hydrogel and biochar offer great potential to enhance crop and tree growing in ASALs. To realize the full potential of these technologies, effective dissemination platforms need to be put in place such as use of demonstration plots and farmer field schools' approach. Inadequate extension services in agriculture and forestry are some of the major impediments to the adoption of SWC technologies in the ASALs that needs to be addressed to ensure farmers have access to quality information for decision-making at household level. Based on the available data, there is also need to validate the data on the potential of selected SWC such as zai pits, trapezoidal bunds, mulching and hydrophilic polymers for tree growing in the ASALs due to unlimited data; most studies are biased towards agricultural crops with short rotational periods.

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