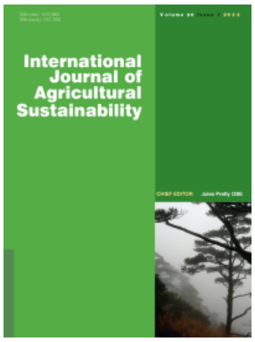

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Opportunities and challenges for conservation agriculture in Botswana

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ABSTRACT

Conservation agriculture (CA) is being promoted as an energy efficient and cost-effective farming system that conserves soil and water and improves crop yields. Adoption of this farming system can contribute to attainment of Sustainable Development Goal (SDG) 2: end hunger, achieve food security and improved nutrition, and promote sustainable agriculture. However, the adoption rate of this new farming technique by smallholder farmers in sub-Saharan Africa (SSA) is low. The trade-offs and synergies related to the three pillars that anchor CA have not, however, been investigated in the context of Botswana. Farmers are faced with trade-offs in the use of crop residue in CA as mulch with traditional use as feed for livestock. This paper reviews the components of CA with a view to contribute to the development of CA strategies for Botswana. We show that adoption of CA in SSA is challenged by lack of weed control measures, the lack of a market for grain legumes and competing uses of crop residue. The paper highlights the discrepancy between CA methods and current government subsidies, issues that may restrain the adoption of CA in Botswana. The paper concludes by making recommendations for research and policy development for sustainable CA practices in Botswana.

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No-till; crop residue; crop diversification; cover crop; crop rotations; challenges; adoption

Introduction

Currently, there are 1.5 billion ha of cultivated land that are used to produce food for the world and 73% of this amount are rainfed farming systems (Mishra et al., 2021). Smallholder farming feeds about two billion people–an equivalent of 83% of the world's agricultural population (Timberlake et al., 2022). Thus, it is the most common type of farming in the world (Lowder et al., 2016), but the majority of those involved experience food insecurity and hunger (Otekunrin, 2022). In sub-Saharan Africa (SSA), smallholder rainfed subsistence agriculture is a source of livelihood for about 757 million people (Li et al. 2023). However, production of food in this region is limited by poor soil fertility, land degradation, frequent drought and sheet erosion on cultivated land (Thierfelder et al. 2013a). In addition, water, including its distribution, has been cited as the main constraint to crop production in SSA (Barron et al., 2003). This dire situation negates achievement of Sustainable Development Goal (SDG) 2: ending hunger and enhancing food security, and therefore, calls for intensification of water conservation and sustainable production practices to achieve this goal.

Conventional tillage systems that use soil inversion implements such as the mouldboard plough are responsible for land degradation and ecological impact in SSA (D'Annolfo et al., 2021). They can potentially accelerate oxidation of soil organic matter leading to a decline in physical, chemical and biological properties of the soil (Johansen et al., 2012) and consequently reduction in crop yields. Crop production in semi-arid dryland regions is

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already constrained by water limitations (Moret et al., 2006) and practices that result in soil and water loss will exacerbate the situation. Apart from degrading the soil, conventional tillage also imposes higher labour, fuel and machinery costs (Moret et al., 2007), increasing the cost of production and reducing profitability.

In light of environmental and socio-economic challenges posed by conventional tillage, conservation agriculture (CA) has been promoted by governments and international development organizations as a sustainable and resilient cropping system that can restore soil health and improve water-use efficiency (Antwi-Agyei et al., 2023). Therefore, this farming system can contribute to attainment of the critical component of SDG 2: promotion of sustainable agriculture. CA is a farming practice underpinned by three key agronomic principles: minimum soil disturbance (zero or no tillage), permanent soil cover (crop residue or cover crops) and diversified crop rotations (Derpsch, 2001; FAO, 2016). Its primary aim is to establish organic soil cover, which will improve water infiltration and reduce surface soil temperature (Bayala et al., 2012). Organic soil cover in no-till fields sequesters carbon and CA can potentially contribute to a reduction in global warming by reducing the contribution of agriculture to global greenhouse gas emissions (Fowler et al., 2009). However, the capacity of CA to increase soil carbon stocks is limited (Cheesman et al., 2016) and is confined to 0–10 cm and declines in the deeper soil profile (Luo et al., 2010; Powlson et al., 2016). The possible economic benefits of CA are lower production costs (reduction in fuel and labour costs) and higher returns based on improved yields (Zotarelli et al., 2012). However, while an increase in yield may be observed under CA in low rainfall seasons, in high rainfall seasons crops under CA may experience yield loss due to waterlogging (Rusinamhodzi et al., 2011). For example, in Malawi, CA improved maize grain yield during the drier years of 2009/10 and 2010/11 (Ngwira et al., 2012). Improved yields under CA are mainly linked to increased water infiltration and higher soil organic matter (Corbeels et al., 2014). In SSA, improved water use efficiency was observed even with simple minimum tillage seeding equipment such as oxen-drawn seeders and manual 'jabplanters' (Thierfelder & Wall, 2009).

The suitability of CA for smallholder farming systems in SSA is hotly contested. Like other agricultural technologies that aim to increase crop production and reduce risk, the adoption of CA is influenced by factors such as prevailing land use practices, production constraints, farmers' goals, envisaged benefits and costs associated with its practice (Giller et al., 2011). These factors are more pronounced amongst resource-poor smallholder farmers in SSA and the introduction of CA in this region may be questionable.

Table 1. CA adoption in Sub-Saharan Africa.

Country	CA area (ha)
Ghana	30,000
Kenya	33,100
Lesotho	2,000
Malawi	65,000
Madagascar	6,000
Mozambique	152,000
Namibia	340
South Africa	368,000
Zambia	200,000
Zimbabwe	332,000
Total	1,188,440

Source: FAO (2016).

Several SSA countries in east and southern Africa are now using CA (Table 1) and the total area under CA is 1,188,440 ha (FAO, 2016). In most of these countries, CA is now included in the government's agricultural policy and forms part of the research strategy of international research institutes, for example the International Maize and Wheat Improvement Center (CIMMYT) and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) (Giller et al., 2015). The New Partnership for Africa's Development (NEPAD), the technical body of the African Union (AU), promotes the adoption of CA and has integrated the farming system into their regional agricultural policies (Friedrich et al., 2012). However, most of the area under CA is on large scale commercial farms with the use of appropriate no-till equipment and herbicides (Wall, 2007). Lack of financial resources (to buy inputs), human resources (labour) and information resources (information to implement CA) have recently been cited as the limiting factors for adoption of CA by smallholder farmers in Africa (Brown et al., 2017). Smallholder farmers in SSA have little access to credit to purchase no-till implements and agrochemicals (Lal, 2009). This is likely to be the case in Botswana where smallholdings are dominated by manual and animal traction systems. Lastly, CA is knowledge-intensive and necessitates fundamental changes in knowledge and farming practices rather than tillage alone (Ofstehage & Nehring, 2021).

Botswana's agricultural sector is characterized by livestock production and arable crop production

(Seleka, 2004). Cattle production plays a significant role in the rural economy as an essential source of revenue, livelihood and welfare (Seleka & Kebakile, 2016). Cattle also provide draught power and organic manure for crop production (Nsoso et al., 2010). In these crop-livestock systems, CA presents farmers with trade-offs in allocation of crop residue among competing uses of mulching and feeding livestock. This discussion is revisited later in this paper.

Dryland arable agriculture mainly involves production of staple cereals of sorghum (*Sorghum bicolor*) and maize (*Zea mays*), for subsistence and commercial purposes (Nthoiwa et al., 2013). Other crops include grain legumes and sunflower (*Helianthus annuus*). Arable agriculture in Botswana comprises traditional (smallholder) and small commercial sub-sectors, with farm sizes of 5–16 and 300–1000 ha, respectively (African Development Bank, 2008). The former is characterized by low-input and low management systems whereas the latter uses more inputs, fertilizers and pesticides, improved seeds, and almost all field operations are mechanized. As a result, the productivity of the large-scale commercial farmers doubles that of the traditional sector (CAR, 2005). In the year 2019, there were about 55,180 smallholder farmers (Statistics Botswana, 2019). Their total area planted with rainfed crops declined from 126,821 in 2017–88,288 ha in 2019. The decline was attributed to low rainfall during the 2018/19 season.

Productivity in the arable sector in Botswana has always been low largely due to low and variable rainfall coupled with poor soil fertility (Abdullahi et al., 2010; Moroke et al., 2010). However, it is the distribution of rainfall over the growing season, not necessarily the total seasonal rainfall, that affects crop growth and yields (Monteith, 1991). Almost 100% of the annual rainfall in Botswana occurs in summer from October to April, but it is rarely uniformly distributed to effectively supply water from crop planting to physiological maturity. The unequal distribution of seasonal rainfall predisposes the crop to a wide range of dry spells, which ultimately result in yield reduction (Barron et al., 2003).

In response to low agricultural productivity, the government of Botswana received international donor funding in 2010 for research and testing of CA through the Ministry of Agriculture in collaboration with Sustainable Intensification of Maize-Legume Cropping Systems for Food Security in Eastern and Southern Africa (SIMLESA) (Misiko et al., 2016). CA was also perceived as a strategy to improve rainfed agriculture in the Botswana Government's Agricultural Services Support Project, co-funded by the International Fund for Agricultural Development (IFAD). In response to food security challenges, the government of Botswana developed a key subsidy programme, Integrated Support Programme for Arable Agriculture Development (ISPAAD), to improve arable sub-sector productivity and food security (MOA, 2016). The number of ISPAAD beneficiaries ranges annually from 110,000 to 180,000 depending on rainfall and availability of tractors. However, this scheme encourages tillage by rewarding tillage practices by either paying farmers directly or the contracted tractor owners for ploughing and disc harrowing.

As stated earlier, the government of Botswana is promoting CA as a strategy to improve rainfed agriculture; however, there is no CA policy or strategy to guide the adoption or implementation of CA principles. The trade-offs and synergies related to the three pillars that anchor CA have not, however, been investigated in the context of Botswana. This review investigates the opportunities and challenges of adopting and implementing CA in Botswana based on the experiences reported for SSA so as to be able to inform policy development. The paper begins by reviewing recent literature on the central role of crop residue management, cover cropping and strategic crop rotations for achieving beneficial agronomic and economic outcomes for farmers using CA systems. Modifying tillage practices can have important effects on farming systems processes such as weed dynamics and climate change impacts. These issues are also reviewed to further understand the potential challenges and opportunities for CA in Botswana.

Methodology

Study area

The study area for this paper is Botswana. The climate of Botswana is semi-arid (Maruatona & Moses, 2022). The climate of Botswana varies from arid in the west to semi-arid from the central to the extreme northeast (Figure 1). The climate is characterized by dry and cool temperatures during winter while the summer months are humid subtropical, interspersed with drier hot periods. Maximum daily average temperatures are between 35°C and 40°C. The main seasons

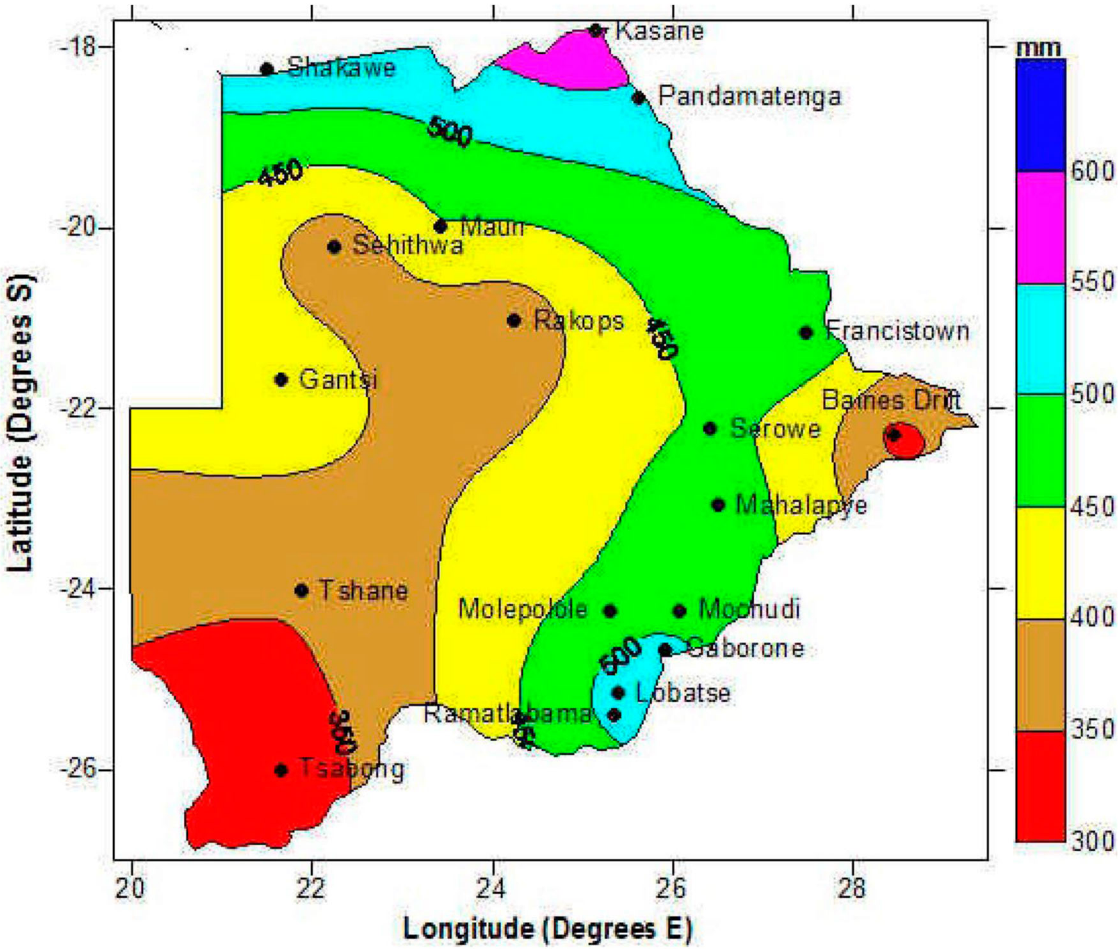

Figure 1. Mean annual rainfall in Botswana (1971–2010).

in Botswana are winter and summer, while spring and autumn (or fall) are practically very short. Generally, summer (also called the wet season) occurs between November and April while winter (the dry season) happens from May to October. Precipitation in Botswana is characterized by high intensity events over a short period of time, leading to run-off (Moroke et al., 2009), and occurs mainly in the summer months. Summer is windy, from late August to early October, and these winds bring moisture from the Indian Ocean. The national annual average rainfall is 460 mm, representing a strong southwest to north rainfall gradient from 250 mm in the arid region to 650 mm in the semi-arid northeast. Rainfall variability is common in semi-arid areas, and climate change is predicted to make this variability worse (Batisani & Yarnal, 2010). As a result, droughts and floods are more likely in Botswana due to rainfall unpredictability. The southwest regions of the country receive little rainfall, have relatively poor soils (Figure 2), and are known as 'sandveld' due to the presence of deep coarse sand. These sandy soils have limited water holding capacity, low levels of nutrients, and little organic matter (Dougill et al., 1998). The eastern areas and further south are referred to as the 'hardveld'. It receives relatively good rainfall and the soils are fairly good due to clay deposits and a higher water-holding capacity (Figure 2).

Secondary data collection

The data for this study were collected from secondary sources in the form of academic journals. Searches for scientific literature published between 2010 and 2023 were made in the Web of Science, Google Scholar, Science Direct and Scopus databases, following

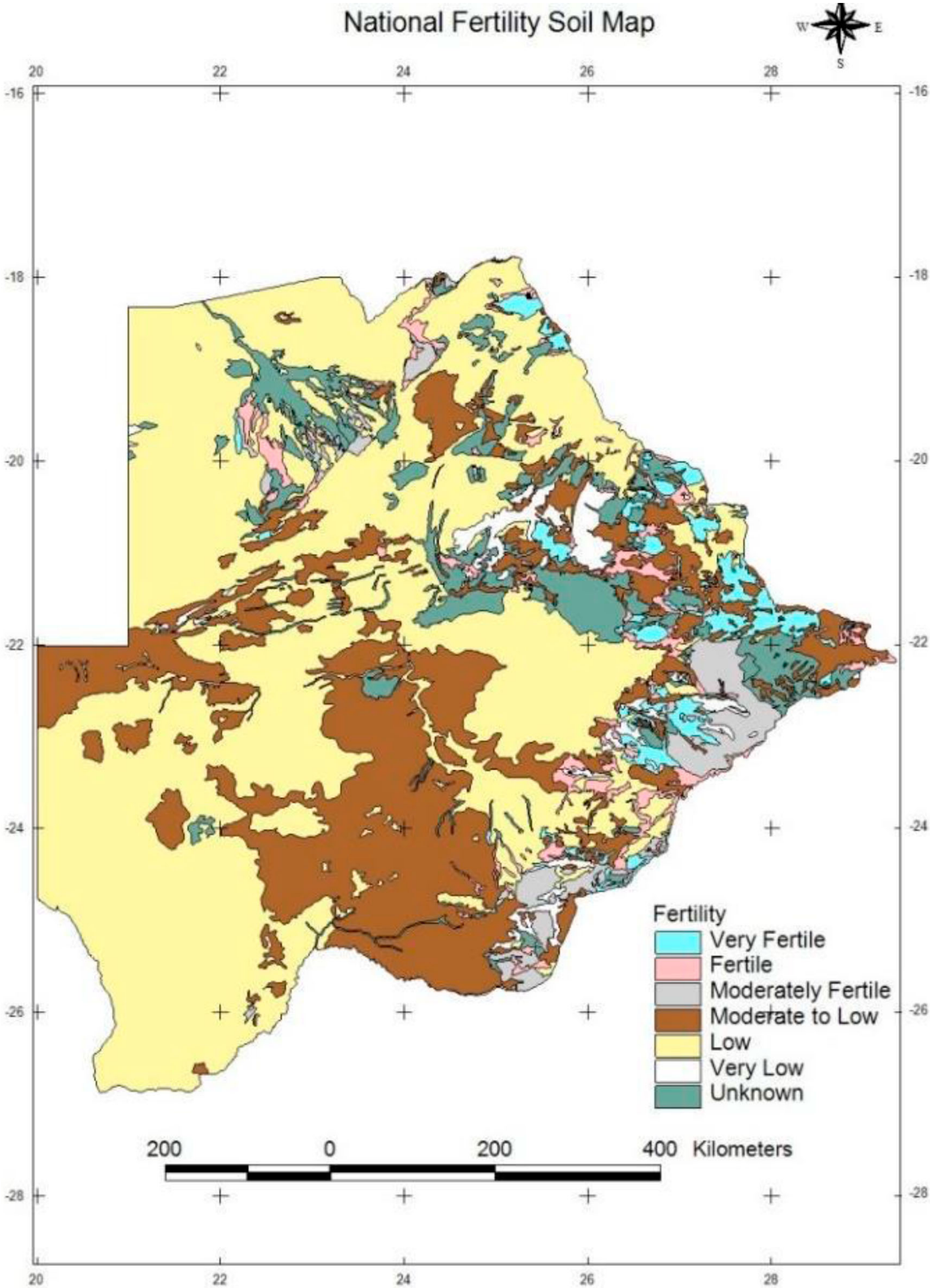

Figure 2. National soil fertility map of Botswana.

Kitchenham (2004) and Sampaio and Mancini (2007). The key search terms used included combinations of conservation agriculture, minimum/reduced/no tillage, diversified crop rotations, crop residue, cover crops and grain legumes. From the output, abstracts were carefully examined for both qualitative and quantitative data on the three pillars anchoring CA: minimum tillage, permanent plant biomass cover and diversified crop rotations. CA has been promoted as a climate smart practice that has the potential to mitigate climate change through soil carbon sequestration. Therefore, soil organic carbon and climate change were included in scrutinizing abstracts. CA primarily eliminates the use of tillage in weed control and therefore farmers opt for herbicides to control weeds. Thus herbicide and herbicide resistance were also included in examining the abstracts. More articles were retrieved by backward referencing from peer-reviewed journal articles that fit the above-mentioned criteria (Gough et al., 2012). This process resulted in 106 peer-reviewed journal articles, 14 books, 13 reports and 3 book chapters being utilized for this review.

Crop residues in conservation agriculture

Crop residues are the principal source of organic matter as C accounts for around 40% of the total dry biomass (Jat et al., 2021). Maintenance of permanent soil cover either by stubble retention or cover crop residues is an essential component of CA. Crop residue, regardless of its position in the soil, can influence many important soil physico-chemical and biological properties (Mu et al., 2016). It reduces runoff, soil erosion and evaporation, and consequently increases water infiltration and rainfall-use efficiency (Thierfelder & Wall, 2009). Organic mulch is a source of food and habitat for soil organisms such as earthworms, whose increase in numbers can improve soil functioning (FAO, 2001). Additionally, the roots of some cover crop species can serve to reduce subsoil compaction, facilitating water infiltration and root growth in subsequent crops (Chen & Weil, 2011). For instance, in Zambia, water infiltration and soil moisture were high in CA compared with conventional plots (Thierfelder & Wall, 2009; Thierfelder et al. 2013b).

However, in SSA, the retention of crop residue is a challenge for resource-poor smallholder farmers where crop production and livestock husbandry co-exist and are interdependent on one another. Animals are a source of draught power, provide food and generate income, and therefore, are expected to continue to be indispensable to smallholder farming systems (Johansen et al., 2012). Such diversified systems reduce farmers' susceptibility to climate shocks and improve their ability to readjust to these shocks (Lemaire et al., 2014; Tui et al., 2015). Animal manure is used as fertilizer to provide nutrients for crop growth while crop residue is used as livestock feed (Magnan, 2015). Across much of Africa, some 67% of the population that produces staple food and animal products to feed vulnerable and poor people do so from mixed farming systems (Herrero et al., 2010). Crop residue is a valuable resource, with competing uses being for fodder, fuel, building material and compost (Tittonell et al., 2015). Cereal crop residue is even more valuable as a fodder for livestock in smallholder farming systems in SSA where there is a severe shortage of feed and scarce communal rangelands (Giller et al., 2009).

Crop residues in Botswana, as in many African countries, are an important source of fodder, and livestock production dominates Botswana's agricultural sector. There are 1.7 million cattle in Botswana (Statistics Botswana, 2013) and 43% of Botswana's rural population own cattle (Seleka & Kebakile, 2016). The livestock industry contributes 80% to the sector's gross domestic product (GDP) (Malope et al., 2007) and over 50% of the adult population depends on agriculture (World Bank, 2015). The livestock subsector employs 15.3% of the total labour force in Botswana (Statistics Botswana, 2013) and provides income, employment, draught power and, most relevant to CA, organic manure (Nsoso et al., 2010). Additionally, cattle provide a cushion against the risks associated with crop failures and inflation (Mahabile, 2013) especially for households with limited opportunities for income generating activities (Mmopelwa & Seleka, 2011). Livestock can be quickly sold for cash when the need arises (Mahabile, 2008). Beef production in particular, is most important as the country has been noted for producing high-quality beef for the European markets (Moreki et al., 2011) and generates valuable foreign exchange for the country (Seleka & Kebakile, 2016).

The intense competition for various uses of crop and animal residues is one of the main hindrances for the adoption of CA in smallholder mixed systems in SSA and also in Botswana (Giller et al., 2009; Tui et al., 2015). The situation is exacerbated by the fact that smallholder farmers are often too poor to opt for other biomass sources (Valbuena et al., 2012).

Additionally, crop yields in smallholdings are usually low and as a result there is little crop residue produced (Vanlauwe et al., 2014). In Botswana, crop yields rarely exceed 1 t ha^{-1}. For example, average grain yields for the period 2013–2017 for maize, millet and sorghum were 206, 286 and 560 kg ha^{-1} respectively (www.fao.org). The grain yields translate to an equivalent stover yield of 247, 343 and 672 kg ha^{-1} respectively. This indicates that crop productivity in Botswana's low-input smallholder systems may be too low to provide enough soil cover to implement CA. However, an on-station research study in Botswana produced maize grain yields of 2.48–2.95 t ha^{-1} under optimal growing conditions and total annual rainfall of 383 mm (Setimela et al., 2007). This implies that under good conditions and in favourable seasons, smallholder farmers may be able to increase their maize grain yields up to 3 t ha^{-1} and thereby derive greater benefits from CA.

Cover crops in conservation agriculture

Cover crops are another important way within CA of maintaining continuous soil cover. Cover crops perform several functions including suppressing weeds, breaking pest and disease cycles, protecting soil from erosion and improving soil fertility (Akhtar et al., 2018; Price & Norsworthy, 2013). However, smallholder farmers traditionally use grain legumes instead of cover crops because they are a source of nutritious food and income (Giller, 2001). Cover crops can be used as live mulch or for crop residue (Scopel et al., 2013). When used as live plants, cover crops suppress weeds through competition, improve soil biological and physical characteristics, and may increase soil nitrogen in the case of legumes (Pekrun et al., 2023). As a source of residue, cover crops may be planted between the rows of the main crop and then terminated mechanically or with a knockdown herbicide. The dead surface mulch and roots provide carbon and plant nutrients to the soil and any cash crops, moderate hydrological flows and suppress weeds through physical impedance or allelopathy (Ahmed et al., 2023; Chamberlain et al., 2020).

Some farming practices such as organic farming depend entirely on cover cropping for weed management (Mirsky et al., 2013). The emergence of herbicide-resistant weeds has also triggered interest in cover crops as an alternative weed management strategy (Korres & Norsworthy, 2015). The efficiency of cover crops in weed management can be improved by using certain species to produce large amounts of different allelochemicals as well as more biomass to inhibit weed emergence and growth. Examples of weed-suppressive cover crops are hairy vetch (*Vicia villosa*), which is capable of reducing weed biomass by 52–70%, and the winter cereal rye (*Secale cereale*), an extensively used cover crop with high biomass and allelochemical production, which has been shown to control 90% of *Amaranthus retroflexus* in cotton (Price et al., 2008). These cover crops can be used to suppress weeds in winter wheat (*Triticum aestivum*), which is sometimes grown under irrigation in Botswana, owing to the lack of winter rainfall. However, given that Botswana is a semi-arid country with no ground water resources (Batisani, 2012), irrigated agriculture may not be sustainable.

In Botswana, cover crops are not grown; instead, intercropping is commonly used by smallholder farmers as an essential farming practice in dryland conditions (Legwaila et al., 2012). Cover crops are generally not relevant to Botswana's cropping systems because rain falls in one distinct wet season over summer from October to April, followed by five months of dry season. In the intercropping system, a cereal and legume crop are grown concurrently in the same field with the legume adding nitrogen to the soil through symbiotic fixation. A number of legume crops such as cowpea (*Vigna unguiculata*), common bean (*Phaseolus vulgaris*), groundnut (*Arachis hypogaea*) and bambara groundnut (*V. subterranea*) and forage crops like lablab (*Lablab purpureus*) and alfalfa (*Medicago sativa*) are intercropped with the main cereal crop such as maize (*Zea mays*), sorghum (*Sorghum bicolor*) and pearl millet (*Pennisetum glaucum*). Intercropping can augment adoption of CA in Botswana as the legume intercrop produces biomass and provides soil cover as mulch during and off the main season for erosion control, moisture conservation and nitrogen addition. However, the retention of crop residue is threatened by high numbers of cattle. The co-existence of cattle with farms for crop production on communal tribal land results in free ranging animals invading arable farms and feeding on crops and crop residue.

Crop rotations in conservation agriculture

Crop diversification such as cover and rotation crops generate the extra biomass required for crop residue management (Rodenburg et al., 2021). Traditional rainfed cropping systems in most parts of SSA are dominated by maize as the main staple food crop. Other crops are sorghum and millet, grain legumes such as common bean, cowpea and groundnut (Thierfelder et al. 2013a). Similarly, in Botswana, cereals (maize, sorghum, millet) and grain legumes are common crops in the traditional (smallholder) sector. The commercial sector is dominated by sorghum more than any other crop. Like in most parts of SSA, farmers in Botswana prefer to grow continuous monoculture maize in response to demand and ignoring the risk (Nthoiwa et al., 2013) and importance of including rotations in cropping systems (Thierfelder et al. 2013a).

Crop rotation forms a critical agronomic principle of CA, and mostly, legume-cereal rotations are the preferred sequence (Giller et al., 2009). Diversification with grain legumes is considered as one of the options to improve yield in maize-based smallholder systems (Droppelmann et al., 2017). Alternating crops, especially those from different botanical families, over several growing seasons, can increase associated biological diversity (including pests, diseases and weeds) and avoids selection pressure favouring specific, often intractable, pest species (Locke et al., 2002).

Legumes are a component of an ecologically based intensification strategy for regions with restricted access to outside inputs (Barnes et al., 2021). Leguminous crops have been used traditionally in rotation or as an intercrop with cereals (Plaza-Bonilla et al., 2016; Rusinamhodzi et al., 2012). Nitrogen fixation by legumes in concert with improved agronomic practices has the potential to restore soil fertility and improve the yield of succeeding crops in SSA (Bekunda et al., 2010; Giller, 2001). It is estimated that if legumes are planted in a 1:4 year rotation, they add about 110 kg of nitrogen per hectare, but the amount will be influenced by the type of legume crop and prevailing conditions (Herridge, 2011). Due to these agronomic and ecological benefits, legumes are an essential pillar of CA (Meyer, 2010). In SSA, the most commonly grown grain legumes are *P. vulgaris*, *V. unguiculata* and *A. hypogaea* (Giller et al., 2009). These crops are generally preferred over other legume species because of their high nutritional value and ability to generate income (Giller, 2001).

Despite the aforementioned benefits and decades of assistance (Barnes et al., 2021), grain legumes in SSA are not widely or frequently grown, constraining their utilization as a rotation crop in CA (Giller et al., 2009). High labour requirements, lack of access to grain markets and low farm gate price make inclusion of grain legumes in crop rotation unprofitable (Snapp & Silim, 2002). Even where the market outlook is economically attractive for legumes, smallholder farmers still continue to grow cereals such as maize in continuous mono-cropping for sustenance and because maize requires less labour.

In Botswana, cereals have been planted on more land area than legumes (Table 2). However, unlike in most countries in SSA, the Botswana Agricultural Marketing Board (BAMB) was established in Botswana by an act of parliament to specifically provide a market for local crops. BAMB buys produce and depending on the grade, the price paid for a 50 kg bag of legume grain may be up to four times that of cereals (Table 3). Ideally, this form of subsidization is intended to encourage farmers to increase legume production that can be included in rotations. Studies indicate that compared with being saved, given, or acquired through a seed distribution, buying legume seed accounts for 50% of transactions, with 89% of those transactions taking place in the informal economy, primarily from local marketplaces, suggesting that farmers rarely employ agro-dealers to purchase legume seed, in contrast to maize (Sperling et al., 2021). Nonetheless, farmers still prefer cereals probably to avoid the intensive labour associated with harvesting and shelling of grain legumes. The adoption of CA systems in Botswana is therefore likely to be constrained by limited crop rotations, especially in the smallholder farming sector.

Minimum tillage in conservation agriculture

The most noticeable and dominant element of CA is minimum soil disturbance, which is also a prerequisite for crop residue mulching as well as an enabling component (Rodenburg et al., 2021). Smallholder farmers in SSA traditionally till the soil with the primary goals being to control weeds and prepare seed beds for germination and seedling establishment but are limited by time, labour and implements. Tillage and cultivation of crops in southern Africa started with the introduction of the ox-plough in the early 1920s (Gebregziabher et al., 2006) and now tillage by animal drawn implements is common in many eastern and southern African countries (Starkey, 1995). In Botswana, mouldboard ploughing using draft power or tractor is a conventional primary tillage practice, followed by disc

Table 2. Area (000 hectares) planted of major crops for the 2011–2019 crop growing seasons.

	Cropping season						
Crop	2011	2012	2013	2014	2015	2017	2019
Maize (*Zea mays*)	151	141	126	130	65	62	39
Sorghum (*Sorghum bicolor*)	70	63	68	65	42	24	17
Millet (*Pennisetum glaucum*)	13	11	12	8	5	3	3
Pulses (*Phaseolus vulgaris, Vigna unguiculata and V. subterranea*)	2	2	1.5	7	7	2	1

Source: Statistics Botswana (2019).

harrowing to level the soil (Moroke et al., 2009). Smallholder farmers traditionally use cattle or donkey pairs to pull a single furrow mouldboard plough. Compacted soils, which are common in bare areas, are sometimes chiselled and ripped to improve water infiltration and crop growth.

Successful implementation of CA requires adequate direct seeding equipment (Wall, 2007). Adoption of CA in SSA is limited by the lack of minimum tillage planting equipment and herbicides to control weeds that traditionally are controlled through tillage. Moreover, farmers have limited access to credit to purchase such resources (Lal, 2009). The high adoption of CA in Brazil was largely driven by massive production of animal drawn and manual no-till seeding machines (Derpsch, 2001) and availability of herbicides (Vanlauwe et al., 2014). The Food and Agricultural Organisation (FAO) promoted and distributed the Brazilian no-till equipment for smallholder farmers in Africa (Derpsch, 2001), but they are currently not available or in use in southern Africa (Thierfelder et al. 2013b).

The constraint of no-till seeding equipment in Botswana could similarly be addressed by engaging machinery manufacturers to produce animal drawn and manual seeding equipment for about 63,000 smallholder farmers. Large scale commercial farmers have access to credit facilities from the Citizen Entrepreneurial Development Agency (CEDA) and National Development Bank (NDB) through the Agriculture Credit Guarantee Scheme (ACGS).

Table 3. Producer price per 50 kg bag for major crops.

	Price in USD*		
Crop	Grade 1	Grade 2	Grade 3
Maize (*Zea mays*)	12.11	9.15	6.40
Sorghum (*Sorghum bicolor*)	12.94	8.77	6.17
Millet (*Pennisetum glaucum*)	12.11	8.48	N/A
Tswana cowpeas (*Vigna unguiculata*)	38.01	26.56	N/A
Jugo beans (*V. subterranea*)	50.95	35.67	N/A
Groundnuts (*Arachis hypogaea*)	45.94	32.16	N/A

Source: Botswana Agricultural Marketing Board (2022); *1 USD = 13.09 BWP (21st November 2022).

Effect of tillage systems on weed species composition

In CA, there is no soil inversion and the majority of weed seeds are located on the soil surface or in the upper soil layer (Singh et al., 2015a), and because of high light intensity and amplitude of temperature fluctuations, more seeds can germinate compared with conventional tillage (Gallandt et al., 2004; Singh et al., 2015b). Weed dynamics and communities change when tillage is replaced by no till or minimum tillage systems with a trajectory towards perennial and grass species (Nawaz & Farooq, 2016; Santín-Montanyá et al., 2013) (Table 4). The reduced soil disturbance in CA systems would be likely to select against annuals and species with short lifespans, while the shift to grasses may be due to habitat preferences similar to the predominant cereal crops (Tuesca et al., 2001). This implies that problem weeds such as the perennial rhizomatous and stoloniferous grass, Cyno*don dactylon*, which is difficult to control, can dominate reduced tillage systems.

In Botswana, *C. dactylon* is prevalent as a weed in both dryland farming and irrigated fields (Abdullahi, 2002). It infests arable cropping systems and forces smallholder farmers to abandon cropping due to heavy infestations (Abdullahi et al., 2001). Another

Table 4. Effect of tillage systems on weed flora community.

Tillage system	Dominant weed life form	Source
Zero tillage	Annual grass weeds	(Shanhzad et al., 2016; Scherner et al., 2016; Tuong et al., 2005)
	Sedges and perennial grasses	(Blackshaw et al., 2001; Nawaz & Farooq, 2016)
	Perennial weeds	Farooq et al. (2011)
	Annual grasses and wind-disseminated species	Streit et al. (2003)
Reduced tillage	Perennial and grass species	Peigné et al. (2007)
Conventional tillage	Annual broadleaved weeds	(Farooq & Nawaz, 2014; Mann et al., 2004)

invasive grass, *Cenchrus biflorus*, is a noxious weed that is spreading rapidly throughout Botswana, largely by burrs that attach to animals, clothes and machinery (Abdullahi, 2006; Makhubu & Marotsi, 2011). The prevalence of these weedy species in Botswana combined with the adoption of reduced tillage systems is likely to promote infestation, exacerbating the weed problem in cropping systems. Additionally, areas initially free of perennial and grass weeds may start to be invaded by these species when they change from tillage to zero or minimum tillage systems. However, infestations of relatively large seeded annual broadleaved weeds such as *Datura ferox*, *D. stramonium* and *Xanthium strumarium*, classified as noxious weeds in Botswana (Abdullahi, 2006), may be significantly reduced in minimum tillage systems. In many broadleaved weeds, seed dormancy is induced by burial through cultivation and buried seeds will become sensitive to light (Scopel et al., 1991). Burial also enhances seed viability and longevity (Mohler & Galford, 1997). In Botswana, *D. ferox* does not emerge in fallowed fields, but germinates and flourishes when farmers plough fields in preparation for growing crops (Abdullahi, 2006).

Farmers in Botswana who own tractors or draught animals receive greater financial rewards in the ISPAAD subsidy programme for ploughing than using minimum tillage (Table 5). Such incentives are likely to encourage farmers to continue practising tillage rather than to adopt reduced tillage systems. While several studies have demonstrated the effect of different tillage systems on weed flora, crop selection is also a key factor determining changes in the functional composition of the weed communities.

Soil organic carbon and conservation agriculture

One of the principal terrestrial repositories of carbon is the soil organic carbon (SOC) pool, which is endowed with about 1500 Pg of carbon (Bird et al., 2004), and can therefore contribute significantly to the global carbon cycle and help mitigate climate change. Its distribution in the soil profile is determined by the intricate interaction of numerous elements, including climate, soil texture, land use, fire frequency and topography (Bird et al., 2001). There are significant spatial variations in the amount of SOC both horizontally according to land cover land use (LCLU) and vertically inside the soil profile (Neba et al., 2022).

Management practices such as tillage and cropping system influence changes in SOC over time (Swanepoel et al., 2015). Cultivation, for instance, has been found to reduce the amount of humic compounds, leading to a reduction in the amount of SOC and nitrogen in semi-arid agro-ecosystems in South Africa (Kotzé et al., 2016). Minimum soil disturbance and permanent plant biomass coverage of the soil minimize topsoil displacement, replenish SOC content, and improve soil moisture and water use efficiency (Rodenburg et al., 2021). In Botswana, there is a dearth of adequate information and scientific evidence regarding the influence of tillage, residue management and crop rotation on soil carbon storage. Nevertheless, experimental data from the hardveld of Botswana showed significantly higher organic carbon in grazing (0.39%) and horticultural lands (0.38%) compared with land tilled using the mouldboard plough (0.29%) (Dikinya et al. 2016). In the greater Gaborone region of Botswana, SOC stocks were greater in tree-dominated areas (1.13 MtC) and shrubland (2.83 MtC) and lower in bare land (0.04 MtC), built-up areas (0.22 MtC) and crop land (0.14 MtC) (Neba et al., 2022). It is not surprising that crop land recorded lower carbon because dryland cropping systems in Botswana are characterized by high soil disturbance during land preparation in the form of mouldboard ploughing as primary tillage and disc harrowing as secondary tillage. These field operations are known to accelerate oxidation of organic matter resulting in the loss of organic carbon. Along a 1000 km moisture gradient in Botswana (Bird et al., 2004), weighted SOC inventories rise as rainfall per annum rises from the southern end (225 mm) to the northern end (650 mm) of the transect at both 0–5 cm (7–41 mg cm^{-2}) and 0–30 cm (37.8–157 mg cm^{-2}) of the soil profile, plateauing at 400–500 mm and remainining roughly constant until the end. The authors linked the plateau to feedbacks between fire frequency and fuel load, whereby an increasing amount of carbon delivered to the soil surface is returned to the atmosphere directly rather than

Table 5. ISPAAD subsidy rates for various farming operations.

Farming operation	USD per hectare
Ploughing and row planting	74.23
Harrowing	33.41
Ploughing, harrowing and row planting	107.64
Minimum tillage (ripping and planting)	46.39

Source: Ministry of Agriculture (2016).

being cycled through the SOC pool by increasing fire intensity or frequency.

While no studies have been done in Botswana to determine the efficacy of CA in sequestering carbon, various studies in the Southern African region suggest that CA systems have greater carbon stocks than conventionally tilled fields, for example, in Zambia (Thierfelder et al., 2012), Zimbabwe (Mupangwa et al., 2013) and Malawi (Ngwira et al., 2012). However, this hypothesis has been questioned by recent studies. The skepticism is justified by the fact that only 50% of more than 100 studies supported the hypothesis that CA systems increase sequestration of soil organic carbon. Moreover, Cheesman et al. (2016), in their findings from on-farm validation trials concluded that there is a slim chance that CA can significantly increase soil carbon stocks even after up to seven years of CA practices.

Conservation agriculture and the development of herbicide resistance

CA largely eliminates the use of tillage for weed control and therefore farmers adopting this system are faced with the need to use alternative methods for controlling weeds (Farooq et al., 2011; Muoni et al., 2013). This challenge is especially serious for resource limited smallholder farmers in SSA. Herbicides have emerged as the dominant option for weed control in no-till systems (Melander et al., 2013; Snyder et al., 2016).

One herbicide which has been used extensively in CA is glyphosate, a post-emergence herbicide with broad-spectrum weed control (Dentzman et al., 2016; Givens et al., 2009). It is reported to have low mammalian toxicity and is considered relatively environmentally safe (Helander et al., 2012). The adoption of glyphosate-resistant crops such as maize (*Zea mays*), canola (*Brassica napus*), soybean (*Glycine max*), cotton (*Gossypium hirsutum*) and sugar beet (*Beta vulgaris*) (Busi & Powles, 2016), has further increased the use of glyphosate in weed management systems where tillage is reduced.

Notwithstanding the effectiveness of glyphosate, reliance solely on glyphosate for weed control has created selection pressure that has led to the development of glyphosate resistant weeds (Owen, 2016). Globally, Heap (2022) has documented 56 weed species which are resistant to glyphosate. The most recent species to be identified as resistant, *Lactuca serriola* and *Salsola tragus*, were identified in 2015, in Australia and the United States, respectively. About 20% (seven species) of glyphosate resistant weed species are already present in Botswana, mostly in cultivated fields and disturbed sites. While the current populations of these species in Botswana may not yet be resistant to glyphosate, some populations, as observed in other countries, may evolve resistance when CA or other reduced tillage systems are adopted with greater use of glyphosate as the herbicide recommended for weed control. In addition to the evolution of glyphosate resistant weeds, there has been a concern about the human and environmental safety of glyphosate (Gasnier et al., 2009; Thongprakaisang et al., 2013).

Farmers in Botswana are provided with free herbicides for 5 hectares and a 50% subsidy for additional hectares through the ISPAAD programme. In this situation, it is imperative that famers be advised to rotate their crops and herbicides with different modes of action to minimize the development of herbicide resistance. In addition, farmers (in particular smallholder farmers) should be trained in the use and application of herbicides, because this is a new weed control technique for many, in clear contrast to tillage, which has been the traditional means of weed control.

Conclusion and policy implications

Crop yields under Botswana's unimodal and erratic rainfall are often low (less than a tonne per hectare), especially amongst smallholder farmers where there is limited application of inputs. As a result, the crop residues and resulting mulch are insufficient to implement CA successfully and thus this undermines attainment of the SDG 2 component of promoting sustainable agriculture. Additionally, the situation is further worsened by the land tenure system where crop production and livestock husbandry co-exist and are interdependent on each other. In such co-existence, free ranging livestock invade arable farms and forage on crops resulting in loss of yield and crop residues. Within a farm there is also competition for use of crop residue as mulch in CA and its traditional use as feed for livestock.

In view of the cultural and economic value of livestock, farmers may prefer to use crop residues to feed their livestock rather than to retain them as mulch in CA systems. Unreliability and seasonal variability of rainfall make rainfed agriculture a risky enterprise and thus justify livestock feeding compared with mulching in the allocation of crop residue for competing uses. It is thus recommended that Botswana undertakes research on how the three agronomic principles of CA can be adapted to local farmers' socio-economic conditions. For large-scale commercial farmers livestock farming may not be a viable livelihood and so this may value crop residue for mulching over livestock feeding.

To curb trade-offs in the allocation of crop residues for multiple uses, fodder and pasture crops should be evaluated for forage production. Research and development is needed to develop alternative sources of feed. The leguminous fodder crop, *L. purpureus* and pasture grass, *Cenchrus ciliaris* are currently being evaluated by the Ministry of Agriculture and should therefore be incorporated into the CA strategy.

Successful implementation of CA requires adequate minimum tillage seeding equipment and herbicides for effective weed control. In smallholdings, CA will increase labour costs for weeding if it is implemented without herbicides. Seeding equipment and herbicides may not be constraints for commercial farmers as they have access to credit facilities to purchase appropriate equipment and agrochemicals. However, for smallholder farmers, the government will need to engage farm machinery manufacturers for mass production of animal drawn and manual seeding equipment. There are about 63,000 smallholder farmers in Botswana, which creates a market for this industry. It is recommended that the government assist smallholder farmers with purchases by subsidizing the equipment through the ISPAAD programme.

The promotion of CA by the Botswana Government, however, is in conflict with the ISPAAD subsidy programme, which is paying farmers or contracted tractor owners substantially more for ploughing and discing compared with minimum tillage. Such monetary incentives are likely to encourage farmers to continue to practise tillage rather than reduce it as is recommended under CA. Rather than rewarding tillage, the government could assist farmers to purchase no-till seeding equipment that can penetrate crop residues during sowing.

The inclusion of herbicides in the ISPAAD programme is a welcome development as it replaces tillage in weed control. However, this paper has identified a number of weed species that may be at risk of developing herbicide resistance in Botswana based on its development in other countries. While it is not known whether the local populations of these species are resistant to glyphosate, heavy reliance on the sole application of glyphosate for weed control is likely to result in the evolution of resistant populations. It is recommended that herbicides with different modes of action should be used to reduce selection pressure on the weed species populations. This can be further enhanced by using a diversity of crops in rotations. Crop rotation ensures that different types of herbicides are used for weed control.

Botswana has established BAMB to buy produce from farmers and for a 50 kg bag, grain legume prices are five times better than cereals. Nonetheless, the area under grain legume cultivation is similar to other SSA countries and small compared with cereals. Drudgery associated with manual harvesting and shelling of grain legumes limits farmer ability to increase the area for their production. It is therefore recommended that Botswana conducts research on the development of mechanical grain legume harvesters to relieve farmers of this labour-intensive manual harvesting process.

In summary, the Government of Botswana should have a clear position with regard to CA. The government is promoting CA on the one hand and on the other its package of incentives is rewarding farmers for practising tillage. In such a scenario, resource poor farmers would be tempted by monetary benefits and continue to till rather than use the ecological and agronomic benefits of CA, which often take some time before they can be realized. The ISPAAD programme should be revised to assist farmers to adopt reduced tillage systems. This can be achieved by paying more for reduced tillage than for ploughing and discing. Lastly, the following undertakings are recommended for successful implementation of CA in Botswana.

(1) Farmers need to learn CA as it is a new farming system. Participatory learning approaches should be used to teach farmers about the principles underlying CA.
(2) In view of the problems often associated with availability of herbicides, there is a need to develop integrated weed management strategies that can be applied in manual and animal traction systems.
(3) Policies and strategies should be developed for successful implementation of CA.

(4) Credit facilities should be provided for farmers to access loans to purchase minimum tillage equipment and agrochemicals.
(5) Research is needed on fodder crops that can be integrated into the farming system and provide feed during the dry season.
(6) Research is also required on potential cover crops that double as food crops to ensure food security in smallholdings.

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