Chapter

Tillage Practices and Their Benefits for a Resilient Soil Environment in Ethiopia

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Abstract

Crop production optimization depends heavily on soil management, which has a direct impact on food security and agricultural sustainability. Site-specific approaches to tillage management are often lacking in conventional soil tillage management techniques. The objective of this paper was to evaluate the numerous studies on tillage techniques, their effects on soil characteristics, and their implications for sustainable farming and soil resilience. The findings of the study showed that reduced tillage techniques are more beneficial than the conventional Maresha tillage systems. In comparison to traditional tillage systems, these benefits include lowering bulk density and soil compaction, increasing organic carbon, enhancing penetration rates and moisture retention, and minimizing soil loss. By lowering soil compaction and breaking hardpans, deep tillage techniques greatly enhance deteriorated soils. This improves both water dynamics and hydraulic conductivity, which impact agricultural and water productivity. When combined with suitable cropping system methods, tillage is more successful. Tillage increases soil organic matter by decreasing soil disturbance and keeping crop residue in the field, both of which affect the carbon sink. Reduced tillage in Ethiopia offers several benefits for climate adaptability, water security, and soil restoration. But for it to be successful, tillage implements that are appropriate for the area and incentives to help farmers are needed. Tillage management strategies that are site-specific are therefore crucial for sustaining a robust soil ecosystem, improving sustainable farming, and recharging water resources.

Keywords: soil health, tillage, surface roughness, sustainable farming, Ethiopia

1. Introduction

Tillage is a fundamental practice in agricultural management and food production since the earliest great civilizations. It can be defined as a method of working the soil either physically, chemically, mechanically, or biologically to create suitable conditions for seedling germination, establishment, and growth. The primary tillage function is to loosen, granulate, crush soil particles, and increase porosity [1]. Tillage has long been regarded as a critical agronomic practice because it can alter soil properties and create a complex soil ecosystem [2, 3]. Although often regarded as an essential part of agricultural management, inappropriate tillage practices can have negative impacts on the sustainable use of land resources and result in environmental damage [4].

In the Ethiopian highlands, deforestation, overgrazing, and expansion of cultivation onto marginal lands have reduced vegetative cover, leaving soils vulnerable to erosion. The removal of crop residues for fuel or animal feed further depletes soil organic matter (SOM). Apart from these drivers of land degradation, long years of conventional tillage practices, particularly the repeated use of the traditional *Maresha* plow, contribute to soil degradation in the form of hardpan formation at shallow depths (15–20 cm), reduced water infiltration, and accelerated soil erosion [5–7]. Conventional oxen plow tillage using traditional Maresha tools leads to soil compaction, organic matter depletion, and erosion, reducing crop yields by 5–10% annually. This has created an urgent need for more resilient soil management practices that can sustain agricultural productivity while mitigating environmental degradation. Empirical studies highlight the urgent need for conservation tillage to enhance soil resilience by maintaining productivity under climatic and anthropogenic stresses.

Tillage practices change the soil's physical properties, such as bulk density, aggregate stability, water movement, and storage [5, 6, 8, 9]. Studies have reported that deep tillage practice enhances water movement and aeration in the soil, and increases rooting depth and growth [7, 10]. Empirical evidence from long-term studies demonstrates that conservation tillage improves the soil structure by reducing bulk density and increases aggregate stability, which indirectly enhances resistance to soil erosion [5–7]. Reduced tillage combined with soil bunds increases soil organic carbon by 32% over a decade, which is critical for nutrient cycling [6]. In low-rainfall areas, reduced tillage performs better to enhance crop yields and its adaptation to climate variability [11] and greater yield stability during dry spells [12]. They reported the improved carbon sequestration potential of conservation tillage practices, which verifies the climate change adaptation potential in a changing climate.

Despite the benefits of conservation tillage, its adoption remains low due to competition for crop residues, labor, and knowledge gaps of smallholder farmers, short-term yield reduction during the transition to conservation tillage practices, initial investment costs of implements, and limited scaling approaches of best practices and innovations [12, 13]. The widespread adoption of resilient tillage practices in Ethiopia requires a multifaceted approach that addresses technical, socioeconomic, and policy dimensions. Recent meta-analysis stresses the need for locally adapted tillage implements, for example, modified Maresha plows, and agroecology and cropping system-specific tillage recommendations [10], establishes learning sites for tillage systems [8], investigates long-term impacts on soil health and productivity [14], offers gender-inclusive extension services to reach gender and local tailored services, and integrates the tillage system innovations with climate-smart agriculture and integrated landscape management programs to ensure a sustainable dissemination and adoption of the improved tillage systems at scale. The objective of this paper was to review the various studies of tillage practices in Ethiopia on soil resilience and sustainable farming, so that a recommendation will be made on how the negative impact of conventional tillage would be overcome.

2. Traditional tillage practices

Animal traction tillage in Ethiopia has been used for thousands of years [15]. Traditional tillage in Ethiopia typically involves using an indigenous ox-drawn plow called a Maresha or ard plow, often repeated several times to create a fine seedbed. Maresha is a traditional tillage implement used in Ethiopia, typically pulled by a pair of oxen, for seedbed preparation and covering seeds. It is characterized by creating V-shaped furrows, leaving strips of unplowed land between passes, which necessitate repeated cross-plowing over the season [13, 16]. Maresha's furrow-making can also be used to create ridges and furrows in high-rainfall areas. While effective for seedbed preparation, long-term Maresha use can lead to soil degradation and reduced rain-water utilization, impacting crop productivity [16]. Farmers often plow repeatedly to completely disturb unplowed strips of land left between adjacent furrows during primary tillage. Unplowed strips are the result of the V-shaped furrows created by the Maresha plow. Farmers generally do not plow before the soil is wetted by rainfall. Wetting and drying cycles due to dry spells occurring between rainfall events force farmers to plow frequently to avoid moisture losses through evaporation and weed transpiration [13, 16]. The conventional plowing frequencies in Ethiopia vary with climatic conditions, crop types, soil types, and farmer conditions [17]. For example, research studies reported tillage frequencies for tef to be 5–9 times [18] and 3–5 times in high-rainfall areas [16]. Tef fields are plowed 4–6 times, while maize, barley, and wheat fields are plowed 3 to 4 times, and most of the pulse crops are plowed 1–2 times [17, 19]. Tillage frequency is higher in heavy soils like Vertisols, sometimes with raised bed and furrow systems, than in light soils [16]. Overall, Ethiopia has varied soil types across the diverse agroecological zones, which respond differently to tillage practices.

Ethiopia's dominant tillage system relies on the Maresha plow that performs shallow tillage (15–20 cm depth) [20]. Repetitive shallow tillage has a direct consequence of hardpans, aggravating water scarcity and yield gaps. Repeated plowing (ranges from 2 to 6 passes per season) with the Maresha creates hardpans at 15–30 cm depth due to repeated shallow tillage, restricting root growth and water infiltration [7], leading to infiltration reduction by 50–70%, increasing runoff and soil erosion [8, 13]. The traditional plow design exacerbates crusting and accelerates organic carbon loss through increased surface exposure [13]. Traditional soil tillage greatly influences the balance between greenhouse gas (GHG) emissions and soil health via decreasing SOM and altering soil structure [21, 22]. Mehra et al. [22] showed that tillage disrupts the soil edaphic environment, specifically soil aggregate fractions, because it accelerates soil C loss through exposure of SOC in inter- and intra-aggregate zones. On higher slopes, conventional tillage causes 68–90% runoff [7, 8].

Soil types respond differently to traditional tillage practices and require variable tillage practices. Clay soils, characterized by high water retention but poor drainage, require repeated tillage management due to wet and dry conditions while preventing compaction. In contrast, sandy soils require conservation tillage combined with moisture conservation practices to improve the soil structure and drainage conditions. Silty soils, which are prone to erosion, require contour plowing to prevent soil loss.

3. Conservation tillage practices and their benefits

Conservation tillage has emerged as a promising alternative to conventional tillage practices, offering multiple benefits for soil resilience and agricultural productivity in Ethiopia. These practices typically involve minimum soil disturbance, maintenance of soil cover, and crop rotation [12]. The ranges of tillage practices include reduced tillage, zero tillage, and deep tillage [7, 8, 10, 12, 14].

3.1 Zero-tillage effect on soil properties

A conservation tillage study in the Ethiopian highlands indicates that tillage's effect on soil properties was spatially and temporally inconsistent [23]. It implies that the effect of zero tillage on soil properties is site-specific and responds to soil physical and hydrological properties. Zero tillage improves soil hydrological properties and bulk density when it is managed with the integration of cereal and legume rotations, residue retention, and nutrient management [24]. A zero-tillage study [25] in the lower Beles River Basin reported a decrease in bulk density in a range of 1–10% compared to conventionally tilled continuous maize cropping practices; the highest reduction was due to zero-tilled maize soya bean intercropping. It also reduced soil compaction by 5% compared with the conventional tillage system [25]. Zero tillage lowers bulk density and improves infiltration rates by 20–30%, relative to conventional tillage [26, 27]. Zero tillage with mulching boosts soil organic matter by 32% over a decade in semi-arid regions [28]. Zero tillage combined with residue mulching reduces soil loss to 16 t ha^{1} yr^{1} compared to 30 t ha^{-1} $yr.^{-1}$ under conventional tillage practice [29]. On average, reduced tillage reduces erosion by 44.8% by maintaining surface roughness [10]. Reduced tillage improves yield gain, where it increases 6–29% crop yields compared to conventional tillage and improves moisture retention and reduces evaporation [5, 6, 8, 9].

3.2 Impacts of deep tillage practices on soil health, water storage, and climate resilience

The agricultural systems, particularly in the highlands, face significant challenges from soil degradation and erratic rainfall. Tillage practices profoundly influence hydraulic conductivity and water table dynamics, affecting both crop productivity and groundwater recharge. Reduced tillage suits moisture retention and improves soil water conductivity to prevent drying, while deep tillage is critical for breaking compaction. Deep tillage involving soil disturbance to depths of 30–60 cm has been shown to significantly improve degraded soils by reducing soil compaction, breaking hardpans, enhancing organic matter, improving water dynamics, and reducing sediment yields [7, 30, 31]. Deep tillage decreases bulk density by 5.6–20% in the 20–30 cm layer compared to conventional tillage with the *Maresha* plow (15 cm depth). The deep ripping disrupts restrictive hardpans with penetration resistance above 2 MPa, which enables deeper root growth below 50 cm [7, 31]. When combined with residue retention, unlike the carbon loss due to conventional tillage, it increases soil organic carbon by 33% over time [30].

Deep tillage markedly improves water infiltration and water dynamics in the Ethiopian highland landscapes. Deep tillage increases plant-available water in root zones, supporting crops during dry spells. It boosts infiltration by 50–70% (up to 261.6 mm/hr) compared to conventional tillage (up to 120 mm/hr) and reduces surface runoff by 30–60% [9, 10, 31]. Deep tillage alleviates perched water tables on Vertisols by enhancing deep percolation [31]. Deep tillage also reduces soil loss by addressing key erosion drivers: lowers sediment loss to 2.6 t/ha from 5.5 to 6.6 t/ha under conventional tillage system [31] and reduces runoff depth by 50–90% by creating micro-depressions that trap water and sediment [32].

Altogether, deep tillage techniques enhance drought resilience through deeper root systems in retaining surface soil water in the depressions and accessing subsoil moisture and mitigating excess runoff and floods in high-rainfall areas through improved infiltration. While maintaining the soil structure and minimizing soil disturbance, deep tillage techniques lower emissions [33]. Deep tillage is most effective for Vertisols, while reduced tillage suits sandy loams and Nitisols [7, 10]. Overall, deep tillage in Ethiopia demonstrates multidimensional benefits for soil restoration, water security, and climate adaptation. However, its success depends on implements like modified subsoilers fit to local conditions, ox traction power, residue retention to sustain organic matter, and incentives to offset adoption costs by smallholder farmers [7, 30, 31]. In general, site-specific approaches for deep tillage management are essential for groundwater recharging and sustainable water management and maintaining a resilient soil ecosystem.

3.3 Tillage roughness effects

Crop-specific tillage practice is characterized by and varies with the tillage frequency, with two to six plow passes leading to variable surface roughness conditions.

Parameter	Conservation tillage	Deep tillage	Conventional tillage (baseline)
Soil organic carbon (%)	1.8–2.5% (30% increase over conventional)	1.2–1.6% (short-term increase)	1.0–1.4%
Bulk density (g/cm^3)	1.10–1.25 (reduced surface compaction)	1.30–1.40 (reduced at 30–50 cm depth)	1.40–1.60
Soil erosion (ton/ha/yr)	5–10 (70% reduction)	15–20 (30% reduction)	30–40
Infiltration rate (cm/hr)	8–12 (2x higher)	10–15 (short-term peak)	4–6
Surface roughness (mm)	25–35 (residue-driven)	10–15 (flattened after tillage)	5–10
Runoff (%)	10–15% of rainfall	20–25%	35–50%

Table 1.
Documented effects of improved tillage on soil properties in Ethiopia.

Parameter	Conservation tillage (reduced/no-till)	Deep tillage (subsoiling)	Key benefits
Soil organic matter	Increases (↑) due to residue retention	May decrease (↓) due to oxidation of organic matter	Conservation tillage enhances long-term fertility.
Soil compaction	Reduces surface compaction over time	Breaks hardpans (↓ compaction in subsoil)	Deep tillage is better for compacted layers.
Soil erosion	Significant reduction (↓) due to the cover	Higher risk (↑) due to bare soil exposure	Conservation tillage prevents erosion.
Infiltration rate	Improves (↑) with residue cover	Temporarily improves (↑) due to loosening	Both help, but conservation is more sustainable.
Surface roughness	Higher (↑) due to mulch and residues	Initially high (↑), but declines quickly	Conservation tillage maintains roughness longer.
Runoff	Reduced (↓) due to better infiltration	May increase (↑) after tillage effect fades	Conservation tillage controls runoff better.

Table 2.
Comparison of benefits of conservation tillage versus deep tillage in Ethiopia.

The mechanisms linking tillage roughness to soil health are related to runoff control, where rough surfaces increase hydraulic resistance and reduce runoff velocity [34], improve aggregate stability [29], and promote infiltration and water storage [7]. The tillage management strategies, such as contour ridging for maize and sorghum that slow runoff, open narrow tillage furrows for wheat and barley, frequent tillage that creates smooth and fine seedbed conditions for teff that increase runoff and sediment loss, and rough tillage surfaces for pulse crops, demonstrate variable effects on soil conservation and productivity [7, 29]. Contour ridges, which are cross-slope tillage, reduce runoff by 90% by creating micro-depressions that trap water and sediment [33]. Prioritizing these practices based on soil context can mitigate erosion and water scarcity while enhancing resilience to climate variability (**Tables 1** and **2**).

4. Implications of tillage systems on soil health and sustainable farming

Soil health is a critical factor in the sustainability of agricultural systems and the optimization of crop production. It encompasses the physical, chemical, and biological properties of soil that collectively determine its capacity to function as a living ecosystem and provide essential ecosystem services. Tillage practices significantly impact soil health, with conventional tillage often having negative consequences, while reduced and deep tillage offer benefits. Conventional tillage can damage soil structure, reduce organic matter, and increase soil erosion, while conservation tillage can improve soil structure and carbon storage, enhance water infiltration, and promote microbial activity [35, 36]. As a result of leaving residue near the surface of the soil, there is more organic matter content present in the soil, which promotes soil quality [17, 23, 25, 28, 37]. The presence of residue in the soil also limits compaction, allowing better water retention and the release of nutrients for crop growth [38]. Conservation tillage improves water-holding capacity, reducing the risk of drought and flooding [26, 39]. Healthy soils that retain moisture have a better chance of withstanding strong winds and water that cause soil erosion. Improved tillage practices promote a more diverse and active microbial community [40] that plays a crucial role in soil health [30]. Conservation tillage can optimize nutrient cycling, reducing the need for synthetic fertilizers and improving soil fertility [12]. Thus, it plays a beneficial role in yield stability and water use promotion as a major agricultural practice for maintaining farm productivity [32]. By these merits, improved tillage methods or reduced conservation tillage is increasingly being considered as a component of sustainable agriculture. On the other hand, the conventional tillage practices using an ard plow need an urgent intervention for soil and water conservation and soil quality restoration purposes, which have a greater impact on crop yield.

Tillage impacts carbon emissions and carbon sequestration. Improved tillage retains crop residue in the field and increases soil organic matter by reducing soil disturbance, leading to an enhancement of the function of soil as a carbon sink induced by the accumulation of soil organic matter [12, 22, 41, 42]. Implementing efficient tillage methods suitable for a farm is a known strategy in carbon farming, in turn, a sustainable farming solution to mitigate climate change. Overall, changing conventional practices to more sustainable ones requires a deep knowledge of sustainable farming practices, including precision tillage management and regenerative agriculture techniques. Modern tillage techniques, particularly no-till or reduced tillage, are crucial for resource efficiency and regenerative agriculture. They minimize soil disturbance, improving water retention, reducing erosion, and enhancing soil health, ultimately leading to increased productivity and carbon sequestration. Improved tillage practice or reduced tillage combined with practices like cover cropping, crop rotation, and composting promotes a thriving soil ecosystem and climate change [34, 43–45].

Most tillage management practices, including improved tillage implements, were not accepted by the local farmers because they did not preserve all the good characteristics of the traditional Maresha [20]. This is the reason why the traditional Maresha has remained unchanged or has been employed with minimal changes for centuries, proving the reliability of the design for agricultural and social systems and the topographical nature of Ethiopia. The challenge is to find a room for improvement of the traditional Maresha while preserving all the existing advantages. To transition smallholder farmers from traditional, oxen-drawn tillage to improved systems, a multifaceted approach is needed, including introducing locally appropriate implements and technologies, providing training and extension services, and addressing economic and social barriers to tillage implement access and affordability.

5. Conclusion

Empirical evidence provided in this review underscores that shifting from conventional shallow tillage practice using local tillage implements to conservation-based and cost-effective practices can significantly enhance soil resilience through improved soil moisture management and aggregate stability and breaking hardpans; mitigating degradation while improving productivity and soil health, and hydrological conditions; and mitigating climate change by helping improve soil carbon levels. Practices, such as reduced tillage or less frequent tillage passes, have shown the potential to improve soil health while reducing environmental degradation. These practices are not only capable of improving the soil health, but improved tillage practices are also capable of improving the productivity and profitability of farming and making soils more resilient to local demands. This review reveals that improved tillage practices could enhance smallholder farm benefits and potentially can be promoted and scaled through cost-effective dissemination strategies and incentives for wider adoption by smallholder farmers.

However, realizing this potential requires addressing the technical, economic, and social barriers to adoption. Technical constraints can be addressed with site-specific and tailored small-scale mechanization technologies and service models fit for purpose under the diverse soil and cropping systems. Systemic barriers require targeted interventions that demonstrate cost-effective practices, integration of local knowledge with scientific approaches, bundled tillage innovations with farm agronomic, and soil management practices that ultimately ensure achievement of long-term environmental health and economic impacts. In response to increasing pressures from climate change and soil degradation, transitioning to more resilient tillage systems will be essential for sustainable agricultural development. This transition requires coordinated efforts across research, extension, policy, and farming communities to create an enabling environment for the adoption and scaling of improved tillage practices.

Conflict of interest

The author declares no conflict of interest.

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