OVERVIEW OF CONSERVATION TILLAGE PRACTICES FOR DEVELOPING AND SUSTAINING CLIMATE CHANGE RESILIENT SOILS IN SUB-SAHARAN AFRICA

A TALAJKÍMÉLŐ MŰVELÉSI RENDSZEREK ÁTTEKINTÉSE AZ ÉGHAJLATVÁLTOZÁS HATÁSAHOZ ALKALMAZKODNI KÉPES TALAJOK KIALAKÍTA ÉS FENNTARTÁSA CÉLJÁBÓL A SZUBSZAHARAI AFRIKÁBAN

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Abstract

Change in hydrological intensity in the form of rainfall is predicted to worsen in Southern Africa. Compounded by consequences of higher global temperatures such as heatwaves, may render many Southern African regions prone to drought. The agricultural sectors of the latter regions are faced with a greater threat. In view of such concerns, the aim of this study is to review the available literature to evaluate climate-smart agricultural practices suitable for the mitigation of climate change challenges faced by farmers. Climate-smart agriculture practices are advocated as alternatives for mitigating and managing climate change problems, increasing food production, and improving rural people's livelihoods. This review paper is aimed at the bestowed benefits of climate-smart agricultural practices on soil physical, chemical, and biological and its association to mitigate or manage predicted climate change effects in SSA.
Keywords: *CA (Conservation Agriculture), Tillage, Sub-Saharan Africa (SSA), Climate change, Climate-smart agriculture (CSA)*
JEL code: *Q1, Q54, Q56*

Összefoglalás

A hidrológiai intenzitás csapadék formájában bekövetkező változása az előrejelzések szerint tovább romlik Dél-Afrikában. A magasabb globális hőmérséklet következményei, például a hőhullámok miatt sok dél-afrikai régió ki van téve a szárazságnak. Ez utóbbi régiók mezőgazdasági ágazatai nagyobb veszélynek vannak kitéve. Az ilyen aggodalmakra tekintettel e tanulmány célja a rendelkezésre álló szakirodalom áttekintése az éghajlati szempontból intelligens mezőgazdasági gyakorlatok értékelése érdekében, amelyek alkalmasak a gazdálkodók előtt álló klímaváltozási kihívások enyhítésére. A klímaorientált okos mezőgazdasági gyakorlatok alternatívát nyújtanak az éghajlatváltozással kapcsolatos problémák enyhítésére és kezelésére, az élelmiszertermelés növelésére és a vidéki emberek megélhetésének javítására. Ez az áttekintés a klímaorientált okos mezőgazdasági gyakorlatok által a talajfizikai, kémiai és biológiai gyakorlatokban rejlő előnyök megismerését célozza, és

ezeknek az összefüggéseknek az éghajlatváltozás előre jelzett hatásainak enyhítését vagy kezelését a Szaharától délre eső területeken.
Kulcsszavak: *talajkímélő mezőgazdaság, talajművelés, Szubszaharai Afrika, éghajlatváltozás, klímaorientált okos mezőgazdaság*
JEL kód: *Q1, Q54, Q56*

Introduction

The agricultural sector plays a vital role in Sub-Saharan Africa (SSA) in, supporting livelihoods and safeguarding food security for many human populations. However, the region is facing various challenges including negative climate effects on agricultural production. Droughts, land degradation, diminishing crop yields, decreased biodiversity, and food insecurity (KIBOI et al., 2017; SHEPPARD et al., 2020). Change in weather affecting the physical, chemical, and biological properties and human well-being poses a threat to sustainable food and fibre production in SSA (BATTISTI - NAYLOR, 2009; SERME et al., 2015). Climate-smart agriculture practices are advocated as alternatives for mitigating and managing climate change problems and developing resilient climate change soils in SSA.

Conservation tillage (CST) refers to an umbrella term describing holistic techniques employed in farming to minimize soil disturbance by preventing erosion, and conserving moisture, and organic matter. Conversely, the conventional tillage (CT) method involves ploughing the soil to a significant depth to invert and break up the soil (OBIA et al., 2020). It is effective in burying crop residues and controlling weeds but can lead to soil erosion and loss of organic matter (ASFAWESEN MOLLA et al., 2021; KARUMA et al., 2014). Distinct from CT, CST promotes the retention of crop residues and maintains permanent soil cover. Reduces soil disturbance (OBIA et al., 2020; SIMWAKA et al., 2020). The significance of these practices in agriculture is but not limited to enhancing soil hydrological dynamics and preventing soil erosion. They also improve water infiltration and enhance carbon sequestration, thus improving the soil's resiliency to the impacts of climate change.

Farming in the SSA region is susceptible to climate change impacts, such as erratic rainfall patterns, recurrent droughts, and increased land degradation (EZE et al., 2020; OBIA et al., 2020). Already many regions of the continent are characterized by soils with low fertility (ZINGORE et al., 2015). Moreover, the practice of CT aggravates these challenges, by rendering the soil prone to run-off, organic matter (OM) oxidation and water loss (GITHONGO et al., 2021; MARTÍNEZ et al., 2017). Therefore, there is a need to adopt conservation tillage practices that can enhance the resilience of soils to climate change and promote sustainable agricultural production.

In view of such concerns, the overview aims to review the developed and implemented conservation tillage practices to evaluate their suitability to the mitigate challenges posed by climate change. This paper will discuss the potential threats of climate to SSA and the benefits of adopting conservation tillage to buffer current and future climate threats. Conservation practices extend an opportunity for the SSA region to safeguard sustainable and productive food and fibre production and livelihood resilience during climate change. Hence after assessing conservation tillage practices in SSA, this overview aims to contribute to the knowledge base and promote wider adoption of these strategies for the benefit of farmers and ecosystems.

Methodology

This review paper was compiled based on various published journal papers related to tillage methods on the physical, chemical, and biological properties of the soil.

I. Soil tillage concepts

- **Conventional tillage/traditional tillage (CT): "**involves primary and secondary cultivation as the major means of seedbed preparation and weed control. Conventional tillage typically includes a sequence of soil tillage, such as disking after harvest, ploughing after the first rain and harrowing, to produce a fine seedbed"(BOTHA et al., 2015)
- **Conservation tillage (CST): "**Conservation tillage is the collective umbrella term commonly given to no-tillage, direct drilling, minimum tillage and or ridge tillage, to denote that the specific practice has a conservation goal of some nature. Usually, the retention of 0.3 surface cover by residues characterizes the lower limit of classification for conservation tillage, but other conservation objectives for the practice include conservation of time, fuel, earthworm, soil water, soil structure and nutrients. Thus, residue levels alone do not adequately describe all conservation tillage practices" (SAH et al., 2008).

Table 1. Distinguishing features between conservation and conventional tillage / 1. táblázat: A hagyományos és a talajvédő talajművelés megkülönböztető jellemzői

Conventional tillage	**Conservation tillage**
Soil preparation, utilising science, and machinery to control nature	Minimal natural activity disturbance
The use of excessive machinery for tilling the soil results in erosion of the soil.	Zero-till/considerably minimised tillage (biological tillage)
Prominent wind and water soil loss	Less wind and water soil loss
Low moisture infiltration	Increased water infiltration rate
Use of synthetic minerals/ FYM/manures	Use of pre-crop residues/manure
Unrestricted movement of farm machinery, elevated soil compaction	Managed traffic, compaction only in permanent wheel lines, cropland free of compaction
Bad stress adaptation and great yield losses resulting from stress conditions	With more stress hardiness, yield losses are less under stress conditions
Efficiency gains diminish with time	Efficiency gains increase with time
Above-ground biomass removal/burning	Mulch retention (permanent cover)

Source: BHAN - BEHERA, (2014) / Forrás: BHAN - BEHERA, (2014)

II. Predicted Changing Climate Effects on the Southern African Region

Consequences of changing climate Increased land degradation (SHEPPARD et al., 2020).

- Decreased soil fertility
- Decreased crop yields
- Loss of arable land
- Decreasing biodiversity
- Negative impacts on livelihoods
- Threat to food security

Predicted climate-changing Impacts in Southern Africa

Southern Africa has been under a dark cloud of adverse weather conditions for the past 4 decades (SHEPPARD et al., 2020) and it seems likely that the situation will change for the better. Projections by climate experts predict future negative impacts owing to climate change in the southern African region (SHONGWE et al., 2011). The predicted climate changes will threaten some of the current conservation goals such as soil and water conservation, enhanced crop yield and carbon sequestration. Throughout central towards southern Africa, mean maximal temperatures are projected to increase (CAIRNS et al., 2012). Extreme average warmth will worsen water scarcity tension in dry times because of high plant transpiration and supplementary decrease of plant-available soil water (CAIRNS et al., 2013; LA ROVERE et al., 2010). Meanwhile, there is an alternate possibility for tropical regions to be wetter (JAMES - WASHINGTON, 2013) whereas sub-tropical areas are further prone more likely to be influenced by changes in present rainfall forms (MAIDMENT et al., 2015; MUTHONI et al., 2019; IPCC, 2014).

In view of climate change in Southern Africa, numerous studies predicted yield variations. Extreme mean temperatures will aggravate water stress in dry periods due to aggravated plant transpiration and more depletion of available water capacity (CAIRNS et al., 2013; LOBELL et al., 2013). The latter may decrease crop yields, threatening southern African people's food availability and sustenance (SHEPPARD et al., 2020). As reported already, repeated water-scarce periods are causing Frequent loss of rain-dependent maize crops, exceeding 40%, in areas of Southern Africa, including north-eastern South Africa and northern Botswana. Furthermore, significant crops like sorghum (*Sorghum bicolor* (L.), wheat (*Triticum* spp.) and millet (e.g., *Eleusine* spp. and *Pennisetum* spp.) were not exempted from climate change consequences. As mentioned by (O'NEAL et al., 2005), weather change is amongst the foremost human-induced agent of erosion through an increased extreme water cycle. Additionally, heightened deterioration of soil, loss of SOC, nutrient loss, and biomass (NIANG et al., 2014). Soil that has a reduced capacity to retain and distribute water and nutrients can offer minimal assistance to crops dealing with the effects of climate change (BALKOVIČ et al., 2018). Therefore, conservation methods have been widely praised as significant techniques to mitigate and enhance the resilience of soils to climate change consequences.

III. Effects of tillage methods on Soil physical, chemical and biological properties and association with climate change adaptation and mitigation

Aggregation is impacted by changes in soil's physical state, chemical composition, and biological factors. Human-induced physical disturbance with mechanical equipment has a dramatic impact on soil structure. Because it creates unsustainable aggregates and pore spaces relative to naturally occurring pores and aggregates. Conservation tillage enhances structural aggregation thus improving soil air and water pore spaces.

Structure and aggregation

Predicted changes in the future of African temperatures may be accompanied by a decrease in precipitation, thus altering soil fertility (SHONGWE et al., 2011). Various researchers stressed about high temperatures and precipitation, increasing the rate of soil fertility loss in the form of SOC and worsening nutrient drainage (ELBASIOUNY et al., 2022). SOC plays a pivotal role in connecting and soil stabilization form, improving nutrient recycling and soil physical properties (BEARE et al., 1994; MARTENS, 2000) as well as regulating atmospheric carbon dioxide (MTYOBILE et al., 2020; NIGUSSIE et al., 2021a; SMITH et al., 2020). As such, soil organic carbon (SOC) improvement may be an approach to alleviate climate change problems (LAL, 2015).

Soil management and synthetic nutrient provision to the soil are among the factors that impact soil structure enhancement and storage of carbon in the soil. Equally the latter practices contribute directly and indirectly effects on the development and biodiversity of plants and microbes, thus enhancing organic contribution in the soil (XIE et al., 2015). For instance, in a study by CHICHONGUE et al. (2022) two tillage systems CA and CT and two fertilizer treatments fertilized and non-fertilized under seven cropping patterns (four sole and 3 intercrops) in Southern Mozambique were evaluated for soil chemical properties including SOC. According to their results, CA practices enhanced SOC and total nitrogen (TN) compared to CT practices. Similarly, MALOBANE et al. (2020) observed microbial biomass carbon (MBC) and enzyme activities as affected by tillage (no-till (NT) and CT), cropping systems and residue retention in South Africa. The results showed that both tillage and residue management were the principal factors affecting the soil biological indicators. Additionally, NT and 30% plant biomass retention extensively improved MBC and selected enzyme activities relative to CT and plant biomass removal treatment, respectively. NIGUSSIE et al. (2021) in Ethiopia in a Cambisol and Chernozem soil type evaluated the Soil management practices (minimum tillage (MT) and CT) and they also observed an improvement in SOC and TN through MT compared to CT. Numerous other studies in SSA also have recommended conservation practices for enhancing SOC and other properties involved in soil aggregation (ASFAWESEN MOLLA et al., 2021; GITHINJI et al., 2011; GOTOSa et al., 2011; NAAB et al., 2017; NWACHUKWU et al., 2020).

Bulk density and total porosity

The relationship between bulk density (BD) and the tillage method has been widely studied (BASSETT et al., 2010; KARUMA et al., 2014; MTYOBILE et al., 2020; SERME et al., 2015; WILLIAMS - TATE, 2022). However, there are still inconsistencies regarding which tillage method promotes an increase in BD. Other, studies reported that they observed an increase in BD after the introduction of NT in the top layer of the soil (SERME et al., 2015). Less intensive such as zero tillage and NT allows the build-up of organic matter, which enhances the abundance and diversity of soil biota. The presence of macrofauna such as earthworms creates permanent burrows by bioturbation thus increasing soil porosity. In turn, residue retention in CA slows the rate of water flow during rainfall, thus allowing the soil to absorb and store more water. Studies by ASFAWESEN MOLLA et al. (2021) reported an increase in total porosity under zero tillage and in zero tillage (ZT) coupled with intercropped treatments. Correspondingly, other researchers observed an increase in BD in NT treatment relative to CT (NAAB et al., 2017; SERME et al., 2015). Furthermore, MALOBANE et al. (2021) reported high mean weight diameter (MWD) under the NT system relative to CT, indicating that the intensive nature of CT decreases MWD which is associated with aggregation thus promoting the formation of macro-pores that are more prone to erosion. Pore structure distinguished by the shapes is as significant like all microscopic structural parameters due to their direct impact on root development, moisture, and air movement through tillage and soil (MALOBANE et al., 2021). BASSETT et al. (2010) highlighted that tillage-induced macropores store more water however, more plant-available water was observed under NT relative to CT due to mesopores and high aggregate stability.

Infiltration/water conservation

The ability of soil to allow water movement is a significant phenomenon in hydrology and ecosystem functions. For that reason, soil surface rainfall might penetrate the soil and enhance moisture storage or replenish water table resources or runoff and result in erosion (BARANIAN KABIR et al., 2020). THIERFELDER - WALL, (2009) mentioned that combining zero tillage, plant biomass retention and crop variability may highly enhance water infiltration quantity. This was attributed to less disturbance, thus improving soil fertility-related properties which enhanced the ability of the soil to absorb and store more moisture. Ascribed increase of hydrometric moisture content due to the accumulation of crop biomass retention under NT, which is associated with improving pore spaces and decreased soil moisture loss (VILAKAZI et al., 2022). Moreover, both NT and five years of CT retained residues which favoured infiltration hence decreasing runoff and evaporation from the land surface. Conversely, MALOBANE et al. (2021), found more disconnected pores in CT relative to NT, due to the physical breakdown which degrades pore functions and lowers aeration and water infiltration. In another study, CT practices improved the pore volume segment of residual pores by 57% relative to CA-maize-legume, whereas CA-sole maize and CA-maize legume improved the volume segment of storage pores by 17% and 24% relative to CT-SM respectively (SIMWAKA et al., 2020).

Chemical properties

Plant nutrients

Tillage type has also been widely shown to affect nutrient distribution within the soil profile. Generally, most soil nutrients are concentrated in the rhizosphere, the top first layer that is impacted due to poor land management. Land management in the manner of intensive soil disturbance owing to the use of a plough promotes soil erosion and SOC decomposition. More so, soil nutrients are associated with an increase in SOC in the soil. Furthermore, the ability of the soil to retain more nutrients is measured by its cation exchange capacity (CEC). Soil CEC impacts soil fertility, structural stability, and pH buffer capacity. As influenced by changes in SOC and pH, there is a possibility that CA systems can positively influence CEC. (SITHOLE - MAGWAZA, 2019) found high CEC in RT and NT treatments. Other scholars also reported improved CEC under CA practices (CHAUKE et al., 2022) however, (WILLIAMS - TATE, 2022) reported low CEC under NT.

Other studies observed an increment in P, K, Ca, and Mg under NT relative to CT (CHAUKE et al., 2022; Mtyobile et al., 2020). However, pH was high under CT relative to CA practices (NT, MT, and RT). (NIGUSSIE et al., 2021a; SITHOLE - MAGWAZA, 2019) obtained low TN under CT relative to MT and a low C: N ratio under MT compared to CT. High NO^{-3}-N, C: N ratio, TN, and NH^{+}-N were observed under NT compared to CT (CHAUKE et al., 2022; THIERFELDER et al., 2022).

Biological properties

SOC

SOC has been widely cited as a key indicator of soil quality (THIERFELDER et al., 2022). It is the earliest soil component to succumb to erosion and strangely the most difficult to restore, presenting significant challenges to modern farming (CHOWANIAK et al., 2020). The latter is affected by land management practices such as tillage, residue retention, cropping system, and crop rotations.

Soil tillage introduces oxygen in the soil thus increasing microbial decomposition (NJAIMWE et al., 2018; VILAKAZI et al., 2022). Tillage also incorporates crop residues left on the soil surface that act as a cushion to protect against structural disintegration by rainfall drops. However, NT or CA systems, present more SOC amelioration (BABATUNDE et al., 2016). Reducing tillage amount or employing NT can potentially reduce SOC quantity loss in the soil by reducing macroaggregate turnover frequency. Furthermore, by elevating the physical protection of particulate organic material, and decreasing residue incorporation (PAGE et al., 2020).

Various authors have reported contrasting findings regarding the relationship between CT and CA in enhancing and conserving SOC. (DIOP et al., 2021) recorded more soil nutrient loss and SOC in hand-applied treatments relative to NT, Plough-plant, plough-harrow-plant and bare plot.

Crop yield

Since the American Dust Bowl, a body of research concerning the ability of CA systems to enhance yield and develop resilient soils has increased globally. The inclusion of intercropping, residue retention and less soil disturbance in CA systems are paramount practices for the projected climate change impacts. These practices provide topsoil runoff decrease of enhanced instance may assist in handling more harsh rainstorms elevated diurnal recurrence dry spells (KASSAM et al., 2009).

Improved soil physical, chemical, and biological properties, directly and indirectly, affect crop yield. For example, SITHOLE - MAGWAZA, (2019) reported higher average, yields in NT and RT relative to CT at a higher rate (200 kg N ha^{-1}) of N application however, there was no impact on yield in the absence of nutrient amendments. Similarly, GITHINJI et al. (2011) obtained a higher yield when CA tillage was coupled with 60kgN/ha relative to CA coupled with 0kgN/ha and CT. SERME et al. (2015) reported that sorghum yield in the South Sudan Zone of Burkina Faso varied based on how soil fertility was managed. A greater sorghum yield was achieved by using ZT along with compost, urea, and NPK compared to using tied ridges. MUONI et al. (2019) reported low grain yield under conventional ploughing (at most 4074 kg/ha) compared to CA and NT treatments (ranging between 3000 and 6000 kg/ha). MTYOBILE - MHLONTLO, (2020) reported an increase in maize grain yield under MT in South Africa compared to CT. KODZWA et al. (2020) observed an increase in maize grain under reduced tillage (RT) relative to mouldboard plough, moreover, the addition of mulch played a significant role during dry spells. SELOLO et al. (2023) reported a 45% higher grain yield in MT compared to CT in the 2019/20 season.

Barring soil moisture as a limiting factor, the maize harvests attained through MT systems were comparable to those of the CT (KIBOI et al., 2017; MUPANGWA et al., 2012). Additionally, in years of below-average rainfall, the MT systems performed even better. Moisture enhances the rate of mineral release from organic or insoluble forms and transports them towards roots (KIBOI et al., 2017). Increased soil moisture promotes root growth and improves the nutrient supply to crop roots. Under high rainfall, THIERFELDER et al. (2016) observed higher yields in NT compared to CT practices. USMAN - ALI, (2021) obtained higher sesame yield in ridge tillage relative to ZT and flatbeds. Araya et al. (2011) reported that permanently raised beds increased wheat yield in 2 years compared to CT tillage practices.

Studies by BABATUNDE et al. (2016) reported higher yields under CT systems, due to well nutrient distribution and higher moisture infiltration. NAAB et al. (2017) reported higher yields of maize and Soybean under CT compared to NT. MASVAYA et al., (2017) obtained high grain in two consecutive seasons under ploughing treatment relative to ripping. Conversely, the addition of fertilizers enhanced yield in ripper relative to ploughing. NIGUSSIE et al. (2021a) reported an increase in maize grain yield under CT relative to MT. NYAMANGARA et al., (2014) in a meta-analysis study evaluating CA (planting basin) and CT (ripper tillage) found that CA obtained higher maize yield relative to CT. JAMES - CHUKWUEBUKA, (2017) reported higher maize grain in deep tillage plots compared to shallow tillage and zero tillage.

Conclusions

The impact of CST on soil physical, chemical, and biological properties was reviewed in SSA. The inclusion of CST in CA could be significant for the African agricultural sector and its environment. However, there lacks sufficient research information on some of the parameters that could aid fast tracking the adoption rate. Most research focuses on parameters such as BD, Porosity, aggregate stability etc. yet information on enzyme activity (beta-glucosidase, acid, and alkaline phosphatase) as early indicators of the impacts of land management practices on soil properties. Generally, CST has proven to be a sustainable pathway to developing climate-resilient soils in SSA.

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