

Review

Challenges of Smallholder Farming in Ethiopia and Opportunities by Adopting Climate-Smart Agriculture

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Abstract: Agriculture is the backbone of the Ethiopian economy, and the agricultural sector is dominated by smallholder farming systems. The farming systems are facing constraints such as small land size, lack of resources, and increasing degradation of soil quality that hamper sustainable crop production and food security. The effects of climate change (e.g., frequent occurrence of extreme weather events) exacerbate these problems. Applying appropriate technologies like climate-smart agriculture (CSA) can help to resolve the constraints of smallholder farming systems. This paper provides a comprehensive overview regarding opportunities and challenges of traditional and newly developed CSA practices in Ethiopia, such as integrated soil fertility management, water harvesting, and agroforestry. These practices are commonly related to drought resilience, stability of crop yields, carbon sequestration, greenhouse gas mitigation, and higher household income. However, the adoption of the practices by smallholder farmers is often limited, mainly due to shortage of cropland, land tenure issues, lack of adequate knowledge about CSA, slow return on investments, and insufficient policy and implementation schemes. It is suggested that additional measures be developed and made available to help CSA practices become more prevalent in smallholder farming systems. The measures should include the utilization of degraded and marginal lands, improvement of the soil organic matter management, provision of capacity-building opportunities and financial support, as well as the development of specific policies for smallholder farming.

Keywords: food security; soil fertility; agroforestry; organic matter; greenhouse gas; agronomy; water harvesting



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1. Introduction

Agriculture is the backbone of the Ethiopian economy and it contributes about 50% of the country's gross domestic product (GDP) and more than 80% of its exports [1,2]. Furthermore, it is one of the main employment sectors with about 80% of the country's population depending on the agricultural sector for their livelihoods [3]. The agricultural sector of Ethiopia is dominated by smallholder farming [4]. Smallholder farms are defined as being smaller than 2 ha and are mainly managed with family labor [5]. In Ethiopia, about 95% of main crops (e.g., cereals, pulses, oilseeds, vegetables, root crops, fruits, and cash crops) are produced by smallholder farms [4]. However, these farms are facing various constraints that hamper crop productivity. Major constraints include poor soil fertility, severe land degradation, high dependence on rainfall, low availability and poor quality of seeds and fertilizers, economic constraints like low income and lack of financial support, as well as insufficient policies and guidelines [3,6,7]. Weather phenomena related to climate change like severe drought and heavy rainfall also affect the agricultural sector.

Smallholder farmers with limited resources have particular difficulties overcoming these obstacles [4,8]. These problems are exacerbated by the rapid population growth and environmental degradation. Consequently, appropriate management practices are urgently needed to resolve the constraints and to increase crop production without altering its potential for future generations [9].

Climate-smart agriculture (CSA) is an agricultural approach that aims to increase agricultural productivity under the new realities of climate change. This includes increasing soil fertility and carbon sequestration, reducing greenhouse gas (GHG) emissions, enhancing resilience to climate change, and a stronger use of natural ecosystem services [10–14]. Managing CSA includes various practices such as mulching, the application of organic materials, intercropping, conservation tillage, crop rotation, integrated nutrient management, water harvesting, and agroforestry [15–17].

Globally, CSA has been recognized as a suitable solution to overcome the challenges of food security and climate change impacts on agriculture especially in vulnerable areas [17]. Thus, the adoption of CSA practices could help smallholder farming in Ethiopia to enhance food security and appropriately manage climate change impacts [18–21]. However, despite these potential benefits CSA is only practiced in some areas of Ethiopia and has not been sufficiently adopted by smallholder farmers [14,22]. This is partly attributed to available labor, knowledge, and level of education [4,23,24], but a shortage of funds as well as policy constraints are further important aspects [6]. Although Ethiopia's agriculture has enjoyed increasing governmental support over the years [25], especially land tenure policy and financial and price support schemes are described as being insufficient or ineffective. This results in an underutilization of techniques for soil and water conservation and hinders the adoption of CSA in Ethiopia [21,25,26]. While many CSA practices are relatively low-cost, they may not be affordable for farmers, who suffer from price distortions, limited land, and low productivity [21,27]. CSA practices can also result in an increased workload. This was for instance shown for conservation tillage, which is often related to a higher occurrence of weeds and may increase the work burden on women, who are usually responsible for manual weeding [28]. Therefore, relevant stakeholders must clearly know the impacts of CSA practices and must also assess their costs and benefits under the respective conditions in order to make decisions on promoting one practice versus another [29].

Holistic approaches are needed as a basis for appropriate future strategies towards sustainable agriculture and rural welfare, as recently suggested for sub-Saharan Africa by Stewart et al. [30] and more specifically for Ethiopia by Amare et al. [31]. Various studies have shown, that CSA approaches exist which have the potential to enhance resilience to climate change and to achieve more sustainability for smallholder farming in Ethiopia [4,23,32]. However, the studies often narrowly focus on individual CSA practices under specific circumstances. An integrative and systematic analysis considering environmental and socioeconomic conditions as well as agricultural policies on potentials and challenges of adopting CSA in Ethiopian smallholder farming systems has not yet been undertaken. The consideration of interlinking influencing factors in our review resulted in four main objectives: (I) to summarize the current situation in smallholder farming in Ethiopia, (II) to explore potential CSA practices for a sustainable improvement of agro ecosystems, (III) to identify relevant obstacles that hinder the application of CSA practices in smallholder farming systems, and (IV) to suggest opportunities and solutions to sustainably develop smallholder farming systems and to empower smallholder farmers to adopt CSA practices.

To provide relevant information on (I) conditions in smallholder farming, (II) sustainable and climate-smart agriculture, and (III) agricultural policy and socio-economic issues and to achieve the aims of this review, a comprehensive analysis of articles in the Web of Science and Google Scholar was done using the following terms: "climate-smart agriculture", or "smallholder farming", or "integrated nutrient management", or "soil fertility", or "sustainable agriculture", or "agroforestry", or "conservation agriculture", or "agricultural policy", or "socio-economic effects" and/or "Ethiopia". These terms are commonly used in

agricultural research with a focus on climate change adaptations and mitigation and they cover the main research outputs about the current status of CSA in Ethiopia. Moreover, the terms include the concepts of CSA pillars (adaptations, productivity, and mitigations). For our study, we mainly focused on developments during the last two decades, when measures to mitigate the impacts of climate change became more relevant.

2. Current Status of Smallholder Farming in Ethiopia

2.1. Agricultural Productivity

In Ethiopia, about 60% of farmers cultivate less than 0.90 ha in very fragmented landscapes [5,20,33]. However, smallholder farming is responsible for a large proportion of Ethiopian food production. It cultivates more than 90% of the total cropland and provides more than 90% of agricultural output [4,34,35]. Smallholder farmers commonly cultivate cereals such as teff (*Eragrostis tef* [Zucc.] Trotter), maize (*Zea mays*), wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), and sorghum (*Sorghum bicolor*) [36,37] (Figure 1). Crop yields in the smallholder farms are very low compared to their potential capacity [36,38] and are also substantially lower (less than 50%) than the yields obtained in experimental farms and research stations (Figure 2). The gap is especially remarkable for maize, with an average yield of 2.6 t ha⁻¹ compared with the potential yield of 7.8 t ha⁻¹ obtained in on-farm trials [36,37,39]. The low crop yields affects food security, with a large amount of grain needing to be imported [40,41]. For instance, 30 to 50% of domestically consumed wheat was imported in the past, due to a lack of production inside the country [40,41].

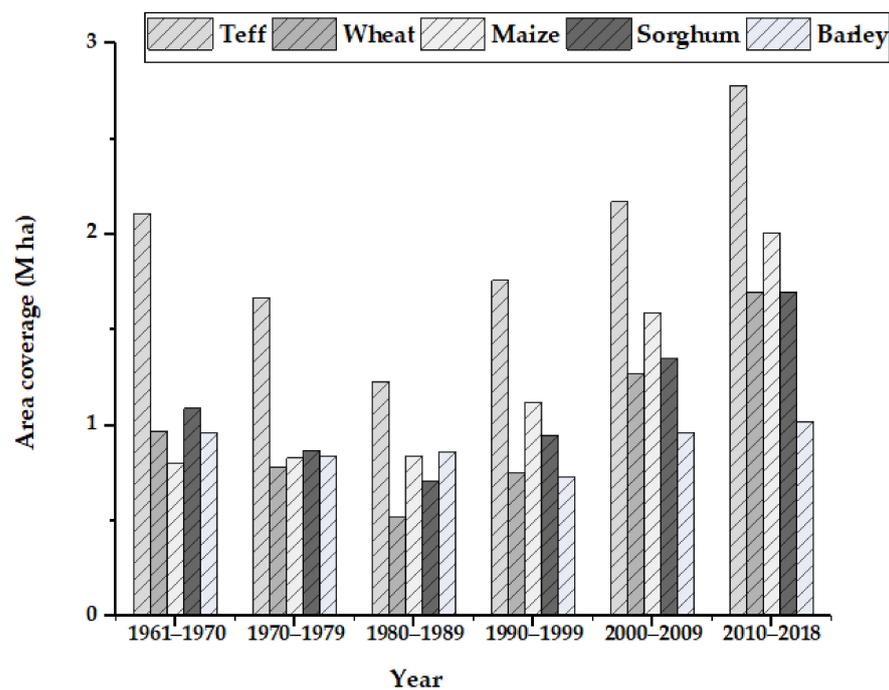


Figure 1. Variation of area coverage of major cereal crops (teff, wheat, maize, sorghum, and barley) in Ethiopia from 1961 to 2018. Source: Taffesse et al., CSA [27,28].

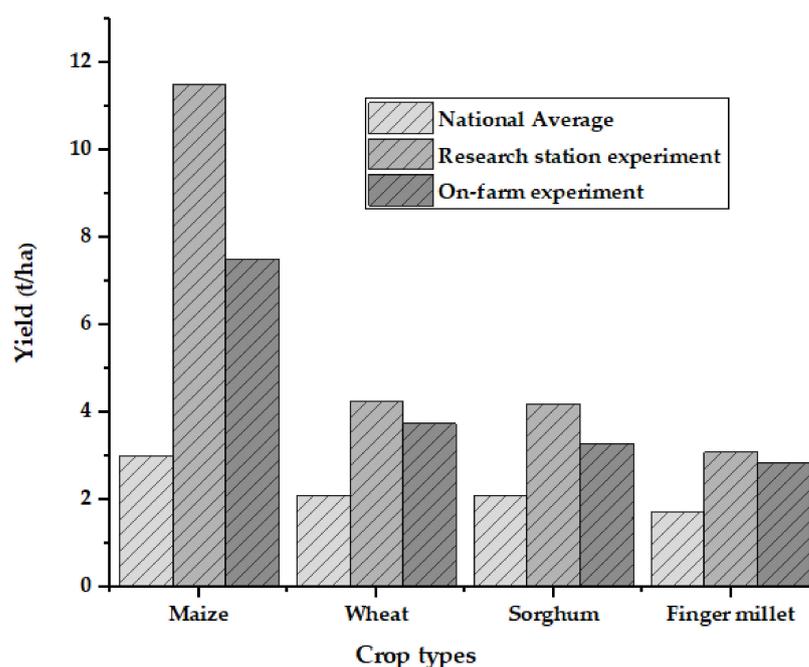


Figure 2. Average of crop yields (t/ha) (1995–2018) compared to the yields from research stations and on-farm experiments in Ethiopia. Source: Taffesse et al., CSA, Marloes et al. [27–29].

Ethiopia has a large livestock resource with about 60 million heads of cattle and about 61 million sheep and goats [42]. The animals belong to various production systems ranging from pastoral to mixed crop-livestock systems with different levels of intensification [24,42]. About 75% of livestock is concentrated in the highlands of Ethiopia. The animals play a critical role in the mixed smallholder farming systems (i.e., livestock and crop production within the same farm unit) as they diversify income sources for smallholder farmers, provide manure as a source of fertilizer, increase the availability of animal traction, and can act as buffer against adverse weather patterns for cropping [43–45]. It has also been shown that livestock ownership can increase the probability of adopting sustainable farming methods in Ethiopian highlands [21].

However, in the face of decreasing grazing lands and high prices for animal feed animal husbandry competes with crop farming for limited resources [43,46–48]. Despite the limited space for the cultivation of fodder crops, the feeding of crop residues is also problematic, as this material is urgently needed to maintain the fertility of soils [46]. High livestock densities may reduce the quality of soils and overgrazing often exposes agricultural lands to erosion and structure deterioration [49–52]. Understanding the trade-offs between number of livestock, total farm size, and sustainable land production is therefore very important [43].

In Ethiopia about 40% of agricultural land is already affected by land degradation resulting in decreased agricultural productivity [53]. In particular, the densely populated highlands of Ethiopia have been experiencing losses in soil fertility for the last three decades [44,50,54]. This is not only related to high livestock densities, but also to improper land management (i.e., tilling steep slopes), an intensive use of water, and the discharge of agrochemicals [53,55].

2.2. Agricultural Land Size

The amount of land dedicated to agriculture has been steadily increasing since 1980 [56]. From 2000 to 2008, croplands were expanded by about 4 million ha, and 80% of this expansion occurred through the conversion of forest land, woodland, and shrub land [57]. Deforestation for the expansion of agricultural land in Ethiopia increased CO₂ emissions from 5.1 Mt in 2005 to 6.5 Mt in 2010 [58]. Although the expansion of cropland

has slowed down in recent years, the amount of agricultural land still increases by about 1.5% every year [56]. In spite of the expansion of cropland, due to the quickly growing population in the rural parts of Ethiopia, the size of cropland per capita has been decreasing drastically [35,59] (Figure 3). Consequently, most Ethiopian farmers are still smallholder farmers. Farm size is usually negatively correlated with population density. For example, the average farm size of less populated areas like Oromia (average farm size: 1.15 ha) and Amhara (1.09 ha) is larger than that of the densely populated Southern Nations, Nationalities, and Peoples' Region (SNNPR) (0.49 ha) [36]. It has been predicted that smallholder farming systems will continue to dominate the agriculture sector and that average farm sizes will continue to decline, since the further expansion of cropland will become more difficult, while the population will continue to increase [20,60,61].

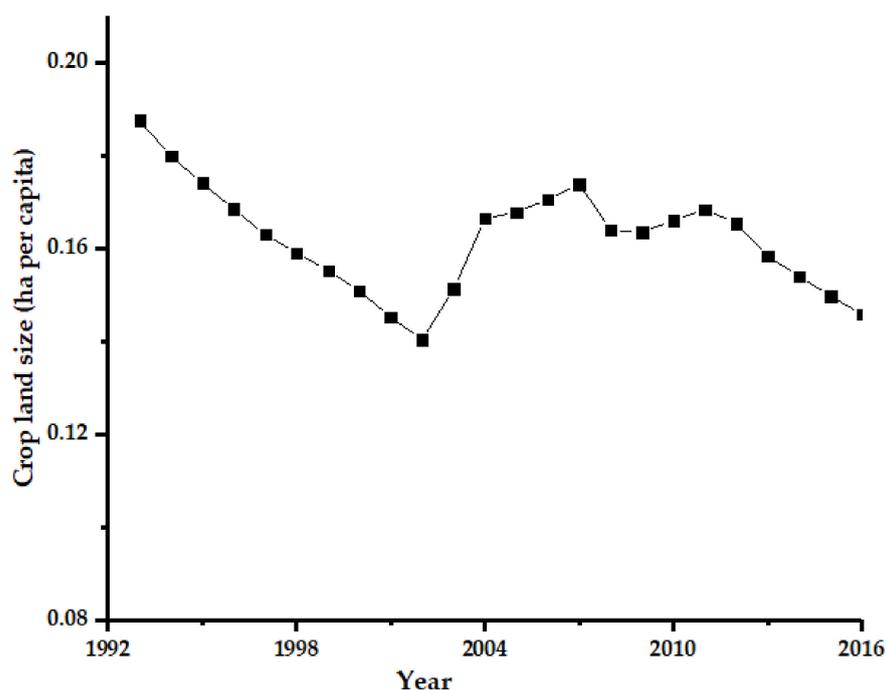


Figure 3. Development of cropland area (ha per capita) in Ethiopia from 1993 to 2016. Source: MoARD, Taffesse et al., CSA [27,28,36].

2.3. Fertilizer Application and Organic Matter Management

For smallholder farmers, the use of fertilizers is often unaffordable resulting in negative nutrient balances in croplands. Inorganic fertilizer consumption, nonetheless, increased between 1961 and 2016 (Figure 4). For more than four decades until 2016, urea and diammonium phosphate (DAP) were the only commercial fertilizers used in Ethiopian agriculture [39,62]. Nowadays DAP is being gradually substituted by a combination fertilizer based on nitrogen (N), phosphorus (P), and sulfur (S) in order to meet the S demand of Ethiopian soils [62,63]. The current application rate of inorganic fertilizer is around 40 kg ha^{-1} [62], which is much lower than in many other countries [64]. A further problem is the substantial imbalance between the nutrients applied, which results in lower nutrient efficiency [65]. For instance, in the Central Highlands, N and potassium (K) fluxes were negative in teff-based systems ($-28 \text{ kg N ha}^{-1} \text{ a}^{-1}$ and $-34 \text{ kg K ha}^{-1} \text{ yr}^{-1}$) and in enset-based systems (*Ensete ventricosum* (Welw.) Cheesman) ($-6 \text{ kg N ha}^{-1} \text{ a}^{-1}$ and $-14 \text{ kg K ha}^{-1} \text{ a}^{-1}$), while P balances were almost neutral or slightly positive [66].

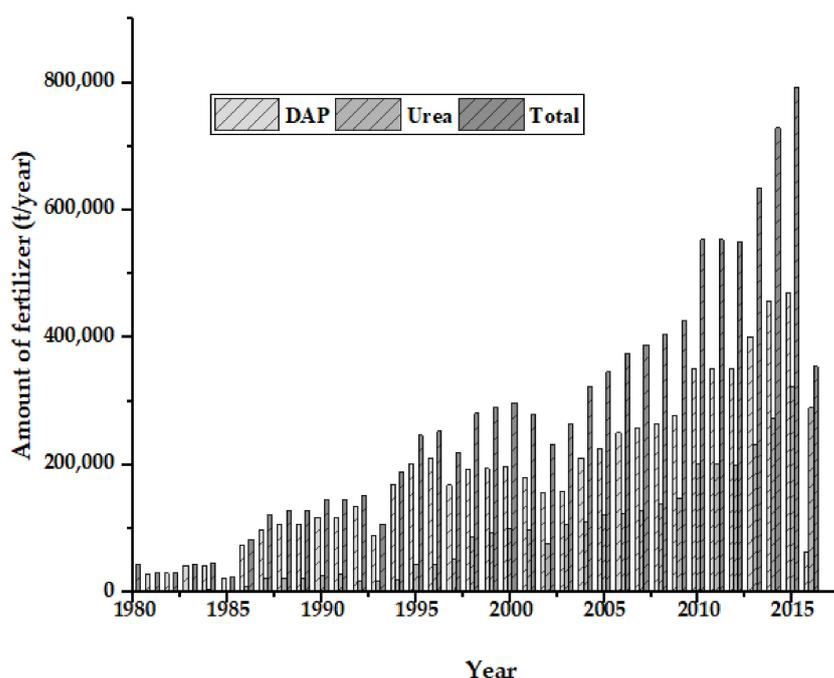


Figure 4. Development of annual urea and di-ammonium phosphate (DAP) fertilizer consumption (t/year) in Ethiopia from 1980 to 2016. Source: CSA, Abraha et al. [30,47].

Despite many positive effects on soil quality, the application of organic fertilizers is limited in smallholder farms, since the majority of available organic matter is used as fuel, animal feed, and construction material [16,67,68]. Ethiopia has a large number of livestock and animal manure should be widely available [45,69]. However, because of its use as a rural energy source, the bulkiness of the material, and lack of transport, manure is only spread on a small part of the agricultural area, mainly restricted to home gardens [24,70]. Additionally, out of 22.4 Mt of crop residues annually available in Ethiopia, about 10.3 Mt are used as fuel [47]. With the removal of crop residues from fields, the nutrient balances turn further negative [71]. The use of cover crops is also very limited, because of the low availability of fields not used for food crops [16,68]. It has been shown that the application of organic fertilization to fields increases when the prices for chemical fertilizers increase [72]. However, as long as organic materials are lacking, organic matter management will remain of little importance [73].

2.4. Water Availability

The vast majority of Ethiopian farms rely on rainfall [7]. Irregular rainfall patterns have often resulted in low agricultural productivity and food insecurity. The increasing occurrence of extreme weather events (e.g., severe droughts and heavy rainfalls) is a further threat to smallholder farms [74,75]. Intensive rainfall often results in surface runoff combined with losses of the fertile soil from the upper soil layer. Lack of rain over long periods combined with high temperatures cause serious deficits in soil moisture [76]. Due to the low distribution of irrigation facilities, water is often not available for many smallholder farms, causing frequent crop failures [41,76,77]. For instance, smallholder farms in Hararge faced great production losses of sorghum in 2013, due to a lack of rainfall in the growing season [78]. It has been estimated that variability of rainfall may cause an average reduction in crop yields for teff, wheat, and maize of 2.4%, 6.2%, and 10.8%, respectively, by 2050 at the national level [79]. If no adaptation measures are taken, the effects of climate change and the resulting unfavorable distribution of rainfall may reduce Ethiopia's GDP by as much as 2.5% per year by 2050 and seriously affect the livelihoods of smallholder farmers [80].

3. Potential Climate-Smart Agriculture Practices for Smallholder Farming Systems in Ethiopia

In order to increase the productivity of small-scale agriculture in a sustainable way, appropriate agronomic management practices and suitable technology are needed [8,15,30,44,54,81,82]. This should be linked with the mitigation of climate change impacts and other relevant environmental problems (e.g., soil degradation, soil erosion, water shortages, salinization) [4,83–87]. In Ethiopia, several CSA practices are applied in smallholder farming systems (Table 1) and their current status and future potential are discussed in this section.

Table 1. Summary of potential climate-smart agriculture (CSA) practices for smallholder farming systems in Ethiopia.

CSA Practices	Main Components	Why It Is CSA
Conservation agriculture *	Reduced tillage	Sequesters soil carbon and reduces greenhouse gas (GHG) emissions
	Crop residue management	Improves soil fertility
	Crop rotation/intercropping with cereals and legumes	Enhances resilience to dry and hot spells
	Diversifying cropping systems	Sequesters soil carbon
Integrated nutrient management *	Compost and manure management, including green manuring	Increases soil resilience to drought
	Efficient fertilizer application techniques (time, place, method)	Improves soil fertility
	Combined use of inorganic fertilizers, locally available organic matter, and soil amendments	Reduces nutrient leaching
Agroforestry (AF)	Tree-based conservation agriculture	Reduces GHG emissions
	Traditionally practiced AF	Increases agricultural productivity
	Improved types of AF	Sequesters soil and biomass carbon
Water harvesting and irrigation	Rainwater and runoff harvesting	Supports resilience to drought
	Small-scale irrigation	Increases agricultural productivity
	Traditional irrigation systems	Increases water availability
		Enhances resilience to dry and hot spells
		Increases agricultural productivity

* as part of Integrated soil fertility management.

3.1. Integrated Soil Fertility Management

Integrated soil fertility management (ISFM), which includes and combines soil conservation practices and integrated fertilizer management, is an important measure to increase crop production and mitigate impact of climate change [18,88]. In recent years, special attention has been placed on ensuring that ISFM technologies are adaptable to farmers' local conditions and are also tailored to different cropping systems and socioeconomic profiles [89–91]. On-station and on-farm studies conducted in Ethiopia in different agro-ecological zones have shown that ISFM had positive effects on yields of teff, wheat, and maize [92]. A further relevant effect for Ethiopian agriculture is increased soil water retention capacity through ISFM practices [93].

3.1.1. Conservation Agriculture Practices

Conservation agriculture (CA) is a farming system that reduces soil degradation and prevents losses of cropland while regenerating degraded lands [3,94,95]. It encompasses three main principles: (I) minimizing soil disturbance through direct seeding, minimal or no-tillage, and the avoidance of excessive compaction by machinery, animals, or humans; (II) maintaining permanent soil cover through suitable crop rotations and the use of cover crops and mulch; and (III) diversifying cropping systems [9,16,68,96]. Conservation agriculture can provide various benefits to Ethiopian smallholder farming systems (Table 2).

Table 2. Summary of major findings of conservation agriculture studies in Ethiopia.

The Role of Conservation Agriculture	Implication for Climate-Smart Agriculture	References
Soil organic carbon increased by about 0.5% at a depth 0–30 cm by minimum tillage compared to conventional tillage in Akaki district.	Carbon sequestration	[9,97]
Soil organic carbon increased from 2.2% to 2.6% at surface horizon by conservation tillage in the Tigray region.	Carbon sequestration	[98]
Soil organic carbon increased by 33% due to conservation tillage compared to conventional tillage in Amhara.	Carbon sequestration	[99]
Bean grain yield increased by 32% and soil organic matter by 0.4% due to minimum tillage at Melkassa research center.	Increased productivity Carbon sequestration	[76]
Mulch increased grain yield of wheat by 28% in comparison to the control in the Tigray region.	Increased productivity	[100]
Intercropped maize with crotalaria and lablab decreased emissions of GHG.	Lower emissions of GHG	[101]
An increase of the crop diversity index by 10% reduced probability of poverty by 17.5%.	Increased productivity and resilience	[102]
Hagarghe highlands with high diversity of cultivated crops had a higher dietary diversity status (73.9%) than in non-diversified areas (15.2%).	Increased productivity and food security	[103]

Minimal or no tillage can enhance soil organic carbon, which is very important for soil fertility and soil structure [9,17]. In Amhara, reduced tillage increased soil organic carbon by 33% compared to conventional tillage [76,99]. Reduced tillage can also increase the stability of aggregates, water holding capacity, and soil moisture and, therefore, protect the soil from erosion compaction [95,98,104–107]. These effects on soil can also contribute to increasing crop yields without increasing GHG emissions [73]. Finally, conservation tillage practices can save labor and costs, which is important for resource-poor smallholder farmers and especially for female farmers [16,96,108,109].

Soil cover by cover crops or mulch can help to prevent losses of soil and nutrients and has additional advantages regarding the conservation of soil moisture. For instance, covering soils by straw mulch reduced soil losses due to surface runoff by almost 100% in the highlands of Bale [87]. In northern Ethiopia, mulching with crop residues increased soil water in the root zone by more than 13% compared to a control treatment without mulch, which also affected the wheat grain yields positively [100].

The diversification of cropping systems is another approach to increase yields while reducing GHG emissions, as recently shown by Raji and Dörsch [110] for intercropped maize with crotalaria (*Crotalaria juncea*) and lablab (*Lablab purpureus*). Diversification of cropping systems also serves as a tool to improve the livelihood of the smallholder farmers [103,111]. In this regard, Dessie et al. [101] demonstrated that the diversification of cropping systems in northwestern parts of Ethiopia is a suitable strategy for risk reduction and to increase food security. Survey results from 15 villages in Ethiopia from 1989 to 2009 revealed that an increase of the crop diversity index by 10% reduced the probability of poverty by 17.5% [102].

Conservation agriculture has been practiced in Ethiopia for the last 20 years and its adoption level among smallholder farmers has increased [68,95]. For example, 70,000 smallholders have adopted CA in the Wolaita area to control soil erosion, improve soil fertility, and address climate variability [95]. The Agricultural Transformation Agency (ATA) of Ethiopia supported about 6000 farmers in seven Woredas (the third-level administrative divisions of Ethiopia) in 2012 and 2013 to increase conservation tillage practices, and trained hundreds of experts and development agents [23]. Apart from these promising facts, Ethiopia still has significant problems in implementing conservation farming methods in the whole country.

3.1.2. Integrated Nutrient Management

Integrated nutrient management (INM) is a holistic approach and can be defined as the maintenance and regulation of soil fertility and plant nutrient supply to an optimum level in an integrated manner. It is based on the combination of organic, inorganic, and biological nutrient sources in a specific cropping system under consideration of local conditions to achieve and sustain optimum yield without harming the soil ecosystem [89,112–114]. Beside the positive effects on the soil nutrient status, INM can also enhance soil organic matter and increase the retention and storage of water [17,115]. Thus, it can increase the resilience of agricultural systems and contribute to increasing carbon sequestration in soils [71,75,116].

Various benefits of INM have been found in Ethiopia regarding crop yields and soil organic carbon (Table 3). A meta-analysis using studies conducted in sub-Saharan Africa including Ethiopia found that mixed application of manure and inorganic fertilizer resulted in 1.1 to 4.7 times higher maize yields compared to sole application of manure or inorganic fertilizer [117]. In the Benishangul-Gumuz region, the integrated use of inorganic fertilizer and compost increased maize yield (3.25 t ha^{-1}) and the harvest index (1.9%) compared to sole inorganic fertilizer application [118]. In the central highlands of Ethiopia, mixed application of NP fertilizer and organic amendments increased the content of soil organic carbon by about 0.5% in comparison to sole application of NP fertilizer [116].

Table 3. Summary of major findings of integrated nutrient management (INM) studies in Ethiopia.

Effects of Integrated Nutrient Management	Implication for Climate-Smart Agriculture	References
Integrated use of compost and NP ($55/10 \text{ kg ha}^{-1}$) resulted in higher maize yield (2.34 t ha^{-1}) than sole application of NP ($110/20 \text{ kg ha}^{-1}$).	Increased productivity	[119]
Integrated use of NP (30/10) and compost produced greater maize yield (3.25 t ha^{-1}) than sole application of NP (60/20).	Increased productivity	[118]
Mixed application organic and inorganic fertilizers increased content of soil organic carbon by about 0.5% in comparison to sole application of NP fertilizer.	Carbon sequestration	[116]
Mixed application of manure and inorganic fertilizer produced 1.1 to 4.7 times higher maize grain yields than sole application of manure or inorganic fertilizer.	Increased productivity	[117]
Compost application increased the soil organic matter by 3.8% and increased the availability of soil nutrients in the Amhara region.	Carbon sequestration Soil fertility	[120]
Straw after compost application resulted in higher yields of cereal grains in the Amhara region.	Increased productivity	[121,122]

As an organic fertilizer, compost plays an important role because of its nutrient contents and its diverse effects on soil fertility and crop productivity. Compost application positively affects soil structure, resulting in higher resistance to erosion, improved water infiltration, and increased water holding potential, which is of great importance in Ethiopia [75]. Effects of compost application on soil chemical properties like pH, cation exchange capacity, and electrical conductivity can result in higher bioavailability of nutrients [120]. The addition of organic matter to soil also positively affects biological soil characteristics and enhances the microbial activity of soils [123,124]. The low technical effort for compost production is very important for countries with a weak economy [120]. Because of these benefits, compost application has been well studied and practiced in Ethiopia. For example, compost application resulted in a better status of soil macro and micro nutrients compared to inorganic fertilizer application in Amhara region [120]. It increased maize yields in Tigray [121,125] and barley yields in Amhara [122] compared to chemical fertilizer applications. In Arsi Negelle, compost application over three years resulted in soil carbon sequestration of about 0.2 t ha^{-1} [126]. Considering the high cost for chemical fertilizer in Ethiopia, smallholder farmers are encouraged to use compost [68,73,127].

However, the availability of organic materials for soil application is a major issue. Theoretically, the annually available organic materials in Ethiopia were estimated to be 8.5×10^9 t of poultry manure, 1.8×10^{10} t of farmyard manure, and 1.6×10^{11} t of compost [128]. This amount of organic materials could be a good basis for sustainable agricultural practices [73,127], but the majority of available organic matter is used for other purposes as fuel, food for animals or construction material (see Section 2.3).

3.2. Water Harvesting and Small-Scale Irrigation

Water harvesting is the collecting and storing of rainwater (from rooftops and local catchments) and of seasonal floodwaters (from local streams) as well as the conservation of water through watershed management [129]. The water collection system can be categorized into I) in-situ water conservation practices, which mainly refers to the collection of water in small basins, pits, and bunds/ridges, and II) runoff-based systems, which mainly refers the collection of water from the catchment and roadside ditches [130,131].

In Ethiopia, the rainfall pattern is characterized by a large variation in spatial and temporal distributions: annual rainfall ranges between 2700 mm in the south-western highlands and less than 200 mm in some parts of the northern and south-eastern lowlands [41,132]. To compensate for the limited precipitation in certain areas, the adoption of water harvesting is very important. In addition, it is a useful mechanism to overcome the recurrent erratic rainfall and dry spell conditions, which often result in crop failures in the smallholder farming systems in Ethiopia [133]. Various benefits of water harvesting and small-scale irrigation have been found in Ethiopia (Table 4). Farmers increased their household income by 5% through using water harvesting for the production of tomatoes and onions in the Tigray region [134]. Onion cultivation with water harvesting provided higher annual income compared to rain-fed teff and wheat cultivation in the Amhara region [130,135]. Application of water harvesting increased the yield of teff by about 0.5 t ha^{-1} , wheat by about 0.7 t ha^{-1} , and barley by about 0.6 t ha^{-1} in Tigray compared to rain-fed crops [132,136]. In addition, small-scale irrigation allows the production of more crops per year on a certain area and consequently contributes to sustainable food security in Ethiopia [137]. Research findings [138,139] revealed that there is a significant welfare difference between farmers applying and farmers not applying irrigation.

Ethiopia has great potential for irrigation with 12 river basins, about 122 billion m^3 annual runoff volume, and 2.6 billion m^3 groundwater [130,132]. Although small-scale irrigation schemes have been promoted in sub-Saharan Africa to ensure food security, less than 5% (640,000 ha) of the agricultural land in Ethiopia is irrigated, which includes 128,000 ha from rainwater harvesting, 383,000 ha from small-scale irrigation, and 129,000 ha from medium and large-scale irrigation [140,141]. Studies on irrigation schemes have shown that much of the perceived water scarcity level is rather attributed to poor water management practices, weak local institutions, unfavorable governance regimes, and financial issues than to the physical scarcity of water [137,142,143]

Table 4. Summary of major findings of water harvesting and small-scale irrigation studies in Ethiopia.

The role of Water Harvesting and Small-Scale Irrigation	Implication for Climate-Smart Agriculture	References
Onion cultivation with water harvesting provided \$2000 higher annual income compared to rain-fed teff and wheat cultivation in the Amhara region.	Increased productivity	[130,135]
Securing adequate water availability for crops through water harvesting in Tigray.	Increased resilience of cropping systems	[136]
In-situ rainwater harvesting provided higher maize yield (25%) than rain-fed crops in northern Tigray.	Increased productivity	[135,144]
Farmers applying small-scale irrigation had a lower incidence of poverty (28%) than the non-irrigation users (67%).	Increased productivity	[137]
Higher yield of teff (0.3–0.6 t ha ⁻¹), wheat (0.5–0.8 t ha ⁻¹), and barley (0.45–0.75 t ha ⁻¹) obtained with small-scale irrigation compared to rain-fed cropping in Tigray.	Increased productivity and resilience	[136]
The annual income of irrigation beneficiaries in the Great Rift Valley of Ethiopia was at about 10,200 Birr per household about 34% higher than that of non-users.	Increased productivity and resilience	[139]
In Ambo district about 60% of farmers without irrigation facilities but only about 35% of farmers with irrigation facilities were estimated to be below the poverty line,	Decreased poverty	[138]

3.3. Agroforestry

Agroforestry is a farming practice of cultivating trees in combination with crops and/or livestock. It can provide additional food, fuel woods, and various ecosystem advantages such as increased soil fertility and carbon sequestration, as well as less soil erosion and land degradation [3,145–147]. Agroforestry allows smallholder farmers to produce various goods and services in an integrated manner to address a broader range of demands [148]. Therefore, it has been widely recognized as a good strategy to cope with food insecurity and climate change in developing countries [146,149].

In Ethiopia, various types of agroforestry have been practiced, e.g., home garden, tree-crop intercropping, parkland or scattered trees in croplands, and shaded perennial-crop systems. They have contributed to enhanced food security, resilience to climate change, and carbon sequestration (Table 5). For example, agroforestry adopters received about 17% higher yields [150] and about 7% higher incomes [31] than non-adopters in the Amhara region. As trees can obtain moisture from the underground water through their deep root systems, they can still grow in times of water shortages [149,150] and produce various fruits, which are sources of supplementary food and income generation for smallholder farmers in Ethiopia [31,145]. Studies conducted in eastern Tigray [151] and the south-eastern Rift Valley escarpment [127] highlighted the increased carbon sequestration by agroforestry while protecting native trees. The increased fertility of agricultural land was the most common reason (about 40%) for farmers to practice agroforestry [27].

Table 5. Summary of major findings of agroforestry studies in Ethiopia.

The role of Agroforestry	Implication for Climate-Smart Agriculture	References
The land productivity of agroforestry adopters is 16.6% greater than non-adopters in the Amhara region.	Increased productivity	[150]
Agroforestry with white acacia (<i>Faidherbia albida</i>) sequestered 9.7 Mg ha ⁻¹ of organic carbon more than rain-fed crop production in the Tigray region.	Carbon sequestration	[151]
Soil organic carbon increased by 52% compared to annual cereal rotation.	Carbon sequestration	[149]
Protection of native trees and increase of annual income by 7% could be achieved by farmland agroforestry in the Amhara region	Resilience to climate change Improved livelihood	[31]
Aboveground and belowground carbon could be accumulated in the south-eastern Rift Valley escarpment while protecting native trees.	Carbon sequestration Resilience to climate change	[152]
Restoration of degraded land in various regions of Ethiopia	Resilience to climate change Improved livelihood	[153–155]
Promotion of ecosystem services in Southern Ethiopia	Resilience to climate change Improved livelihood	[156]

Despite these advantages, the practice of agroforestry is still limited in many parts of Ethiopia due to increases in fuelwood demand, agricultural intensification, and lack of knowledge about the conservation of trees [31,157]. Unsecured or ambiguous land tenure and shortage of labor were identified as further limiting factors [27,158].

4. Challenges for Adoption of Climate-Smart Agriculture Practices in Smallholder Farming Systems

Despite the advantages of CSA, there are still various challenges hindering the adoption of CSA in smallholder farming systems. The most commonly identified challenges in Ethiopia are discussed below.

4.1. Shrinking Cropland and Land Tenure Issues

The size of the land holding is a major challenge for Ethiopian smallholder farmers in the adoption of new technology and practices [159]. Due to growing population pressure and the limited availability of unexploited land the size of cropland per capita has been decreasing (see Section 2.2). Farm size plays a critical role in the adoption of new technologies. Farmers with larger farms were found to be more likely to adopt CSA practices, since they could use one part of the farm for trying new techniques and the other part for conventional practices [160]. In contrast, farmers with small farms are hesitant to apply CSA practices, since they are afraid of the uncertainty of obtaining the claimed benefit [160]. As consequence, pressure on land has caused land degradation and reduced agricultural productivity in many parts of Ethiopia [24].

Land tenure is another issue for smallholder farmers. In Ethiopia, the current land management system allows farmers to use and manage the land, but they are often not the owners of the land [161,162]. This discourages farmers from investing [162,163] and, accordingly, there is a consensus that the more responsibility farmers have for the long-term management of their land, the more they are willing to undertake larger investments in land management [148]. This is especially important for the establishment of agroforestry systems, because of the long growing periods of trees. Another example is the long-term investment in stone terraces as important soil conservation structures against soil erosion, which is associated with secure land tenure [164].

Declining fertility of soil and unsustainable farming practices are often related to insecurity of farmers about their land tenure and suitable policies are needed to create an environment, which enables individual farmers as well as communities to invest in sustainable long-term land management [19].

4.2. Lack of Adequate Knowledge and Information Transfer

Lack of adequate knowledge and skills is a major constraint in the adoption of CSA practices in Ethiopia [16,23,68]. Ethiopia has five agro-ecological zones based on climatic factors such as temperature [165] and the amount and distribution of rainfall [166] for which completely different recommendations regarding suitable CSA are needed. Some CSA practices are more important in temperate and humid climates with higher yield levels, e.g., integrated nutrient management. Others, however, are more effective in arid and semi-arid conditions, where soil moisture needs to be conserved, e.g., conservation tillage [83,167]. Furthermore, changing rainfall pattern in combination with warming trends make agriculture more risky in Ethiopia and increase the demand for specific, locally adapted agricultural knowledge and technologies [54,167]. These also require additional resources in agricultural research and extension services in order to provide the data basis for appropriate decisions and recommendations [28,168]. However, new research and technology must not result in neglecting indigenous knowledge, which is also needed to make agriculture sustainable in Ethiopia [168].

Another constraint is the inefficient transfer of knowledge, skills, and technologies from governmental institutions and development agencies to the local farming communities [23,68]. Smallholder farmers are often afraid of adopting new practices before seeing clear evidence of successes and getting clear explanations regarding benefits and risks of the practices [6,7,41]. For instance, it is still a great challenge to adopt methods of water harvesting and small-scale irrigation technologies in Ethiopia. This is partly due to a lack of awareness among the farmers and insufficient information about advantages of small-scale irrigation, like diversification of crops grown, increased household income, employment opportunity, and participation in community decisions [129,130,132].

Additionally, exposure to new technology remains highly gendered, with most of the related initiatives targeted at men [169]. Women usually have less access to new technology, information, and training related to climate adaptation and CSA [170].

4.3. Slow Return of Benefit and Lack of Financial Support

One of the major challenges that hinder the adoption of CSA in Ethiopia is its slow return on investment. Many CSA practices, such as agroforestry, take time to provide tangible benefits to the farmers [4], but, due to the low status of the economy and lack of finance, most farmers need immediate benefits from a specific technology or practice [16,68]. As a result, the preference for the adoption of CSA is often lower than that of other agricultural practices with fast yield effects [4]. Farmers may also give up suitable technologies after a few years of using them due to a shortage of materials for construction, maintenance and operation, as shown for water harvesting technologies by [171]. Thus, incentives and support during the transition period as well as guarantees in the case of failure are necessary for the extension of CSA practices [16,172].

Access to finances is a critical factor for smallholder farmers [173]. Financial support systems in Ethiopia can be separated into informal and formal institutions. Informal financial support institutions are (I) self-support groups for social development (*Idhir/Meredaja Mahiber*) and (II) traditional voluntary cooperatives (*Iqub*). Formal institutions are microfinance schemes, state-owned banks, and private commercial banks [173]. There are, however, problems concerning financial and institutional support. The informal financial institutions often lend money at high interest rates, so smallholder farmers face challenges paying back the loan on time. The formal finance providers support commercial farmers, but often ignore smallholder farmers [4].

5. Opportunities for Enhancing Climate-Smart Agriculture Practices in Smallholder Farming Systems

In order to successfully implement CSA practices, coordinated actions by farmers, researchers, the private sector, civil society, and policymakers are needed [11]. In the

following, promising opportunities to extend the application of CSA practices in Ethiopia are discussed.

5.1. Utilization of Degraded and Marginal Lands

Instead of expanding agricultural lands at the expense of forest, the widely distributed degraded lands and marginal lands (around 26% of the country; [174]) should be restored and utilized. To achieve this will involve two key changes: greater access to organic materials for soil management and alternative energy sources to reduce land clearing and degradation.

Access to and use of organic inputs is one of the most suitable methods to increase the fertility of degraded soils and an important CSA practice [16,30,68,175] (see also Section 3.1). However, biomass is commonly used as an energy source in the rural part of Ethiopia [176,177] (see also Section 2.3). Therefore, it is important to introduce and adopt appropriate measures to increase energy efficiency and to use alternative energy sources. Various types of improved cook stoves have been developed in Ethiopia (e.g., Mirt, Mirchaye, Lakech, and Rocket stoves) and their fuel efficiency is about 30 to 40% higher than conventional cook stoves (e.g., open fire) [178–180]. This can reduce significantly the use of biomass as an energy source. Furthermore, Ethiopia has great potential to produce renewable energy from sources other than biomass [178]. Potential renewable energy sources in Ethiopia are solar energy (500 MW km⁻² in the lowlands and 100 MW km⁻² in the highlands), hydropower (about 45 GW potential), wind energy (about 10 GW potential), and geothermal energy (about 5 GW potential) [58]. Increasing awareness among smallholder farmers to fully exploit the locally available organic materials can also help to provide organic fertilizers to soils. For example, coffee husk is especially common in the highland area of Ethiopia. In the Shabedino district in southern Ethiopia, a small coffee-producing village dumps about 7000 t of dry coffee husk in rivers annually [181]. This suggests a large quantitative potential of coffee wastes as organic soil amendment in regions with coffee production. The coffee husk can be used as a mulching material to prevent moisture losses and as a feedstock for producing compost, which can improve soil fertility and crop production [181,182]. Residues from khat or chat (*Catha edulis*) are other locally available and cheap organic sources and can be a basis for compost production. It was found that khat vermicompost had relatively high nutrients (1.6% N, 0.6% P) [183]. Another promising opportunity of using wastes to increase the fertility of soils is to produce biochar from wastes of the meat processing industry [65]. In addition, composting organic waste such as food waste and garden waste, which is disposed of in urban Ethiopia, can also be sources of organic fertilizer for agricultural use, as long as it does not contain critical levels of harmful substances [183–185].

Salinity and waterlogging are also key issues for Ethiopia's agriculture and often reasons for land degradation [186]. Appropriate water management practices, drainage systems, and irrigation methods can mitigate these problems and increase the availability of productive agricultural land [187]. For example, in the Awash Basin, reclaimed saline fields increased sugarcane production by 50% [188]. Challenges in relation to costs and technology in the design, implementation, and operation of drainage and irrigation systems can be overcome by introducing low-cost technologies [186]. For instance, an improved water management and surface drainage method, called "broad bed and furrow", has been introduced in several parts of Ethiopia [189]. The mapping of spatial and temporal dimensions of waterlogging and salinity can help to better describe their impacts on the agricultural productivity and thus to initiate appropriate measures [186].

Degraded land which is not suitable for the pure production of crops should be converted to agroforestry, since agroforestry is one of the most promising CSA practices [190] and has a great potential to improve soil fertility [7,19,146] (see also Section 3.3). In particular agroforestry systems that contain leguminous tree species are vital since they provide additional value due to biological nitrogen fixation [191].

On-farm trees and a return to a more diverse agricultural landscape mosaic may provide provisioning and other ecosystem services [52,153,192]. Especially in landscapes dominated by cropland, the benefit of such tree-planting is very high and linked to greater livestock numbers, improved resilience and diversification of income sources, and increased biodiversity [155]. Thus, trees can be seen as a sustainable intensification of agriculture [153]. Eucalyptus is often chosen for tree-planting, as it is a lucrative form of income [32]. However, eucalyptus trees can have a negative impact on the environment (e.g., due to their high water consumption) and more emphasis should be placed on the establishment and management of mixed-species woodlots [154,156].

Interdisciplinary landscape approaches that promote agricultural productivity as well as ecological functions should be applied in order to regenerate agricultural land, contribute to rural livelihood, and conserve biodiversity in landscapes where farmers co-exist with nature [32,148,153,154]. This is also addressed in the Forest Landscape Restoration (FLR) program. With 15 million ha, Ethiopia is one of the countries with the most ambitious FLR targets [52]. A main objective of this strategy is to restore degraded and marginal landscapes in order to mitigate impacts of climate change [193,194]. This program will have particular advantages for smallholder farmers as the most vulnerable to landscape degradation and the greatest beneficiaries of restoration [159].

5.2. Providing Microfinance for the Adoption of Climate-Smart Agriculture Practices

Access to financial support services strongly influences the decision of smallholder farmers to apply suitable CSA practices [73]. Financial support, however, also requires an increased awareness of the farmers of the financial opportunities [195], and often farmers must be trained regarding their rights of credit use and the obligation to repay in time [7]. There are various international programs that support climate funds in Ethiopia which can be useful for smallholder farmers to shift their farming system to CSA and to overcome barriers such as poor equipment and lack of inputs [14]. They include the Scaling-Up Renewable Energy Program for low-income countries (SREP) of the Climate Investment Funds (CIF), the Global Environment Facility (GEF), and the Clean Development Mechanism (CDM) [4,196]. They provide financial support for climate-related projects either to mitigate the impact of climate change or to increase the resilience potential of the agricultural and environmental sectors. In addition, the REDD+ program is a relevant CSA funding option administered directly through United Nations agencies and implemented by the United Nations Environment Programme (UNEP) [14,74,80]. This program makes investments in small and medium-sized enterprises dealing in clean energy solutions in rural areas, thereby increasing climate change mitigation.

Some regional organizations like banks and microfinance institutes also provide financial support for CSA investments of smallholder farmers. For example, Oromia Cooperative Bank of Ethiopia (OCBE) supports local agri-businesses related to sustainable agricultural production in smallholder farming systems [7]. The development of specialized finance schemes throughout the country and a strong framework from federal schemes to local institutions could provide even more effective support of CSA practices in smallholder farming [4,196].

5.3. Education, Empowerment, and Capacity-Building

Training is an important capacity-building tool to disseminate CSA practices and for agricultural extension workers to pass on their knowledge to the farmers in a targeted manner [3,96]. Besides theoretical information, the practical aspects should also be transferred in order to increase the adoption of CSA practices. For example, practical training is often needed regarding suitable soil nutrient management, compost preparation from locally available materials, conservation agriculture, and water harvesting techniques, because these practices are very dependent on the respective local circumstances [4,162]. As a result of such targeted teaching, the farmers would have more experience and can easily familiarize themselves with CSA practices [96]. Most farmers prefer to see at firsthand

the workability and applicability of new technologies and practices and to compare them with their own farming practices. Knowledge-sharing and joint educational activities allow farmers, extension workers, NGOs, and researchers to learn about success stories and the challenges associated with local CSA practices [23]. Ultimately, farmers should be empowered to develop solutions and make decisions on their own [197].

Women usually have less access to new technologies and training related to climate adaptation and CSA [169,170] (see also Section 4.2). Gender mainstreaming can increase women's potential to access useful information and training on new technologies [3,166]. Education and training on CSA practices can also enhance opportunities and reputation of women in rural areas [23]. For example, a study indicated that women's skills have been increased through training on compost preparation from locally available materials, water harvesting systems, and small-scale irrigation schemes [28]. This training has finally increased the income of women in rural Ethiopia [198]. Empowering women means increasing their power to think and act freely, exercise choice, and to fulfil their potential as full and equal members of society [199]. However, gender empowerment cannot only be achieved through training and education. Allowing the participation of women in the process of decision-making and giving them access to inputs and resources is just as important [28,200]. In addition, increasing the engagement of women in political, social, and economic issues can in turn increase the adoption of CSA among smallholder farmers in Ethiopia [28,198].

In addition, theoretical and practical aspects of CSA should be more incorporated in higher education curricula [201]. As education raises the awareness on both problems and solutions of land management, it also has a positive impact on investments in CSA practices [85].

5.4. Policy Support for the Implementation of Climate-Smart Agriculture Practices

Policy support is fundamental for the spread of CSA practices in the country. In the past decades several policies and strategies have been established for the agriculture sector to reduce poverty, especially for rural smallholder farmers in Ethiopia. These include the Agricultural-Led Industrialization (ADLI), according to which a rapid growth in agricultural production, increased income for rural households (especially for crop producers), and national food self-sufficiency can be obtained [61,202]. ADLI was later complemented by programs such as the Sustainable Development and Poverty Reduction Program (SDPRP) (2000 to 2005), a Plan for Accelerated and Sustained Development to End Poverty (PASDEP) (2005 to 2010), and the Growth and Transformation Program I (2010 to 2015) and II (2015 to 2020 [203]. The development of these programs show that compared to other sub-Saharan African countries, Ethiopia has an admirable record of supporting agriculture [25].

However, it becomes clear that the effects of climate change on agriculture can hamper the progress achieved so far and that practices more relevant for climate change adaptation and mitigation need to be promoted by means of specific policies. While Ethiopia does not have a standalone CSA strategy, significant efforts are made to develop policies and strategies relevant to climate change [3]. One important example is the Climate Resilient Green Economy (CRGE) strategy, which was established in 2011, targeting climate change adaptation and mitigation [166] with the aim of achieving a carbon-neutral middle-income status by 2025 in Ethiopia [3]. The policy incorporated CSA and sustainable land management for improving crop and livestock production, food security, integrated watershed management, and farmer income, while reducing GHG emissions (limiting emissions to 150 Mt CO₂-e in 2030) [204,205]. It also explicitly includes the protecting and re-establishing forests [3] and it indicates that agroforestry is one of the initiatives to reduce pressure on forest resources while preventing soil erosion and land degradation [27]. Forest protection and extension is also a responsibility of the forest proclamation [206], which was approved in 2018 and regulates options for forest development, conservation, and utilization. The forest proclamation also contains tenure reform and states that communities and associa-

tions can have forest ownership rights. This is an important factor to overcome the current impediments regarding forest landscape restoration (FLR), agroforestry, and the adoption of other CSA practices [207] (see Section 4.1).

These measures indicate that climate change and CSA have been recognized in the process of establishing policies and strategies in Ethiopia. However, considering the challenges described in Section 4, several suggestions can be made in order to enhance the implementation of CSA among smallholder farmers. First, a strong awareness among the community members of the need to improve their land use systems for sustainable livelihood and environmental protection must be achieved. In this regard, it is also necessary that communities are involved in relevant decision finding processes and that land use rights are clarified [19,207]. No policy or strategy will be especially successful without the involvement of the local community and the integration of the local farmers as a basic stakeholder [96]. For example, the CRGE was established at the national level to implement the projects. Since Ethiopia has five institutional levels (federal, regional, zonal, woreda, and kebele), the CRGE should also consider these structural administrative levels [80]. Second, agricultural development policy and strategy should carefully consider the specific issues related to small-scale farming and should place more emphasis on capacity-building, information dissemination systems, and institutional and financial support [6]. Third, formulating policies and strategies that promote the adoption of CSA should better consider the differing characteristics of climatic conditions and agro-ecology that are found across the country (e.g., different rainfall and temperature patterns) [3,167].

6. Conclusions

Agriculture in Ethiopia is dominated by smallholder farming systems, which together produce more than 90% of agricultural output and cultivates more than 90% of the entire cropland. In recent decades, agricultural production has made some progress; however, it needs further transformation to increase crop production in smallholder farming systems while adapting to and mitigating climate change. Various CSA practices have been adopted locally and studies have identified their various benefits, including increased drought resilience, household income, carbon sequestration, and GHG mitigation. However, the adoption of CSA is still low in smallholder farms due to a lack of land, resources, adequate knowledge, and financial and policy support. In our study, we comprehensively evaluated currently available CSA practices, which allow us to suggest opportunities and solutions for a sustainable improvement of smallholder farming systems. In this regard, we have particularly emphasized the following measures: (1) Improvement of soil quality and restoration of degraded and marginal land instead of expanding cropland through deforestation; (2) Providing training, education, and capacity-building for farmers and extension workers; and (3) Development of specific financing schemes and policies for smallholder farming systems. Although our study focuses on the situation in Ethiopia, the results may also be relevant for other countries, which aim at increasing agricultural production while mitigating the effects of climate change.

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