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The potentiality of agroforestry practices as essential land use option for forest rehabilitation and livelihood improvement, case study of Nabag Reserved Forest, South Kordofan State, Sudan

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The potentiality of agroforestry practices as essential land use option for forest rehabilitation and livelihood improvement, case study of Nabag Reserved Forest, South Kordofan State, Sudan

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Abstract

The overall objective of the research was to assess the potentiality of agroforestry practices as essential land use option for forest rehabilitation and livelihood improvement. A mixed method approach including the analysis of remote sensing data and socioeconomic survey were implemented in this research. Data was analyzed using descriptive and inferential statistics. The results of remote sensing data revealed that through *Taungya* agroforestry, there was a considerable increase in forest cover over the addressed period. The results of socio-economic survey showed that Taungya agroforestry program contributed significantly to farmers' income. Furthermore, farmers in the study area have expressed strong positive perceptions toward the benefits of participation in Taungya agroforestry program. The regression results revealed that extension services, farmer's Taungya experience, family size, educational level, land size, and gum Arabic production have a positive influence on farmers' perception. Contrary, farmers' age and gender were found to have a negative association with farmers' perception. Farmers' participation was encouraged by the high productivity within the forest and access to free fertile land. Contrary, lack of extension services and supervision from Forest National Corporation, overgrazing and crop destruction, land size limitation, and crop species restrictions were identified as major challenges.

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List of acronyms and abbreviations

FAO	Food and Agriculture Organization of the United Nations
FRA	Forest Resources Assessment
NTFPs	Non-Timber Forest Products
ICRAF	International Council for Research in Agroforestry
GIAS	Global Inventory of Agroforestry Systems
CO2	Carbon dioxide
GHG	Greenhouse gases
AGFORWARD	AGroFORestry that Will Advance Rural Development
FNC	Forest National Corporation
CIFOR	Center for International Forestry Research
NGOs	Non-governmental organizations
DPRK	Democratic People's Republic of Korea
LMAV	Lower Mississippi River Alluvial Valley
BLH	Bottomland Hardwood Forests
NRF	Nabag Reserved Forest
MMR	Mixed Methods Research
TM	Thematic Mapper
OLI/TIRS	Operational Land Imager/Thermal Infrared Sensor
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
GPS	Global Positioning System
SCP	Sim-automatic Classification Plugin
ROI	Region of Interest
BR	Bare Land
AF	Agricultural Field
LF	Light Forest
DF	Dense Forest
MLC	Maximum likelihood classifier
UA	User Accuracy
PA	Producer Accuracy
OA	Overall Accuracy
K	Kappa Coefficient
PCC	Post-classification comparison method
SSQ	Semi-structured questionnaire
KIIs	Key informant interviews
FQDs	Focus group discussion
DFOs	Direct field observations
SPSS	Statistical Package for Social Science
VIF	The Variance Inflation Factor
WARGFP	Wan Abdul Rachman Grand Forest Park
SDG	Sudanese pound
Mukhamas	local unit of land measurement equivalent to 0.75 hectare

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CHAPTER 1

INTRODUCTION

1.1 Research background

Forests contribute significantly to ecosystem services, climate change mitigation, and rural livelihoods improvement (Fekadu et al. 2021). International agreements and national policies recognize forest conservation, forest rehabilitation, and adaptation of sustainable forest management to climate change as critical for human livelihoods and climate stability (Buckingham et al. 2016). Despite the critical role forests play in sustaining ecosystem function and human needs, the pace of deforestation and forest degradation continues to rise (Keenan et al. 2015).

Globally, forests constitute approximately 31% of the total land area. About 25% of the total forest land belongs to the European Union, 21% in South America followed by North and Central America with 19%, while Africa, Asia, and Oceania account for 16%, 15%, and 5% respectively (FAO 2020). However, forest cover has decreased dramatically during the last millennium, declining from approximately 6 billion ha to 4 billion ha (Agevi et al. 2016). According to the last Forest Resources Assessment (FRA) provided by the Food and Agricultural Organization of the United Nations (FAO), approximately 420 million ha of the world's forests has been lost due to deforestation estimated at 10 million ha between 2015-2020. Africa experienced the largest annual net loss rate at 3.9 million ha (FAO 2020). The main causes of deforestation and forest degradation include agricultural expansion and forest over-exploitation (Plata-Rocha et al. 2021, Hamunyela et al. 2020).

Sudan covers a land area of 1.9 million km^2, of which 29.8 million hectares are classified as forest cover (FAO 2020). Sudan's forest resources play an essential role in providing livelihood needs. Particularly in the rural areas, the majority depend on wood and non-wood forest products as the main sources of income and daily food consumption (Mohamed et al. 2021, Suleman – Ibrahim 2018). According to Daur et al. (2016), forest products supplement the primary source of income for rural livelihoods in most remote areas of Sudan. For instance, in the study region, the selling of Non-Timber Forest Products (NTFPs) represents a subsistence, food security and income strategy for rural households (Ibrahim et al. 2015, Adam et al. 2013). Nonetheless, Sudan’s forest cover has witnessed massive changes during the last decade (Gadallah 2020). According to Abdon

(2020), Sudan's vegetation cover area has decreased dramatically from 40% to 10.3% with an annual removal rate of 1.6%, resulted in deforestation and land degradation. Another factor of land degradation could be attributed to mechanized rain-fed agriculture and shifting cultivation (Biro et al. 2013). This has created renewed interest in adaptation and mitigation technologies that could reduce the impact of climate change on agro ecosystems by introducing promising practices of land use systems (Swamy et al. 2017). Agroforestry practices, where trees, crops, pasture and/or animal are integrating together for economic, social, and environmental benefits can help to reduce this tremendous pressure on natural forests and contribute to sustainable livelihood of rural people (Zamora et al. 2016).

During the last decade, the degree of research interest in agroforestry has been widespread (Dagar 2016), and the practice recognized as adaptation mechanism of climate change due to its impact on improving livelihood for small-holder's farmers (Mondol et al. 2021, Do et al. 2020, Udawatta et al. 2019), and recommended as a feasible tool and cost-effective for forest rehabilitation (Gadallah et al. 2019, de Oliveira – Caryalhaes 2016). Several authors have conducted studies to assess and evaluate forest rehabilitation and livelihood improvement under different agroforestry practices (Budiastuti et al. 2021, Miccolis et al. 2019, Agevi et al. 2016, Blay et al. 2008). In Sudan, however, the current research on tree cropping systems and its impact on forest rehabilitation and livelihood improvement is still not advance but, some conclusions can be drawn from few studies. For instance, Fahmi (2018), has investigated agroforestry parkland in arid and semi-arid of Sudan and found the system is the most profitable and leading to increase crop productivity in contrast with monocultures systems. Similarly, Fadl et al. (2015) studied the perceptions of farmers towards agroforestry systems in Kordofan region and concluded that the forms of agroforestry practices have a vital role in agricultural productivity and providing income to the poorest farmers in the area. However, there is striking paucity and little is known about the value of agroforestry as a viable tool for forest rehabilitation and livelihood improvement. Understanding these values will be the first step towards improving theoretical understanding of agroforestry practices and developing practical approaches to improve it.

1.2 Problem statement and research rationale

Over the last few decades' wide debate over land degradation, deforestation, land use conflicts and the absence of effective solutions in Africa continent let the people hope that agroforestry studies could contribute to new solutions. In Sudan, Agroforestry practices has not been widespread in many parts of it due to several reasons related to performance of agroforestry practice, socioeconomic aspects of the farmers and their opinion towards retaining trees in their farmland, added to that, there is lack of solid and precise information regarding agroforestry practices. There are known gaps in the agroforestry assessment such as the lack of tree crops systems, agroforests, due to difficulties in classifying land use rather than land cover (Kumari 2017). On the other hand, few studies have undertaken to assess agroforestry practices and its contribution to forests rehabilitation and rural livelihood improvement in Sudan and there is still a significant gap in the literature. Majority of the studies (e.g., Eltahir 2015, Gibreel 2013) carried out in the country have focused exclusively on a general vision of agroforestry practices and overlooked to shed the light and measure the value of agroforestry on the above-mentioned traits.

However, to improve the livelihood of poor farmers in the rural areas of Sudan suffering from crop failure, drought and food insecurity, as well as to rehabilitate the degraded forests, there is urgent need to assess and quantify the prevailing agroforestry practice and its contribution to forest rehabilitation and livelihood improvement hence the information generated by this research will fill the gap of knowledge in understanding the inextricable linkage between agroforestry practices and add knowledge on the value of this practices in forests rehabilitation and livelihood improvement. This will be useful in setting recommendations for decision-makers in Sudan to create/develop or design active agroforestry projects and cooperatives that could be adopted as an appropriate mechanism for climate change adaptation and hence contribute to sustainable forest management, food security and rural livelihood improvement.

1.3 Research aims and hypotheses

The overall aim of this research was to assess the potentiality of Taungya agroforestry practice as essential land use option for forest rehabilitation and livelihood improvement.

The research attempt to address the following specific objectives:

1. To quantify and map the forest rehabilitation under Taungya agroforestry program.

2. To examine the socio-economic characteristics of Taungya farmers.
3. To assess the program's contribution to farmers' income generation.
4. To determine farmers' perceptions and attitudes towards participation in Taungya agroforestry program.
5. To determine the socioeconomic factors influencing their perception of the benefits of the Taungya program.
6. To highlight the major incentives and constraints associated with Tuangya farmers.

1.4 Research assumption

This research assumed that Taungya agroforestry has the potential to contribute positively to forest rehabilitation and farmer's livelihood improvement.

1.5 Research questions

Several research questions were set to understand the relationship between the Taungya agroforestry practice, forest cover rehabilitation and farmers livelihood, these questions include:

- Dose Taungya agroforestry help in forest rehabilitation?
- Does Taungya agroforestry contribute to farmer's income?
- What are the socio-economic characteristics of Taungya farmers in the study area?
- What are farmers perceptions and attitude towards Taungya agroforestry Program?
- What are the factors influencing farmers' participation in Taungya agroforestry practice?
- What are the major incentives and constraints associated with Tuangya farmers in the study area?

1.6 Dissertation structure

This research is organized in five chapters as depicted in figure (1) below:

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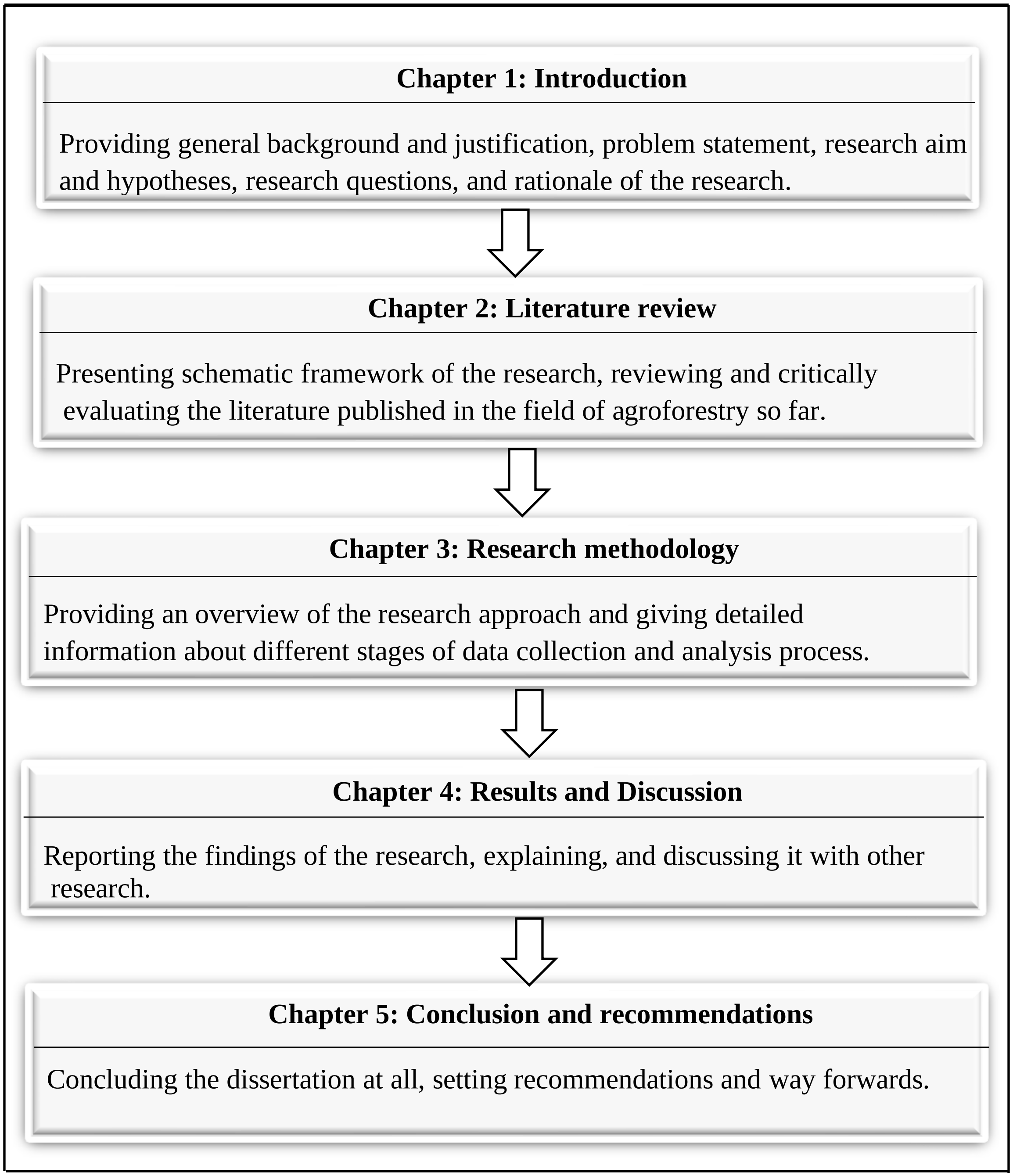

Fig. 1.1: Structure of dissertation

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CHAPTER 2

LITERATURE REVIEW

2.1 Historical background

The history of agroforestry could be traced back for thousands of years as an agricultural practice, when the farmers started practicing shifting cultivation on their land and growing trees to improve the soil fertility (Torquebiau 2000, Nair 1993). For instance, in Central America, farmers produced trees (e.g., papayas, coconut, and citrus), shrubs (e.g., coffee and cacao) in combination with annual crops (e.g., maize, squashes and bean). Likewise, in Asia, Farmers deliberately spread the trees in their agricultural land as means of reducing the excessive evaporation after the rice season. In Africa, the situation was different, since the farmers planted a mixture of maize, pumpkin, and beans under scattered trees (King 1987). Recently, agroforestry systems have been widespread worldwide, and trees cover 10% of all agricultural lands (den Herder et al. 2017). According to Zoomer et al. (2016), agroforestry systems cover about one billion hectares of the land. This illustrates that farmers and practitioners come to ponder agroforestry systems as a pivotal source of diversifying production, income generation and services.

2.2 Concepts of agroforestry

The term agroforestry was first coined in 1977 to describe the existence of agricultural crops with trees in the same piece of land (Smith 2010). Indeed, there was some ambiguity and difficulties in defining agroforestry, even those scientists and practitioners who have experience and knowledge about agroforestry were unable to define it. The situation was later discussed in the first issue of Agroforestry Systems (Vol. 1, No. 1, PP. 7-12; 1982) and several definitions have been generated by different authors. However, the comprehensive and widely accepted definition of agroforestry was created by the International Council for Research in Agroforestry (ICRAF): *''Agroforestry is a collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land-management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence. In agroforestry systems there are both ecological and economical interactions between the different components''* (Lundgren – Raintree, 1983). On the other hand, the Food and Agriculture Organization of the United Nations (FAO 2015) defines agroforestry as ''Land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence.” Moreover, a brief definition was used by the European Commission (2013), according to which agroforestry comprises *“land use systems in which trees are grown in combination with agriculture on the same land”*. From these definitions one can conclude that trees are the main component of the system, the system has at least one to two species, two or more output, and provide multiple benefits (socio, economic and environmental benefits), and there is ecological and economical interaction between components of the systems.

2.3 Classification of agroforestry systems

The classification of agroforestry systems considers as a challenging task owing to the complexity nature of the system’s components and the interaction between them. The first attempt of agroforestry classification was through a Global Inventory of Agroforestry Systems (GIAS) conducted by International Council for Research in Agroforestry (ICRAF) between 1982-1987. The inventory systematically collected and evaluated many such land use systems around the world. However, Nair (1987 a) used some criteria to classify different agroforestry systems, these includes the structure of the system (composition and arrangement of components), function of the system (role and output of components), the socio-economic scale and level of management, ecological spread (ecological zone where the system exists). Later, these criteria extended by Dwivedi (1992) into seven basis includes structure, physiognomic, function, floristic, socio-economic, history and ecological.

Currently, various authors and experts in agroforestry systems have updated developed and used different approaches to classify agroforestry system. For instance, Sinclair (1999), evaluates ICRAF inventory of agroforestry systems to update the agroforestry classification. He suggested to use the ‘practice’ rather than the ‘system’ as the unit of classification and argues that classification of the main types of agroforestry practice proceeds primarily according to the arrangement, density, diversity of the tree components involved and the major usage of the land. He also argued that agroforestry researchers should be able to “advise on the spectrum of land use options in a particular context, from agricultural activity without trees, through agroforestry combinations to pure forest and woodland scenarios, rather than being over-zealous about one particular form of land use” (Herder et al. 2015).

Mosquera-Losada et al. (2016), classified agroforestry systems in Europe into six basic types of agroforestry including: silvoarable, silvopasture, forest farming, riparian buffers, improved fallow, and multipurpose trees. Similarly, McAdam et al. (2009), reviewed the existing classification methods, adapted it to a European context and complemented it with a classification based on the functions of agroforestry systems (Herder et al. 2015). However, the most common classification of agroforestry includes agro silvicultural system (also called silvoarable) (trees + agricultural crops), silvopastoral (trees + livestock), and agrosilvopastoral (trees + livestock + agricultural crops) (Shin et al. 2020, Rosenstock et al. 2019, Feliciano et al. 2018). More details about agroforestry classification and practices are shown the Table 2.1.

Table 2.1: Diverse types of agroforestry practices worldwide (modified from Shin 2020, Brown et al. 2018, Herder et al. 2017, Atangana et al. 2014 a, Nair 1993).

Classification	Type of practice	Definition	Components
Agroisilvicultural System/Silvoarable	Traditional Bush fallow	planting woody species and shrubs through the fallow face to replenish soil fertility and gaining economic benefits	fast growing trees + agricultural crops
	Taungya	growing agricultural crops with trees as initial stages of plantation establishment	trees species + agricultural subsistence crops
	Forest Farming	forested areas used for production or harvest of naturally standing specialty crops for medicinal, ornamental or culinary uses	trees + non timber products
	Alley Cropping	rows of trees with a companion crop growing in the alley ways between the rows	fast growing and leguminous + agricultural crops (Coppiced trees preferred)
	Multistory Agroforestry	multispecies, multi layers dense plant associations with no organized planting arrangement	different woody components of varying forms and growth habits, shade tolerant ones
	Multipurpose Trees	trees intercropped with annual or perennial crops; trees randomly or systematically in cropland for the purpose of providing fruits, fuel wood, timber and other services	multipurpose trees + other fruit trees
	Home Gardens	multistory combination of trees and crops (usually vegetable production) around homestead for subsistence	fruit trees, woody species + shaded-tolerant

		support	crops
	Wind break, Shelterbelts, Hedge rows, live fences	trees used as fence around plots and/ or extended wind break of living trees and shrubs established and maintained to protect farmland and animals or provide fodder	combination of tall-growing types with agricultural crops at the locality
	Fuel wood Production	interplanting firewood species on / or around agricultural land	Firewood species
	Riparian Buffer Strips	areas along rivers and streams planted with trees, shrubs, and grasses to Protect water quality	adjacent to perennial, intermittent, and ephemeral streams and lakes
Silvopastoral Systems/Forest Grazing	Tress/shrubs in in rangelands or pastures	trees scattered irregularly or systematically on pasture for providing fruits, fuel wood, timber and other services	multipurpose trees usually of fodder value
	Protein Banks	production of protein-rich trees fodder on farm, rangelands for cut and carry fodder production.	leguminous fodder trees
	Plantation crops with pastures and animals	livestock under woody perennials	growing crops/e.g. cattle under coconuts
Agrosilvopastural Systems/ Agrosilvipasture	Apiculture with Trees	trees fruits, leaves, flowers being used for insects	trees and shrubs preferred by insects such as bees
	Aqua forestry/ Silvofishery	trees lining fishponds, tree leaves being used as forage for fish	trees and shrubs preferred by fish
	Multipurpose Woody hedgerows	woody hedges for browse, mulch, green manure and soil conservation	fast growing and coppicing fodder shrubs

2.4 Agroforestry benefits

2.4.1 Ecosystem services

Ecosystem services are the goods and services that ecosystems contribute to people. Human well-being and development fundamentally depend on these services. Ecosystem services are classified into four main categories including provisioning (e.g., production of food or fiber), regulating (control of climate or pests and diseases), supporting (e.g., nutrient cycling and plant pollination), and cultural (e.g., recreational, spiritual, or aesthetic). (Kadykalo et al. 2019, Kinyili et al. 2020). However, agroforestry can contribute to providing all these services (van Noordwijk 2021, Fagerholm et al. 2016). Several studies have investigated the role of agroforestry in providing different ecosystem services (Castle et al. 2022, Jose – Udawatta 2021, Shin et al. 2020, Moreno et al. 2016). Kinyli et al. (2020) in their study of the trade-off between agroforestry and ecosystem services, showed that small holder farmers who adopted agroforestry system achieved many ecosystem services. Likewise, Biswas et al. (2022), found that agroforestry system has the potential to provide multiple ecosystem services to millions of people in northeast India. Similarly, Kay et al. (2018), have compared the ecosystem services provisions of agroforestry and non-agroforestry practices in three European regions and confirmed that traditional agroforestry systems regardless of type, region and composition have the positive impact on the supply of regulating ecosystem services at the landscape scale. However, it worth mentioning that, if agroforestry systems are established and managed properly in a sustainable way (eg. by putting right trees in the right place) a multitude of ecosystem services will be protected and hence creates multiple benefits both for farmers through secure and diverse yield and sustainable livelihoods and for the surrounding landscapes in terms of pollination, water infiltration and recreation (Castro et al. 2019, Gordon et al. 2017).

2.4.2 Carbon sequestration

Carbon sequestration is considered as one of the indirect benefits (e.g., pest control, pollination, biodiversity, soil fertility and nutrient cycle) of agroforestry systems (Chiputwa et al. 2020, Temesgen et al. 2018). Recently, the potentiality of agroforestry systems as an effective mechanism in carbon sequestration (either in plant or in soil) has received growing attention in the body of literature (Vikrant et al. 2022, Sarkar et al. 2021, Temgoua et al. 2020, De estefano et al. 2018). The general discourse is that agroforestry can sequester more carbon than monoculture. This has been confirmed by Mbow et al. (2014) who stated that agroforestry systems have a high carbon sequestration potential and hence contribute to climate change mitigation and food security in comparison with croplands. Similarly, Cardinael et al. (2017) assessed five silvoarable systems and one silvopastoral system in France, their study demonstrated the potential of agroforestry to increase carbon stock in both the soil and tree biomass under different climatic conditions. In India Chavan et al. (2020) have estimated the potential of agroforestry existing in five districts by using dynamic CO2FIX v3.1 model for a simulation period of 30-years, their results showed that traditional agroforestry in arid zone could be sequestered at a rate of

0.26 Mg C ha^{-1} year^{-1} at a tree density of 9.71 ha^{-1}. In Africa, Toru et al. (2019) studied carbon stock under different land use systems including natural forest, coffee agroforestry, grazing land and cropland and found that land uses with woody perennials have higher carbon stock than those without. Several measurements (IPCC 2006, FAO 2008) indicate that agroforestry is the best option for linking carbon sequestration with agricultural systems. There is a potential for agroforestry activities on 630 x 106 ha around the globe (Kandji et al. 2006). As shown in Table 2.2, the most important regions for carbon storage are the humid tropical southlands of Asia and America, as well as North America.

Table 2.2: Carbon sequestration potential of agroforestry systems (Adapted from Kandji 2006)

Region	**Ecoregion**	**System**	**Mg C ha^{-1}**
Africa	Humid tropical high	Agrosilvicultural	29-53
South America	Humid tropical low	Agrosilvicultural	39-102
Southeast Asia	Humid tropical dry	Agrosilvicultural	12-228
	lowlands		68-81
Australia	Humid tropical low	Silvopastoral	28-51
North America	Humid tropical high	Silvopastoral	133-154
	Humid tropical low	Silvopastoral	104-198
	Dry lowlands	Silvopastoral	90-175
Northern Asia	Humid tropical low	Silvopastoral	15-18

2.4.3 Biodiversity enrichment

Agroforestry systems provide manifold habitats for different flora and fauna species owing to their heterogeneous composition with diverse vertical and horizontal structure. Over the last two decades adoption of agroforestry as a mechanism for biodiversity conservation and improvement has received increased attention around the globe (Torralba et al. 2016, Bohn et al. 2014) because agroforestry (1) provides habitat for species that can tolerate a certain level of disturbance; (2) helps to preserve germplasm of sensitive species; (3) helps to reduce the rates of conversion of natural habitat by providing a more productive, sustainable alternative to traditional agricultural systems that may involve clearing natural habitats; (4) provides connectivity by creating corridors between habitat remnants which may support the integrity of these remnants and the conservation of area-sensitive floral and faunal species; and (5) helps to conserve biological diversity by providing other ecosystem services such as erosion control and water recharge, thereby preventing the degradation and loss of surrounding habitat (Udawatta et al. 2019, Jose 2012).

The positive impacts of agroforestry on biodiversity have been reported in many studies in both temperate and tropical regions (Udawatta et al. 2021, Szigeti et al. 2020, Warren-Thomas et al. 2020, Boinot et al. 2019). Various studies have demonstrated significantly greater agroforestry biodiversity in contrast with agriculture and forests management (Terfassa 2021, Santos et al. 2019, Sharma et al. 2015). According to meta-analysis conducted by Bhagwat et al. (2008), the mean values for richness in agroforestry systems are greater than 60% of the forest values. Likewise, Santos et al. (2019) reported up to 45% to 65% more benefits in biodiversity and ecosystem services in agroforestry systems than conventional production systems. Another meta-analysis in Europe revealed that agroforestry enhances biodiversity and ecosystem service provision compared to conventional agriculture and forestry (Toralba et al. 2016).

2.4.4 Climate change mitigation and adaptation

Agroforestry plays a significant role in climate change mitigation due to its tree's diversification and component. Trees intake carbon dioxide (CO_2) and most greenhouse gases (GHG) in their biomass and soils (Sana et al. 2020, Aertsen et al. 2013). Besides climate change mitigation agroforestry has a potential to address on-farm adaptation needs through providing with assets and income, wood for energy, improve soil fertility and local climate conditions (Hernández-Morcillo et al. 2018, Mbow et al. 2014). A brief of agroforestry benefits for climate change adaptation and mitigation are presented in Table 2.3

Several studies have confirmed the positive impact of different agroforestry practices on climate change mitigation and adaptation. For instance, in Brazil, Bosi et al. (2020) demonstrated the role of silvopastoral system under Eucalyptus trees in attenuate the effect of climate change through protecting pastureland from intense solar radiation and wind, thereby reducing evapotranspiration and, consequently, improving soil water availability for the understory crop. In West Africa Tschora et al. (2020) revealed that agroforestry practices offer multiple–win solutions to address climate change challenges and rural development. Likewise, Mulatu et al. (2019) provided empirical information on the role of agroforestry in climate change mitigation and adaptation, their result revealed that agroforestry has played a greater role in climate change mitigation than monocropping but less than natural forest. In Europe, Mosquera-Losada et al. (2018) recognized agroforestry as one of the most important tools to mitigate and adapt to climate change.

Table 2.3: Agroforestry benefits for climate change mitigation and adaptation (adapted from Hernández-Morcillo et al. 2018, Schoeneberger et al. 2012)

Climate change activity	Major climate change Functions	Agroforestry roles in mitigation and adaptation
	Sequester carbon	Accumulate C in woody biomass
		Accumulate C in soil
Mitigation	Reduce GHG emissions	Reduce fossil fuel consumption in equipment
		Reduce CO_2 emissions from farmstead structures
		Reduce N_2O emissions by greater nutrient uptake and reduced N fertilizers
		Reduce CH_4 by enhancing forage quality
Adaptation	Enhance resilience	Maintain quality and quantity of products
		Increase habitat diversity
		Increase structural and functional diversity
		Foster diversified production opportunities
	Reduce threats	Reduce impacts of extreme weather events
		Reduce stress in flora and fauna
		Provide corridors for movements of wildlife

2.4.5 Microclimate conditions

Agroforestry plays a significant role in microclimate conditions. It regulates fine-scale microclimate by intercepting sunlight, reducing ambient temperature, lowering wind speed, and increasing water use efficiency in some cases (Rosenstock et al. 2019). Furthermore, trees improve the microclimate by shading crops and cooling the surrounding air by increasing the transpiration, an energy consuming process (Ellison et al. 2017). Several studies have casted the light on the potentiality of agroforestry systems in microclimate conditions. For example, in the Central Rift Valley of Ethiopia, the parkland agroforestry *of Faidherbia albida* trees have showed positive effect in reducing photo synthetically active radiation to optimum levels and midday air temperature was about 6 °C less under the trees than in open field (Sida et al. 2018). Similarly, in cocoa agroforestry trees also have lowering mean temperatures and buffering extremes temperature at field level (Niether et al. 2020) as well as improving soil fertility (Sitohang et al. 2022)

In central America, Merle et al. (2022), have investigated the relative importance of simple agroforestry systems on microclimate modifications and concluded that the presence of shade trees resulted in a buffer effect, reducing daily maximum air and leaf temperatures, and increasing daily minimum air and leaf temperatures. Similarly, in Brazil Carvalho et al. (2021) in their study on the effect of shaded agroforestry coffee systems on microclimate, soil and water loss have reported that shaded agroforestry coffee systems improve microclimate conditions and deepwater drainage compared with unshaded coffee systems.

In Hungary, Szigeti – Vityi (2019), have compared some microclimate conditions (soil microclimate and soil temperature) between alley cropping system and monoculture system and found that the soil microclimate and soil temperature were more balanced in agroforestry system than in monoculture. Also, a similar study in the same region has been conducted by Kovacs et al. (2020), reported that soil microclimate was more favorable in the intercropping system and contributes to the better development of seedlings.

In Sub-Saharan Africa, an extensive review conducted by Kuyah et al. (2016) mentioned that microclimate conditions have been ameliorated under agroforestry systems in 61% of studies, while the rest of the systems were negatively alerted. In semi-desert areas of Northern Sudan, Shapo – Adam (2008) have studied the effect of alley cropping system in microclimate and food crop productivity by using *Acacia stenophylla* trees, their results indicated positive effect of the system in improving microclimate conditions including water use efficiency and increasing crop yields. Despite the positive effects of agroforestry in microclimate conditions, however, the establishment of agroforestry can cause microclimatic changes that can affect negatively if the systems are improperly planned (Bosi et al. 2020). For instance, the shade of trees can sometimes reduce the photosynthetic active radiation reaching crops. This has shown in semi-arid areas of Burkina Faso, where unpruned trees decreased photosynthetic active radiation by more than 50% compared with opened field (Bayala et al. 2002). In addition, trees can compete with crops for water, depleting soil water close to them (Rosenstock et al. 2019). Thus, it is important to know the dynamic between microclimate components and agroforestry practices to adopt and manage microclimate as a proactive approach for improving landscape.

2.4.6 Socio-economic benefits

The social and economic benefits of agroforestry are important for both traditional and modern agroforestry systems. These benefits emphasize the relationships between agroforestry systems and humankind. According to recent estimation provided by FAO (2020), the area of Agroforestry constitutes about 45 million hectares and 1.2 billion people in developing countries rely on agroforestry practices as a source of income generation and subsistence. The socio-economic aspects of agroforestry could be summarized as: rural employment and cultural practices, income diversification, increasing agricultural productivity, food and nutrition security and livelihood improvement (Mukhlis et al. 2022, Duffy et al. 2021, Elagib et al. 2020, Plieninger et al. 2015).

Many research on the socio-economic aspects of agroforestry have been carried out over the years ranging from local to regional and global scale. Jiru et al. (2020) have analyzed the socio-economic contribution of agroforestry systems to smallholder farmers in southwestern of Ethiopia, their results showed that agroforestry provides farmers with more cash income and substances and enables them to fulfill their family needs. Similarly, In Rwanda, Anstase et al. (2020) have compared the agroforestry socio economic benefits between agroforestry practitioners and non-practitioners and found that agroforestry has significant impact on increasing income of agroforestry practitioners than others.

In Europe, an international agroforestry project called AGFORWARD (AGroFOREstry that Will Advance Rural Development) was conducted with participation of 23 organizations have attested the socio-economic contribution of agroforestry practices (Burgess et al. 2018). Likewise, Lehmann et al. (2020) have analyzed the socio-economic aspects of diverse agroforestry systems in five European countries and found that agroforestry can enhance productivity and economic returns.

In Bangladesh Islam et al. (2021) have evaluated the socio-economic outcomes of traditional agroforestry systems and their results approved that the agroforestry system has a higher economic gain and increased the rural economic development through enhancing farm productivity and the cost-benefit ratio of the system was much higher than the general agricultural practices. Similarly, Rahaman et al. (2017) have examined the economic and social potential of agroforestry systems in Indonesia and found that agroforestry has high monetary value and help in strengthen and improve the social cohesive in communities. In India, research conducted by Kumari – Khare (2022), have highlighted the contributions of agroforestry on enhancing the socio-economic conditions of the farmers.

Agroforestry practices can also create new employment opportunities in rural areas for non-agricultural activities such as crop drying, wood cutting, and furniture making (Iskandar et al. 2016). Increased employment opportunities may also benefit women, as they may be able to participate directly in production activities, thereby enhancing gender equality in rural areas (Kiptot et al. 2014). Moreover, rural employment may prevent rural emigration (Ollinaho – Kröger 2021) and therefore contribute to an improved rural economy. Agroforestry may also promote socio-cultural engagement among adopters.

For instance, farming communities can meet to discuss cultivation methods, the selection of tree species or crop varieties, fertilizer management, and other relevant topics. According to research conducted by Mungmachon (2012), gathering is an integral part of the culture of small forest communities in Thailand. They frequently discussed their problems and found solutions jointly. They began by studying their problems collectively, rediscovering conventional wisdom and existing knowledge, and then incorporating new information. Through peer-to-peer discussion and community participation, the community will become more knowledgeable and involved.

2.5 Agroforestry practices in Sudan

2.5.1 Historical background and extent of agroforestry in Sudan

Agroforestry systems in Sudan have been practiced for long time in various forms in different parts of the country. For instance, in dry lands of Sudan diverse types of indigenous agroforestry systems existed including agrosilviculture, agrosilvopastural and silvopastoral systems. It is worth mentioning that the government of Sudan has introduced the investment act of 1990 and the ministerial order 345/59 which obliged all land proprietors to allocation of 10% and 5% of their mechanized rain fed schemes and irrigated schemes respectively for forestry in shape of shelterbelts or forest cover (FNC 2003). However, farmers used to practice traditional bush fallow systems in sequential phases of crops and trees when the land was not a constraint. They started to manage trees on their small farmland with existence of agricultural crops and livestock in different shape of agroforestry such as park lands, shelterbelts, alley cropping and home gardens. The change from bush fallow systems to co-existence of trees and agricultural crops and/or livestock has become a promising solution to land constraints in Sudan.

2.5.2 Type of agroforestry practices in Sudan

2.5.2.1 Traditional bush-fallow system

This system considers an old age traditional agroforestry system, in which *Acacia senegal* trees (locally called Hashab) is planted with agricultural crops such as, sesame, sorghum, hibiscus and watermelon as a mean of improving soil fertility and contribution to income generation for the small-scale farmers. Typically, the cycle of the system consists of a relatively short period of cultivation followed by a prolonged period of fallow. The cycle starts by cleaning old Acacia trees for the cultivation the crops. Trees are cut at low stumps and left for coppicing. The cleared area is cultivated for a period of 4-6 years, when the soil fertility decline, the area is left as fallow under *Acacia senegal* trees. Trees are tapped for gum Arabic production until the age of 15-20 years; then the area is cleared again for crops cultivation. The system provides farmers with income from selling gum Arabic and subsistence from high yield of crops (Gaafar et al. 2006).

2.5.2.2 Taungya system

Taungya is one of agroforestry systems, where annual agricultural crops grow temporarily with forestry trees at the early stage of forest plantation establishment, the land is owned by state/government. Depending on factors such as tree species, growth rate, and planting spacing, the co-habitation of agricultural crops and trees can take three to five years (Ndomba et al. 2015). Due to its ease of operation, the Taungya system encompasses numerous land use techniques involving the production of trees and agricultural commodities, especially because it does not necessitate a high level of education or ability to apply (Wiro – Ansa 2019).

The system was originally developed in Myanmar in the early 19th century (Tani 2000) and has been widely used in different countries as an effective and inexpensive technology for rehabilitation the forests cover and livelihood improvement of the farmers (Fatma et al. 2020). In the past, it was a local term for shifting cultivation, but it is now also used to describe afforestation. Today, various names are used to refer to the Taungya system. For example, in German-speaking regions, it is known as haumfeld-wirtschaft, brandwirtschaft, or waldfeldbau. In Puerto Rico, it is called the parcelero system, in Brazil consor- ciarcao, in Libya tahmil, in the Philippines kainginining, in Indonesia tumpangsari, in Malaysia ladang, in Kenya the shamba system, in Tanzania the licensed cultivator system, and in India variously described as dhya, jhooming, kumri, punam, taila, and tuckle. In most countries, including Sudan, it is known as taungya (Nair 1993).

Taungya systems can be broadly divided into two categories. The traditional and departmental systems. In the traditional Taungya system, the local farmers surrounding the reserved forest are recruited by the forestry department to undertake agricultural activities in allocated areas within the reserved forest. While departmental Taungya differs from traditional Taungya in that agricultural crops and plantations are raised by the forest department by employing daily paid workers or labourers to work. The ultimate aim of raising agricultural crops along with the plantation is to keep the land free of unwanted vegetation or weeds. By so doing, the tree plantation is properly taken care of (Wiro – Ansa 2019).

In Sub-Saharan Africa, there are different forms of Taungya. In Nigeria, Taungya consisted of interplanting young Gmelina (Gmelina arborea) and/or teak (Tectona grandis) with maize, yam or cassava. After analysis of the agricultural production in taungya system, it was found to be profitable in Nigeria (Azeezet al. 2017). In Kenya, there is a modified form of Taungya called the 'Shamba system' (Witcomb – Dorward 2009) where each household works for the forest department for 9 months each year to clear bush cover from an area of about 0.5 ha. The farmer is allowed to cultivate crops (usually maize, potatoes and vegetables) for a period of 2–3 years with the sole right to all such produce. The forest department plants trees on the cleared land. Within 2 years after clearing, farmers are allowed at least four shambas of 0.5 ha each.

In Ghana, between 1970 – 1980, Taungya system was established to rehabilitate 75,000 hectares of degraded reserved forests (Agyeman 2006). The system was suspended in 1984 due to problems such as a lack of long-term land ownership for the farmers, the long interval between tree planting and harvesting, the competition for land and labor between trees and crops, and poor management (Blay et al. 2008, Kalame et al. 2011). In 2002, a modified Taungya system was introduced as a collaborative project between Ghana Forestry Commission and local communities. The main differences between the old system and the modified one are that farmers are allowed to share a 40% of timber benefits in return for their contribution to tree planting and protection as well as decision making power in the management of the scheme (Ros-Tonen et al. 2013). In Uganda, Tuangay system has been applied for a long time and is acknowledged as a good practice because it helps to prevent weed invasion, maintain soil cover, and make maximum use of land as both crops and trees are grown. Additionally, a substantial amount of jobs was created, and the cost of establishing and maintaining forests was reduced (Ndomba et al. 2015).

In Sudan, However, the Taungya system has been adopted by Forest National Corporation (FNC) as a participatory management approach for the rehabilitation of degraded forests and as means of livelihood improvement for the communities surrounding the reserved forests. In the system the FNC allocated a predetermined area inside the reserved forests and provide the farmers with tree seeds/seedling and technical assistance. The farmers are responsible for planting specific crops allowed by FNC such as sesame (*Sesamum indicum* L.), cowpea (*Vigna guiculata* L.), groundnut (*Arachis hypogaea*), and roselle (*Hibiscus sabdariffa* L.) for one to three years until tree canopy closure and then repeating the cycle in a different area (El Tahir et al. 2015). The first trial was applied in Gazair Riverine Forest in Sinnar State. Two crops were intercropped with *Acacia nilotica* seedlings, namely maize (*zea* *mays*) and dura (*sorghum vulgare*). The system was successful in reducing the establishment cost of plantations, protecting newly planted areas, improving the well-being of the farmers, and supplying crops and vegetables to the local market in the area (Suliman 2003). Afterwards, in 1964, Taungya system was introduced in the eastern part of Sudan to rehabilitate the tropical dry forests and widely spread over the region, where mechanical ploughing using tractors was applied. Row intercropping was the dominant method for planting and singling of seedling rows at 4x4m was practiced. The system had clear contribution for *Acacia senegal* and *Acacia seyal* plantations in Eastern Sudan (Suliman 2003).

Taungya system has been seen and recognized as a promising practice to solve some of Africa's land use problems by offering a wide range of benefits to farmers. Studies in several parts of Africa have highlighted multiple benefits of Taungya system in terms of improving crop productivity income generation, socioeconomic wellbeing of rural populations (Suang et al. 2020, Kalu et al. 2011) as well as its considerable role in restoring the degraded forests (Ebenzer et al. 2018). It can be mentioned as a matter of interest that agroforestry systems similar to the *Taungya* exist all over the world and can also be found in Hungary. (Nair 1993, Chamshama et al. 1992, Watanabe et al. 1998). According to documents from the early 19th century, this practice in Hungary has its roots in the long past. While in the past the cultivation of the land between the trees served to reduce the costs of afforestation and ensure livelihoods, nowadays this practice is primarily aimed at the survival and optimal growth of seedlings, thus improving the efficiency of afforestation. Since these systems have now lost their original purpose, the way of life typical of the old days has ceased to exist, but the practice has survived scatteredly and is sometimes used in the early years of afforestation. (Kovács et al. 2019).

2.5.2.3 Parkland agroforestry system (scatter trees in farmland)

Parkland agroforestry is a traditional land use system where farmers retain or grow trees in their farmland for the benefits from ecological and economical values of trees (Akpalu et al. 2020, Bayala et al. 2015). In Sudan, parkland agroforestry is widely spread in Sinnar, Gedaref and Central Darfur States. In Sinnar and Gedaref States farmers deliberately preserve Acacia trees with agricultural crops/livestock in irregular arrangement, while in Central Darfur the farmers grow their subsistence crops under *Faidherbia albida* treers. In this system the farmers' benefits from the existing trees as a source of fodder for livestock, firewood for local consumption, improvement of soil fertility and increasing crops productivity. According to Fahmi et al. (2018), agroforestry parkland in Sinnar State proved to be economically profitable system and potentially feasible for securing livelihoods and income generation for the household.

2.5.2.4 Traditional Jubraka agroforestry

This system is a form of traditional home gardens agroforestry where small-scale farmers use their small-scale backyard around housing for growing subsistence crops that quickly grow such as sorghum, sesame, and cowpea as source of food and partially income generation through the year, but particularly at the end of dry season and onset of rainy season (Makki et al. 2009). *Jubraka* practice considers as the most common type of home gardens of small-scale farmers in the semi-arid zone of Sudan and distributed from Darfur in the western part of Sudan to South Kordofan in the South. The system is practicing in Nuba Mountains in Sudan and typically managed by women. According to study conducted by Murakah et al. (2014), Jubraka agroforestry practiced by women in Nuba Mountains region was contributed to household food security by 52% while 82% from their farm income was spent in their family needs.

2.5.2.5 Shelter belts and wind break agroforestry system

In this system farmers grow several rows of trees across the prevailing wind direction to reduce wind speed around their farms and buildings. Recently, these systems have widely been spread in most agricultural schemes in Sudan (e.g., Gezira, Rahad, Elsuki and Kinana schemes). The effectiveness of these systems on crops yield, environmental services, and livelihood improvement have been highlighted in many studies. For instance, Abdalla et al. (2015), have assessed the impact of shelterbelts established in Al Rahad Agricultural Scheme, Sudan on crop yield and microenvironment and found significant increase in crop yield in the protected zone compared to the open area. Similarly, El Amin et al. (2014), reported that shelterbelts established in the rain fed agricultural scheme in Gedaref State, Sudan, have several socio-economic benefits and environmental service including increased crop productivity, firewood, income generation and soil conservation. Likewise, study carried out in shelterbelts in the Gezira Agricultural Scheme in central Sudan showed tangible multiple benefits of shelterbelts. Households and farms located close to the tree shelterbelts were less affected by desertification and obtained high agricultural production and income in contrast to those ones far from the tree shelterbelts (Muneer 2011).

2.5.3 Socio-economic aspects of agroforestry in Sudan

The farming systems in Sudan are classified into three categories namely, mechanized rain fed, irrigated rain fed, and agro-pastoral traditional rain fed (CBOS 2013). Most of the population relies on these farming systems as a main source of their livelihood (Glover – Elsiddig 2012). The unsustainable use of these systems has been the main cause of deforestation and land degradation and hence exacerbated the phenomenon of climate change. However, agroforestry systems (traditional and modern) have been practiced in these systems as smart technology of socio-economic improvement, food security, improvement of soil fertility and as effective tool of climate change mitigation and adaptation. The socio-economic aspects of agroforestry for rural people of Sudan have widely been shown in the literature. Numerous studies carried out in the various parts of the country have confirmed the potentiality of agroforestry in supporting socioeconomic of the farmers. Hammad et al. (2014), have analyzed different agroforestry practices in gum Arabic belt in western region of Sudan and found that agroforestry systems have significant effects in improving soil properties, increasing crops yield and land area saving. According to Fadl et al. (2015), agroforestry systems in Kordofan region play a key role in sustaining agriculture production and providing income to the poorest farmers. A similar result was reported by Fahmi et al. (2018). Likewise, EL Tahir et al. (2015), investigated the economic value of agroforestry at the local scale in eastern region of Sudan, and their results concluded that agroforestry practices had main direct marketable and sustainable high value products including food, cash crops, firewood, gum, fodders, and medicine and hence had significantly contributed to the livelihoods of the local communities. A recent study carried out by Hemida – Adam (2019), in Galabat locality in Sudan illustrated the significant contribution of agroforestry farmland to farmers livelihood as farms trees were ranked as the second important source of income after agriculture, which led many farmers to adopt farm trees as a key livelihood strategy to increase and diversify their income sources and strengthen their capacity and ability to improve their livelihoods.

2.5.4 The role of agroforestry in modern agriculture, forestry, and rural development in Sudan

The expansion of monoculture practices particularly the irrigated rain fed, and mechanized rain fed schemes considers a main cause of land degradation in Sudan (Sulieman 2018). Mechanized rain fed agriculture is the process of using agriculture machinery to mechanize the work of agriculture to improve productivity. It was initiated in Sudan by British colonization in the 1940s. Since then, it has spread very rapidly all over the country and currently covers 6.5 million hectares (ELhadary 2010). Despite the significant role that monoculture plays in providing food and nutrition for Sudanese people, its impact in the environment, degradation of ecosystem services and loss of biodiversity is a genuine problem. However, practicing agroforestry could tackle this problem since agroforestry on one hand can advance agriculture by providing people with the main needs of living such as, improvement of soil properties, food production, water quality and biodiversity conservation and on the other hand can advance forestry by its contribution in rehabilitation of degraded forests.

Many studies carried out in Sudan have proved the positive role of agroforestry in modern agriculture and forestry (Gadallah et al. 2019, Fadl et al. 2015, Raddad et al. 2013). As the most of the environmental problems (deforestation and land degradation) in Sudan caused mainly by practicing traditional agriculture, application of agroforestry can be a win-win solution by providing economic (e.g. income and subsistence), social (e.g. education, self-employment and hence gradual decrease in migration) and environmental service (biodiversity conservation and climate change mitigation), that contribute to serve the cultural heritage and landscape amenity of the rural farmers and hence positively affect rural development in Sudan.

2.5.5 Conclusion

Agroforestry systems in Sudan, has a long tradition practice. The Sudanese small-scale farmers have started practicing traditional agroforestry such as bush fallow and gum Arabic agroforestry for long time. Currently, different kinds of agroforestry systems have been practiced by farmers, these include Taungya system, parkland, *jubraka* (home garden), alley cropping, shelterbelt, and windbreaks. The application of these systems has positively contributed to improvement of farmer's livelihood and deceased environmental degradation. However, despite tangible and intangible values of agroforestry practices, the degree of adoption is still insufficient. This could be attributed to several factors related to Sudanese land tenure policy and farmer's perceptions and attitudes on planting or keeping trees on their farmland. Thus, the extension services for the farmers should be activated and land use policies of Sudan should be revised.

2.6 Deforestation and forest degradation

Deforestation and forest degradation are grave threats to forests and livelihoods of forest-dependent people in the tropics. Scientific literature and policy reports have frequently cited small scale farmers as significant agent of deforestation and forest degradation (Duguma et al. 2019). For instance, during the last century, approximately 30% of the global forest cover has been lost and 20% has been degraded (Keenan et al. 2015). This has led to the loss of cropland of 0.2% annually, with an expected reduction of 12% in global food production by 2040 (Tully et al. 2015). Despite the fact that the rate of global forest loss has decreased significantly over the last five years (2015-2020), 1.5 billion people are responsible for the loss of 2 billion hectares of deforested and degraded land. (Sanz et al. 2017), resulting in biodiversity loss, food insecurity and hence affected human livelihood (Gilbey et al. 2019, Vásquez-Grandón et al. 2018). This has generated needful attention to rehabilitate degraded forests, conserve ecosystem services, and build resilience to climate change (Djenontin et al. 2020).

The main underlying causes of deforestation and forest degradation are attributed to agricultural expansion (Plata-Rocha et al. 2021, Hamunyela et al. 2020) and forests overexploitation (Lestari et al. 2019). According to a study conducted by Hosonuma et al. (2012) for assessing the drivers of deforestation and forest degradation in 46 developing countries show that commercial agriculture is the main driver of deforestation, while the primary causes of forest degradation are timber harvesting (52%), firewood and charcoal production (31%), uncontrolled forest fires (9%), and overgrazing (7%). Likewise, Jayathilake et al. (2021), have investigated the drivers of deforestation and forest degradation in 28 tropical conservation landscapes and found that commercial and subsistence agriculture were the main drivers of deforestation, followed by settlement expansion and infrastructure development.

In this context, Sudan is considered as a hotspot of deforestation and forest degradation particularly in dry forests (Sulieman 2018). The main causes of deforestation and forest degradation that contributed to forest loss are expansion of mechanized rainfed agriculture, illegal tree felling and lack of forest management plans (Yasin et al. 2022, Gadallah et al. 2021, Badri 2012). For instance, Sulieman (2018) investigated drivers of forest degradation and fragmentation in Erwashda forest between 1973 and 2015 and found dramatic change of bare land from 5.3% to 22.2% due to expansion of mechanized farming into forest area. Another study conducted by Gadallah et al. (2020) in Wad Albashir dry forest reported sizable land use land cover change between 1985 and 2017 driven by crops farming inside forestland and illegal tree cutting.

2.7 Forest rehabilitation concept and process

Forest rehabilitation and forest restoration concepts are frequently used interchangeably in the literature on interventions to recover the degraded forest (Jones et al. 2022, Stanturf et al. 2014). Forest rehabilitation is the process of establishing tree cover on previously forested grasslands, brushlands, scrublands or barren land (Chokkalingam et al. 2005) while forest restoration refers to restoring the conditions of forests to their original situation before degradation has occurred (de Jong et al. 2021). However, for the purpose of this research, the definition of CIFOR (2003), which defines forest rehabilitation as ‘‘Deliberate activities aimed at artificial and/or natural regeneration of trees on formerly forested grasslands, brushlands, scrublands or barren areas for the purpose of enhancing productivity, livelihood and/or environmental service benefits’’ was adapted. This definition was used because, in the case of Sudan, forest rehabilitation in general, and interventions in the study area as particular, target forested lands exposed to different degrees of degradation.

Forest rehabilitation encompasses a variety of practices that are planned, funded, implemented, and monitored by different actors such as governments, NGOs, and smallholders (de Jong 2010). Ultimately, rehabilitation is needed to halt degradation, expand forest cover, as well as conserve primary forests and environmental quality (Kobayashi 2004). Forest rehabilitation generates various benefits to the adjacent communities, including ecosystem services (Nugroho et al. 2020), socioeconomic, and livelihood improvement (Etongo et al. 2021, Adams et al. 2016). To ensure the success of forest rehabilitation, Hahn et al. (2004) outlined several guidelines including: reduce the use of clear cutting; use local variation and natural succession to secure constant supply of species and promote rare; native species, use only native species except in circumstances where exotic species fulfill requirements such as site adaptation and biological integration; promote and use natural regeneration techniques; apply an ecosystem-based technique that will have minimal impact on the environment and on the local communities; and involve local communities in the process of forest rehabilitation. Similarly, Elliott et al. (2013) recommended some steps as crucial for forest rehabilitation such as eliminating stressors (e.g., forest overexploitation and overgrazing), and depending on the degree of degradation, the area may be augmented with animals and plants. Furthermore, Budiharta et al. (2014) highlight the significance of determining the characteristics of the degraded sites and level of degradation before selecting the rehabilitating techniques. For instance, the forested area with high degradation needs extensive tree planting with high cost in comparison to less degraded area. Moreover, the biodiversity of the area is also crucial factor as the key biodiversity areas are hotspots that require special attention for rehabilitation to restore ecosystem goods and services (Etongo et al. 2021)

2.8 Role of agroforestry in forest rehabilitation

Recently, there are global goals towards forests rehabilitation (Shahanim et al. 2022, Ota et al. 2020). International conventions and national policies state the need for forests conservation, forests rehabilitation, and adaptation of forest management to climate change as essential for human livelihoods and climate stability (Buckingham et al. 2015, Löf et al. 2019). As noted by UN Environment (2019) the aspiration is to reach 350 million hectares of forests restoration by 2030. In this regard, agroforestry systems have been found to be environmentally friendly practices and cost-effective strategies for forest rehabilitation (Oliveria – Carvalhaes 2016) and promoted as best land use practice to halt the problem of deforestation and land degradation (Hasannudin et al. 2022, van Noordwijk et al 2020). Dagar et al. (2020) reported that agroforestry systems can assist in efficient restoration by promoting natural regeneration and diversifying tree species throughout farms, fields, and forests. For instance, silvopastoral systems have the potential to rehabilitate most degraded lands through improvement of soil quality (Dagar et al. 2020). Similarly, Budiastuti et al. (2021) noted that sustainable agroforestry system was approved to be the best vegetation management to solve the problem of deforestation. Some experiences around the world, including Niger, Mississippi, the Democratic People's Republic of Korea (DPRK), and Sudan have successful restoration program through agroforestry adoption.

In Niger, farmers have restored 5 million hectares by planting more than 200 million trees through productive agroforestry practices. This has gained number of benefits in the region including, increased food security, income generated, increased resilience, and improved natural environment (Buckingham – Hanson 2015b). In Lower Mississippi River Alluvial Valley (LMAV), agroforestry systems have been explored for restoring Bottomland Hardwood Forests (BLH) (Dosskey et al. 2012). Likewise, in DPRK, successful participatory agroforestry projects have been shown to be effective tool for arresting the deforestation and land degradation (Xu et al. 2012). In Sudan, Tuangya agroforestry system has been implemented through participatory approach between Forest National Corporation (FNC) and local communities for rehabilitating the degraded dry forests.

2.9 Farmer's perception towards agroforestry systems and factors influencing their perception

Farmers' perception was defined by Maswadi et al. (2018) as ‘‘the knowledge and behavior of farmers in something’’. In this study, perception is centered on the benefits of practicing in Taungya agroforestry program. Farmers' perceptions refer to their amount of information and comprehension about its benefits, as well as their socioeconomic situation (Tokeda et al. 2020). It plays an essential role in a farmer's decision to adopt a technology (Mwangi – Kariuki 2015). Since farmers choose the actual land use in the field, their perception toward agroforestry and comprehension of its benefits are crucial to the construction and management of these systems (Tsonkova et al. 2018). Farmers' positive attitudes toward their way of thinking may have a positive effect on the development of agroforestry program (Suparwata 2018). According to Mayele – Bongo (2022), understanding farmer's perceptions towards agroforestry benefits is essential in sustainable agroforestry practices and integrating their perspectives into agroforestry management will boost strategy in commensuration of future agroforestry developments and challenges (Mayele – Bongo 2022).

Numerous studies have reported farmer's perceptions of agroforestry benefits. For instance, in Europe, the perception of farmers towards agroforestry practices in 11 European countries was investigated by García de Jalón et al. (2018). The authors' result reported both positive and negative aspects of agroforestry practices as perceived by the farmers. Likewise, Graves et al. (2017) evaluated the farmer's perception of benefits for silvoarable systems in England and found that most farmers thought that these systems would not be profitable on their farms and that benefits would tend to be environmental or social rather than economic. In Sub-Saharan Africa, a recent study conducted by Owusu et al. (2021) has analyzed farmers' perceptions of the benefits of cocoa agroforestry shade levels. Their results concluded that farmers' perceptions play a critical role in the establishment of agroforestry shade levels. In Asia, extensive fieldwork has been conducted by Susanti et al. (2020) in Indonesia to explore smallholder farmers' perceptions of oil palm agroforestry and found that farmers have various perceptions ranging from very positive to very negative. Similarly, in India, Phondani et al. (2020) investigated the benefits of indigenous agroforestry systems from farmer's perspectives and concluded that their perceptions towards the tangible benefits were highly favorable while their attitudes towards the intangible benefits were indifferent.

Farmers' perceptions towards agricultural technologies such as agroforestry practices are influenced by a variety of factors, including socio-economic and institutional factors (Gebru et al. 2019, Jha et al. 2019, Mwangi – Kariuki 2015). Age, gender, education level, land size, and family size are the socio-economic factors (Saha et al. 2018, Gao et al. 2014, Tey – Brindal 2012). Institutional factors include the existence of agricultural association, access to credits and extension services (Mwaura et al. 2021). Maswadi et al. (2018), found that land size, family size, age, and education have a positive effect on farmers' perceptions. Likewise, education level, land size, access to training, and extension services were found to have a positive and significant influence on farmers' perceptions of the benefits of practicing agricultural technologies (Moges – Taye 2017). Similarly, factors such as agricultural extension, family labor, marital status, and gender were found to be determinants of farmers' perceptions towards the economic benefits of rice farming in Thailand (Fakkhong et al. 2016). A study by Wang et al. (2019) investigated the socio-economic factors influencing local farmer's perceptions of a reforestation program in China. The authors found that technical support, age, gender, income difference, and education are important determinants of farmers' perception. Although these factors have been found to influence perceptions, the findings are inconsistent and not thoroughly understood (Meijer et al. 2015). Thus, a better understanding of farmers' perceptions of technologies and the socio-economic factors that hinder their perceptions is critical for providing valuable information to technology providers and essential for the success of the policy and program (Oo – Usami 2020, Thompson et al. 2019). This will undoubtedly contribute to the improvement of farming practices for conservation and sustainability (Zafeiriou et al. 2021). Particularly in Sudan, the number of studies assessing farmer's perceptions and the factors that affect their perceptions towards Taungya agroforestry is relatively small and has been limited (El Amain – El Madina 2014). Thus, this study will build on the existing literature by analyzing the farmer's perceptions and its socioeconomic determinants. Understanding these factors could facilitate implementation of other agroforestry technologies in the future.

2.10 Remote sensing concept and applications

Remote sensing is formally defined as ‘‘the acquisition of information about the state and condition of an object through sensors that do not touch it’’. (Chuvieco 2016). Remote sensing activities include the operation of satellite systems, the acquisition and storage of image data, the subsequent data processing, interpretation, and dissemination of the processed data and image products (Chuvieco – Huete 2010). Since 1932, remote sensing has been used in Europe and America for forest mapping and surveying (Moir 1932). Recently, remote sensing applications in forest resource management and protection have been implemented in most countries, including those in Asia, Africa, and Australia (Moradi – Sharifi 2023, David et al. 2022, Chamberlain et al. 2020). It being one of the most common methods in monitoring forest cover change (Kumar et al. 2021). In a changing world scenario, the economic importance of remote sensing for monitoring forest and agricultural resources is critical to the development of agroforestry systems (Guimaraes et al. 2020). According to Dang – Trung (2022), applying and integrating remote sensing data with field investigations and surveys improves the accuracy and reliability of research results. Remote sensing data sets such as Landsat, SPOT, MODIS, and Sentinel are very popular and have been widely used by scholars for mapping and detecting change in forested land (Thien – Phuong 2023, Bao et al. 2022, Ullah et al. 2016, Zhang et al. 2016). However, Landsat is exceptional and has gradually become a first choice for forest monitoring and mapping due to its convenient access, historical and ongoing archive of imagery with high spatial resolution, and available free of charge (Mohamed et al. 2020, Lu et al. 2019).

2.11 Image classification

Image classification is a remote sensing technique used to catalog all pixels in an image into a finite number or individual land use cover classes to produce beneficial thematic maps and information (Alwamy et al. 2020). It is a multi-step process that begins with the design of a scheme for classifying the desired images. Then images are subjected to preprocessing, including image clustering, image enhancement, scaling and so on. Afterwards, the desired regions of the images are identified, and initial clusters are generated. Then, the algorithm is applied to obtain the desired classification. The final step is to assess the accuracy of this classification (Mehmood et al. 2022). There are several methods of image classification, in which supervised and unsupervised classifications are the most common techniques used by researchers (Faruque et al. 2022, Ewunetu et al. 2021 Guo et al. 2021, Saad et al. 2020). In the unsupervised classification method, the user does not use or generate the training datasets to determine the classes, instead, a computer algorithm identifies and clusters areas with similar spectral characteristics inherent in the image, while in supervisor classification the user creates and uses a groups of training datasets of predetermined classes for image classification (Sigdel 2019).

2.12 Accuracy assessment

Accuracy assessment is an important step in studying image classification for better understanding and estimating the land cover change correctly. It explores to what extent the classification results correspond with the reference data on the ground (Cheruto et al. 2016). The best approach for getting higher accuracy of classification is to collect reference points from the study area (Belayneh et al. 2020). The most common technique for accuracy assessment is called Error Matrix and consists of User's Accuracy or commission error (UA), Producer's Accuracy or omission error (PA), Overall Accuracy (OA) and Kappa Coefficient (K). UA identifies how well pixels classified as a certain land cover type match the land cover type on the ground, while PA measures the probability that pixels of the certain class were correctly extracted. OA illustrates the proportion of correctly classified samples in the imagery by dividing the total number of correct samples by the total number of samples. K describes the measure of overall agreement between the classified map and reference data. Its value ranges between 0 and 1, with higher values indicating high levels of agreement (Congalton – Green 2019). Accordingly, when the value of Kappa is equal to or greater than 0.75, the classification performance is strong, while when the value equal to or less than 0.40, the classification performance is weak (Sahin et al. 2022).

2.13 Land use land cover change detection

The term "land-use" refers to how humans use land cover to survive. It discussed the methods and motivations for changing the biophysical characteristics of the land. Land use includes crop cultivation, mining, housing, and infrastructure development (Lambin et al. 2006). In contrast, "land-cover" describes the biophysical state of the earth's surface and immediate subsurface, including human modifications, topography, and soil-like infrastructures (Lambin et al. 2006). Land use land cover changes refer to increases or decreases in the area of a particular land use or land cover type.

Change detection is the process of identifying a change in an object or phenomenon by observing it at different times (Luo – Moiw 2021). It is useful in applications related to land degradation (Kumar et al. 2020), deforestation (Torres et al. 2021), forest rehabilitation (Kibetu – Muangi 2020) and other cumulative changes (Shekar – Methew 2023). Assessment of land use land cover change helps to determine the extent of human impact on the environment. According to many scholars, it is a significant process that affects the natural environment and socioeconomic condition locally, regionally, and globally (Wubie et al. 2016). Most land use land cover changes are caused by anthropogenic activities and human settlements, all of which have various effects on the biosphere and climate (Rawat – Kumar 2015). Consequently, change detection assessment is crucial for managing both the environment and living conditions (Rao – Reddy 2004). Over last three decades, several techniques for change detection have been developed using remote sensed data such as change vector analysis, principal component analysis, image rationing, image overlay, and post-classification comparison change detection (Asokan – Anitha 2019). However, the reviews of these techniques and their applications can be found in (Zhang et al. 2023, Shi et al. 2020, Asokan – Anitha 2019, Singh 1989).

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Overview

This chapter is specified to define the research approach, describe the study area, materials and methods used for collecting the primary and secondary data. The chapter also provides an overview of the analytical approach used to analyze the collected data.

3.2 Research approach

The research applied a case study approach (Yin 2014). This approach enables problem-oriented analysis of issues relating to natural resources, with a particular emphasis on local context and connections between people and natural resources (Grossman 2015, Smith et al. 2012). Moreover, the case study method has a long and honorable history in agroforestry studies (Romanova et al. 2022, Hasannudin et al. 2022, Heredia et al. 2020, Desmiwati et al. 2021, Musa et al. 2019, Bouzekraoui et al. 2016). Thus, case study of Nabag Reserved Forest (NRF), South Kordofan State, Sudan was chosen to achieve the research objectives. The unit of analysis was the households including farmers who participated in the Taungya agroforestry program in the study area. The research approach was a holistic approach in which the household was the basic unit of analysis.

3.3 Study area

3.3.1 Criteria for selection of the study area

The study area (Nabag Reserved Forest (NRF)) lies in South Kordofan State, south central part of Sudan. The area was selected as a case study due to two reasons: Firstly, the area has experienced a long history of drought-prone and rainfall shortages, which have led to forest degradation and negatively affected many communities who rely heavily on this forest for their livelihoods. Secondly, an active Taungya agroforestry program has been applied to rehabilitate the study area.

3.3.2 Description of the study area
3.3.2.1 South Kordofan state

South Kordofan state is located in the south-central part of Sudan. It bordered by North Kordofan state from the north, the Unity state, and Upper Nile state from the south and the White Nile state form the north-eastern border. Geographically, it lies between latitude 10˚ - 13˚ N and longitude 29˚ - 33˚ E with the total area of about 141,096 km² divided into eight localities namely: Kadugli (capital of the state), Rashad, Abu Jubeiha, Talodi, Dilling (locality of the study area), Lagawa and Abyei (Abtew et al. 2012) (Fig. 3.1).

Topographically, most of the state's areas are covered with hills intersected by seasonal watercourses. The soil types are clay plains, sandy clay (locally known as Gardud), and sandy soils. The clay plains constitute about 32% while the Gardud and sandy soils comprise about 27% and 21% of the total state area, respectively (Mohammed 2011).

The climate of South Kordofan state lies within the savanna zone, in which the main annual rainfall ranges from 350mm in the north to 850mm in the southern parts of the state. The rainy season extends from mid-May to mid-October and the greatest amount of rain falls is in July, August, and September (Bello – Allajabou 2016). The average temperature ranges from 20° during winter season (November – March) to 35° during summer season (April – June) (Maalla et al. 2015).

According to the last Sudan population census (2008), the total population of the state is about 2.3 million people with a variety of ethnic groups. The main livelihood activities are agriculture, livestock breeding and natural forest products such as fuel wood production, building materials, gum Arabic and fruits harvesting (Hamad et al. 2015). The total area of land suitable for agriculture is about 6300000 hectares, of which seven million feddans are demarcated and allocated for mechanized farming (Mohammed 2011). The most important agricultural crops comprising sorghum, maize, cotton, millet, in addition to subsistence crops such as sesame, hibiscus and groundnut.

The vegetation cover in the area is relatively poor and scattered in the northern part of the state, while in the south medium and a dense stands of different tree species and shrubs are dominated due to rainfall increases in the south (Mohammed 2011). The dominant huge and perennial trees are *Tamarindus indica, Acacia sieberana, Ficus sycomorus, Faidherbia albida*, *Tectona grandis, Acacia nilotica, Hyphaene thebaica, Dalbergia melanoxylon* and others. Shrubs such as *Acacia mellifera, Acacia orefota, Boscia senegalensis, Calotropis procera and Pilostigma reteculata*, also exist (Ibrahim 2017). The abundance of herbs and grasses such as *Asparagus sp., Triumpfetta flavescens and Hibiscus cannabinus* make the area favorable and attractive for pastoralists for grazing.

3.3.2.2 Nabag Reserved Forest (NRF)

NRF is located in EL dilling district, South Kordofan state, approximately 90 km from El obied city (North Kordofan headquarter) and about 60 km from EL dilling city between latitude 12° 30' 0" N to 12° 36' 0" N and longitude 29° 36' 0" E to 29° 58' 0" E (Fig. 3.1). The forest has been reserved from 1961 as a state forest and managed by Forest National Corporation in Sudan (FNC). It covers an area of 4174.2 hectares. The dominant tree species is *Acacia senegal* which has been planted at the earliest time in 1976. The other natural tree species include *Azadirachta indica, Balanites aegyptiaca, Sclerocarya birrea, Guiera senegalensis and Ziziphus-spina christi*. In addition, some herbs such as *Cenchrus biflourus* are also endemic in the area (Abu Zuaid 2015).

Due to natural factors and anthropogenic activities (more than 13 villages have surrounded the forest) the forest cover has been degraded and its composition has been changed. Accordingly, The FNC has introduced the Taungya agroforestry Program to rehabilitate the forest cover and improve the livelihood of the communities around the forest (Mohamedain et al. 2012). The program was started in 2004 and still on going so far, as a contract between the FNC and farmers, where the FNC was responsible for allocating the land for farmers, providing tree seedlings and technical support, while farmers cultivating their crops between tree spacing. This arrangement continues for 2-4 years according to tree closure, then farmers must shift to another area inside the forest.

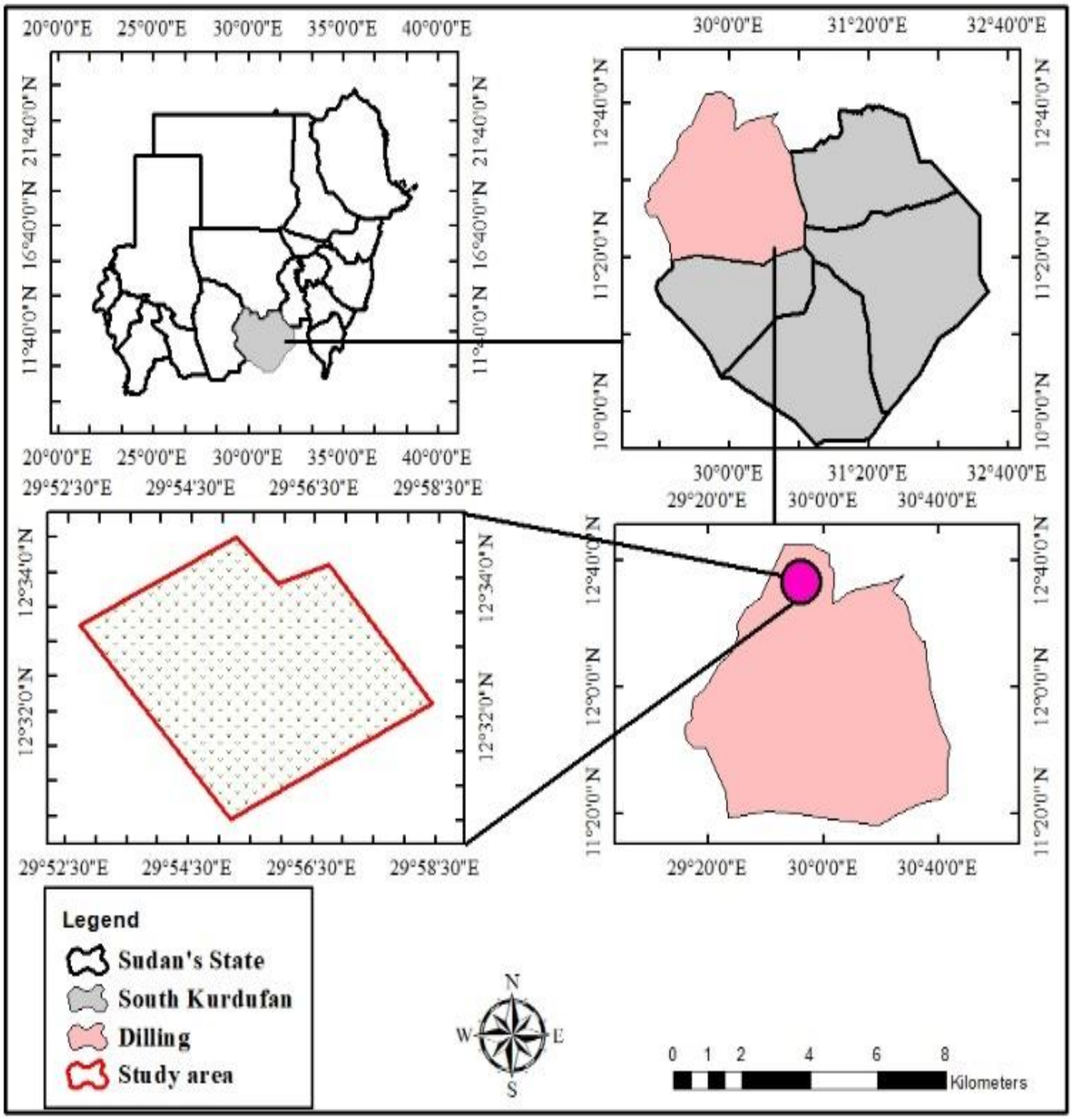

Fig. 3.1: Map of the study area

Source: Author's analysis

3.4 Methods of data collection

In this study, Mixed Methods Research (MMR) that combines quantitative and qualitative data was employed to collect the required data. MMR allows researcher to collect a richer and stronger array of evidence than can be accomplished by any single method alone (Yin 2014). Recently, MMR approach has widely been used in various agroforestry research (Islam et al. 2022, Quandt 2021, Sultana – Bari 2021, Chyono et al. 2020). MMR approach can draw on the strengths and minimize weaknesses of each research paradigm. In this study, the major data collection methods employed were primary data which constitute remote sensing data, and socioeconomic survey, and secondary data which is a review of previous studies relevant to the research. This section will go through each phase of the data collection that was applied.

3.4.1 Primary data

3.4.1.1 Remote sensing data

Remote sensing data was acquired to detect forest cover change under Taungya agroforestry rehabilitation program (first objective of the research). To detect the temporal and spatial changes in forest cover, at least two time series satellite images are required (Ebnenezer et al. 2018). For the purpose of this study, four satellite images of Landsat 5 Thematic Mapper (TM), and Landsat 8 Operational Land Imager/Thermal Infrared Sensor (OLI/TIRS) from the years 1991, 2001, 2011, and 2021 were selected respectively (Table 3.1). The selection of images was based on the availability of free cloud cover (<10%) satellites data, and the purpose of the investigation of forest cover change before and after implementation of Taungya agroforestry program. Thus, the images of 1991 and 2001 were used to detect the status of the forest cover before starting of Taungya agroforestry program, while images of 2011 and 2021 were used to detect the status after the program.

Table 3.1: Source details of the satellite images used in the study

Satellite name	Sensors	Resolution	Acquisition date	Path/Raw	Used band
Landsat 5	TM	30m	1991-01-20	175/051	B1- B7
Landsat 5	TM	30m	2001-01-15	175/051	B1- B7
Landsat 5	TM	30m	2011-01-11	175/051	B1- B7
Landsat 8	OLI/TRIS	30m	2021-01-06	175/051	B1- B7

Source: USGS, earthexplorer.usgs.gov 2021

First, the coordinate of the study area was specified, and the boundary of the forest was delineated and reviewed in the Google Earth Pro Engine Platform (earthengine.google.com) (Fig. 3.2), afterwards, the images of the study area were downloaded from the free website of the United States Geological Survey (USGS, earthexplorer.usgs.gov). The images of the period of dry season (January) were acquired for creating the training data set and land cover classification, as

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this was the suitable period in the study area for getting free cloud cover satellite images and hence facilitate in differentiation between the different land cover classes.

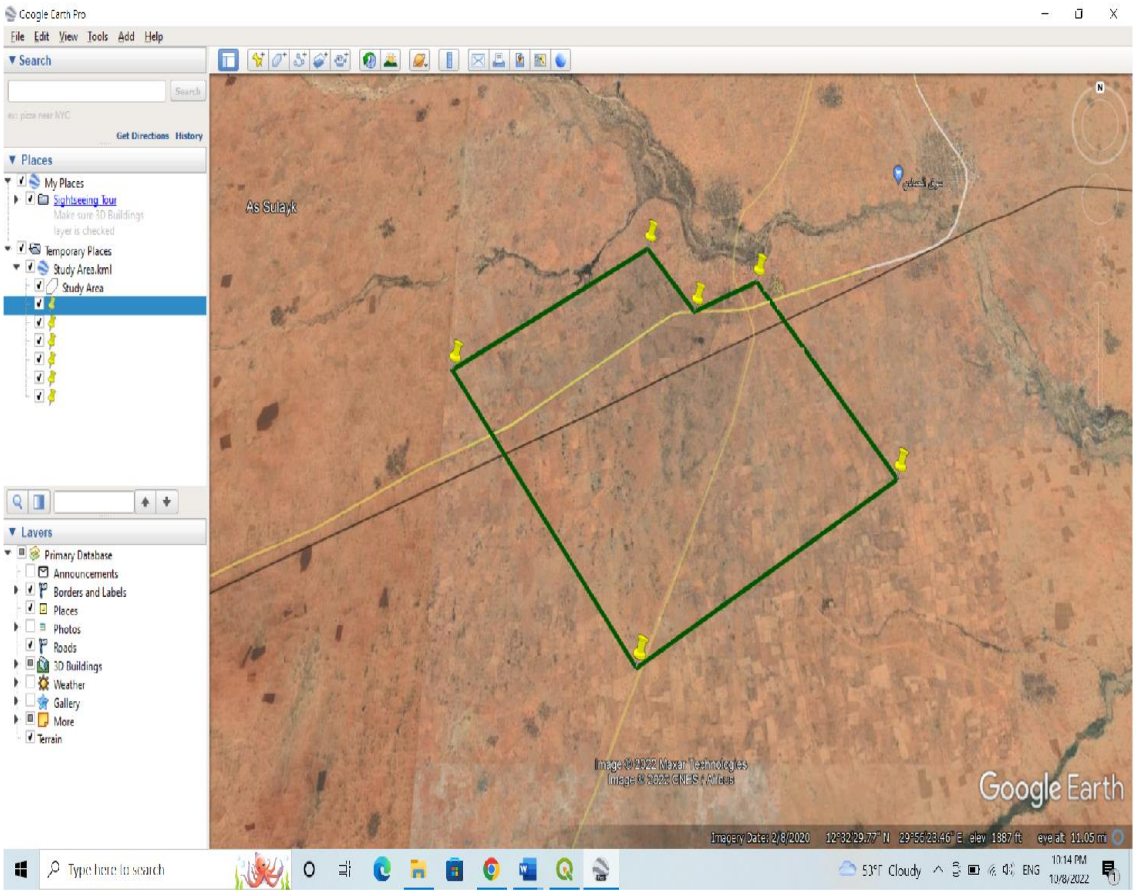

Fig. 3.2: Delineation and reviewing the boundary of the study area in the google earth.

Source: Author's analysis

Second, image pre-processing was performed to all acquired images by using QGIS software version 3.16. First, all the bands of the four images scenes were downloaded and saved as separate image files (.tiff format) (Fig. 3.3). Then, the individual bands were combined sequentially from band 1 to band 7 by using virtual raster creation, during this step, a false color composite was performed for display purpose (Fig. 3.4). Finally, a subset was generated from the virtual raster and clipped to get the full extent of the study area which was used for creating the training dataset for image classification (Fig. 3.5). All images were projected to the Universal Transverse Mercator (UTM) Zone 36N with WGS 84 projection coordinate system.

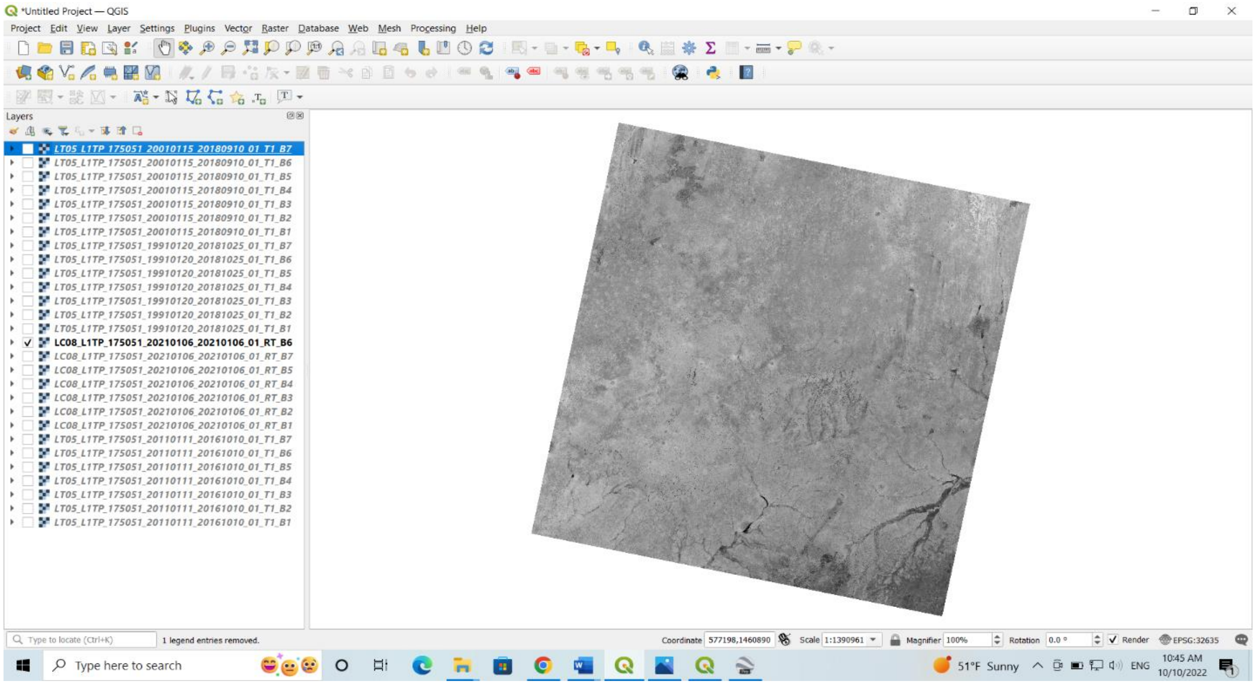

Fig. 3.3: Bands of the four images scenes imported to QGIS software.
Source: Author's analysis

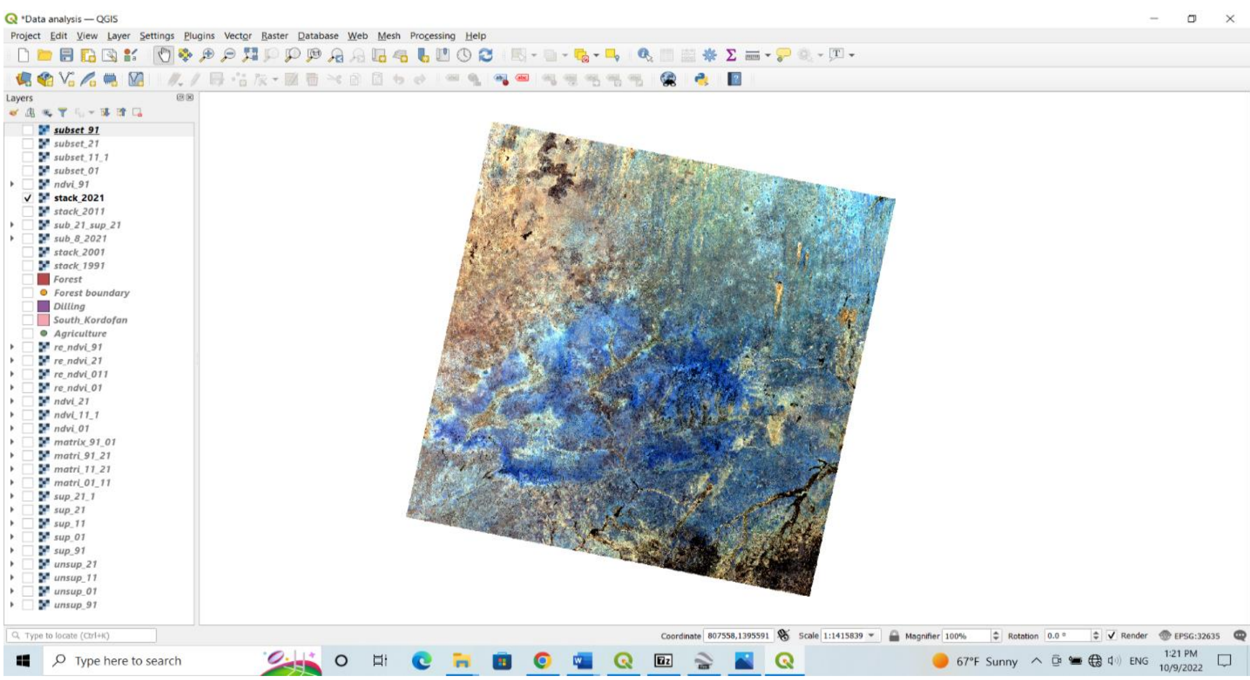

Fig. 3.4: Virtual raster creation and a false color composite was performed for display purposes.
Source: Author's analysis

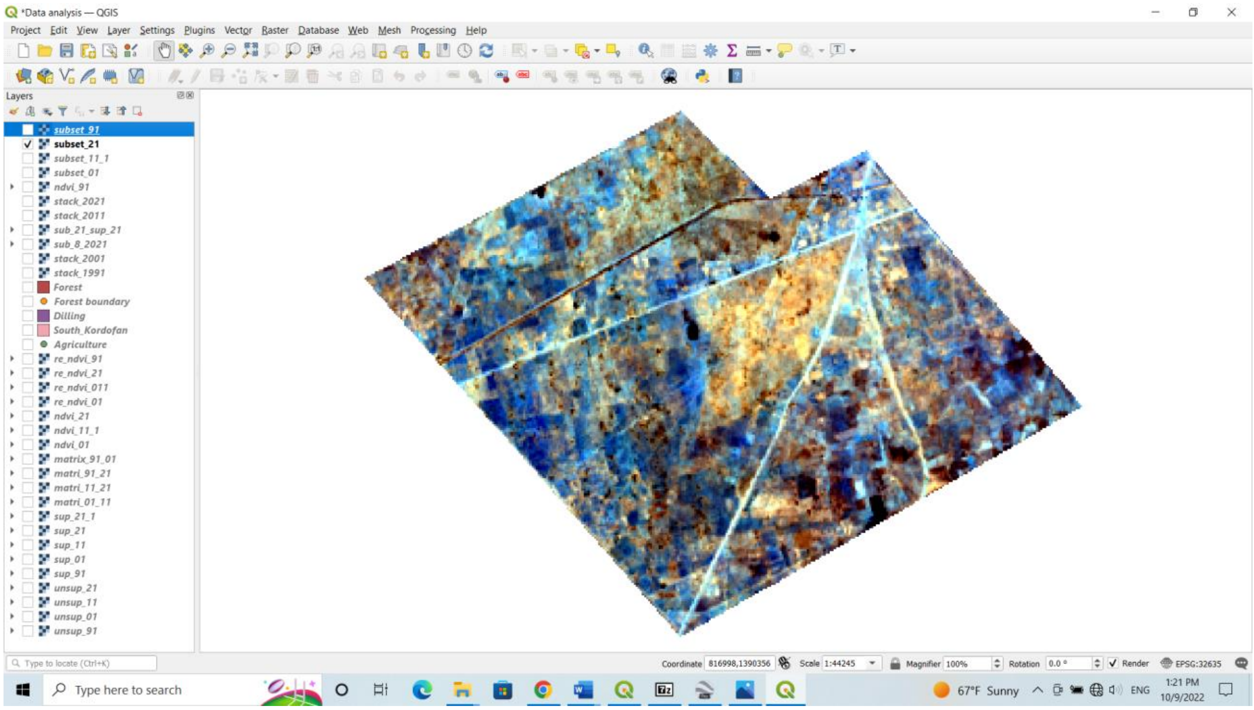

Fig. 3.5: Subset was generated from the virtual raster and clipped to get the full extent of the study area.
Source: Author's analysis

Third, the ground truth survey was carried out in the study area during the summer of 2021 for validation of land cover classes, generating training sample and accuracy assessment of the classification results. There is no specific criterion for determination of the sample size of ground truth point (Gedefaw et al. 2020). In this study, a total of 250 ground truth points were generated randomly in QGIS software using random sample technique (Stehman et al. 2022, Ahmad et al. 2016, Wanger – Stehman 2015), and then exported to Google Earth Pro platform for visual interpretation (Fig. 3.6). Afterwards, all sample points were entered into Global Positioning System (GPS) and used for the field survey validation.

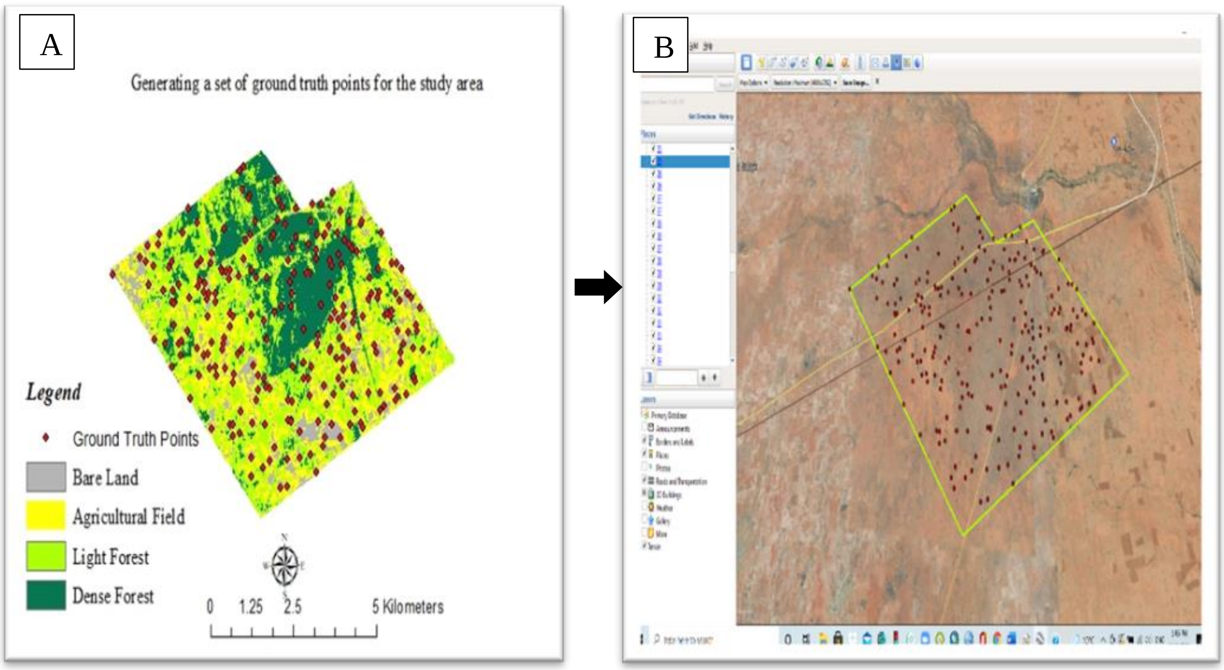

Fig. 3.6: Generating ground truth points in QGIS (image A) and displaying the points in Google Earth Pro (image B)
Source: Author's analysis

Fourth, unsupervised and supervised classifications were employed to classify the images by using QGIS software (Sim-automatic Classification Plugin, SCP). First, unsupervised classification was performed to discriminate various land use types in the study area and to avoid the mixed pixels between different land-use classes, and hence improving the classification accuracy (Munthali 2020, Teferi et al. 2013). Afterwards, supervised image classification was applied. At first, a set of training signatures were created for each predetermined land cover class by using Polygon delineated (ROI), this was done based on the visual interpretation (False color composite interpretation), prior knowledge of the study area, focus group discussion with the elders in the study area, forestry officials implemented the Taungya agroforesty program and google earth time series images. Accordingly, a total of four land types of classes were identified namely, bare land (BL), agricultural field (AF), light forest (LF), and dense forest (DF) (Mishra et al. 2020, Sulieman 2018). The characterization of these land types is presented in (Table 3.2 & Fig. 3.7). Then, the maximum likelihood classifier (MLC) was run to obtain the final output of the classification.

Table 3.2: Definition of different land use classes used in this study

Land use classes	Class description
BL	Areas no vegetation cover consisting of exposed soils
AF	Areas covered by temporal crops followed by harvest period
LF	Areas covered at least 10% and less than 40% of tree canopy
DF	Areas covered by more than 40% of tree canopy

Note: BL= Bare Land; AF= Agricultural Field; LF= Light Forest; DF= Dense Forest
Source: adapted from Sulieman 2018; Mishra 2020

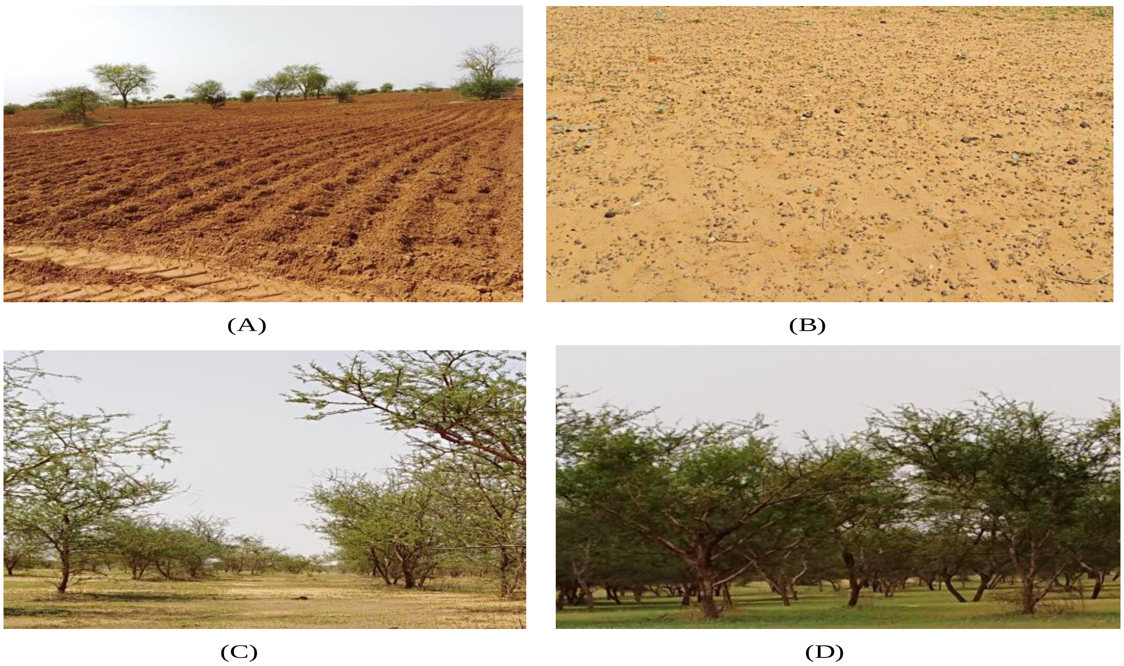

Fig. 3.7: Illustrative photographs of different land-use classes taken during the field survey in NRF.
A= Agricultural Field; B= Bare Land; C= Light Forest; D= Dense Forest
Source: Field survey, 2021

Fifth, an accuracy assessment was performed for land cover maps following an approach suggested by (Congalton – Green 2019) and based on the ground truth data, Google Earth time slider, local elders' interview, and the prior knowledge of the area under investigation by using the following equations (Guo et al. 2022, Chughtai et al. 2021):

$$UA\,(\%) = \frac{P_{ii}}{P_{i+}} \times 100 \qquad (1)$$

$$\text{PA (\%)} = \frac{P_{ii}}{P_{+i}} \times 100 \quad (2)$$

$$\text{OA (\%)} = \frac{\sum_{i=1}^{n} Pii}{\text{N}} \times 100 \quad (3)$$

$$\text{Kappa (\%)} = \frac{N\sum_{i=1}^{n} Pii - \sum_{i=1}^{n}(P_{i+} \times P_{+i})}{\text{N}^2 - \sum_{i=1}^{n}(P_{i+} \times P_{+i})} \quad (4)$$

Where: n = the total number of classes, N = the total numbers of validation samples, P_{ii} = the number of correctly classified samples in the i-th row and i-th column of the confusion matrix, P_{i+} and P_{+i} = the total number of samples in the i-th row and i-th column.

Finally, the post-classification comparison method (PCC) was adopted to detect the forest cover change under Taungya agroforestry rehabilitation program. It is done by computing the magnitude and the percentages of change between different classes during the four years using the trajectory change matrix approach described by (Wu et al. 2015). This method has been reported and proven to be the most suitable and commonly used in detection analysis of land use land cover change (Opedes et al. 2022, Mezaal et al. 2022, Close et al. 2021, Vivekananda et al. 2021, Wu et al. 2017). Using PCC procedure, the statistical change was computed for each class during the addressed period. PCC results were saved and imported into an excel sheet for change detection analysis and graphical presentation of change for the different time periods. Generally, all steps of remote sensing approach used in this study are presented in (Fig. 3.8).

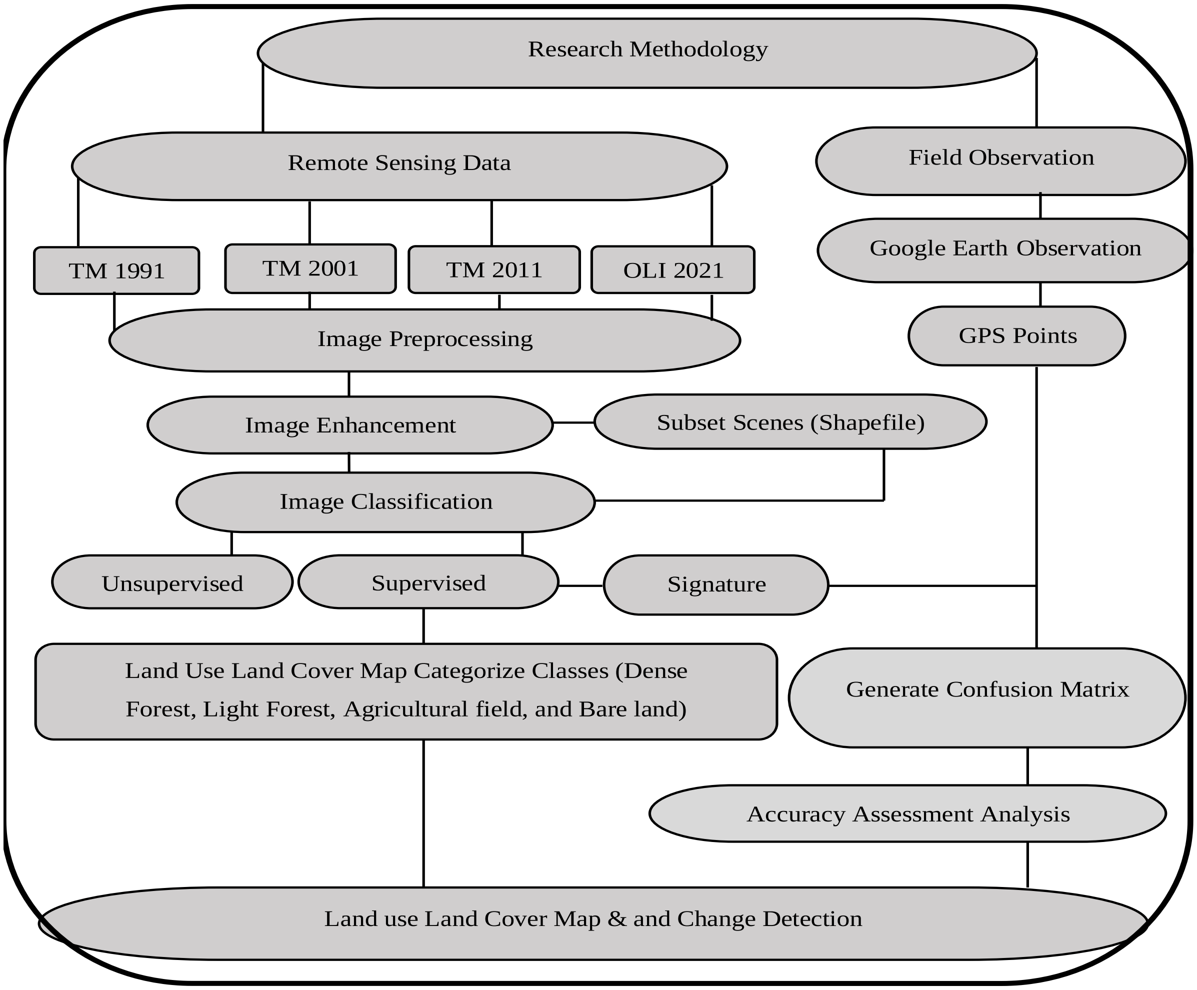

Fig. 3.8: The methodological framework of remote sensing data

Source: Author's analysis

3.4.1.2 Socio economic data

3.4.1.2.1 Reconnaissance survey

A reconnaissance survey was conducted in the study area at the early stage of the data collection process. The purposes of this step were:

- to gather information pertaining to all issues under study;
- to get better insight of the study area;
- to self-introduction and establish contacts with villages leaders, and forestry officials for facilitating the process of data collection;

- to select field assistants and enumerators who have enough knowledge of the study area and the social connections with the research communities (farmers).

3.4.1.2.2 Questionnaire design and pre-test

A semi-structured questionnaire (SSQ) was developed to gather socioeconomic data. The development of the questionnaire was based on the literature reviews (Sagastuy et al. 2019, Patra 2019), and the conceptual framework of the research. Afterward, some consultations were made with supervisors, forestry officials in the study area, and with experts as well. This information helped in strengthening the questionnaire and generated new ideas about the questions and answers of the questionnaire. Prior to the formal interview with the farmers, the developed questionnaire was rigorously pre-tested with a cohort of 10 farmers to test its reliability and validity. Accordingly, some modifications were made by omission of irrelevant questions and addition of new relevant ones.

3.4.1.2.3 Sampling method

A purposive sampling technique was applied in this study to select the respondents for an interview. The sampling frame was comprised of 400 Taungya farmers. The list of the total numbers of the farmers who participated in the Taungya agroforestry program was taken from the FNC office and then a random sampling technique was used to select the targeted farmers. The sample size was determined by applying a formula of Yamane (1967) as shown in equation (5). This formula has widely been used in several studies for calculating the sample size (Abide – Asfaw 2022, Pello et al. 2021, Kiprop et al. 2020, Amare et al. 2019, Acheampong et al. 2016)

$$n = \frac{N}{(1+N(e)^2)} \qquad (5)$$

Where:

n = the sample size

N = the total population

e = the level of precision (error) equal to 0.05 at 95% confidence level

Accordingly, 200 farmers representing 50% of those who participated in the Taungya program were selected from nine villages surrounding the reserved forest. The exact numbers of respondents in the specified villages were, Eid (n = 37), Daggea (n = 35), Alsbeka (n = 30), Alkambi (n = 29), Nabag (n = 21), Alhamadi (n = 16), Eridebo (n = 15), Alsilaik (n = 9), and Umkanayt (n = 8). The selection of the villages was based on the recommendations provided by the forestry officials in the study area, while the selection of the farmers was made randomly according to their availability and willingness to participate.

3.4.1.2.4 Farmers interviews

Face-to-face interviews took place with farmers from June to July/2021 by the author of this thesis, field assistants, and enumerators (Fig. 3.9). The selection of the enumerators and field assistants was based on their familiarity with the community of the study area. Before starting the interviews of the farmers, each respondent was informed about the purpose of the research, questionnaire protocol, and timelines and given the full right to response to our interview or to refuse it. This ethical issue was important to build confidence between enumerators and respondents as well as to be voluntary work. The interview takes 45-60 minutes and is carried out mainly in Sheikh (village leader) house, village markets, and farmers' homes.

Important information collected through the interview includes (*see annex 1*):

- farmers socio-economic characteristics (i.e., gender, age structure, marital status, family size, education, Taungya experience, size of cultivated land and source of income);
- participation in the Taungya agroforestry program and resource endowments (i.e., kind of crops planted, productivity, costs, revenues, and farm characteristics);
- farmer's perception and attitudes towards the benefits of participation in Taungya agroforestry (i.e., in terms of its contribution to: (1) help in the provision of land; (2) help in improving income; (3) help during the time of hardship; (4) help in purchasing livestock; and (5) its contribution to education expenses;
- incentives, challenges, and constraints confronting the farmers in Taungya agroforestry program.

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Fig. 3.9: A glance of the interviews with farmers in the study area
Source: Field survey, 2021

3.4.1.2.5 Key informant interviews (KIIs)

The purpose of the key informant interview was to gather information on the Taungya agroforestry program from progressive farmers depending on their own knowledge, experience, and understanding. As well as to cross-check the information given by the other interviewees to validate the data and revealing any ambiguities. Face-to-face interviews took place with elders who had experience and traditional knowledge of the Taungya agroforestry program and the history of the study area (n=5), forestry officials including the director (n=1), forest inspectors (n=3), and forest guards (n=5). The interview was focused on many issues including the general idea of the Taungya agroforestry program, particularly that one which is applied in the study area, the objectives of the program, the total number of farmers and the criteria used for selecting them, the contribution of the program to farmers livelihood improvement, challenges and obstacles confronting it, and the general evaluation of the program.

3.4.1.2.6 Focus group discussion (FGDs)

Focus group discussions aim to ‘‘collect specific information from a purposely selected group of individuals rather than a statistically presentative sample of a broader population’’ (Nyumba et al. 2018). As the number of respondents to be invited to the discussion is a crucial consideration, the generally accepted number of respondents range between 6-8 respondent per group as recommended by (Krueger – Casey 2014). In this research, the focus group discussion was carried out with a group ranging between 5-8 respondents (farmers, village leader, and forestry official) to discuss specific topics related to Taungya agroforestry program. The topics discussed and the questions addressed during the focus group discussion sessions included the major land use challenges facing by the farmers, the major causes of deforestation and forest degradation in the study area, and contribution of Taungya agroforestry program to their income and livelihood. The discussion was organized and guided by the author of this thesis with the presence of forestry officials. The presence of forestry officials facilitated the discussions and communication between the researcher and respondents. The information generated from this FGD was used to check and triangulate the key responses from the survey.

3.4.1.2.7 Direct field observations (DFOs)

Direct field observation was also considered to detect the real situation of the study area and to take photos as a visual supporting of the data collection Fig. 3.10. These observations provided accurate information of the Taungya agroforestry aspects and used to cross-check the information collected through the interviews.

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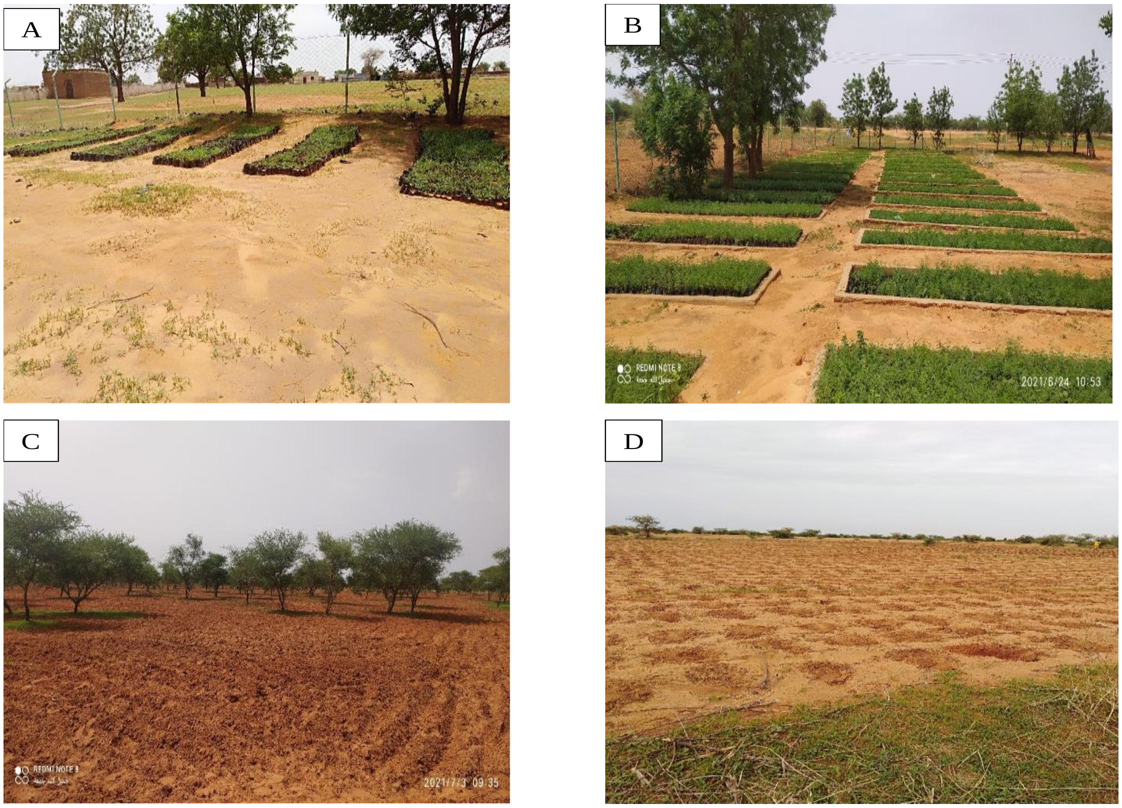

Fig. 3.10: Illustrative photograph of different stage of Taungya rehabilitation program in the Study area *(A&B: Seedling production in NRF Nursery; C&D: Targeted area for rehabilitation with Taungya system)*
Source: Field survey, 2021

3.4.2 Secondary data review

The secondary data review was used to give a general vision about the different aspects of the Taungya agroforestry practice in the study area and to provide information for a better understanding of the research communities. This secondary data plays an important part during primary data collection as it facilitates the selection of the villages around the forest and the sampling process as well. A wide range of documents, archival records, reports of Forest National Corporation (FNC), available literature (articles, books, policy briefs), and results of previous studies were collected and studied. This secondary data was also used to determine the indicators and factors that can be used in the study and design the questionnaire for data collection. Generally, the methodological framework of all steps of the survey are summarized in Fig. 3.11.

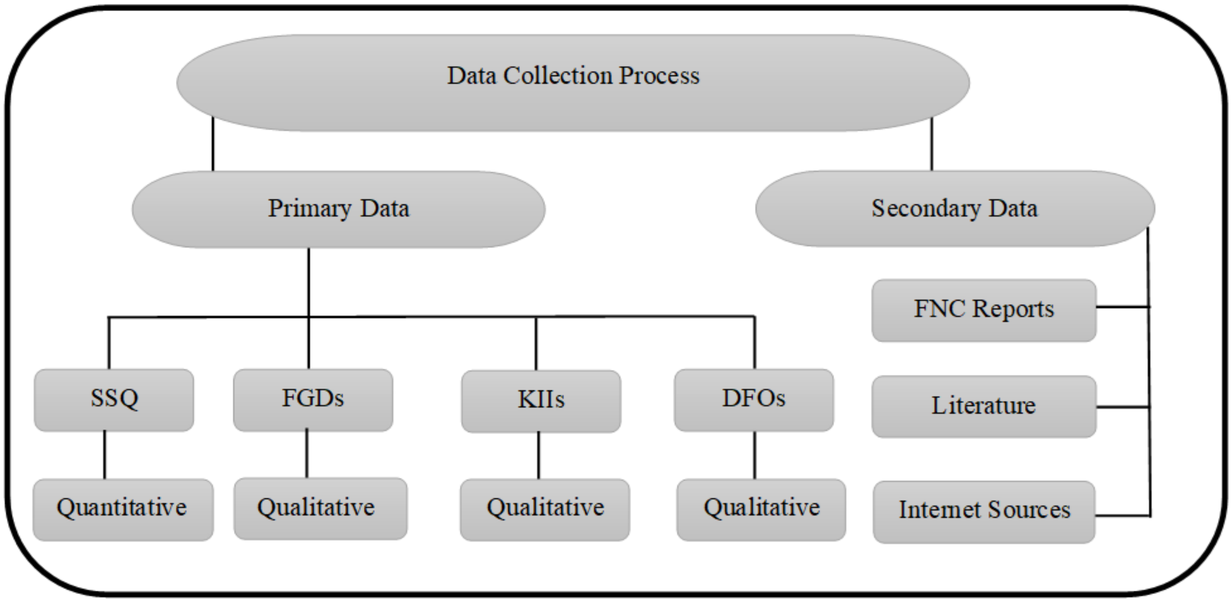

Fig. 3.11: Methodological framework of socioeconomic data
SSQ= Semi-Structured Questionnaire, FGDs= Focus Group Discussions, KIIs= Key Informant Interview, DFOs= Direct Field Observations

3.5 Data analysis

The study obtained a range of both remote sensing and socioeconomic data which was subjected to various statistical techniques to achieve the study's objectives as the following:

3.5.1 Remote sensing data analysis

Land cover changes were analyzed for different periods of satellite images between 1991-2001 and 2011-2021 using QGIS version 3.16 with the aid of Microsoft Excel 2013. Percentage changes of land cover categories were calculated for the period times before and after the implementation of Taungya program in the study area. All pixel counts were divided by a conversion factor of 10000 to obtain their ha equivalent.

3.5.2 Socio-economic data analysis
3.5.2.1 Descriptive statistic

Descriptive statistic such as means, standard deviations, frequencies and percentages were applied to examine the socioeconomic characteristics of the Taungya's farmers (objective 2) and to highlight the major incentives and constraints associated with Tuangyas's farmers (objective 6). The data were first filtered, coded into numerical values, and organized in an excel sheet using Microsoft Excel 2013. The data were then imported into the Statistical Package for Social Science (SPSS, version 22).

A Likert scale rating technique was implemented to evaluate and score farmers' perception of the Taungya benefits (objective 4). According to Wadgave – Khairnar (2016) ''Likert scale is a psychometric response scale primarily used in questionnaires to assess a subject's perception.'' A 4-point rating scale ranging from strongly disagreement to strongly agreement indicating the perception of the farmers was used in this study. Scoring numbers from 1 to 4 were assigned to each response as follows: 1 = strongly disagree; 2 = disagree; 3 = agree; 4 = strongly agree (Osei-Asibey et al. 2022, Kadigi et al. 2021). The reason for using a 4-point rating was to avoid the midpoint options for neutrality and to understand the farmers' perceptions by forcing them to choose agreement or disagreement (Antolín-López et al. 2022, Chyung et al. 2017). To ensure the reliability of the items used in the Likert scale, Coronbach's alpha coefficient was used. The value of the coefficient was 0.61, which is considered acceptable (Taber 2018). The mean score for each item was calculated similar to (Sharmin et al. 2021, Akinwalere 2016, Islam et al. 2015), as follows:

$$MS = \sum (fn\ xn)/N \qquad (6)$$

Where: MS = Mean score; fn = Frequency of 'n' occurrence; xn = Scores assigned to 'n' occurrence; N = Total number of respondents. The mean score of farmers based on the 4-point rating scale was calculated and a cut-off point of 2.5 was computed and used as an inference of the overall farmer's perception, where the mean score (MS) of ≥2.5 represents a positive perception and the mean score (MS) of ≤2.5 represents a negative perception (Oni 2015).

3.5.2.2 Inferential statistic

A paired sample t-test at a 5% level of significance was used to test and compare the distribution of farmers' costs and revenues before and after the implantation of the Taungya agroforestry program (objective 3).

An ordinal logistic regression model was applied to analyze the socioeconomic factors that influence farmer's perception of Taungya program and its potential benefits (objective 5). The ordinal logistic regression was chosen because it has been widely used to study the factors that influence farmers' perceptions of different technologies (Li et al. 2022, Mwaura et al. 2021, Abegunde et al. 2019, Ntshangase et al. 2018, Zamasiya et al. 2017). Furthermore, when the outcome variables are ordinal rather than continuous and have more than two categories, the model is considered a suitable analytical method (Williams 2016). The validity of the model assumptions was checked by testing the two key assumptions; first: the multicollinearity between the independent variables, and second: the parallel line or proportional odds assumptions by following (Chandra et al. 2022, Williams 2006). The Variance Inflation Factor (VIF) was used to test for multi-collinearity, with a value of > 10 indicating severe collinearity, whereas for the parallel line assumption, the model should not be violated to ensure that the estimated effects are the same across all categories by setting the P value to not significant (Chandra et al. 2022). The results of these tests are available in annex 4.

By considering an outcome variable with k ordered categories with associated probabilities for each category donated as $\pi 1$, $\pi 2 \ldots$, πk. Thus, the general model equation can be summarized as follows (Mwaura et al. 2021):

$$\text{Logit (Y)} = ln\,[\pi j/(1-\pi j)] = \alpha j + \beta i\, X\, i \quad j = 1..., k-1 \qquad (7)$$

Where: Y = dependent variable (perception), ln = natural log, j = Likert scale ranging from 1 to K-1, αj = threshold values where α the intercept, βi (i = 1, …, n) is the logit coefficient to be estimated, and $X\, i$ (i = 1, …, n) is the explanatory variable.

The potential benefits of Taungya to help in the provision of land, help in improving income, help during the times of hardship, contributing to education expenses, and help in purchasing livestock were used as dependent variables to estimate the coefficients in the model. On the other hand, a set of explanatory variables (independent variables) were proposed to influence the farmer's perception of the benefits of Taungya. These include family size, education level, age, gender, land size, years of participation in Taungya program, participation in gum Arabic production, and access to extension services (Table 3.3). The selection of variables was based on the available literature review and economic theory (Beshir et al. 2022, Majbar et al. 2021, Gebru et al. 2019, Meijer et al. 2015).

Table 3.3: A general description of the variables used in the logistic regression model

Variable name (code/unit)	Variable description
Dependent variable	
Farmer's perception of Taungya benefits	Positive perception ≥ 2.5 Negative perception ≤ 2.5
Independent variables	
Family size (number)	Family members (continuous variable)
Education level	Illiterate =1; Khalwa* =2; Primary =3; Secondary =4; University =5
Age (years)	Age of the farmers (continuous variable)
Gender	Gender of the farmers (male =1; female=2)
Land size (Mukhamas**)	Number of Mukhamas cultivated inside the forest (continuous variable)
Taungya experience (years)	Years of participation in the Taungya program (continuous variable)
Gum Arabic production	Participation in gum Arabic production (yes =1; no = 0)
Extension	Access to extension services (yes =1; no =0)

* A religious school in which Muslims learns the Holy Quran and Quran studies
** Land unit in the study area (1 Mukhamas = 0.75 hectare). Source: Field Survey Data

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Overview

In this chapter, the results of this study are presented, discussed, and linked with the existing relevant studies. Results were presented under the following main subjects: (a) quantifying and mapping the forest cover change under Taungya agroforestry program, (b) socio-economic characteristics of Taungyas' farmers, (c) contribution of Taungya agroforestry program to farmers' income generation, (d) farmers' perceptions and attitudes towards the benefits of participation in Taungya agroforestry program and (e) the socio-economic factors influencing their perceptions of the benefits of the Taungya program and (f) the major incentives and constraints associated with Tuangyas's farmers in the study area.

4.2 Quantifying and mapping the forest cover change under Taungya agroforestry program (Objective 1)

4.2.1 Forest cover change detection

Table 4.1: Areas and percentage of land use land cover changes in NRF between 1991-2021

Class	**1991**		**2001**		**2011**		**2021**	
	area/ha	**%**	**area/ha**	**%**	**area/ha**	**%**	**area/ha**	**%**
BL	889.76	21.3	1004.85	24	809.64	19.4	479.93	11.5
AF	1415.27	33.9	1440.54	34.5	1550.79	37.2	780.70	18.7
LF	1287.02	30.9	1406.52	33.7	1435.86	34.4	1289.74	30.9
DF	582.06	13.9	322.20	7.8	377.82	9.0	1623.74	38.9
Total	4174.11	100	4174.11	100	4174.11	100	4174.11	100

Note: NRF= Nabag Reserved Forest; BL= Bare Land; AF= Agricultural Field; LF= Light Forest; DF= Dense Forest
Source: Author's analysis (classified images 1991, 2001, 2011, 2021)

The results of land use land cover change maps of NRF during the period of 1991-2021 are illustrated in Fig. 4.1, while the individual land-use classes area and related data are summarized in Table 4.1. The results of the temporal analysis of image classification showed that the total area of NRF was 4174.2 hectares (ha). NRF has witnessed two trends of forest cover change. First, a decline in forest cover occurred between 1991 and 2001. In 1991, the total area of the bare land class was 889.76 ha (21.3%) of the total area of NRF. It increased to 1004.85 ha (24%) in 2001.

Similarly, the dense forest class faced a sharp reduction as the area radically declined from 582.06 ha (13.9%) to 322.20 ha (7.8%) (Table 4.1). This radical depletion of dense forest and the increment of bare land could be attributed to anthropogenic activities, severe climatic conditions, and a lack of forest management plans in this period. This assertion was supported by Abdel Magid – Mohamed (2015), and Mohamedain et al. (2012), who reported that NRF faced severe deforestation and degradation caused by the rural communities living surrounding the forest. Similar studies carried out in the study region have demonstrated that reserved forests have witnessed a massive reduction in tree cover during this period due to anthropogenic and natural factors (Yasin et al. 2022). According to Elgubshawi et al. (2016) approximately 38% of the forested area was lost between 1986-2005, with an annual rate of 1.8%. The authors further argue that forest clearance increased two-fold between 1999-2005 (Elgubshawi et al. 2016). However, it is well established that the increment of the quantity of bare land and deforestation rate in forest areas have a detrimental effect on soil properties, hydrological regimes, and biodiversity enrichment (Veldkamp et al. 2020, Reis – Dutal 2019, Sulieman 2018, Rahman et al. 2012). This also was observed through the field survey where the regeneration of *Acacia senegal* seedlings was penurious in the bare land as compared to other land-use classes. Conversely, the other two land-use classes of agricultural field and light forest faced a slight increment of 1415.27 ha (33.9%) to 1440.54 ha (34.5%) and of 1287.02 ha (30.9%) to 1406.52 ha (33.7%) respectively.

Second, an increase in forest cover was observed in the period from 2011-2021. The major increment was detected in the dense forest class. Its share increased significantly from 377.82 ha (9%) in 2011 to 1623.74 ha (38.9%) in 2021. On the other hand, the bare land class declined gradually from 809.64 ha (19.4%) in 2011 to 479.93 ha (11.5%) in 2021. Studies done on forest rehabilitation show that planting trees can typically speed up forest vegetation recovery (Holl 2013). Therefore, the increment in forest cover during this period could be explained by *Taungya* agroforestry program established by the FNC. According to the field visit and discussions held with the forestry officials working in the forest, the *Taungya* agroforestry program started at the beginning of 2004 to date. A study conducted by Salih (2013) reported a positive impact of the *Taungya* program in the rehabilitation of 3024 ha of NRF between 2005 and 2013. Another study conducted in Nigeria showed that *Taungya* system is beneficial for forest conservation and regeneration (Azeez et al. 2017). In contrast, the agricultural field and light forest, which were the dominant land-use classes in 2011 with areas of 1550.79 ha (37.2%) and 1435.86 ha (34.4%) decreased to 780.70 ha (18.7%) and 1289.74 (30.9%) respectively in 2021. It is noteworthy that other factors, such as environmental, political, and agricultural context, could also be responsible for these changes in the reserve during this period. These conditions play a critical role in land use and land cover changes (Gadallah 2018, Hosonuma et al. 2012). As evidenced by reviewed literature, the history of the study region has witnessed a series of recurring dry years since 1982, as well as frequent civil wars that led to the loss of the vegetation cover (Deafalla et al. 2019).

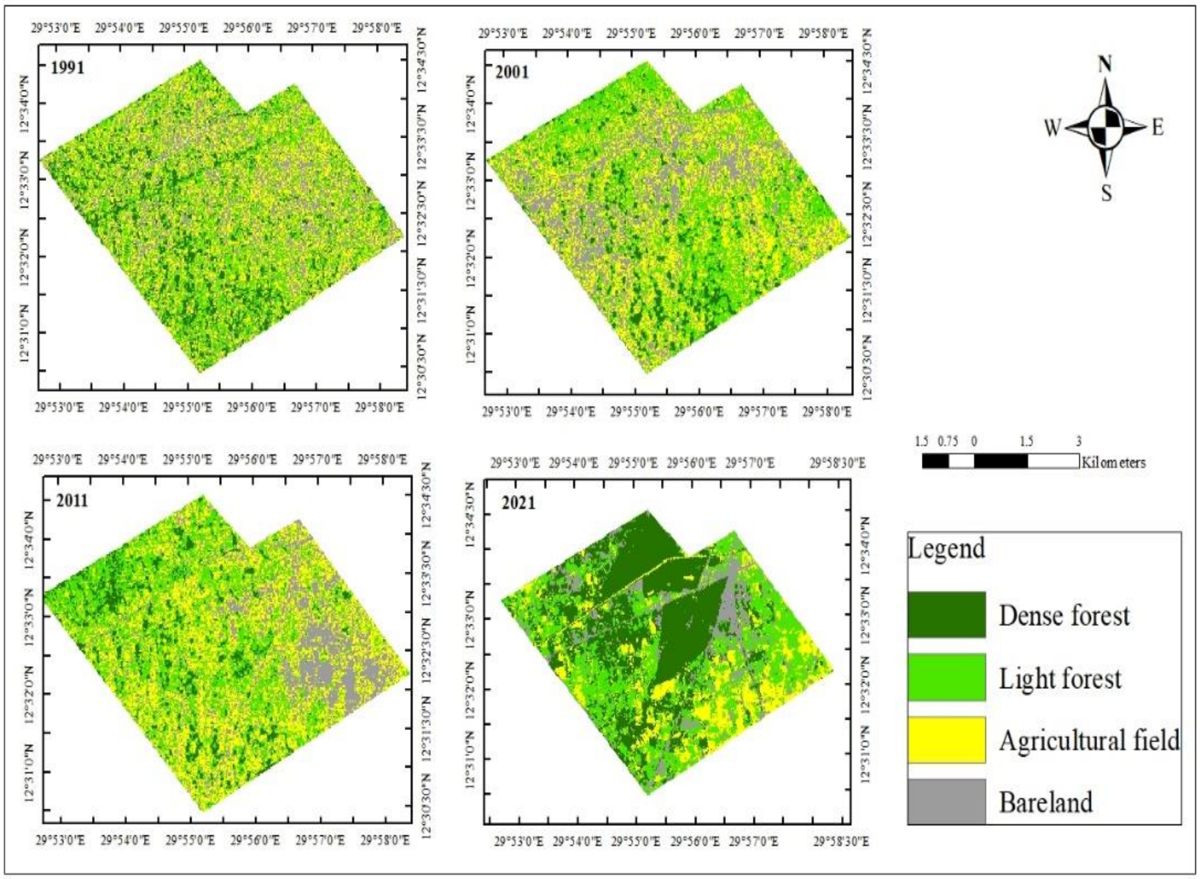

Fig. 4.1: Maps of land cover change in NRF between 1991 – 2021
Source: Author’s analysis (classified images 1991, 2001, 2011, 2021)

4.2.2 Land use land cover change trajectories matrix

Table 4.2: Land use land cover change trajectory matrices between 1991-2021 in NRF

Class	BL area/ha	%	AF Area/ha	%	LF Area/ha	%	DF Area/ha	%	Total/ha
1991-2001									
BL	**300.69**	33.8	377.31	26.7	269.67	20.9	57.18	9.8	1004.85
AF	337.86	38.1	**534.87**	37.8	453.33	35.2	114.48	19.6	1440.54
LF	238.74	26.9	467.79	33.1	**484.2**	37.6	215.79	37	1406.52
DF	12.47	1.2	35.3	2.5	79.82	6.3	**194.61**	33.6	322.20
Total/ha	889.76	100	1415.27	100	1287.02	100	582.06	100	4174.11
2001-2011									
BL	**243.52**	24.2	334.33	23.2	219.84	15.6	11.95	3.7	809.64
AF	429.66	42.8	**581.76**	40.4	496.80	35.4	42.57	13.2	1550.79
LF	309.44	30.8	468.56	32.5	**549.12**	39	108.74	33.7	1435.86
DF	22.23	2.2	55.89	3.9	140.76	10	**158.94**	49.4	377.82
Total/ha	1004.85	100	1440.54	100	1406.52	100	322.20	100	4174.11
2011-2021									
BL	**140.39**	17.3	185.30	11.9	127.98	8.9	26.26	7.0	479.93
AF	158.01	19.5	**284.01**	18.3	246.66	17.2	92.04	24.3	780.71
LF	306.21	37.9	510.60	33	**392.79**	27.3	80.13	21.2	1289.74
DF	205.03	25.3	570.88	36.8	668.43	46.6	**179.39**	47.5	1623.74
Total/ha	809.64	100	1550.79	100	1435.86	100	377.82	100	4174.11
1991-2021									
BL	**113.67**	12.8	167.31	11.8	141.80	11	57.15	9.8	479.93
AF	143.61	16.1	**242.01**	17.1	252.56	19.6	142.53	24.5	780.71
LF	273.63	30.8	456.92	32.3	**414.50**	32.2	144.68	24.9	1289.74
DF	358.85	40.3	549.03	38.8	478.16	37.2	**237.70**	40.8	1623.74
Total/ha	889.76	100	1415.27	100	1287.02	100	582.06	100	4174.11

Note: Bold values illustrate areas and percentages of the unchanged classes
NRF= Nabag Reserved Forest; BL= Bare Land; AF= Agricultural Field; LF= Light Forest; DF= Dense Forest. *Source:* Author's analysis (classified images 1991, 2001, 2011, 2021)

The land-use-land-cover change trajectory matrices of NRF during the periods 1991-2001, 2001-2011, 2011-2021, and 1991-2021 are shown in Table 4.2. Its maps are presented in Fig. 4.2. The values depicted with bold letters illustrate areas of the unchanged land-use classes, while the other values represent the magnitude of change from one land-use class to the other for the given periods.

Throughout 1991-2001, the total stability of the land-use classes in the study area attained 1514.37 ha, while major change was detected from agricultural field to bare land. About 337.86 ha (38.1%) and 238.74 ha (26.9%) of agricultural field and light forest, respectively, were converted to bare land, while a slight increase of 57.18 ha (9.8%) of bare land was changed to dense forest. Likewise, the dense forest class also declined as converted to light forest, agricultural field, and bare land accounted for 215.79 ha (37.0%), 114.48 ha (19.6%), and 57.18 ha (9.8%), respectively (Table 4.2). This substantial change indicates the magnitude of deforestation and degradation that took place in the forest in this period. However, throughout 2001-2011, the light forest and agricultural classes reached the highest stability with 549.12 ha (39%) and 581.76 ha (40.4%) respectively, the lowest persistence was observed in bare land with 243.52 ha (24.2%). The reason for this is that during this period the *Taungya* agroforestry program has already been launched by FNC in 2004, and accordingly, the bare land class witnessed the conversion to agricultural field, light forest, and dense forest with 334.35 ha (23.2%), 219.84 ha (15.6%), and 11.95 ha (3.7%) respectively (Table 4.2).

Between 2011 and 2021, the highest stability of land use classes was gained by dense forest and light forest, accounting for 179.39 ha (47.5%) and 392.79 ha (27.3%) respectively. Conversely, the bare land class declined to 140.39 ha (17.3%), whereas 92.04 ha (24.3%) of the agricultural field was converted to dense forest. Similarly, during the period between 1991-2021, the dense forest class was shown the highest persistence with 237.7 ha (40.8%) followed by light forest and agricultural field with 414.50 (32.2%) and 242.01 (17.1%) respectively, while the bare land class was less persistence with 113.67 ha (12.8%). This result affirms that during this period, the application and management of *Taungya* agroforestry succeeded in converting the bare land to forest cover, either in the shape of light forest or dense forest. This finding is in line with Eltayeb et al. (2013). The study reported that *Taungya* agroforestry was a successful approach to rehabilitate the bare land in EL Rawashda forest reserve in the eastern part of Sudan. Elsewhere in Ghana, Taungya system succeeded in rehabilitating about 250 ha of degraded forest areas (Blay et al. 2008). Generally, the trajectory matrix results (Table 4.2) revealed an increasing trend of forest cover both in dense forest and light forest classes followed by a substantial decline in bare land class during the study period.

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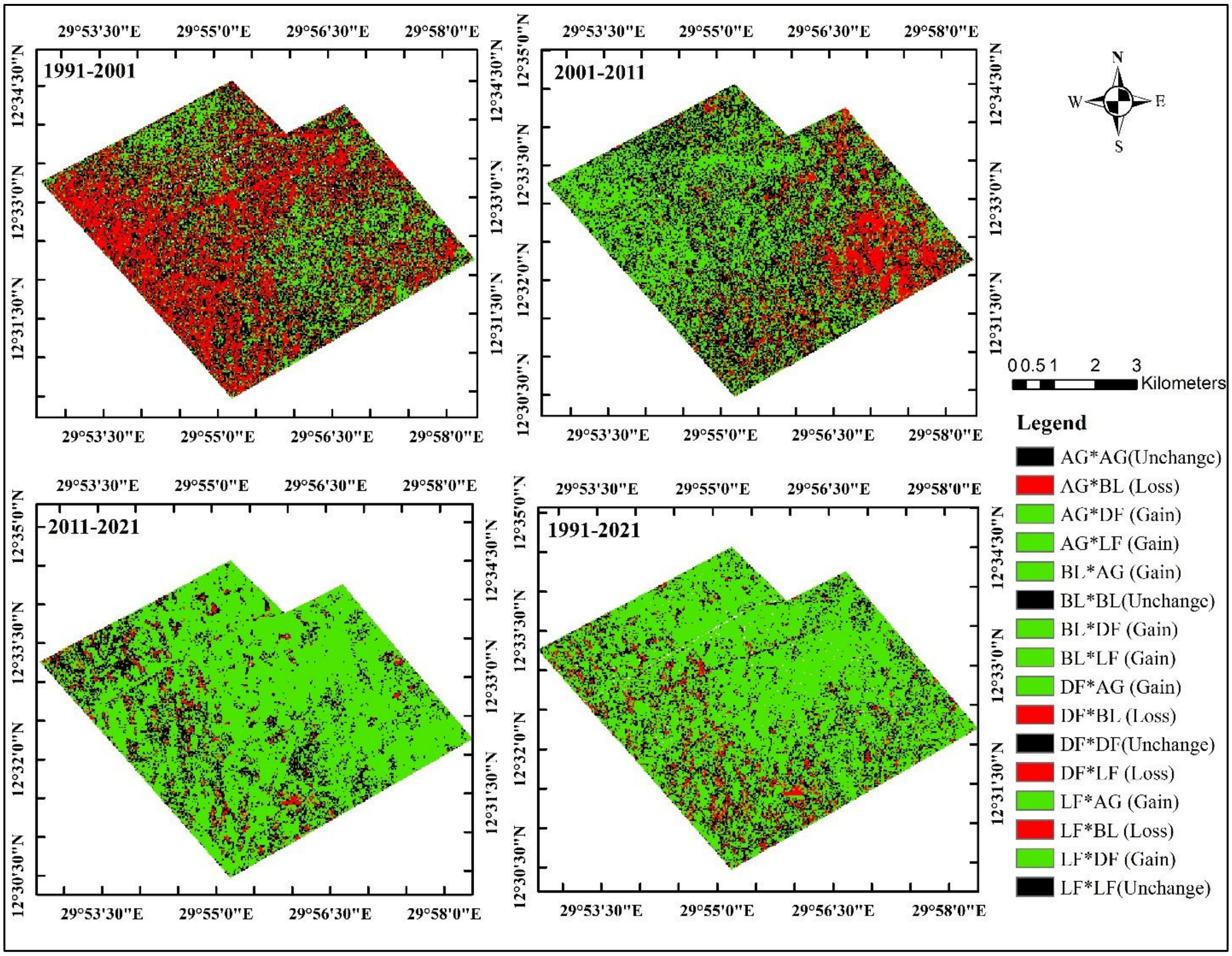

Fig. 4.2: Trajectory matrix in NRF between 1991-2021
Source: Author's analysis (classified images 1991, 2001, 2011, 2021)

4.2.3 Overall gain and loss of classes in NRF from 1991-2021

Table 4.3: Overview of changes in different classes (ha) in NRF between 1991-2021

Class	Net change (1991-2001)	Net change (2001-2011)	Net change (2011-2021)	Overall change (1991-2021)
BL	115.09	-195.21	-329.71	-409.83
AF	25.27	110.25	-770.09	-634.57
LF	119.5	29.34	-146.12	2.72
DF	-259.86	55.62	1245.92	1041.68

Note: NRF= Nabag Reserved Forest; BL= Bare Land; AF= Agricultural Field; LF= Light Forest; DF= Dense Forest.
Source: Author's analysis (classified images 1991, 2001, 2011, 2021)

The overall gain and loss of different land-use classes in NRF from 1991-2021 are indicated in Table 4.3. Results of this study showed that the dense forest was the major land-use classes in NRF, which shows a substantial gain of 1041.68 ha during the study period. Another slight gain was also detected in the light forest class with 2.72 ha. In contrast, Agricultural field, and bare land classes showed significant losses. The overall loss was found to be -634.57 ha and -409.83, respectively (Fig. 4.3). Although natural regeneration could be a reason for forest gain in the study area, the process is slow and it needs favorable conditions (Scheper et al. 2021), hence these gains and losses between different land-use classes in the study area could be due to *Taungya* agroforestry rehabilitation program. Thus, the analysis of our results suggests that every bare land and area covered by agricultural field is likely to be converted to forest cover (dense forest or light forest) in the future. This has been observed during the study period from 2001-2011 and 2011-2021 respectively where the *Taungya* agroforestry program was launched. This reinforces the view of Gadallah et al. (2019) who noted that agroforestry practices could contribute significantly to recovering Sudan's forest cover if it involved in the forest management plans and strategies of the country. Observations similar to our results was reported by Mishra et al. (2020) through their study of land use land cover change detection in India. In their study, traditional agroforestry systems were the main reason for increasing forest cover and decreasing the quantities of agricultural field and bare land area. This assertion was supported by Appiah et al. (2021) who analyzed the patterns of forest cover change in the Tano-Offin forest reserve in Ghana, their outcome concluded the possibility of agricultural land being converted to forest cover. Likewise, in Indonesia, study results by Murniati et al. (2022) have reported a significant increase (40.2%) in forest cover in Wan Abdul Rachman Grand Forest Park (WARGFP) using agroforestry system.

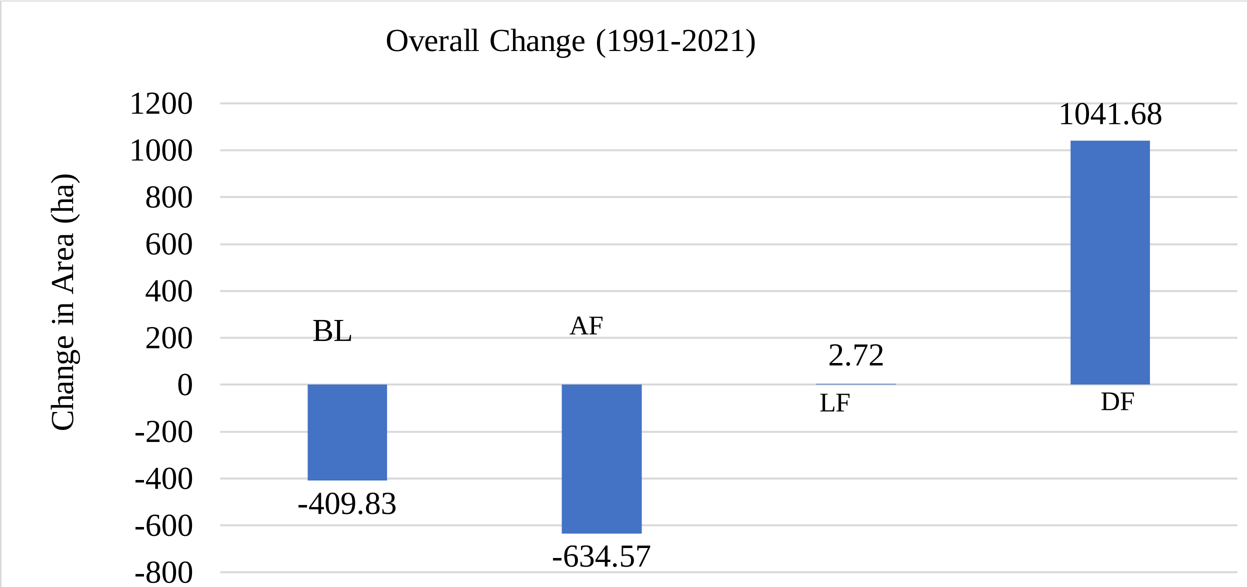

Fig. 4.3: Graphical illustration of forest cover changes in NRF
Source: Author's analysis

4.2.4 Accuracy assessment of classified images

Accuracy assessment was used to validate the classified map of the study area which determines the quality of gathered information by justifying whether or not image pixels from remote sensed data are well classified. These accuracy assessments can be made qualitatively by comparing the classified map data with on-the-ground situation, or quantitatively to identify and quantify comparing classified map data with reference data, which is critical for developing results assessment and decision-making (Chughtai et al. 2021).

The accuracy assessment report includes user's accuracy (UA), producer's accuracy (PA), overall accuracy (OA), and kappa coefficient (K) of classified maps of 1991, 2001, 2011, and 2021 illustrated in Tables 4.4 – 4.8, respectively. The bold values show the pixels that have been correctly classified, while the other values are incorrectly classified for the classes that across them (Tables 4.4. – 4.7). For classification accuracy for each class as shown in Tables 4.4 – 4.7, it can be observed that user's and producer's accuracy for bare land class (BL) for classified images of 1991 and 2001 increased from 75% and 85.23 % (Table 4.4) to 81% and 86.17% respectively (Table 4.5). Similarly, user's and producer's accuracy for agricultural field (AF) were also increased from 80% and 83.33% (Table 4.4) to 83% and 89.25% respectively (Table 4.5). User's accuracy decreased for light forest class (LF) from 85.71% (Table 4.4) to 82.86% (Table 4.5), while producer's accuracy increased from 65.22% to 69.05% respectively. Regarding dense forest class (DF), full user's accuracy was achieved for the classified maps of 1991 and 2001, whereas producer's accuracy decreased from 75% to 71.43% as shown in Tables 4.4 and 4.5 respectively.

Table 4.4: Accuracy assessment of classified map of 1991

class	BL	AF	LF	DF	Total	UA%
BL	**75**	16	9	0	100	75
AF	13	**80**	7	0	100	80
LF	0	0	**30**	5	35	85.71
DF	0	0	0	**15**	15	100
Total	88	96	46	20	250	
PA%	85.23	83.33	65.22	75		

Note: Bold values illustrate the corrected classified pixels
BL= Bare Land; AF= Agricultural Field; LF= Light Forest; DF= Dense Forest; UA= User's Accuracy; PA= Producer's Accuracy
Source: Author's analysis

Table 4.5: Accuracy assessment of classified map of 2001

class	BL	AF	LF	DF	Total	UA%
BL	**81**	10	9	0	100	81
AF	13	**83**	4	0	100	83
LF	0	0	**29**	6	35	82.86
DF	0	0	0	**15**	15	100
Total	94	93	42	21	250	
PA%	86.17	89.25	69.05	71. 43		

Note: Bold values illustrate the corrected classified pixels
BL= Bare Land; AF= Agricultural Field; LF= Light Forest; DF= Dense Forest; UA= User's Accuracy; PA= Producer's Accuracy
Source: Author's analysis

Concerning the classified maps of 2011 and 2021 as depicted in Table 4.6 and 4.7, bare land class (BL) witnessed decreasing in both user's and producer's accuracy from 85% to 81% and from 94.44% to 90.38% for classified map of 2011 and 2021 respectively. On the other hand, user's and producer's accuracy for agricultural field class (AF) were increased from 89% and 87.25% (Table 4.6) to 92.25% and 93.70% respectively (Table 4.7). For light forest class (LF), user's accuracy was increased from 82.86% to 89.66% but producer's accuracy decreased from 78.38% to 74.29% for maps of 2011 and 2021 respectively. In contrast, producer's accuracy for dense forest class

(DF) increased substantially from 71.43% (Table 4.6) to 80.56% (Table 4.7), in addition, full user's accuracy was achieved.

Table 4.6: Accuracy assessment of classified map of 2011

class	BL	AF	LF	DF	Total	UA%
BL	**85**	13	2	0	100	85
AF	5	**89**	6	0	100	89
LF	0	0	**29**	6	35	82.86
DF	0	0	0	**15**	15	100
Total	90	102	37	21	250	
PA%	94.44	87.25	78.38	71.43		

Note: Bold values illustrate the corrected classified pixels
BL= Bare Land; AF= Agricultural Field; LF= Light Forest; DF= Dense Forest; UA= User's Accuracy; PA= Producer's Accuracy
Source: Author's analysis

Table 4.7: Accuracy assessment of classified map of 2021

class	BL	AF	LF	DF	Total	UA%
BL	**47**	7	1	3	58	81
AF	4	**119**	3	3	129	92.25
LF	1	1	**26**	1	29	89.66
DF	0	0	5	**29**	34	85.29
Total	52	127	35	36	250	
PA%	90.38	93.70	74.29	80.56		

Note: Bold values illustrate the corrected classified pixels
BL= Bare Land; AF= Agricultural Field; LF= Light Forest; DF= Dense Forest; UA= User's Accuracy; PA= Producer's Accuracy
Source: Author's analysis

The overall accuracy (OA) and kappa coefficient (K) values are shown in Table 4.8. Overall accuracy of 80%, 83.2%, 87.2%, and 88.4% was achieved for different classified maps of 1991, 2001, 2011, and 2021 respectively. Whereas the associated Kappa's values were found to be 73.4%, 75%, 81%, and 82% respectively. It is worth mentioning that these Kappa's values show acceptable classification.

Table 4.8: Recap of accuracy assessment of classified maps

Year of classified Maps	Overall Accuracy (%)	Kappa Coefficient (%)
1991 classified map	80	73.4
2001 classified map	83.2	75
2011 classified map	87.2	81

2021 classified map	88.4	82

Source: Author's analysis

4.3 Socio-economic characteristics of Taungyas' farmers (Objective 2)

The socio-economic characteristics of the farmers were studied, and results were presented under this title. It covered demographic characteristics such as gender, marital status, education, occupation, age, family size in addition to socioeconomic characters that include main sources of livelihood, main source of energy, cultivated land size, and Taungya experience. Research results with regard to this respect are presented in Tables 4.9 to 4.13. The intention was to provide a general background about the farmers and their situation in the study area. This is crucial for understanding their participation process in the Taungya agroforestry program and how their socio-economic characteristics could influence their perception of the program.

4.3.1 Gender and marital status of farmers

Table 4.9: Gender and marital status of farmers

Variable	Category	Frequency	Percentage
Gender			
	Male	154	77
	Female	46	23
Marital status			
	Single	11	5.5
	Married	188	94
	Widowed	1	0.5

Source: Author's analysis, Field survey data, 2021

The study results revealed that, 77% of farmers were male while 23% were female. This indicates that Taungya practiced in the study area was dominated mainly by male farmers (Table 4.9). This could be explained by the fact that in most African countries in general and in the Sudan's rural communities in particular, men are the primary landowners and are in charge of providing their families with food and other necessities of life. (Muaura et al. 2021, Kobbail 2012, Mugwe et al. 2009). These results coincided with previous studies conducted in the study area by (Abuzwaid 2015). Similarly, in Nigeria, Azeez et al. (2017) found that only male farmers were practicing Taungya agroforestry.

The results in Table 4.9 also showed that the majority (94%) of respondents were married. This could be attributed to the fact that the household, which was the unit of analysis of this study, constitute of a father, mother and children, this is the normal and obvious situation in the study area and in Sudan as general and marriage is the only way for establishing a family. In the study area having a spouse could increase a household's access to land and the possibility of extra family labor (children), which is necessary for such a program.

4.3.2 Education and occupation of farmers

Table 4.10: Education and occupation of farmers

Variable	Category	Frequency	Percentage
Education			
	Illiterate	42	21
	Khalwa*	46	23
	Primary	69	34.5
	Secondary	33	16.5
	University	10	5
Occupation			
	Farmer	158	79
	Farmer&Trader	16	8
	Farmer&Laborer	24	12
	Farmer&Teacher	2	1

* A religious school in which Muslims learns the Holy Qoran and Qoran studies
Source: Author's analysis, Field survey data, 2021

The educational levels of the farmers in the study area were classified into four categories, according to the results shown in Table 4.10. The percentage of farmers in these categories are: Khalwa 23%, primary 34.5%, secondary 16.5%, and university 5%, while illiterate farmers constitute 21%. It is obvious that most of farmers in the study area have attained at least formal or informal education, meaning that they are more likely to easily understand the extension programs and have access to up-to-date agricultural technologies compared to illiterate farmers (Ibrahim et al. 2021, Adolwa et al. 2012). Eric et al. (2014) have reported the importance of education in improving agricultural productivity. They argue that such formal education opens the minds of farmers to knowledge, while informal education gives them hands on training and allows them to share the experience gained.

The results in Table 4.10 shows that practicing agriculture as a full-time job or considered as main occupation, was reported by the majority (79%) of farmers in the study area, while the rest of the respondents had additional or secondary occupations such as trading 8%, laboring 12%, and teaching 1% (Table 4.10). This indicates that agriculture was the main source of livelihood for most of the population in the study area. This could be attributed to the absence of development services and income generating opportunities in the study area. These results are in line with the findings of Fadl et al. (2015) and Ali et al. (2020) who reported that agriculture constitutes the main source of livelihoods and income generation for most of the population of Sudan. On the other hand, the participation of some farmers in other secondary jobs may be due to a need to maximize income. Ibrahim et al. (2015) reported that farmers in South Kordofan State were engaged in a variety of activities for income generation. However, full-time farmers are more likely to use a different strategy to boost farm productivity compared to farmers with alternative activities and income sources (Mugi-Ngenga et al. 2016, Martey et al. 2014).

4.3.3 Main source of energy for farmers

Table 4.11: Main source and place of energy of farmers

Variable	Category	Frequency	Percentage
Source of energy			
	Firewood	176	88
	charcoal	22	11
	Gas	2	1
Place of energy			
	Forest	173	86.5
	Markets	25	12.5
	Forest & agricultural residues	2	1

Source: Author’s analysis, Field survey data, 2021

The study results in Table 4.11 revealed that the majority (88.5%) of farmers rely on firewood for domestic consumption and most of them (86.5%) were dependent on the forest as source of energy. This could be attributed to the absence of alternative energy sources and due to proximity of forest to the villages in the study area. Ballal et al. (2014) reported that women and children in South Kordofan State were highly involved in firewood gathering from adjacent forests.

4.3.4 Age and family size of farmers

Table 4.12: Age and family size of farmers

Variable	Category	Frequency	Percentage	Mean (SD)
Age				
	18-25	20	10	
	26-35	45	22.5	40.96(12.36)
	36-55	115	57.5	
	>55	20	10	
Family size				
	1-5	97	48.5	
	6-10	84	42	5.97(3.43)
	11-15	16	8	
	>15	3	1.5	

Source: Author's analysis, Field survey data, 2021

The study found that more than half (57.5%) of the interviewed farmers were within the age range of 36-55 years and had an average age of 40.96 years (Table 4.12). According to Putirulan et al. (2019), human age could be classified into three categories including young age (<30 years), adult age (30-50 years), and old age (>50 years). This suggests that most of the farmers in the study area were above youthful age but still considered within an economically active age range. This means that they could participate effectively in different agricultural activities in Taungya agroforestry program. The existence of economically active farmers in the study area could be due to farmer's satisfaction with Taungya program. On the contrary, it could be argued that the small proportion of youthful farmers aged between18-35 may be attributed to the rural-urban migration looking for education, jobs and better life. This assertion was supported by previous studies (Adel Rahim – Kodeal 2020, Bello et al. 2015). Likewise, the World Bank (2013) reported that the majority of young people in developing countries express a desire to leave farms. This was further supported by the European Economic and Social Committee (2011) which noted a general decline in the number of young farmers in developing countries as well as the abandonment of farming.

Regarding family size of farmers as depicted in Table 4.12, 48.5%, 42%, 8%, and 1% of them had a family size ranging between 1-5, 6-10, 11-15, and > 15 persons, respectively (Table 4.12) with an average family size of 5 members. This indicated that most of respondents had small family size which may affect the availability of household labor for farm activities (Ibrahim 2018). In the case of the study area the availability of labor is not a big problem as the land area allocated for each household is so small. This assertion was discussed by a previous study by Kindt et al. (2004) who reported that more family members providing more labor for home gardening agroforestry resulted in more stems and species in home gardening agroforestry practices in Kenya. Likewise, Gebru et al. (2019) argue that a large family size indicates the availability of labor within the family to implement integrated agroforestry.

4.3.5 Cultivated land size and Taungya experience of farmers

Table 4.13: Land size and Taungya experience of farmers

Variable	Category	Frequency	Percentage	Mean (SD)
Land size/Muhamas*				
	1-5	154	77	
	6-10	29	14.5	4.66(3.77)
	11-15	14	7	
	>15	3	1.5	
Taungya experience				
	1-5 years	115	57.5	
	6-10 years	46	23	6.70(3.50)
	11-15 years	31	15.5	
	>15 years	8	4	

***** Land unit in the study area (1 Mukhamas=0.75 hectare).
Source: Author's analysis, Field survey data, 2021

Traditionally, farmers in these rural communities have local unit of land measurement called Mukhamas. This unit is equivalent to 0.75 hectare. This study found that 77% of farmers cultivated between 1–5 Mukhamas, while the other farmers cultivated a total land ranging between 6–10 Mukhamas, 11–15 Mukhamas, and more than 15 Mukhamas, respectively (Table 4.13). The mean total of cultivated land was 4.66 Mukhamas. The small land area cultivated by farmers could be attributed to two factors: First is the nature of the contract between FNC and farmers. Second is the limitation of the specific area targeted inside the reserved forest and the intension of FNC to distribute land to large number of farmers for benefit sharing. This study's results corroborated with other literature in Ghana by (Obiri et al. 2021) and Myanmar by (Aung 2018) where the average land size of Taungya farmers was limited.

The average number of years of participation in Taungya program was 6.70 years (Table 4.13). Most of the farmers, 57.5% had Taungya experience ranging between 1–5 years, while the

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others, 23%, 15.5%, and 4% had an experience of between 6 –10 years, 11–15 years, and more than 15 years, respectively (Table 4.13). This implies that Taungya practice is well accepted by the farmers and the number of adopters is increasing, at the same time, farmers in the study area have enough experience in practicing Taungya agroforestry. It suggests that they are aware of different silvicultural operations and technologies. Thus, they are likely to continue to participate in the Taungya program. The result is in agreement with Adeoye et al. (2015), who noted a positive correlation between years of experience and household participation in Taungya system in Oluwa Forest Reserve in Nigeria.

4.4 Contribution of Taungya agroforestry program to farmers' income generation (Objective3)

4.4.1 Crops cultivated and crop combination by farmers

The study results as presented in Fig. 4.4 illustrated that five major crops were cultivated by Taungya farmers in the study area. These are groundnut, sesame, cowpea, watermelon, and hibiscus. Groundnut and sesame were found to be the main crops cultivated by 79.5% and 75.5% of farmers respectively (Fig. 3). This could be explained by the fact that groundnut and sesame are considered major cash crops in the study area (Abdalla et al. 2015). According to the focus group discussions, farmers revealed that roughly 80% of them obtained their household incomes from cultivating groundnut and sesame. On the other hand, cowpea was cultivated by 40.5% of farmers mainly for subsistence and food security, whereas watermelon and hibiscus were cultivated by 38% and 17.5% of Taungya farmers, respectively, to provide additional income. Elsewhere in Nigeria, a variety of agricultural crops were found to be cultivated by Taungya farmers including, groundnuts, maize, and beans (Adegeye et al. 2011), while in Myanmar Taungya farmers prefers to cultivate sesame, maize and vegetables (Maung – Yamamoto 2008). This could be interpreted that Taungya practice is a flexible land use system and it give chance to farmers to cultivate crops according to their wills and needs.

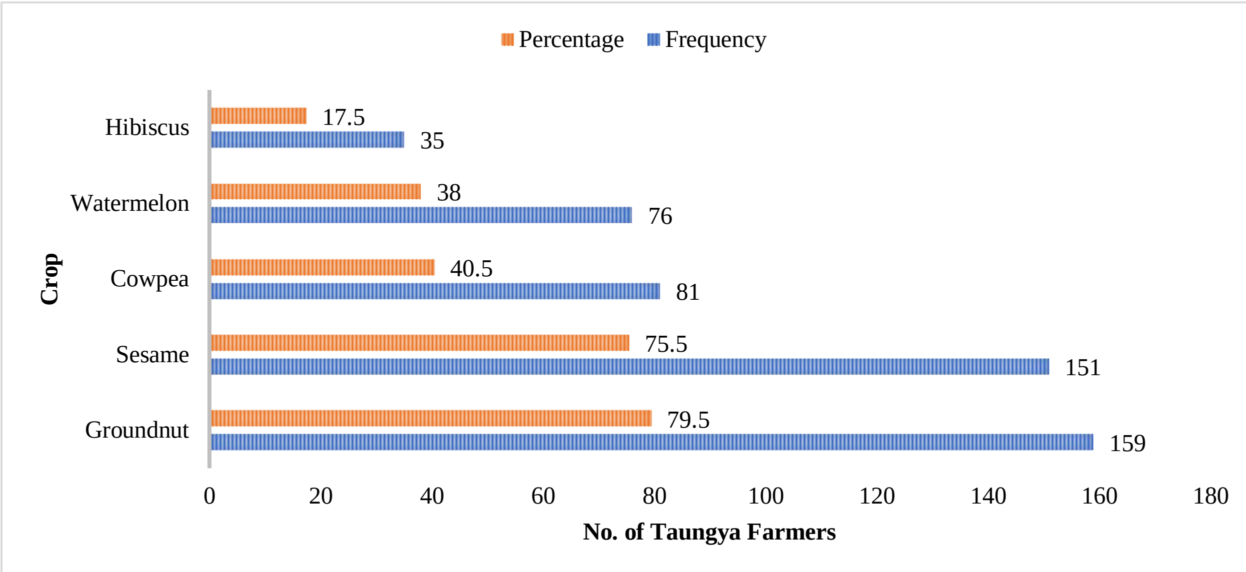

Fig. 4.4: Taungya farmers with respect to different crops
Source: Author's analysis, Field survey data, 2021

Further, the study results revealed that approximately ten kinds of cropping patterns, intercropping, were identified in the study area (Fig. 4.5). Among these, the major cropping patterns were groundnut and sesame, which were practiced by 23.5% of the farmers, while the cropping patterns that included groundnut and watermelon were found to be less practiced and is reported only by 1%.

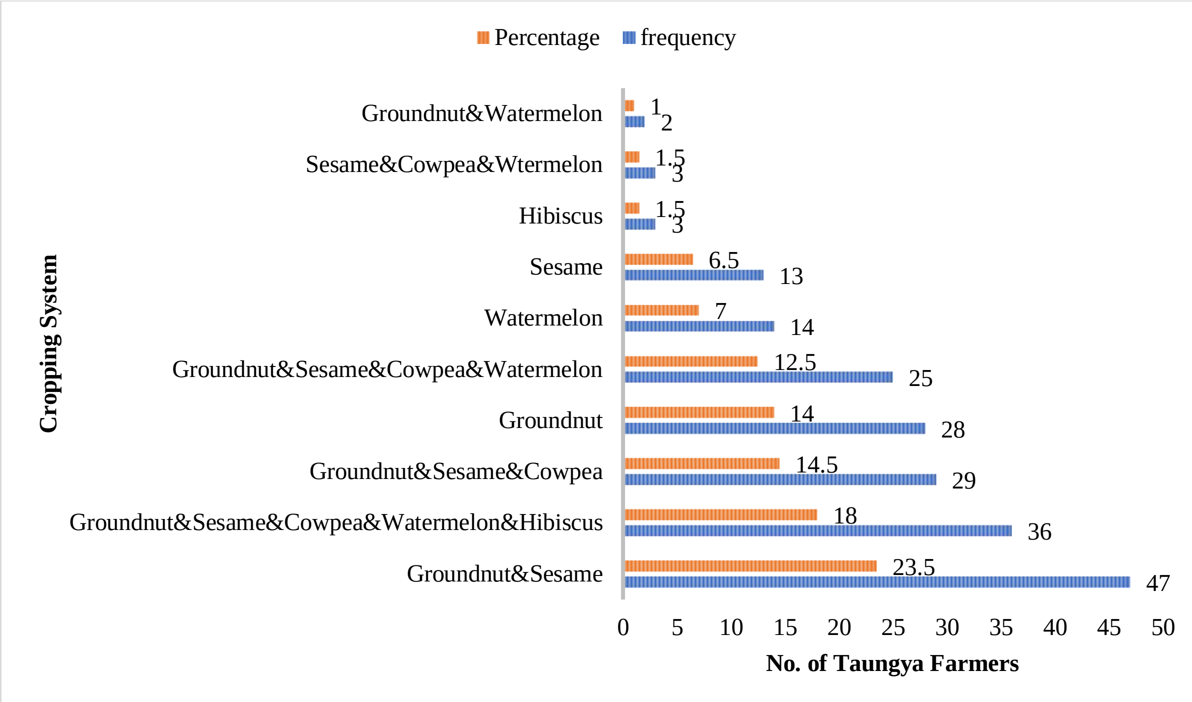

Fig. 4.5:Cropping combination of Taungya farmers in the study area
Source: Author's analysis, Field survey data, 2021

4.4.2 Distribution of costs and revenues of farmers before and after Taungya program

Table 4.14: An annual estimated cost (N= 200)

Range of cost (SDG)	Cost before Taungya Frequency (%)	Cost after Taungya Frequency (%)
0-20000	124 (62.0)	138 (69)
21000-40000	32 (16.0)	15 (7.5)
41000-60000	10 (5.0)	16 (8.0)
61000-80000	11 (5.5)	11 (5.5)
81000-100000	9 (4.5)	7 (3.5)
>100000	14 (7.0)	13 (6.5)
Minimum	0	0
Maximm	437000	217000
Std.Dev	57592.255	41771.329

Mean cost before Taungya = SDG 32851.75 (Sudanese pound)
Mean cost after Taungya = SDG 25107.50 (Sudanese pound)
Figures in parenthesis are percentages
Source: Author's analysis, Field survey data, 2021

The annual total costs of farmers before and after participation in the Taungya program are shown in Table 4.14, while annual net incomes from crops are summarized in Table 4.15. The annual mean cost before participation was SDG 32851.75 but was reduced to SDG 25107.50 after participation. The specific annual costs before and after participation in the Taungya program ranged between SDG 0 – 437000 and SDG 0 – 217000, respectively (Table 4.14). It was well observed that after participation in the Taungya program, the annual total costs have been reduced drastically for most of the farmers. This was further detected by using a paired-sample t-test as the statistics showed a significant difference among the farmers before and after participation in the Taungya program with (T = 2.154) at a level of significance (P = 0.032) (Table 4.16). The dramatic cost reduction can be ascribed to two reasons. First, land possession outside the forest is more expensive, which may lead to an increase in the cost of renting. This was also explored during the focus group discussion with the farmers. They mentioned that lack of land was one of the main reasons for participating in Taungya program, at the same time large area of land is needed as productivity is low, while inside the forest a small piece of land may be enough for providing subsistence needs. Second, the Agricultural and silvicultural operations costs could be lower inside the forest compared to operation costs of farms with solely crop production outside the forest since there is no cost for first weeding as ploughing is made by FNC, so the only cost would be for the second weeding. This was also reported by (Kalu et al. 2011) but, in this case cost reduction is attributed to the fact that there was no need for purchasing fertilizer to improve soil nutrient content for maximum production. These results are corroborated with a study by Salih (2013), who reported that Taungya agroforestry contributed to reducing and saving the initial establishment cost of the plantation. Also, Kalame et al. (2011), concluded that Taungya system was cost-effective, with the benefits exceeding the costs.

Table 4.15: An annual estimated net income (N= 200)

Range of net income (SDG)	**Net income before Taungya Frequency (%)**	**Net income after Taungya Frequency (%)**
0-20000	123 (61.5)	43 (21.5)
21000-40000	23 (11.5)	34 (17.0)
41000-60000	20 (10.0)	22 (11.0)
61000-80000	11 (5.5)	22 (11.0)
81000-100000	1 (0.5)	19 (9.5)
>100000	22 (11.0)	60 (30.0)

Minimum	0	0
Maximm	560500	655000
Std.Dev	86294.926	124410.000

Mean net income before Taungya = SDG 35298.25 (Sudanese pound)
Mean net income after Taungya = SDG 91839.50 (Sudanese pound)
Figures in parenthesis are percentages
Source: Author's analysis, Field survey data, 2021

The annual mean net income of the farmers before participation in the Taungya program was SDG 35298.52. This increased substantially to SDG 91839.50 after participation. The specific annual net incomes before and after participation in the Taungya program ranged between SDG 0 – 560500 and SDG 0 – 655000 respectively (Table 4.15). Most farmers (61.5%) earned net income between (SDG 0 – 20000) before joining the Tuangya program. This percentage was reduced sharply to (21.5%) after joining the program. In contrast, the number of farmers (11%) who earned net income (SDG > 100000) significantly increased to (30%) (Table 4.15).

Table 4.16: Paired sample T-test of cost and net income before and after Taungya program (N= 200)

Paired variables	**T value**	**DF**	**P-values**
Cost before Taungya /SDG - Cost after Taungya/SDG	2.154	199	0.032*
Net income before Taungya/SDG - Net income after Taungya/SDG	8.034	199	0.000*

* Is 5% level of significance
Source: Author's analysis, Field survey data, 2021

These results were further affirmed through a paired-sample t-test as statistically significant differences (P = 0.000; T = 8.034) were found between farmers' net income before and after participation in the Taungya program (Table 4.16). However, it is obvious that in addition to boosting land use, Taungya agroforestry was designed to promote product diversification and income stability. It was expected that when the price of one crop decreased another crop price would increase to compensate. Previous studies indicate that agroforestry is important for enhancing the standard of living in rural communities, particularly for improving income and crop productivity (Akter et al. 2022, Hanif et al. 2018). Therefore, the observed increment of income could be attributed to the increasing productivity of crops under Taungya agroforestry. Meaning that, Taungya farming in the study area was the main source of farmer's livelihoods. This assertion was supported by several studies (Appiah et al. 2020, Wiro – Ansa 2019, Kalu et al. 2011). This study's results agree with the study by Suang et al. (2020), who found that farmers inside the forest had a much higher cash income (80%) compared to farmers outside the forest (32%). Similarly, this study is in line with Nigussie et al. (2020), who in a financial analysis study concluded that the Taungya system significantly contributed to income generation. The results also support Murniati et al. (2022), who found that income generated from agroforestry systems contributed significantly (75.6%) to total farmers' income in Indonesia.

4.5 Farmers' perceptions and attitudes towards benefits of Taungya agroforestry program (Objective 4)

Table 4.17: Farmers' perception of Taungya's benefits in the study area

Item of perception benefit	SDA	DA	A	SA	TRS	MS(SD)
Help in the provision of land	0(0)	0(0)	5 (2.5)	195(97)	795	3.9(0.15)
Help in improving income	0(0)	17(8.5)	39(19.5)	144(72)	727	3.7(0.63)
Help during the time of hardship	0(0)	5(2.5)	105(52.5)	90(45)	685	3.5(0.54)
Contributes to education expenses	5(2.5)	32(16)	112(56)	51(25.5)	609	3.0(0.71)
Help in purchasing livestock	59(29.5)	37(18.5)	92(46)	12(6)	457	2.3(0.95)

SDA=strongly disagree, DA=disagree, A=agree, SA=strongly agree, TRS=total raw score, MS= mean score, SD=St. Deviation
Figures in parenthesis are percentages
Source: Author's analysis, Field survey data, 2021

Table 4.18: Item total statistic of Cronbach's alpha analysis

Item-Total Statistics

Items used	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
Taungya program help in improving income	10.69	6.054	.372	.562
Taungya program help during times of hardship	10.35	6.490	.323	.586
Taungya program contributes to the education expenses	10.71	5.966	.471	.510
Taungya program help in the provision of land	10.35	6.398	.414	.543
Taungya program help in purchasing livestock	11.61	6.582	.285	.606

Cronbach's Alpha = 0.61, Number of items = 5
Conclusion: Acceptable

The study results in Table 4.17 show the distribution of farmers' responses to the Likert scale test on their perceptions of the benefits of Taungya agroforestry program, while results in Table 4.18 show Item total statistic of Cronbach's alpha analysis. Results with regards to the five items assessed by the farmers, showed that, the top four benefits mentioned by respondents were: help in the provision of land; help in improving income; help during the time of hardship; and contributing to education expenses. For all these benefits, the mean score of respondents exceeded the cut-off point of 2.5, which was used as an inference of the overall farmer's perception. However, the other item, helping in purchasing livestock had a mean score of 2.3 (Table 4.17). The value of Cronbach's alpha coefficient was 0.61, which is considered acceptable (Table 4.18)

The vast majority of the farmers (97%) strongly agreed that the Taungya agroforestry program has provided them with land for cultivation. This item received the highest mean score of 3.9 of perception among other items (Table 4.17). This could be explained by the fact that farmers in the study area were facing some land scarcity and ownership issues. Thus, their perception towards such a program could be motivated by their priority to get secure land for cultivation. Jha et al. (2021) argue that when farmers perceive constraints in land security, their participation in the agroforestry system may be motivated. Similarly, Kalame et al. (2011) noted that the availability of land was the most pressing and critical issue for farmers' participation in Taungya system. This is consistent with Azeez et al. (2017) results, which indicates that farmers admitted the advantages of Taungya system as a provisional solution to their problem of land tenure. In another study, Blay et al. (2008) show that access to farmland was ranked by farmers as the most important benefit they gained from participation in the modified Taungya system in Ghana.

Most of the farmers (72%) in the study area perceived Taungya agroforestry program as a source for improving income. The mean perception of this item was 3.7 (Table 4.17). This could be attributed to the high crop productivity inside the forest. This assertion was observed through the focus group discussion as the farmers mentioned their benefits from selling crops in the village markets as a source of cash income behind subsistence benefits. Moreover, some farmers were engaged in gum Arabic tapping and production as an additional benefit to improving their income. This result is in line with the finding of a study carried out by Akinwalere (2019) which showed that farmers perceive increasing income as the greatest benefit of agroforestry practice. Likewise, a recent study by Dewi et al. (2021) has reported a positive perception of farmers towards agroforestry development as a very profitable practice that can increase household income. Similarly, a study by Appiah et al. (2020) shows an improvement in the income status of 53% of women through Taungya agroforestry program. In contrast, these results contradict the study results of Aung et al. (2018), who reported unchangeable economic profits of Taungya farmers in Myanmar due to their institutional system as economic profit of local Taungya cultivators was not greater enough for life persistence.

52.5% of respondents perceived Taungya practice to help farmers during times of hardship. The mean score of this perception was 3.5 (Table 4.17). It is evident that farmers in the study area depend on Taungya practice for much more than simple food production. Indeed, it was well observed that Taungya practice was perceived by farmers as a vital safety net to sustain their livelihoods during the lean seasons when farmers were not getting enough earning opportunities and facing severe shock and uncertainty, by participating in gum Arabic production and collecting other non-timber forest products.

More than half of respondents (56%) agreed that Taungya practice was contributed to their education expenses. The overall mean score of perception was 3.0 (Table 4.17). It is noteworthy that most of the respondents in the study area have just attained primary education because of the financial conditions as mentioned by several respondents during the session of the focus group discussion. For instance, one farmer stated that *''in the past, we were unable to send our children to school due to economic conditions and the high cost of education expenses. Instead, most farmers in this village were sending their children to the big cities to work as casual labor and provide extra income to overcome the economic situation, but after participation in the Taungya program, this situation has changed.''* Thus, participation in such a program may help to expand the sources of income and increase the households' ability to achieve education attainment. Ebenezer et al. (2018), observed that Taungya system has contributed significantly to forest-fringe communities and their ability to bear the expense of their children's education has increased. Also, this research result is in line with Rahman et al. (2012), who found that income from agroforestry practices assists in meeting the education expenses of both boys and girls in Bangladesh. They estimated the average percentage contribution of agroforestry at 72% of household educational expenditure per year.

Less than half (46%) of respondents agreed that Taungya practice had helped them in purchasing livestock. This item had an average score of 2.3 (Table 4.17). This indicates that farmers in the study area perceived these benefits negatively. One possible explanation could be the lack and/or deterioration of rangeland in the study area, which demotivates farmers to invest in livestock breeding. Added to that, the introduction of livestock to reserved forest land is prohibited, especially when there are tree seedlings in the area. Furthermore, the frequent conflicts between nomads and farmers in the study area could be another reason that makes them reluctant to purchase livestock. This assertion is supported by several scholars (e.g., Broche 2022, Abdelrahim – Kodeal 2020) who noted that land-use conflicts between sedentary farmers and nomads are a dominant dilemma in different parts of Sudan.

Generally, the results show that farmers in the study area have positive perceptions of the benefits of Taungya agroforestry. This is consistent with the results of several other studies carried out in different parts of the world which found that farmers had positive perceptions towards agroforestry practices and their benefits (Ahmad 2021, Mahmood – Zubair 2020, Saha et al. 2018).

4.6 Socioeconomic factors influencing Farmers' perception of the benefits of the Taungya program (Objective 5)

Table 4.19: Ordinal logistic model results of the factors influencing farmer's perception of the benefits of Taungya agroforestry

Variables	Coef. (β)	Std. Error	P-Values	Exp (β)
Extension services	0.771	0.31	0.013*	2.162
Gender	-0.43	0.322	0.182	0.651
Family size	0.043	0.045	0.345	1.044
Age	-0.028	0.013	0.03*	0.978
Educational level	0.065	0.119	0.583	1.067
Land size	0.056	0.035	0.11	1.058
Taungya experience	0.126	0.04	0.002*	1.134
Gum Arabic production	0.032	0.322	0.92	1.033

* Indicates a significant difference at $p < 0.05$

Source: Author's analysis, Field survey data, 2021

According to the ordinal logistic model results as depicted in Table 4.19, farmers' perceptions towards Taungya agroforestry benefits are affected by several socio-economic factors at a 5% level of significance. Results revealed that out of eight explanatory variables included in the model, six variables were found to have a positive influence on farmers' perceptions towards the benefits of Taungya agroforestry practice. These include extension services, family size, educational level, land size, Taungya experience, and gum Arabic production (Table 4.19). On the contrary, the gender (β = -0.43, P = 0.182) and age of the farmers (β = -0.028, P = 0.03) had a negative association with farmers perception (Table 4.19).

The extension service was a crucial factor and had a positive and significant effect on farmers' perception with the odd ratio of (2.162, $P < 0.05$). This means that access to extension services could lead to raising farmers' perception by a factor of 2.162 (Table 4.19). This could be explained by the fact that extension services provide farmers with information such as farming technologies that could be used to increase farm productivity and boost farmers' skills and awareness, hence raising their perception. This result is in line with other studies by Kabir – Rainis (2012) and Tatlidil et al. (2009), that reported an increase in farmers' perception with the increasing extension services and contacts.

Similarly, the study results in Table 4.19 revealed that Taungya experience had a significant positive effect on farmers' perception with an odd ratio of 1.134 ($P <0.05$). This suggested that the probability of increasing farmers' perception of the benefits of Taungya agroforestry increased by 1.134 times with an increase of years of participation in Taungya program. A reasonable explanation for this result could be that farmers who have enough Taungya experience are more likely to get and use the information relevant to silvicultural operations and production which may result in increasing their perception of the Taungya benefits. This result agreed with Adeoye et al. (2015), who reported a positive correlation between years of experience and farmers participation in Taungya system in Oluwa Forest Reserve in Nigeria.

The family size variable was found to have a positive effect on farmers' perception of the benefit of Taungya agroforestry. The results indicated that as family size increases, the likelihood of farmers' perception increases by a factor of 1.044 (Table 4.19). This could be a reasonable outcome because, in most cases, having more family size means having more labor available to diversify household income. The positive association between family size and the likelihood of raising perception towards agroforestry adoption can be found in other studies (Nyamweya – Moronge 2019, Basamba et al. 2016, Irshad et al. 2011).

The educational level attained by farmers showed a positive influence on farmers' perception towards Taungya benefits in the study area. The result shows an increase in the educational level attained by farmers would increase their perception by a factor of 1.067 (Table 4.19). This is not a surprising result since farmers with some formal or informal education are more likely to understand the consequent benefits of agroforestry practice as they are easily able to digest new knowledge and are more able to change their perception in comparison to illiterate farmers. In the same way, study result is consistent with the result of Waktola – Fekadu (2021) who reported the positive influence of education levels on farmers' awareness about the benefits and values of coffee shade agroforestry technology in Ethiopia. Also, Mbwiga (2016) in Tanzania found that educated farmers are aware and more active participants in agroforestry practices. However, it is surprising that the results obtained are inconsistent with the studies carried out by (Mfitumukiza et al. 2017, Gyau et al. 2014, Matata et al. 2010) who stated no influence of education on farmers' perception of agroforestry adoption. The reasonable explanation for such unexpected results could be due to the statistical approach used in the analysis or the socio-cultural variation in the study regions (Dhakal et al. 2015, Knowler – Bradshaw 2007).

The survey results show that farmers in the study area had limited farmland. Land size cultivated by farmers was found to have a positive effect on farmer's perception. The odd ratio results in Table 4.19 revealed that an increase of land size by one unit would increase the farmer's perception by the factor of 1.058. A similar positive association between farm size and farmers perception was observed in previous studies on agroforestry practices (Admasu – Jenberu 2022 Mahmood et al. 2020, Maswadi et al. 2018, Ashraf et al. 2015). The result, however, is inconsistent with the studies of Akinwalere (2016) in Nigeria and Mwaura et al. (2021) in Kenya, who observed negative correlation between total land cultivated and farmer's perception on the benefit of using new agricultural technologies.

The effect of participation in gum Arabic production on farmers perception is like that to land size. The participation of farmers in gum Arabic production probably increases their perception of the benefits of Taungya agroforestry by the factor of 1.033 (Table 4.19). This is probably because participation in gum Arabic production provides farmers with additional source of income that motivates them and raises their perception towards the benefits of Taungya agroforestry. It implies that farmers who participated in gum Arabic production were more aware about the benefits of Taungya agroforestry. This assertion was affirmed through the focus group discussion as most of the farmers mentioned that benefits from selling gum Arabic production in the village markets encouraged them to participate in the program.

The predicted coefficient of age variable was found to have a negative effect on farmer's perception on the benefits of Taungya agroforestry. Showing that as the age of the farmers increase by one year their perception would decrease by a factor of 0.978 (Table 4.19). This could be attributed to the fact that elder are generally less interested or reluctant to adopt new technologies and approaches and they resist innovations compared to the younger farmers. Moreover, the reality in the study area showed that the majority of farmers lie within an economically active age range that rise their knowledge and perception. This is supported by the results of Mahmood et al. (2020) in Pakistan and Sharmin – Rabbi (2016) in Bangladesh which reported that younger farmers are more knowledgeable about the benefits of agroforestry than old farmers. Similarly, the results from regression analysis in Table 4.19 also show that the sex of farmers had a negative influence on farmers perception. This result indicates that changing in gender of the farmers could decrease the perception by the factor of 0.651(Table 4.19). Since the male farmers constituted the majority of respondents in the study area, (*See Table 4.9, section 4.3.1*), it implies that they perceived the Taungya agroforestry as beneficial in comparison to female farmers. This claim is supported by studies of Catacutan – Naz (2021) and Diawuo et al. (2019) who highlights that woman have higher constraints in practicing agroforestry compared to men due to their less education level, poor access to extension assistance and multiple domestic responsibilities. Likewise, Galabuzi et al. (2021) and Jahan et al. (2022) found that male farmers were more positive than the female towards agroforestry practices. On the other hand, study findings of Akpabio – Ibok (2009), found that women farmers were more favorably disposed than male respondents to the utilization of agroforestry practices in Nigeria. In contrast, study results contradict other studies by Zafeiriou et al. (2021) and Sanou et al. (2019) that stated positive association between farmers perceptions of agroforestry practices and their gender.

4.7 The major incentives and constraints associated with Tuangyas's farmers (objective 6)

The study results expressed in Figs. 4.6 and 4.7 explored several incentives and constraints associated with Taungya farmers in the study area. According to the interview and FGDs, farmers highlighted having three main incentives or motivations to participate in Taungya program (Fig. 4.6). These included the high productivity inside a forest in comparison to an open area, which was mentioned by 69% of the farmers. Other motivations were the access to free land and the fertile soil inside a forest, as mentioned by 27% and 4% respectively (Fig. 4.6). An old farmer stated that: *"All the farmers in these villages are aware of the increased agricultural production and income generation found within NRF. As a result, they were more motivated to acquire land within the NRF."*

Another farmer added: *"I am currently employed in the capital city, Khartoum, but when the agricultural season started, I left my job and returned to my village to take part in the Taungya program as the land is free, and crop productivity is higher."*

However, it is worth mentioning that land tenure is considered the main obstacle confronting farmers in the study area. Kansanga – Luginaah (2019), Meaza et al. (2016), have noted that farmers surrounding the reserves prioritize secure land tenure and crop cultivation as the main motivation, while their willingness to join such rehabilitation programs is determined by the benefits attained (Acheampong et al. 2020). Thus, the practice is well appreciated by farmers, but due to canopy closure of the forest, the sustainability of this system would not be guaranteed, as there is no possibility for crop production under such dense canopy. Study results are in line with other studies carried out in Nepal (Adhikari et al. 2014), Burkina Faso (Coulibaly-Lingani et al. 2011), and Ghana (Acheampong et al. 2018). This literature reported similar incentives for farmers to participate in forest rehabilitation projects.

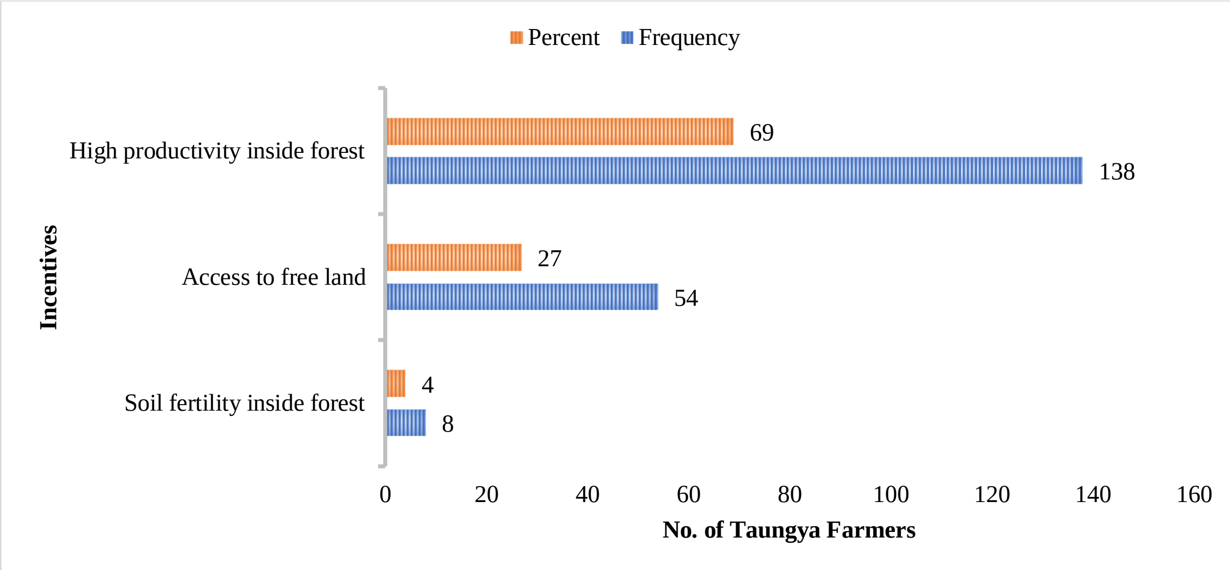

Fig. 4.6: Incentives associated with Taungya farmers in the study area.
Source: Author’s analysis, Field survey data, 2021

The study results (Fig. 4.7) further uncovered four main constraints confronting Taungya farmers in the study area. More than half 52.5% of farmers indicated that a lack of extension services and supervision from FNC are the main challenges. This is followed by overgrazing and crop destruction, as claimed by 33%, while land allocation constraints within the forest and crop species restrictions by FNC were asserted by 8% and 6.5% respectively (Fig. 4.7). However, access to forestry extension services and technical assistance is crucial for the success and sustainability of agroforestry schemes (Nketiah et al. 2016). Farmers expressed their concerns about the extension services and training provided by FNC through FGDs and KIIs. They indicated that the main services provided by FNC officers were allocation of land inside the forest and providing them with seedlings of *Acacia Senegal* trees for planting. There was no additional subsequent technical support. It noteworthy that the weak connections between extensionists and farmers are frequently observed in developing countries (Ullah et al. 2022). To overcome this challenge, the study suggests that the priority budget allocation should be given to the extension services that could empower farmers and guarantee the transfer and delivery of the extension services adequately. This could have a substantial positive impact on boosting agricultural knowledge, enhancing farmers skills for implementing innovative farming technologies, and enhancing farm productivity (Ojijo et al. 2022). Moreover, it could enable building friendly relationships with forestry advisers and farmers, which can facilitate and enhance farmers' participation in forest restoration practices (Ullah – Khan 2019, Amare et al. 2016). These results agree with Fahmi et al. (2015) and Azeez et al. (2017) and contradict the results of Akinwalere – Okunlola (2019), who reported no significant relation between extension services and sustainable adoption of agroforestry practices among farmers in the southwest of Nigeria.

Overgrazing and crop destruction were the second challenges claimed by Taungya farmers in the study area. It was obvious through DFOs and FGDs that overgrazing has been severe in NRF. This could be attributed to the location of the forest on a seasonal livestock grazing route followed by nomadic pastoralists as well as due to the degradation of rangeland in the study area, which directs the nomads' attention towards the NRF for feeding their livestock. This has created continuous destruction of crops and tree regeneration and hence exacerbated the land use conflicts between farmers and nomads. It is worth mentioning that land-use conflicts between sedentary farmers and nomads are a dominant dilemma in different parts of Sudan (Adam et al. 2015). However, to address this issue, Taungya farmers could use the live fences to protect their farms, and FNC could facilitate this by allowing farmers to use the branches of failed trees and dead wood during the migration season of pastoralists. Adoption of cut and carry as a proper grazing system for fodder could also be examined. Furthermore, the land use policy in Sudan should be revised to provide pastoralists with rangeland.

Land size allocation and crop species restrictions have been recognized as additional barriers for Taungya farmers (Fig. 4.7). Discussions with forestry officials in the study area indicated that the limited allocation of land plots to farmers is due to the nature of the rehabilitation program, which focuses on specific degraded plots within the forest, which was less than the number of motivated farmers who expressed an interest in participating. So, to solve this problem and make sure farmers had equal access to land, an average of 1– 4 mukhamas was given to each farmer. This approach was found to be like several Taungya agroforestry schemes in developing countries (Adjei et al. 2020, Wiro – Ansa 2019).

Regarding crop species restrictions, while the FNC officials restricted farmers from growing specific crops in the Taungya system, the farmers had their own preference for crops. For instance, some of the interviewed farmers expressed a preference to planting the sorghum crop due to its importance as daily food consumption for their livelihood. One farmer explained that by saying: *''I and most of the farmers have no other land except NRF to grow subsistence crops. If we are not allowed to grow the sorghum inside the forest, we must buy it from the market at a very high price to feed our families.''*

On the other hand, FNC authorities argue that intercropping *Acacia senegal* trees with sorghum have a negative impact on seedling growth and survival during the early stages of tree establishment. In contrast, in Hungarian experiments carried out by Kovacs – Vityi (2022), found that intercropping Oak with Maize (which is also relatively high plant compared to the Oak seedlings) can help the survival of seedlings by encouraging the seedling to grow faster to get enough light. Furthermore, the interplant protected the seedling from wild animals since they like better the corn than the seedlings, so they didn't harm the seedlings (Kovacs – Vityi 2022). To address this issue, FNC in collaboration with the extension division could find an appropriate way to provide farmers with intercropping sorghum, such as by allocating them to some degraded plots under young or mature trees. In this respect it is recommended to pursue further study to investigate appropriate tree spacing that allows the existence of farmers throughout and avoids canopy closure. This way, farmers would be able to have a steady and sustainable supply of food and thus achieve the win-win outcomes of the Taungya program. Acheampong et al. (2016) reported a similar issue in Ghana, where farmers were prohibited from cultivating cassava crops under the modified Taungya program.

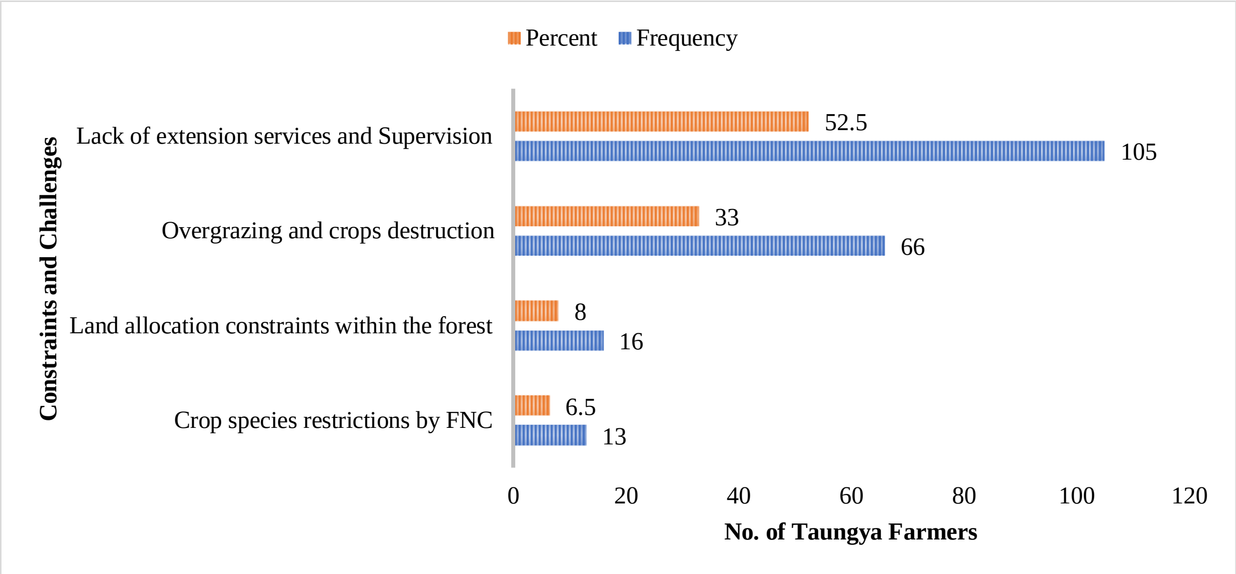

Fig. 4.7: Constraints and challenges associated with Taungya farmers in the study area.
Source: Author's analysis, Field survey data, 2021

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CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

- This research initially assessed the Taungya agroforestry program practiced by farmers within Nabag Reserved Forest (NRF) in South Korofan state, Sudan, and how the program has contributed to forest recovery and farmers' livelihood improvement.

- Before implementation of Taungya agroforestry program, NRF witnessed a massive reduction in forest cover classes, while after the establishment of Taungya program, a substantial augmentation in forest cover has been observed. Thus, the study concludes that Taungya agroforestry could be a successful, suitable, and viable land-use option for forest rehabilitation in the drylands of Sudan.

- Taungya farmers cultivated both cash crops and subsistence crops as means of their livelihoods. Thus, there is no doubt that Taungya agroforestry program in the study area improved crop production, increased income generation, and reduced poverty. This was more clearly confirmed through the focus group discussions, and interviews with FNC officials, who affirmed that most of the Taungya farmers obtained their livelihood needs and household income from selling their crops as well as harvesting the non-timber forest products from NRF, which helped improve their financial capital.

- Moreover, farmers have reported other benefits of Taungya program such as access to land (improving natural capital), income generation (improving financial capital), and improvirng their ability to achieve education attainment (improving human capital).

- Several interconnected factors impeded farmers' perceptions towards Taungya agroforestry program, including extension services, family size, educational level, land size, Taungya experience, and gum Arabic production.

- A number of challenges and constraints confronted the farmers. These issues related to a lack of extension services and supervision from Forest National Corporation, overgrazing and crop destruction, land size limitation, and crop species restrictions.

5.2 Recommendations

- The FNC in Sudan should sustain the *Taungya* agroforestry program at NRF and imitate it in areas where forest rehabilitation is needed.
- Much attention should be given to socioeconomic factors before implementing any agroforestry rehabilitation program in the future.
- The priority budget allocation be given to the extension services that could empower farmers and guarantee to transfer and deliver the extension services adequately.
- Taungya farmers could use the live fences to protect their farms and FNC could facilitate this by allowing farmers to use the branches of failed trees during the migration season of pastoralists.
- The FNC should reconsider farmers' interest in having intercropping sorghum on their farms by revising tree spacing in the future. Alternatively, new degraded plots could be allocated to farmers for sorghum production to improve their livelihood.

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6 Summary

The decline of the forest cover due to deforestation and anthropogenic activities in Sudan has reached a critical situation. This affects the rural communities that depend on the forest for their livelihood. To safeguard against deforestation as well as to rehabilitate the degraded forest, many interventions and schemes have been developed and introduced. One of these schemes is the Taungya agroforestry system, where the farmers can cultivate their subsistence crops with forest trees simultaneously at the early stage of tree plantation inside reserved forest. This dissertation tackled Nabag Reserved Forest (NRF) in South Kordofan state, Sudan as a case study to assess and explore Taungya agroforestry system as a practice used for forest rehabilitation and livelihood improvement in the study area. The research focused on

i. Quantification of forest recovery under Taungya agroforestry program
ii. Socio-economic traits of Taungya farmers
iii. Impact of Taungya agroforestry on farmers income generation
iv. Farmer’s perception and factors influencing their perception towards participation in Taungya agroforestry program
v. Major incentives and challenges associated with Tuangya’s farmers

A mixed method approach including remote sensing data and socioeconomic survey were implemented in this study. Satellite images of Landsat 5 Thematic Mapper, and Landsat 8 Operational Land Imager/Thermal Infrared Sensor of 1991, 2001, 2011, and 2021 were used to generate forest cover maps. Both unsupervised and supervised classifications, as well as ground truth points, were applied to classify the vegetation cover in the study site. The socio-economic data was collected using semi-structured questionnaires, focus group discussions, key informants’ interviews, and direct field observations. The study applied purposive sampling technique to select the respondents. Two hundred farmers representing 50% of those who participated in the Taungya program were selected from nine villages surrounding the reserved forest. The exact numbers of respondents in the specified villages were, Eid (n = 37), Daggea (n = 35), Alsbeka (n = 30), Alkambi (n = 29), Nabag (n = 21), Alhamadi (n = 16), Eridebo (n = 15), Alsilaik (n = 9), and Umkanayt (n = 8). The selection of the villages was based on the recommendations provided by the forestry officials in the study area, while the selection of the farmers was made randomly according to their availability and willingness to participate. Prior to the interview, verbal consent was obtained from the farmers to take part in the interview. The collected data was analysed using descriptive and inferential statistics including means, standard deviations, frequencies, and percentages, paired sample t-test, Likert scale rating, and ordinal logistic regression model.

The results of remote sensing data revealed that two trends of forest cover changes occurred in the study area between 1991-2001 and 2011-2021. It was well explored that through Taungya agroforestry, there was a considerable increase in forest cover over this period. This could be clearly detected by increasing dense forest and light forest cover by 1041.68 ha (24.95%) and 2.72 ha (0.07%) respectively and decreasing of bare land and agricultural field by 409.83 ha (9.81%) and 634.57 ha (15.20%) during the addressed period.

The results of socio-economic survey showed that 77% of farmers were males, with an average age of 41 years. Most farmers (79%) had attained education. About 77% of farmers cultivated an average land area of 3.5 hectares. Fifty seven percent of farmers had an average of 6.70 years of experience in Taungya. The study revealed that Taungya agroforestry program contributed significantly to farmers' income. Furthermore, farmers in the study area have expressed strong positive perceptions (MS >2.5) toward the benefits of participation in Taungya agroforestry program.

The regression results revealed that extension services, farmer's Taungya experience, family size, educational level, land size, and gum Arabic production have a positive influence on farmers' perception. Contrary, farmers' age and gender were found to have a negative association with farmers' perception. Farmers' participation was encouraged by the high productivity within the forest and access to free fertile land. Contrary, lack of extension services and supervision from Forest National Corporation, overgrazing and crop destruction, land size limitation, and crop species restrictions were identified as major challenges.

7 New scientific results

1) Taungya agroforestry program in the study area plays a vital role in forest rehabilitation

Before the implementation of the Taungya agroforestry program in the period between 1991 and 2001, the research site has witnessed a massive reduction in forest cover classes (dense forest and light forest), followed by a significant increase in bare land and agricultural field classes. While the Taungya agroforestry program was implemented between 2011 and 2021, a substantial increase in forest cover has been detected. Within the study period of analysis (1991-2021), results indicated that forest cover classes (dense forest and light forest) were increased by 1041.68 ha (24.95%) and 2.72 ha (0.07%), respectively, due to the establishment of Taungya agroforestry program. As a result, bare land and agricultural field areas decreased by 409.83 ha (9.81%) and 634.57 ha (15.20%), respectively. According to the results, every bare land covered by an agricultural field will most likely be successfully converted to forest cover in the future. Hence the study concludes that Taungya agroforestry could be a successful, suitable, and viable land-use option for forest rehabilitation in the drylands of Sudan.

2) Taungya agroforestry program in the study area contributed significantly to farmer's income

Taungya agroforestry program contributed significantly to farmers' income. Evidence to that was the sharp reduction in mean annual costs from SDG 32851.75 to SDG 25107.50, and a substantial increase in the mean annual net incomes of the farmers from SDG 35298.52 to SDG 91839.50 before and after participation in the program, respectively. Most farmers (61.5%) earned net income between (SDG 0 – 20000) before joining the Tuangya program. This percentage was reduced sharply to (21.5%) after joining the program. This means that 40% more farmers earned net income above SDG 20000. Furthermore, the number of farmers (11%) who earned net income SDG > 100000 significantly increased to (30%).

3) Taungya farmers in the study area have different socio-economic characteristics

Statistical analysis showed that there was variety in the socioeconomic traits of the farmers in the study area. However, Taungya practice was dominated by male farmers, and most of them were above youthful age but still considered to be within an economically active age range, meaning that they could effectively participate in the agricultural activities. Taungya's farmers had attained different levels of education, ranging from Khalwa to university, meaning that they are more likely to easily understand the extension programs and have access to up-to-date agricultural technologies compared to illiterate farmers. Farmers cultivated an average of five mukhamas of land. However, the limitation of the land area could be explained by the nature of the agroforestry rehabilitation program, which targets specific land areas inside the forest reserve. The average number of years of participation in the Taungya program was 6.70 years. Most of the farmers, 57.5%, had Taungya experience ranging between 1 and 5 years. This implies that farmers accept Taungya agroforestry practices and that the number of adopters is growing, while farmers in the study area have sufficient experience in practicing Taungya agroforestry. It suggests that they are aware of different silvicultural operations and technologies. Thus, they will likely continue participating in the Taungya agroforestry program.

4) **Taungya farmers have a positive perceptions of the benefits of participation in Taungya agroforestry program**

Likert scale analysis showed that farmers in the study area have expressed strong positive perceptions (MS >2.5) toward four out of five items, bordering on the benefits of Taungya agroforestry program, including the provision of land, improving income, help during times of hardship, and contribution to education expenses. However, only one item, ‘‘Taungya help in purchasing livestock’’ was perceived by farmers negatively (MS <2.5).

5) **Different factors are influencing farmer’s perceptions of the benefits of Taungya agroforestry program**

Several factors were found to have positive and negative effects on farmer’s perception. The ordinal logistic model analysis showed that farmers’ perceptions of Taungya agroforestry benefits are affected by several socio-economic factors at a 5% level of significance. Out of eight explanatory variables included in the model, six variables were found to have a positive influence on farmers’ perceptions towards the benefits of Taungya agroforestry practice. These include extension services ($\beta = 0.771, P = 0.013$), family size ($\beta = 0.043, P = 0.345$), educational level ($\beta = 0.065, P = 0.583$), land size ($\beta = 0.056, P = 0.11$), Taungya experience ($\beta = 0.126, P = 0.002$), and gum Arabic production ($\beta = 0.032, P = 0.92$). Farmer’s gender ($\beta = -0.43, P = 0.182$) and age ($\beta = -0.028, P = 0.03$), on the other hand, had a negative association with their perception. This implies that farmers’ perceptions were strongly correlated with their socioeconomic factors.

Therefore, a better understanding of these factors is crucial for the planning and implementation of such agroforestry programs in different farming communities in the future.

6) **Several incentives and challenges are associated with Taungya farmers in the study area**

Taungya farmers in the study area had different incentives and constraints confronting their participation in the program. The main incentives for farmers to participate in the program were the high productivity inside the forest, access to free land, and the highly fertile soil inside the forest, while the major constraints were the lack of extension services and supervision from FNC, overgrazing and crop destruction, land size allocation, and crop species restrictions. Therefore, prioritizing extension services, providing live fences, and reconsidering farmers' interest in intercropping sorghum on their farms to improve their sustenance will overcome the constraints and further boost farmers' productivity.

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10 Annexes

Annex 1: Farmers questionnaire

Survey to Examine the Contribution of the Taungya Agroforestry System to Forest Rehabilitation and Livelihood Improvement, Case Study of Nabag Reserved Forest, South Kordofn State, Sudan

Introduction to the study

My name is …………………………. We are conducting research on the contribution of Taungya agroforestry system applied by the Forest National Corporation (FNC) in Nabag reserved forest to forest rehabilitation and livelihood improvement, so I would like to ask you some questions related to the study and ask you kindly to answer them for the best of your knowledge. All information you provide will be confidential and for the purpose of study only. You are welcome to ask any questions during or after the interview.

Farmer's name	Village name	Phone number	Collection date	Site Coordinates

Part 1: Personal-demographic characteristics of the Farmers

(1) Sex:

Male ( ) Female ( )

(2) Age:

20-30 ( ) 31-40 ( ) 41-50 ( ) 51-60 ( ) > 60 ( )

(3) Marital status:

Unmarried ( ) Married ( ) Divorced ( ) Widowed ( )

(4) Family members:

None ( ) 1-5 ( ) 6-10 ( ) 11- 15 ( ) >15 ( )

(5) Educational levels:

Illiterate ( ) Khalwa ( ) Primary ( ) Secondary ( ) University ( )

(6) Main occupation:

Farmer ( ) Trader ( ) Teacher ( ) Laborer ( ) Other, specify ………………………………….

(7) The main Source of income:

Agriculture (   ) Agriculture & Grazing(   )Agriculture &Trade(   )Employee (   ) Other, specify(   )

(8) How many years did you practice agriculture?

1-5 (   )   6-10 (   )   11- 15 (   )   >15 (   )

Part 2: Participation in the Taungya agroforestry program and resource endowments (land ownership and farm characteristics)

(1) When did you participate in the program?

2002-2005 (   ) 2006-2010 (   ) 2011-2015 (   ) 2016-2020 (   )

(2) What is the total area of the land?

1 Mukhamas (   ) 2 Mukhamas (   ) 3 Mukhamas (   ) Other, specify ………………………………

(3) How was land acquired?

Forest land (   ) Owned (   ) Inherited (   ) Other, specify ……………………………………

(4) If the land was owned by the Forest National corporation (FNC), how is the contract between the farmers and the FNC made?

....

....

....

(5) Do you have Agricultural land other than Taungya system?

Yes (   ) No (   )

(6) If the answer was yes, how was the land acquired?

Owned (   ) Rented (   ) Inherited (   ) Other, specify ……………………………………………..

(7) What is the total area of the land?

1 Mukhamas (   ) 2 Mukhamas (   ) 3 Mukhamas (   ) Other, specify (   )

(8) What kind of crops do you grow?

....

Part3: Input and crop production

(1) Which equipment do you use to prepare your land?

Machine (   ) Manual plow (   ) Animal (   ) Other, specify ………………………………….

(2) What is the source of fund of crops cultivation?

Personal (   ) Bank loan (   ) From FNC (   ) Other, specify ………………………………….

(3) What is the source of fund of tree cultivation?

Personal ( ) Bank loan ( ) From FNC ( ) Other, specify …………………………………...

(4) How do you cultivate trees?

Seeds ( ) Seedlings ( ) Seeds +Seedlings ( ) Other, specify ………………………………...

(5) What is the shape of cultivating trees with crops?

Alley cropping ( ) Live fences ( ) Randomly ( ) Other, specify ………………………………….

(6) What is the source of labor?

Family members ( ) Labor renting ( ) Family +Renting ( )Other, specify ……………………….

(7) If the answer is labor renting? What is the cost of labor renting (Mukhamas/SDG)?

....

(8) Name the crops species you have planted in the forest?

....

(9) Who was responsible for choosing crops species to be planted (Farmer or FNC)?

....

(10) Name the trees species you have planted in the forest?

....

(11) Who was responsible for choosing trees species to be planted (Farmer or FNC)?

....

(12) What silvicultural activities do you performed on crops and trees?

....

(13) Have women participated in the Taungya program?

Yes ( ) No ( )

(14) If the answer is yes, what kind of participation?

Remove weeds & Cultivation & Protection ( ) Cultivation & protection ( )Gum Arabic tapping ( )

Other, specify ………………………………….

Part 4: Source of energy, livestock and source of fodders

(1) What is your main source of energy?

Fuelwood ( ) Charcoal ( ) Gas ( ) Other, specify ………………………………….

(2) Where do you get it?

From the forest ( ) Purchase ( ) Forest + Purchase ( ) Other, specify ……………………………

(3) Do you have Cattle?

Yes ( ) No ( )

(4) If the answer is yes, specify?

....

(5) What is the source of fodder?

From the forest ( ) Purchase ( ) Forest + Purchase ( ) Other, specify ……………………………

Part 5: Operating and harvesting costs

(1) How much revenue was from harvesting crops last year? What are the total costs?

Type of the crop	Total costs (SDG)	Total income (sack)	Price per unit

(2) Where do you sell crops?

Personal consumption ( ) Village market ( ) Other, specify …………………………….

(3) According to your estimation, what was your income from Gum Arabic tapping last year?

....

(4) Where do you sell the Gum Arabic production?

Village market ( ) Auction ( ) Production associations ( ) FNC ( ) Others, specify ……………

(5) Did you benefit from other tree species in the forest?

Yes ( ) No ( )

(6) If the answer is yes, determine the tree species and the kind of benefit?

Tree species	Type of benefit

Part 6: Taungya system and Livelihoods

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(1) Does anyone in your household have a salary job?

Yes ( ) No ( ) Don't know ( )

(2) Does your household receive remittance from some relatives?

Yes ( ) No ( ) Don't know ( )

(3) Do anyone in your household have a bank account?

Yes ( ) No ( ) Don't know ( )

(4) Do you have a steady income from agriculture, livestock, or any source outside the farm?

Yes ( ) No ( ) Don't know ( )

(5) Does the Taungya program help to support living expenses?

Yes ( ) No ( ) Don't know ( )

(6) How do you assess your income before participating in the Taungya program?

Not at all ( ) A little ( ) Average ( ) Very much ( )

(7) How do you assess your income after participating in the Taungya program?

Not at all ( ) A little ( ) Average ( ) Very much ( )

(8) In general, how would you describe your family's health status before participating in the Taungya program?

Very poor ( ) Poor ( ) Average ( ) Good ( )

(9) In general, how would you describe your family's health status after participating in the Taungya program?

Very poor ( ) Poor ( ) Average ( ) Good ( )

(10) To what extent that Taungya program helped you with the provision of treatment in case of disease?

Very little ( ) little ( ) Average ( ) Much ( )

(11) To what extent that Taungya program helped you in purchasing livestock?

Very little ( ) little ( ) Average ( ) Much ( )

(12) Have you ever rehabilitated your house from the Taungya program?

Yes ( ) No ( ) Don't know ( )

(13) Through your participation in Taungya program, have you received any extension services or training?

Yes ( ) No ( ) Don't know ( )

(14) If the answer is yes, to what extent have these services contributed to strengthening the relationships between farmers?

Very little ( ) little ( ) Average ( ) Much ( )

(15) Do you or any family member have a participation in any of the agricultural associations?

Yes ( ) No ( ) Don't know ( )

(16) If the answer is (yes), to what extent have these associations contributed to strengthening social relations between farmers?

Very little ( ) little ( ) Average ( ) Much ( )

Part 7: Farmers perception and attitudes towards Taungya agroforestry program

(1) Taungya agroforestry program helps in the provision of land

I strongly disagree ( ) I disagree ( ) I agree ( ) I strongly agree ( )

(2) Taungya agroforestry program helps in improve income

I strongly disagree ( ) I disagree ( ) I agree ( ) I strongly agree ( )

(3) Taungya agroforestry program helps during times of hardship

I strongly disagree ( ) I disagree ( ) I agree ( ) I strongly agree ( )

(4) Taungya agroforestry program contributes to education expenses

I strongly disagree ( ) I disagree ( ) I agree ( ) I strongly agree ( )

(5) Taungya agroforestry program helps with the purchase of livestock

I strongly disagree ( ) I disagree ( ) I agree ( ) I strongly agree ( )

(6) What are the main factors encouraging your participation in Taungya program?

....

....

....

....

(7) What are the problems and constraints that you experience through your participation in Taungya program?

....

....

....

....

(8) How do you evaluate the forest situation before Taungya program?

Bad (   )   Average (   )   Good (   )   Very good (   )

(9) How do you evaluate the forest situation After Taungya program?

Bad (   )   Average (   )   Good (   )   Very good (   )

(10) Any suggestions from your side for improving Taungya program?

....

....

....

....

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Annex 2: Test of multicollinearity for independent variables where the variance inflation factor (VIF) results show no multicollinearity between independent variables used in the model

Variables	Tolerance	VIF
Extension services	0.852	1.173
Gender	0.836	1.197
Family members	0.641	1.560
Age	0.616	1.624
Educational level	0.841	1.189
Land size	0.883	1.133
Taungya experience	0.813	1.230
Gum Arabic production	0.870	1.149