Investigating tagasastes' potential for agricultural climate mitigation and adaptation within the context of South Africa

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DECLARATION

I attest that I am aware of the implications of plagiarism, and hereby affirm that the content presented in the dissertation is my original work. Furthermore, I confirm that all sources have been appropriately credited and acknowledged.

Signed by candidate

Leah Ord-Armstrong
6 June 2024

To Bugga,

who encouraged me to question deeply and to find my fire.

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ABBREVIATIONS AND ACRONYMS

AI	aridity index
CAM	crassulacean acid metabolism
C	carbon
CH_4	carbon monoxide
CO_2	carbon dioxide
CO2e	carbon dioxide equivalent
FAO	Food and Agriculture Organisation of the United Nations
GDP	gross domestic product
GHG	greenhouse gas
GWP	global warming potential
OH	hydroxyl radicals
IPCC	Intergovernmental Panel on Climate Change
K	potassium
Mg	megagram
N_2O	nitrous oxide
NBI	National Business Initiative
NO_3^-	nitrate
P	phosphorous
S	sulphur
SSA	sub-Saharan Africa

CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

Land provides the primary source of food, clean water, timber, biodiversity, and ecosystem services, all of which are necessary for human survival (IPCC, 2019). Climate regulation, erosion and flooding prevention, organic waste decomposition, air and water purification, carbon sequestration, supporting biodiversity, and pollination of food crops are all significant functions of land and vegetation. The interconnectedness of the Earth System's stability and resilience with human well-being is fundamental, yet is frequently overlooked (Rockström et al., 2023). According to Rockström et al. (2023), the carbon water and nutrient cycles constitute the foundation of the earth's life-giving systems, all of which have been altered by human influence. The negative impact that humans have had on the earth has resulted in long-term climatic consequences and have heralded a new geological epoch, the Anthropocene, the results of which are referred to as anthropogenic climate change (Zalasiewicz et al., 2017). In the absence of anthropogenic influence, the Holocene epoch, characterised by consistent temperatures, an abundance of freshwater and biogeochemical cycles remaining within a relatively narrow spectrum, would potentially have persisted for several millennia (Berger & Loutre, 2002 and Rockström et al., 2009).

The future capacity for soil, water, air and biodiversity to remain productive is threatened by the possibility that anthropogenic influences could destabilise environmental systems beyond the point of no return (Rockström et al., 2009). Food insecurity poses an existential threat to humanity now and in the future (Bradshaw et al., 2021), and is a complex issue with many interconnected linkages, necessitating a multidisciplinary, holistic approach (Ortiz et al., 2021). It is anticipated that climate change will place additional stress on an already struggling agricultural sector, particularly in impoverished regions. Global food security is influenced by both demand (population growth and increased affluence) and supply (land under cultivation, water resources, research and investment) factors (Yunusa et al., 2018) and is largely dependent on healthy ecosystem services and biophysical resources (Myers et al., 2017).

A proposed framework has been developed by Rockström et al. (2023) to ensure basic access to water, food, energy, and infrastructure for all, as well as a fair and equitable limit on the maximum acceptable human impact on biophysical systems, to establish a secure and just pathway in the long term. The framework builds on previous Planetary Boundaries Framework (Steffen et al., 2015), Doughnut Economics (Raworth, 2017), and the Sustainable Development Goals (UN General Assembly Resolution 70/1, 2015) to include both biophysical and social goals and boundaries.

The Planetary Boundaries Framework, first developed by Rockstöm et al. in 2009 and later updated by Steffen et al. in 2015, identifies nine critical Earth system processes that regulate the planet's stability and resilience. These include climate change, biosphere integrity, land-system change, freshwater use, biogeochemical flows, ocean acidification, atmospheric aerosol loading, stratospheric ozone depletion and

novel entities (referring to human-made substances such as radioactive materials and plastics). Doughnut Economics (Raworth, 2017) is a framework developed to balance both social and ecological priorities. The inner boundary represents the social foundation essential for human wellbeing, including access to food, clean water, education and healthcare. Falling below the threshold leads to social deprivation. The outer boundary represents the ecological ceiling, delineating the limits of planetary systems such as climate stability, biodiversity and resource utilisation. Exceeding this boundary results in environmental degradation. The area between these two boundaries constitutes the safe and just space for humanity, where societal needs are met without breaching ecological constraints. The Sustainable Development Goals (SDG's) were adopted by the United Nations in 2015 and provide a roadmap for addressing interconnected social, economic and environmental challenges. The SDG's are comprised of seventeen goals to eradicate poverty, end hunger, achieve gender equality, ensure access to clean water and sanitation, promote peace and justice, among other objectives (UN General Assembly Resolution 70/1, 2015). The goals are designed to achieve a balance between economic growth, social inclusion and environmental inclusion by 2030.

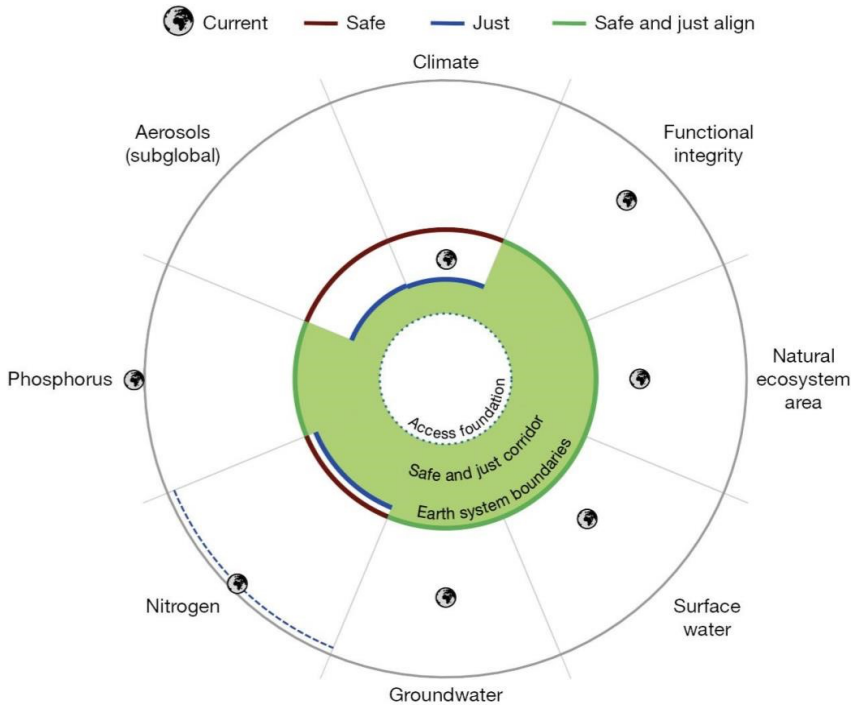

Figure 1. Visualisation of safe earth system *boundaries (dark red), just earth system boundaries (blue), cases where safe and just boundaries align (green) and current global states (Earth icons). Radial axes are normalised to safe earth system boundaries. Headline or central estimate global boundaries are plotted to support comparison with the current global state, subglobal boundaries have also been defined and multiple likelihood levels for many domains. For aerosols, the subglobal boundaries are displayed to compare safe and just boundaries. For nitrogen, a plotted dashed blue line indicates the boundary quantification for harm from nitrate in groundwater while noting that the just boundary must also incorporate safe considerations via eutrophication, leading to a more stringent safe and just boundary. Minimum access to water, food, energy and infrastructure for all humans (dotted green line) could constitute the foundation of a safe and just 'corridor' (green filled area), not quantified here (Rockström et al., 2023).*

1.2 MOTIVATION AND RESEARCH QUESTION

Choosing to conduct research on this topic is motivated, on the one hand, by a desire to find agricultural solutions to the negative effects of conventional farming, and on the other hand, to explore solutions that support the diverse needs and cultures of farmers. This could result in positive spin-offs/co-benefits of enhancing food and nutritional security, conserving soil health and biodiversity, reducing long-term reliance on donor funds and costly inputs as well as building resilience to climate-related shocks.

Modern conventional agricultural methods, commonly associated with intensive monoculture crop production, have been linked to soil degradation. These practices contribute to chemical pollution, salinification due to excessive use of fertilisers and inefficient irrigation practices, and acidification resulting from the over-application of nitrogen-based fertilisers (Guo et al., 2010). Acidification reduces soil pH, impairing nutrient availability and potentially limiting crop productivity. Additionally, inadequate drainage systems also exacerbate soil degradation by causing waterlogging, which adversely impacts soil structure and aeration (Qadir et al., 2000). Poor irrigation techniques further contribute to secondary salinisation, where salt accumulates in the soil, reducing agricultural productivity (FAO & ITPS, 2015).

Annually, 12 million hectares of land are estimated to be degraded globally (Beddington et al., 2012), primarily due to urbanisation, deforestation, overgrazing and unsustainable agricultural processes and industrial development (Roy et al., 2022). Furthermore, the globalisation of agricultural products has created a spatial divide between production and consumption (Ortiz et al., 2021). Frequent imports from less developed countries result in the "outsourcing" of relative biodiversity losses and the escalation of environmental pressures in areas already under stress. Hence, it is crucial to identify suitable solutions that enhancing long-term sustainability of agricultural intensification in developing nations.

The mixed use of perennial and woody legumes presents a possible avenue for mitigating and adapting to climate change, intensifying agriculture, reducing land use change, and lifting rural communities out of poverty. With diminishing natural forests and woodlands resulting from the encroachment of agriculture, agroforestry is becoming an important feature in sub-Saharan Africa (SSA) (Dawson et al., 2014). Since ancient Greek and Roman times, intercropping and rotating legumes in agriculture has been known to increase crop yields, but it was only in the late 1800s that it was understood and proven that this was achieved through the symbiotic relationship with rhizobium bacteria fixing atmospheric nitrogen into the ground (Adams et al., 2010). The characteristics and use of herbaceous and woody leguminous plants are already well established, but their capacity for mitigating and adapting to climate change is not well documented (Wambugu et al., 2011).

Biological carbon sequestration relies on both the photosynthetic capabilities of plants and microorganisms in the soil (Nayak et al., 2022). Plants grazed by livestock have active regrowth, which in turn speeds up photosynthesis and allows plants to fix atmospheric carbon (C) into the earth (Cusworth et al., 2022). According to Cusworth et al. (2022), plants that are actively growing trap the most carbon, indicating that

livestock grazing pasture aid in maintaining plant growth for active carbon sequestration. The authors add that the methane (CH_4) produced by livestock is broken down after ten to twelve years through the process of atmospheric elimination into the same amount of carbon dioxide (CO_2) that was in the atmosphere before it was photosynthesized by plants, and before ruminants consumed the plants. This process is referred to as the biogenic carbon cycle, or the naturalisation of methane (Cusworth et al., 2022).

Intercropping legumes with cereals or other crops enhances nitrogen (N) fixation, reducing the need for synthetic fertilisers, lowering overall agricultural input and mitigating GHG emissions (Wambagu et al., 2011; Li et al., 2009). Furthermore, legumes improve nutrient cycling, increasing phosphorous (P) availability in the soil, as well as improving phosphatase and enzymatic activity in the soil (Gong et al., 2024; Wambagu et al., 2011). Legumes also influence potassium (K) and sulphur (S) dynamics, contributing to improved soil fertility and crop yield (Gong et al., 2024). Unlike synthetic nitrogen fertilizers, which contribute to nitrous oxide (N_2O) emissions through microbial processes such as nitrification and denitrification, nitrogen-fixing legumes release minimal N_2O. Synthetic fertilizers lead to N_2O emissions when excess nitrogen remains in the soil and undergoes denitrification, a process where nitrate (NO_3^-) is converted into N_2O under anaerobic conditions (Zhu et al., 2019). In contrast, legumes fix atmospheric nitrogen through a symbiotic relationship with rhizobium bacteria, converting nitrogen from the air into plant-available forms. Although rhizobia require a small portion of the plant's photosynthates to support nitrogen fixation, this cost is outweighed by benefits such as improved nitrogen availability, enhanced soil structure, and increased water use efficiency through better nutrient cycling and deep rooting (Atkins, C., 1984; Giller et al., 2013; Wambagu et al., 2011). As such, legumes provide a more sustainable nitrogen source, helping to reduce GHG emissions associated with conventional farming practices.

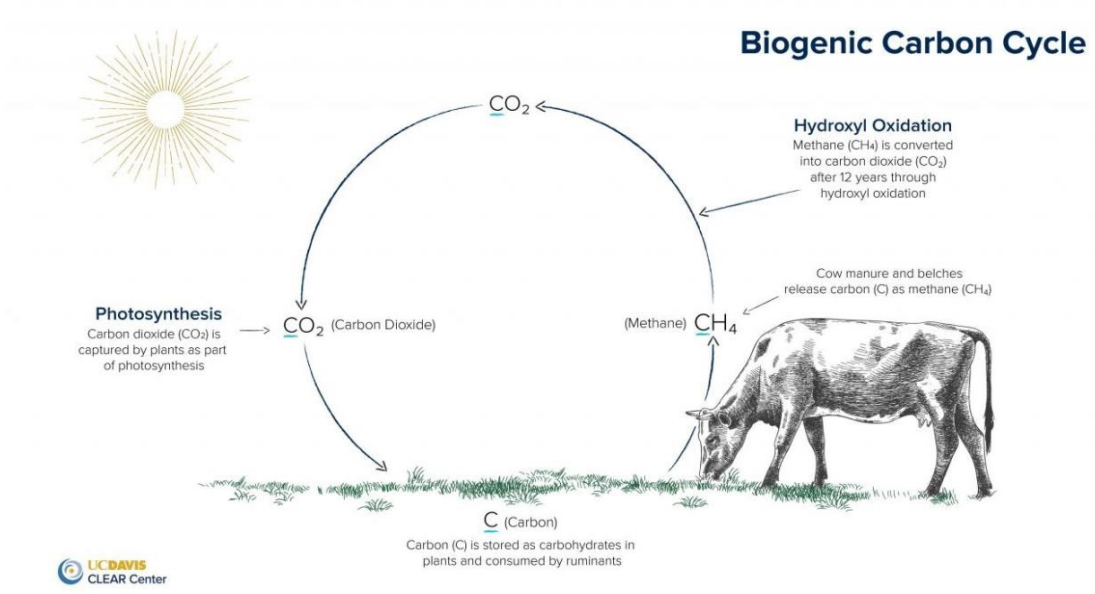

Figure 2. The Biogenic Carbon Cycle *(Cusworth et al., 2022).*

Figure 2 illustrates the relationship between CO_2, CH_4 and C in the atmosphere and biosphere, known as the biogenic carbon cycle (Cusworth et al., 2022). Plants absorb CO_2 via photosynthesis and convert it into

organic carbon, which is cycled through various trophic levels via consumption and decomposition (Lal, 2004). CH_4, primarily produced by biological processes such as enteric fermentation in livestock, enters the atmosphere where it undergoes hydroxyl oxidation, reacting with hydroxyl radicals (HO) to form CO_2 and water vapor (Lal, 2004). This process reduces CH_4 concentrations but contributes to increased CO_2 levels, which persist in the atmosphere for longer periods (IPCC, 2021). Chemical fertilisers — particularly N-based fertilisers — contribute towards nitrous oxide (N_2O) emissions through their manufacture and through biological processes such as nitrification and denitrification (Butterbach-Bahl et al., 2013). CH_4, CO_2 and N_2O emissions impact climate change, contributing to radiative forcing.

Radiative forcing refers to the change in the climate system energy balance caused by variations in GHG concentrations, which results in global warming (IPCC, 2021). CH_4, has a higher global warming potential (GWP) in the short-term and induces stronger radiative forcing compared to CO_2, while N_2O is has a GWP almost ten times higher than CH_4 (Lynch & Kirk, 2020; IPCC 2021; IPCC 2013). Carbon sequestration plays an important role in capturing and storing CO_2 in natural reservoirs such as vegetation, soils and oceans (Lal, 2008). Carbon fluxes, such as photosynthesis, respiration, and decomposition, represent the movement of C between reservoirs and are central to the C cycle (Chapin et al., 2011). A challenge in maintaining this cycle's efficacy is carbon leakage, where stored C is unintentionally released back into the atmosphere through soil disturbance, ecosystem degradation, or land-use changes. Such leakage can undermine sequestration efforts and emphasizes the importance of sustainable land management practices to ensure long-term storage stability (Bradford et al., 2019).

Perennial leguminous plants have the potential to directly and indirectly reduce GHG emissions in agriculture, improve above and below ground biodiversity, increase crop and livestock production due to their high feed value, and sequester carbon (Wambugu et al., 2011). This indicates that there is potential for perennial leguminous fodder crops to form meaningful carbon sinks in degraded agricultural lands, while increasing agricultural output, minimising environmental stress and supporting environmental services, such as enhancing nutrient and water cycles. To investigate this theory, the woody legume *Chamaecytisus palmensis*, commonly known as tagasaste, was chosen for this study because of its multi-purpose characteristics, its high nutritional value to livestock and its hardiness and adaptability to different environmental conditions. Tagasaste can increase livestock production due to the high protein content and total digestibility of the leaves and tender green stems (Dawson et al., 2014) and has been widely used to combat erosion, for soil rehabilitation and shelterbelts (Orwa et al., 2009).

This raises the question: can the use of the leguminous fodder shrub tagasaste contribute to climate change related adaptation pathways in agriculture, while simultaneously mitigating agricultural greenhouse gas emissions and facilitating carbon sequestration? Adaptation refers to decreasing the risks associated with current or projected climate extremes and mitigation refers to the reduction of GHGs in the atmosphere by minimizing the use of fossil fuels or by trapping/sequestering GHGs in carbon sinks (NASA, 2023).

1.3 AIM AND OBJECTIVES

This research seeks to understand the environmental consequences of agricultural practices and the feedback loops between agriculture, biodiversity, human pressures and anthropogenic climate change from an agricultural standpoint. Secondly, it explores how agricultural output may be optimised while reducing GHG emissions and negative environmental impacts, through the use of leguminous fodder crops in sustainable farming systems, in this instance tagasaste. While the advantages associated with woody leguminous plants are recognised, their potential contributions to climate change mitigation and adaptation have not been extensively researched. Assessing precise and quantifiable measures of their adaptation and mitigation capabilities remains a challenge (Wambugu et al., 2011) and the adoption of legume intercropping remains relatively low in SSA (Hassen et al., 2017).

Therefore, the aim of this research is to assess the potential agricultural mitigation and adaptation avenues offered by tagasaste, within the South African context.

To achieve this, the following objectives were defined:

1. Determine the current use of tagasaste in South Africa; and
2. Examine the characteristics of tagasaste relevant to its potential role in mitigating and adapting to climate change.

This study investigates the potential of tagasaste as a climate-smart agricultural intervention in South Africa. It focuses on the shrub's role in climate change mitigation through carbon sequestration and adaptation by enhancing soil health, agricultural productivity, and rural community resilience. The study is geographically confined to regions in South Africa where tagasaste is currently grown. It relies on secondary data, personal communications and farmers' perceptions gathered through an online survey. The study does not include long-term field trials or address other agroforestry species beyond tagasaste. Broader economic analyses, such as cost-benefit assessments at national or regional scales, are also beyond the scope of this research.

CHAPTER 2. LITERATURE REVIEW

2.1 LAND AND PEOPLE

2.1.1 The most vulnerable populations

Nearly one billion people live in poverty, with the vast majority living in remote regions of the Global South (Ahmadzai et al., 2021), and over two billion people are undernourished (FAO, 2015), even though food supply has increased by approximately 30% since the 1960s (IPCC, 2019). Agriculture accounts for 40% of gross domestic product in SSA countries, and about half of the labour force is fully dependent on the sector for livelihoods and employment (Hassen et al., 2017). According to Hassen et al. (2017), food insecurity not only leads to poor health, but also social issues such as unrest and crime, as well as increased poverty. Due to their reliance on ecosystem services, the poor are particularly susceptible to climate change (Rosegrant et al., 2009), whilst women, who are traditionally the caretakers of families, are among the most vulnerable in SSA (Gengenbach et al., 2018).

Agricultural production is projected to decline by 15 to 35% due to climate change, and population growth coupled with a lack of awareness in rural communities may exacerbate food security issues (Hassen et al., 2017). Without proper adaptation, these challenges—along with rising food demand, climate change trends, and increased biophysical stresses—are anticipated to worsen poverty and drive the conversion of previously arable land into less productive uses. Population growth, rising food demand, climate change trends, and increased biophysical stresses are anticipated to exacerbate poverty and lead to the conversion of previously arable land into marginal, less arable land (IPCC, 2019). Over 46% of the planet's surface is already classified as dryland, and three billion people live in these marginal regions (IPCC, 2019). Drylands are areas where the ratio of annual precipitation to potential evapotranspiration — known as the aridity index — falls below 0.65. The Aridity Index (AI) is calculated by dividing annual precipitation by potential evapotranspiration (the amount of water that would evaporate and transpire if freely available). Based on this index, drylands are classified into four categories: hyper-arid (AI < 0.05), arid (0.05-0.20), semi-arid (0.20-0.50), and dry sub-humid regions (0.50-0.65) (UNCCD, 2011; UNEP, 1992). Increasing desertification results in decreased agricultural yields, food insecurity, increased albedo, the spread of invasive plants and excessive groundwater extraction for irrigation (IPCC, 2019). This means that the already struggling populations in these regions are potentially faced with a humanitarian crisis.

Physical labour is a crucial aspect of agriculture, especially in the less developed rural areas where mechanisation and technology are scarce (Myers et al., 2017). Myers et al. (2017) explain that, at a basic level, physical labour necessitates good health (not being malnourished) and the capacity to regulate body temperature. The authors continue that it is unknown exactly how climate change will affect the ability of humans to perform strenuous physical tasks, but there are concerns about the significant and disproportionate impacts in the tropics and marginal areas, where heat stress is already prevalent, and agriculture is most dependent on physical labour. According to Myers et al. (2017), the agricultural sector

in tropical and subtropical regions faces heightened vulnerability due to heat waves and other extreme weather conditions. This susceptibility is compounded by the pre-existing challenges associated with heat, which already impede physical performance.

In terms of access to food, the socioeconomic gap between the wealthy and the poor is significant. While 29.6% of the global population (2.4 billion people) experience moderate to high food insecurity, 13.1% are obese (FAO, 2023). As presented in the 2023 Food and Agriculture Organisation (FAO) of the United Nations Statistical Yearbook, Africa has the highest rates of undernourishment in the world, with 60.9% of its population experiencing food insecurity. North America, Oceania and Europe have the highest rates of obesity, with ~28% of people over the age of 18 considered obese. According to Ramankutty et al. (2018), this points to an unequal distribution of food on a global scale, as the food system falls short in providing sufficient caloric and nutritional access to all individuals, particularly in developing countries, while simultaneously facilitating developed countries to engage in overconsumption. Furthermore, one-third of all food produced is estimated to be wasted or lost due to various factors such as post-harvest handling, processing and household practices (Ramankutty et al., 2018; FAO, 2011). The connection between inequality and climate change presents a unique dynamic in Africa, and it is anticipated that the continent will experience a disproportionate share of the adverse impacts (Linus, 2020; Critchley et al., 2023).

According to the World Bank Poverty and Inequality Platform, South Africa has the highest rates of inequality in the world (World Bank, 2018), associated with significant racial divides as a result of Apartheid, gender inequality and poverty, particularly in rural areas and within older generations (Mtintsilana et al., 2022). Previously disadvantaged small-scale farmers are especially vulnerable, due to a common lack of infrastructure, access to water and land, electricity and transport routes (Johnston et al., 2024). Overall, more than 20% of the South African population is food insecure, and ~25% of children are undernourished, suffering from impaired growth and development (Stats SA, 2020).

Over and above insufficient caloric and nutritional intake, there is a correlation between food insecurity resulting from supply shocks and global food price fluctuations and social unrest and crime (Hassen et al., 2017; Lagi et al. 2011). Rural crime in South Africa that contributes to significant social, economic, physical and political ramifications include farm attacks and stock theft (Clack & Minnaar, 2018). In a study on farmers' perspectives on quitting or remaining in agriculture in South Africa, it was found that many farmers feel apprehension regarding rural safety issues in the form of violent farm attacks, as well as uncertainty surrounding land redistribution and financial difficulties, and intend to leave the sector (Cloete et al., 2022). In a review on farm attacks and stock theft in South Africa, Clack & Minnaar (2018) assert that these challenges directly affect rural economies and livelihoods, including those of both commercial and subsistence farmers, as well as farmworkers and their families. In addition, following the onset of the global economic crisis in 2008, there was a noticeable rise in the presence of organised crime syndicates who adopted stock theft as a means of swiftly accumulating wealth, as opposed to the theft of livestock driven by hunger (Clack & Minnaar, 2018). According to combined South African Police Service, AfriForum and AgriSA statistics, there has been an average of sixty farm murders a year between 1996 and 2017, which

is statistically high in comparison with international figures (Clack & Minnaar, 2018). The authors add that an average of 150 000 to 200 000 livestock have been stolen annually in the last 20 years (Clack & Minnaar, 2018). These factors compound the risks experienced by already vulnerable people in rural areas.

2.1.2 Agricultural advancements and rural development initiatives

The Green Revolution marks a time when agriculture and food production increased significantly through the introduction of high-yielding crop varieties, predominantly wheat (*Triticum aestivum*), rice (*Oryza sativa*) and maize (*Zea mays*). These advancements were supported by the use of agrochemicals including synthetic fertilisers and selective poisons such as herbicides, pesticides and fungicides, alongside controlled irrigation methods and mechanisation in the 1960s (Brinkley & Morris, 1997). The new technology meant that farmers could begin 'double cropping', planting two consecutive crops on the same land to increase their annual yield (Paddock, 1970). The cereal crop yield tripled, with only a 30% increase in cultivated land areas (John & Babu, 2021). This intensification reduced the need for land conversion, thereby limiting further habitat loss and a its associated impacts on biodiversity and ecosystem services (Searchinger et al., 2019).

The Green Revolution reduced food insecurity, alleviated rural poverty and increased economic stability in various developing regions, particularly in Asia and Latin America. In Mexico, the introduction of high-yielding wheat varieties and improved practices resulted in production meeting domestic demand by the late 1960s (Evenson & Gollin, 2003). In India, the introduction of wheat and rice varieties, alongside expanded irrigation and increased fertiliser and pesticide use, increased grain production to address food shortages and rural poverty (Pingali, 2012; Hazell, 2009). Similarly, the Philippines increased rice yields through the dissemination of new high-yielding varieties developed by the International Rice Research Institute (IRRI) (Pingali, 2012). However, the benefits of the Green Revolution were not evenly distributed across regions (Carter, 2021). Robust institutional frameworks, infrastructure investments and supportive policies in countries such as India and the Philippines enabled greater increases in agricultural productivity (Pingali, 2012). In SSA, reliance on rain-fed agriculture, limited infrastructure, diverse agro-ecological conditions and lower levels if investment and policy support constrained the adoption of Green Revolution technologies (Pretty et al., 2011; Jayne et al., 2019). In 1960, the yield gap between SSA and regions such as Asia and South America was under half a tonne per hectare. By 2017, this disparity had expanded to three tonnes per hectare (Gegenbach et al. 2017). In the 1990's, ~17% of the global population living in poverty resided in SSA; by 2018 this proportion had increased to ~51% (World Bank, 2018). According to Gegenbach et al. (2017) this region remains the most food insecure area in the world.

The intensification of agriculture exerts a dual impact on crop yields, demonstrating positive short-term effects of increased production attributable to the introduction of synthetic fertilisers, herbicides, pesticides, and improved plant and livestock varieties (Ramankutty et al., 2018). However, in the long term, this intensification causes negative consequences, stemming from the overexploitation of natural resources, chemical pollution, and biodiversity loss (Brussaard et al., 2010). The nutritional value of crops is also

affected by these diverse and interconnected influences associated with agricultural intensification. Despite increased caloric availability, micronutrient deficiencies and malnutrition are on the rise (Myers et al., 2017). It has been found that protein, zinc, iron, phosphorus, potassium, calcium, magnesium, copper and manganese concentrations are often lower in crops grown under intensive agricultural systems compared to traditional farming practices (Davis et al., 2004; Fan et al., 2008; Myers et al., 2014; Pingali, 2012; and Das & Mandal, 2015). A diet deficient in calories, protein or micronutrients results in malnutrition, which can lead to an increase in disease and other adverse outcomes (Ramankutty et al., 2018; WHO, 2021).

The use of selective and non-selective poisons results in chemical residues on crops and in the soil as well as chemical contamination of water resources (John & Babu, 2021). The authors explain that soil microorganism populations also decrease dramatically, resulting in diminished soil health, and even more aggressive use of fertilisers. These practices have negatively affected biodiversity by disrupting insect populations, contributing to pest infestations and increasing dependence on pesticide applications. The intensified use of chemicals has led to the development of resistance in pests and diseases, diminishing the efficacy of these chemicals in controlling infestations and outbreaks (Pingali, 2012). The primary production of agrichemicals as well as the mechanisation of agriculture releases GHGs, further worsening environmental challenges. Human health has also been impacted, with exposure to agrichemicals and consumption of products containing chemical residues linked to various health issues (John & Babu, 2021).

In response to rural poverty, African countries signed the Maputo Declaration in 2003, committing to invest a minimum of 10% of national budgets to rural development policies and agricultural growth (African Union, 2003). The Alliance for a Green Revolution in Africa (AGRA) was thus established in 2006 by the United Nations (Carter et al, 2021), co-funded by the Gates and Rockefeller Foundations (Gengenbach et al., 2018). Ten countries have since also introduced input subsidy programmes to assist farmers with Green Revolution technologies, predominantly by providing improved and GM seed and fertiliser products at below market rates (Schnurr, 2019). While AGRA has attempted to integrate smallholder farmers into the international food system economy, the initiative has been criticised for taking a top-down approach that does not prioritise the needs of the farmers themselves (Vicedom & Wynberg, 2023). Vicedom and Wynberg (2023) argue that AGRA has been unsuccessful in stimulating sustainable agricultural reforms in Africa because of a linear political and corporate bias that is not inclusive and aims to influence environmental governance processes both on national and international platforms.

A more grassroots movement that takes a bottom-up approach led to the Declaration of Nyéléni in 2007, signed by representatives of 80 countries who met for the International Forum for Food Sovereignty in Mali to advocate global food sovereignty. The Declaration of Nyéléni provides a comprehensive exposition of the tenets and objectives of the food sovereignty movement. It places a focus on people's right to control their own food and agricultural systems, safeguard their natural resources, and have access to nutritionally dense food that is culturally appropriate (Declaration of Nyéléni, 2007). Another movement, the New Green Revolution for Africa (GR4A), (Gegenbach et al., 2017), is an alliance between governments, the G8 and

philanthropic foundations aimed at reducing food insecurity in SSA by integrating smallholder farmers into more formal markets and providing access to modern inputs. Gegenbach et al. (2017) explain that even though the role of women in the SSA agricultural sector (see 2.1.1 The most vulnerable populations) is acknowledged, GR4A assumes that increasing crop yield is the most important factor in achieving food security. However, the authors argue that there are a variety of complex factors such as cultural background, social hierarchy and gender dynamics that play an even more crucial role. Similar to AGRA, GR4A has been criticised for taking a top-down approach centred on Global North approaches rather than looking at the complex challenges and needs of the farmers it intends to help. Bradshaw et al. (2021) argue that developing comprehensive global policies to foster climate change mitigation and adaptation practices presents challenges due to disparities in wealth, consumption, and geographic land and climate conditions. Nevertheless, they assert that addressing systemic issues in the global economy to address inequality and poverty is integral to environmental sustainability and human survival (Bradshaw et al., 2021).

Several trade initiatives and policies have been established, such as the Bio Trade Initiative, set up at a United Nations Conference on Trade Development that encourages countries to integrate conservation and economic development (Ortiz et al., 2021). Fair Trade International is another example of an initiative for sustainable agriculture that prioritises farmers and their livelihoods, although the benefits often do not reach farm worker level (Meemken et al., 2019). The need to produce more food for a growing population with increasing wealth desiring a more diverse diet, while land and water resources become increasingly scarce, poses a challenge for policymakers and other stakeholders (Ahmadzai et al., 2002). In addition, the agricultural sector's challenges, such as climate change and land and resource scarcity, will increase the need to pay attention to resource-poor, marginal areas for food security, poverty alleviation, and biodiversity. Increased wealth can have both positive and negative effects on food availability, prices, and agricultural production. Agriculture is a significant source of employment and income in the Global South, as well as a major contributor to national gross domestic product (GDP).

Agricultural frameworks and policies have traditionally prioritised yield increases in high-potential areas dominated by monoculture practices (Ortiz et al., 2021). While these intensive agricultural practices have successfully increased food production, they have also led to environmental challenges in many areas, including soil salinization from irrigation practices and impacts from long-term agrochemical use (Mateo-Sagasta et al., 2017; Zhu et al., 2019). Studies have shown that intensive agriculture can affect soil health, water quality, and ecosystem functioning through various pathways including soil degradation, nutrient leaching, and changes in soil microbial communities (Singh, 2018). While the environmental impacts of the original Green Revolution raise valid concerns, SSA's current position provides an opportunity to develop agricultural systems that both address urgent food security needs and maintain environmental sustainability (Nagendra et al., 2018). This could allow SSA to pursue agricultural development pathways that learn from both the successes and mistakes of the original Green Revolution, while adapting solutions to local conditions and cultural structures. In their paper, Nagendra et al. (2018) suggest that the concept of leapfrogging is the potential for developing countries to bypass conventional developmental phases observed in developed countries in the Global North. The need to increase agricultural produce to reduce

hunger and ensure future food security, while restricting land use change, presents opportunities for SSA to find sustainable solutions specific to local conditions and cultural structures.

Policies surrounding agriculture and support for, or discrimination of, farmers in South Africa mainly pertain to land tenure, starting with the Native Lands Act of 1913, which dictated the size and location of land that indigenous South Africans could occupy (Gwiriri et al., 2019), giving preference of large tracts of arable land to white farmers (Johnston et al., 2024). This set the stage for South Africa's present day dual agricultural economy, characterised by major commercial farms producing the majority of the country's agricultural output, coexisting with a vast number of small-scale farms that are mostly unable to function beyond levels of subsistence (Strydom et al, 2019). Gwiriri et al. (2019) report that the policies that followed since the abolishment of Apartheid, intended to reform the agricultural landscape and assist small-scale farmers to gain access to land and become more commercial, have not made a big enough impact. The authors argue that the policies are not defined enough and allow for the "capture" of land and resources by an "elite" portion of the population who are already financially savvy, leaving subsistence farmers to fall through the cracks (Gwiriri et al., 2019). While the government provides some support for these farmers in the form of agricultural extension services, the provision of planting material and veterinary services, there is a deficiency in funding to effectively assist them to become more competitive in the current market (Johnston et al., 2024).

2.1.3 Water resources

Food production depends on access to water in the form of precipitation, irrigation from dams and rivers, or extraction of groundwater reserves (Calzadilla et al., 2013). Calzadilla et al. 2013 explain that changes in precipitation and surface temperatures affect soil moisture content, while an increase in surface water runoff influences river flow and groundwater resources. Over-abstraction of groundwater resources lowers groundwater tables and will cause intrusion of salty water in coastal regions, limiting irrigation options in areas where water is already in short supply (Rosegrant et al., 2009). The UN World Water Development Report (2018) highlights projections indicating a significant rise in water scarcity attributable to climate change, while demand for water is projected to increase by one third by 2050. According to the report, water scarcity is defined as an inadequate availability of freshwater to meet the needs of both society and the environment, or as insufficient access to safe water resources (UN Water, 2018).

Agriculture is both the largest user and polluter of freshwater resources worldwide (Mateo-Sagasta et al., 2017; Rosegrant et al., 2009). One of the most significant negative impacts of agriculture on water resources is the leaching of agro-chemicals and nutrients into surface water and groundwater bodies, alongside the accumulation of agricultural sediments carried to water bodies by soil erosion (Zahoor & Mushtaq, 2023; Evans et al., 2019). Rivers across all continents show evidence of agricultural impacts: in Asia, Africa, and Latin America, increasing levels of pollution have been documented since the 1990s (UNEP, 2021; UN Water, 2018); in North America, the Mississippi River system shows extensive nutrient pollution from agricultural runoff (Stackpoole et al., 2019); and in Australia, the Murray-Darling Basin faces ongoing challenges with agricultural pollutants and salinization (Chen et al., 2020). Irrigated crops and

pastures are the largest users of freshwater supplies within the agricultural sector, responsible for 70% of blue water withdrawals (Rosegrant et al., 2009). Enhancements in irrigation infrastructure have played a pivotal role in fostering agricultural price stability, elevating crop yields, and fortifying food security (Calzadilla et al., 2013). While rain-fed agriculture, dependent on soil moisture levels and seasonal precipitation, remains the predominant source of global food supply (FAO, 2016), both rain-fed and irrigated systems face distinct but significant climate change vulnerabilities. Rain-fed agriculture is particularly susceptible to precipitation variability, including extreme rainfall events and drought (Calzadilla et al., 2013). Although irrigated agriculture offers some buffer against climate-related shocks such as heat waves and short-term drought, it faces long-term risks from groundwater depletion and declining surface water availability (Taylor et al., 2013). During extended drought periods, both systems are stressed as insufficient precipitation fails to replenish surface and groundwater sources (Calzadilla et al., 2013). While historical approaches focused on developing new water supplies (Rosegrant et al., 2009), current strategies emphasize water reallocation, reuse, and recycling initiatives to address growing water scarcity challenges (Bjornlund & Bjornlund, 2019).

According to the 2023 United Nations World Water Development Report (UN Water, 2023), almost four million people in SSA live without access to safe drinking water, particularly people living in rural areas (UN Water, 2023). South Africa is considered a water scarce country, and a national Department of Water and Sanitation report estimates that water demand will exceed availability in some catchments by 2025 (DWS, 2017). Agriculture in South Africa is mostly rain-fed or reliant on stored water for irrigation, making it vulnerable to changes in the climate. Major rivers and dams provide water for high value horticultural crops (including vegetables and fruit) via regulated water supply schemes, often also serving urban centres (Edokpayi et al., 2020). However, in periods of water scarcity due to drought, priority is granted to household water consumption over agricultural use (Johnston et al., 2024). Rural and low-income areas in South Africa are particularly vulnerable to water shortages, many lacking essential water supply and sanitation infrastructure, or facing issues with water quality (Edokpayi et al., 2020). There are also negative environmental impacts that result from reduced water quality and availability (Skowno et al., 2018). According to the 2018 National Biodiversity Assessment report, 30% of South Africa's estuaries have been negatively affected by agricultural and other pollution, which in turn impacts marine ecosystems (Skowno et al., 2018).

2.2 ADVERSE IMPACTS AND OPPORTUNITIES

2.2.1 Climate risks

Globally, climates have become warmer and drier overall as a result of anthropogenic climate change (Roberts & Craig, 2022). The authors argue that temperature increases will accelerate permafrost melting and cause a cascading effect, and that this rapid release of carbon stored in the permafrost into the atmosphere will compromise the integrity of boreal forests, cause sea levels to rise, and displace coastal

communities and ecosystems. They add that climate change causes tropical regions to become hotter and drier. Fragile ecosystems will become more susceptible to climate extremes, disrupting their natural cycles (Rockström et al., 2009). According to the IPCC the majority will be unable to adapt quickly enough and will either perish or relocate as the climate changes (IPCC, 2019). Extreme weather events, such as floods, heat waves, droughts and cyclones are becoming more frequent as a result of anthropogenic climate change, and this trend will continue (UN World Water Development Report, 2018).

This will impact food security, ecosystems, land processes, and the fluxes of GHGs (IPCC, 2019). The 2019 IPCC report asserts that elevated temperatures will increase the number of wildfires, resulting in further economic losses, food insecurity, biodiversity loss and GHG emissions. Furthermore, the report asserts that loss of vegetation due to drought, frequent heat waves, and wildfires will increase water runoff and soil erosion, which is exacerbated by increased rainfall or flooding. Erosion causes land degradation, which in turn increases albedo and additional heating of the atmosphere. Land degradation and loss of vegetation reduces the capacity for carbon sequestration, which has the potential to further exacerbate localised climate change (IPCC, 2019). In addition, the seeds of many invasive alien plants germinate readily on degraded land or when exposed to fire, forming impenetrable thickets on agricultural land (Adams et al., 2010). For example, the encroachment of alien invasive species has increased by 20% on commercial farms and by 10% on small-scale farms in South Africa in the last 60 years (Trisos et al., 2022). As extreme weather conditions and interdependence increase, so do the risks of food system disruptions. Climate change affects the quantity and quality of food produced by the agricultural sector, with yields negatively affected by extreme weather events, air pollution, pest infestations, and pathogens (Meyers et al., 2017). These are some examples of causal feedback loops between climate change, agriculture and biodiversity described by Ortiz et al. (2021), which the authors argue are not understood well enough to predict the implications accurately. The impact of climate change is expected to affect Africa disproportionately compared to the rest of the world, and in relation to the continent's overall contribution to climate change (Nyiwul, 2020).

Climate change is projected to exacerbate the inherent climate variability experienced in southern Africa, with more frequent droughts and other extreme weather events (Roberts & Craig, 2022). The climate of southern Africa is diverse and complex due to its varied topography, proximity to the Atlantic and Indian Oceans, prevailing trade winds and latitudinal orientation, creating distinct climate zones (Reason, 2017). According to the Köppen-Geiger Climate Classification system, the five predominant zones include tropical, dry, temperate, continental and polar climates (Beck et al., 2018), across four distinct geographical regions, the western plateau slopes, the Cape Fold Belt, the interior plateau and the eastern plateau slopes (Climate Knowledge Portal, 2021).

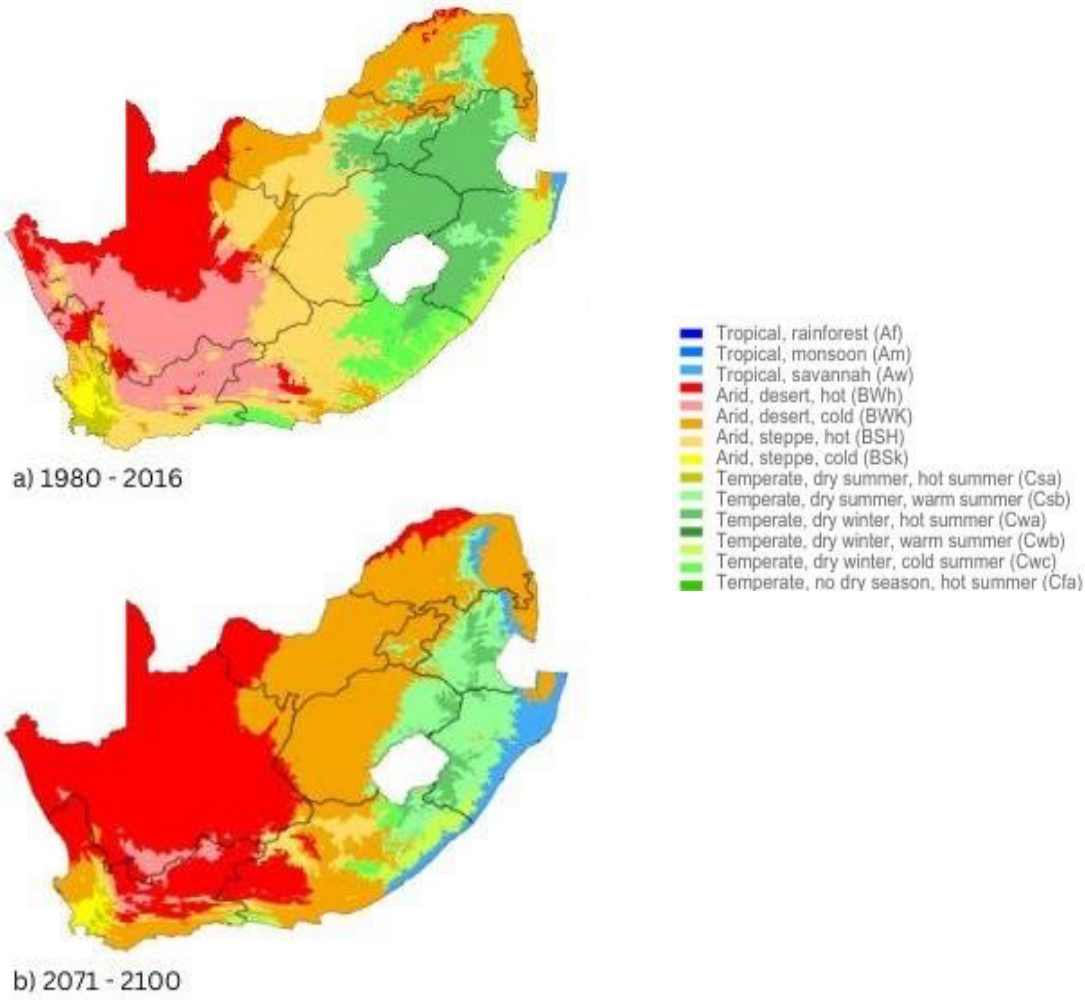

Figure 3. Köppen-Geiger Climate Classification maps for South Africa*: a) present 1980 - 2016; and b) future 2071 -* 2100 (*adapted from Beck et al., 2018).*

The availability of moisture in the soil for crop production is projected to decrease throughout southern Africa, even in areas where an increased overall precipitation is projected (Landman et al., 2017). In South Africa, the average inland temperature is anticipated to be 2°C to 4°C hotter than pre-industrial temperatures by 2050, which is twice the average global temperature increase, and annual rainfall could decrease by more than 60 mm per annum in the majority of the country's western and northern regions (NBI, 2021). Anthropogenic climate change is the primary catalyst for the increase in extreme weather events in South Africa, in particular heat waves, droughts and flooding (Johnston et al., 2024). Johnston et al (2024) explain that climate change affects society, agriculture, the economy and ecosystems both directly and indirectly, and that the risks and severity of the implications depend on factors such as income, demographic and location (Johnston et al., 2024).

2.2.2 Farming systems

The agro-industrial and monoculture cropping systems have caused unprecedented ecosystem destruction, including biodiversity loss, land degradation, over-abstraction of water, and chemical contamination of soil and water, and have contributed significantly to climate change (Mukhovi & Jacobi, 2022). Ortiz et al. (2021)

argue that while these industrial farming systems have led to an increase in food security, improved livelihoods, and economic stability in some areas as a result of the Green Revolution, the global food system is characterised by inherently complex exchanges and interactions within the agriculture-environment-trade nexus that remain insufficiently understood, and result in both long and short term negative effects (Ortiz et al., 2021). Agricultural GHG emissions that contribute directly to climate change stem from various sources, including fertilisers, ruminant digestion, crop cultivation, and the use of fossil fuels (Beddington et al., 2012). Beddington et al. (2012) assert that the clearing of land for agricultural purposes, particularly through deforestation, also makes a substantial contribution to atmospheric GHGs.

Agricultural systems in developing countries face multiple challenges, including inherently poor soil fertility in many regions, low or unreliable rainfall, and increased vulnerability to climate change impacts (Mbow et al., 2014; Vanlauwe et al., 2015). While agricultural intensification has increased productivity in some areas, many regions struggle with fundamental resource constraints that limit agricultural potential regardless of farming methods (Tittonell & Giller, 2013). The global food system faces multiple interconnected challenges: increasing production to sustain a growing population, adapting to climate change impacts, managing land use change, and developing context-appropriate agricultural practices that work within local environmental limitations (Beddington et al., 2012; Ortiz et al., 2021).As a result of the growing need to mitigate the negative ecological impacts of the conventional intensification of agriculture, there is widespread interest in the promotion and development of more sustainable agricultural practices (Garibaldi et al., 2017; HLPE, 2019) that consider the true cost of global agrifood systems (FAO, 2023). Sustainable agriculture is often used as an umbrella term that includes various types of non-industrial and traditional farming methods (Garibaldi et al., 2017). Sustainable agriculture encompasses various farming approaches that aim to minimize environmental impact while maintaining productivity (Garibaldi et al., 2017). These include established systems like organic agriculture, which prohibits synthetic inputs; biodynamic agriculture, which integrates ecological and holistic management principles including cosmic rhythms (Reganold, 1995); and conservation agriculture, which focuses on minimal soil disturbance and permanent soil cover (FAO, 2017). While technological innovations like sustainable intensification and precision agriculture focus on resource optimization (Tittonell et al., 2022), three approaches — agroecology, regenerative agriculture, and agroforestry — have gained particular attention for their holistic approach to agricultural sustainability (Tittonell et al., 2022 and Mbow et al., 2013).

These approaches share several agricultural and environmental practices, including the combination of both annual and perennial crops and other plants such as multi-purpose trees and shrubs, which increase biodiversity and photosynthetic potential, the restoration of soil, ecosystem services and biological interactions (Tittonell et al., 2022). There are, however, some important differences. Agroecology and agroforestry are rooted in traditional practices and are most often associated with small-holder or subsistence farming systems in developing countries (Tittonell et al., 2022, Mbow et al., 2013 and Garibaldi et al., 2016). Agroecology has a generally accepted and clear definition. According to a report by the High

Level Panel of Experts on Food Security and Nutrition (HLPE, 2019), agroecology is based on three distinct tenets:

1. Science: i) the study of the global food system, including economic, social and ecological aspects; ii) the application of ecological concepts and principles to the design and management of sustainable food systems; and iii) the amalgamation of research, action and education aimed at instilling reform and sustainability to all parts of the food system: economic, social and ecological.
2. Practice: leveraging functions of nature, fostering beneficial synergistic biological interactions and utilising ecosystem services and processes as well as the implementation and development of these practices.
3. Social movement: respond to climate change and malnutrition, transform the 'industrial' model to construct locally appropriate food systems that boost economic sustainability in rural areas through short marketing chains and fair and safe food production. Supporting diverse forms of smallholder and family farming methods to endorse rural communities, food sovereignty, social justice, local culture and identity and rights to indigenous seed and breeds.

Regenerative agriculture and agroforestry on the other hand, often lack the wider social and political factors, but they are scalable to commercial operations and offer a solution to reducing GHG emissions and sequestering carbon on a large scale (Giller et al., 2021; Tittonell et al., 2022 and Mbow et al., 2013). Regenerative agriculture is gaining traction as increasing numbers of commercial farmers are adopting regenerative practices, particularly in the United States, Australia and parts of Europe and the United Kingdom (Cusworth et al., 2022). According to Cusworth et al. (2022), as consumers become more conscious of climate change and responsible consumption, large companies and corporations such as Burger King, Danone, Nestle, General Mills and McDonalds are following suit and starting to rebrand their agricultural image to regenerative agriculture (Cusworth et al., 2022). According to Tittonell et al. (2022), the majority of smallholder farmers in SSA use mixed cropping systems with a livestock component and very few external inputs, allowing for greater biodiversity. These agricultural sectors face multiple challenges that extend beyond investment levels. While research and development is important, agricultural development is influenced by a complex web of factors including institutional capacity, policy frameworks, market access, land tenure security, infrastructure limitations, knowledge transfer systems, and socio-economic constraints (Pingali et al., 2019; Barrett et al., 2020). Furthermore, the relationship between agricultural investment and food security is mediated by various factors including governance structures, distribution systems, and local capacity to implement new technologies (Yunusa et al., 2018; World Bank, 2021). The effectiveness of agricultural support also depends on its appropriateness to local contexts, including environmental conditions, cultural practices and existing farming systems.

Agriculture is a major economic driver in South Africa, accounting for 10% of total exports, and contributes significantly to the country's GDP, constituting ~3% in 2021/2022 (Johnston et al., 2024; Statista, 2023). However, the sector declined by ~10% in 2023, mainly due to an avian flu outbreak affecting the poultry industry, and floods in the Western Cape affecting field crops (Stats SA, 2023). The agricultural industry employs ~21% of the total number of people employed in the country, with the Western Cape providing the

highest rates of employment and salaries paid, as well as contributing the most economically (Johnston et al., 2024; Stats SA, 2022). Approximately 80% of South Africa's total land area is designated for agricultural purposes, ~75% of which is under commercial agriculture (Johnston et al., 2024; FAO, 2013).

2.2.3 Biophysical stresses

The escalation in food demand due to population growth and increased consumption in high income countries has led to the rapid expansion of agriculture and consequential alterations in land use, exerting adverse impacts on the ecosystem services upon which agriculture depends (Bradshaw et al., 2021). Ecosystem services also provide vital sources of sustenance and pharmaceutical resources in both advanced and emerging economies, as well as supporting tourism and recreation sectors (Constanza et al., 2014). Constanza et al. (2014) assert that global assessments indicate that the overall economic worth of ecosystem services exceeds USD 125 trillion annually, nearly twice the value of the global economy.

The impacts of agricultural intensification on biodiversity vary depending on the specific practices employed, local contexts, and management approaches (Kremen & Miles, 2012). While some forms of intensive farming can reduce biodiversity through habitat loss, chemical inputs, and landscape simplification (Ramankutty et al., 2018), well-managed intensive systems can maintain biodiversity through integrated approaches such as field margins, habitat corridors, and conservation areas (Tscharntke et al., 2021). These agricultural landscapes and their biodiversity influence the distribution and prevalence of pests and diseases, which pose significant challenges to natural resources, agricultural productivity, and ecosystem services (Campbell et al., 2023). For example, plant pathogens can disrupt ecosystems severely enough to contribute to food insecurity and displacement, with estimated global economic impacts of USD 220 billion (FAO, 2021; Campbell et al., 2023).

Agricultural fertiliser use, particularly nitrogen-based fertiliser, contributes to environmental impacts through multiple pathways. Nitrogen fertilizers directly release nitrous oxide into the atmosphere, while both nitrogen and phosphorus fertilizers can cause environmental pollution and degrade freshwater and marine ecosystems through runoff and leaching (Robertson et al., 2013; Rockström et al., 2009). Rockström et al. (2009) argue that anthropogenic activities have elevated the rate of biodiversity loss to a magnitude comparable to that observed during the last worldwide mass extinction. A rapid decline in biodiversity reduces the efficacy of the ecosystem services it provides, resulting in reduced air and water quality, soil degradation, wildfires, decreases in pollination of important food crops, reduced carbon sequestration and increased occurrence and severity of floods (Bradshaw et al., 2021). Modern farming systems play a substantial role in exacerbating climate change (Bradshaw et al., 2021) and thus contribute significantly to disruptions in planetary environmental stability that could cause irreversible damage and be detrimental to civilisation (Rockström et al., 2009).

Even though nearly 14% of the planet's surface is protected, with over 130 000 distinct protected areas, biodiversity loss has continued unabated (Brussaard et al., 2010). The authors argue that while this is partly due to the appropriation of more land for development and agriculture, isolated protected areas are unable

to meet all habitat needs to maintain sufficient biodiversity (Brussaard et al., 2010). Even though above-ground biodiversity has been extensively studied, it is not fully understood due to the intricate interdependencies between habitats, fauna, and flora populations (Cappelli et al., 2022). Cappelli et al. (2022) argue that biodiversity below ground is even less understood, despite its potential to help sequester carbon and improve the sustainability of agriculture.

South Africa has a rich biodiversity heritage, hosting three out of the 36 biodiversity hotspots recognised globally (Johnston et al., 2024), and this biodiversity contributes to the country's economy, to society and to the wellbeing of its people (Skowno et al., 2018). According to the 2018 National Biodiversity Assessment report, around half of all ecosystems are threatened in South Africa, with inland wetlands and river systems being the most threatened, while 12% of all animals and 14% of all plants are listed as threatened (Skowno et al., 2018). The report asserts that biodiversity and healthy ecosystems provide resilience against the risks associated with climate change (Skowno et al., 2018). As biodiversity supports agricultural processes and services, it is essential to understand and enhance the role of a healthy ecosystem within the food system (Brussaard et al., 2010), to avoid the cascading effects that are likely to occur (Campbell et al., 2023).

2.3 OPPORTUNITIES FOR INCREASED SUSTAINABILITY IN AGRICULTURE

2.3.1 Fodder trees

Farmers across Africa have long incorporated tree foliage into the diets of their livestock, utilising indigenous trees present on their farms (Franzel et al., 2014) as part of traditional mixed cropping systems (Tittonell et al., 2022). In developing countries, livestock are inextricably linked to the sustenance of rural livelihoods and local economies, and often constitute the primary asset that rural households possess (Herrero et al., 2012). According to Herrero et al. (2012), livestock serve not only as a trade commodity and a source of manure for crop cultivation, as well as for traction for ploughing and transportation, but also as a critical provider of nutrient-dense food. In smallholder livestock systems, which are typical in rural areas in developing countries, lack of sufficient protein is the predominant limiting factor in animal nutrition (Mekonnen et al., 2021). Research on established tree-livestock systems demonstrates that woody fodder species can improve animal nutrition while providing environmental benefits (Jose et al., 2019). These systems are valuable in semi-arid regions where conventional pasture productivity is limited (Murgueitio et al., 2011). New, multi-purpose tree species have been introduced in the last few decades, with higher nutritional content to increase fodder value, to provide firewood and contribute to sustainable land management, but adoption has remained relatively low (Wambugu et al., 2011; Franzel et al., 2014). Fodder trees can also provide bee fodder for apiculture (beekeeping), planting and fencing stakes as well as boundary hedges, which also act as wildlife corridors, shade for livestock and windbreaks (Wambugu et al., 2011). According to Wambagu et al. (2011), the contribution of fodder trees to small-scale farmers in developing countries is estimated to be USD 3.8 million per annum, and the estimated potential income is

USD 81 million. Woody leguminous shrubs and trees are generally planted in SSA as semi-permanent features around property and field boundaries as part of agroforestry practices (Dawson et al., 2014).

Herbaceous leguminous plants are used in some parts of SSA in intercropping systems with maize, wheat, sorghum, millet and root crops (Hassen et al., 2017). Hassen et al. (2017) explain that legume intercropping reduces soil erosion, retains soil moisture, and improves soil fertility and biodiversity through a symbiotic relationship with microorganisms that fix N into the soil. While legumes' nitrogen-fixing capabilities can reduce the need for N fertilisers when intercropped with cereals, other essential nutrients such as P, K, and S may be required either through fertilisers or other sources to maintain optimal plant growth (Hassen et al., 2017; Wambugu et al., 2011; Vanlauwe et al., 2019). Nevertheless, the reduction in nitrogen fertilizer use through legume intercropping can help decrease both agricultural input costs and GHG emissions associated with N fertiliser production and application. Furthermore, studies have shown that there is an increased phosphorus uptake due to nitrogen fixing enzymatic activity (Wambugu et al., 2011). Soil biodiversity aids crop growth and disease and fungus resistance (Cappelli et al., 2022). The symbiotic relationship between the roots of legumes and rhizobium bacteria[1] in the soil is well documented and is recognised as integral to preserving soil fertility and bolstering crop yields, thereby promoting agricultural sustainability (Liu et al., 2023; Yadav, 2021; Wambugu et al., 2011). In a recent study, Liu et al. (2023) found that arbuscular mycorrhizal fungi[3] and rhizobia also form symbiotic relationships with each other to stimulate their colonisation in plant roots, further enhancing nitrogen fixation and plant growth. This reinforces the argument that biodiversity above and below ground is integral to sustainable agricultural pathways and underpins the health of the soil (Capelli et al. 2022; Ortiz et al. 2021; Hassen et al., 2017).

Fodder trees have the potential to alleviate production deficits during periods of severe climatic conditions, such as droughts (Franzel et al., 2014). However, Franzel et al., (2014) explain that some fodder plants that are already widely cultivated as feed for livestock contain lower protein levels than other species that would be equally suited to the purpose and growing conditions. Expanded utilisation of fodder trees to supplement or substitute other feed options presents opportunities for mitigation through improved dietary intake, carbon sequestration and reduced concentrate consumption (Dawson et al., 2014). Fodder trees with high protein content increase dairy and meat production (Franzel et al., 2014). Figure 4 illustrates how increased use of fodder trees for feeding dairy cows contributes to climate change mitigation by reducing greenhouse gas emissions through carbon sequestration, reduced reliance on conventional feeds, and enhanced dairy enterprise efficiency.

[1] Rhizobium bacteria are a genus of soil microorganisms specific to leguminous plants (Lodwig & Poole, 2003). [3] Arbuscular mycorrhizal fungi are among the most ubiquitous organisms on Earth, forming symbiotic relationships with many terrestrial plants across most terrestrial ecosystems, spanning from subpolar regions to tropical rainforests, and occasionally occurring in aquatic ecosystems (Rosendahl, 2008; Smith & Smith, 2012).

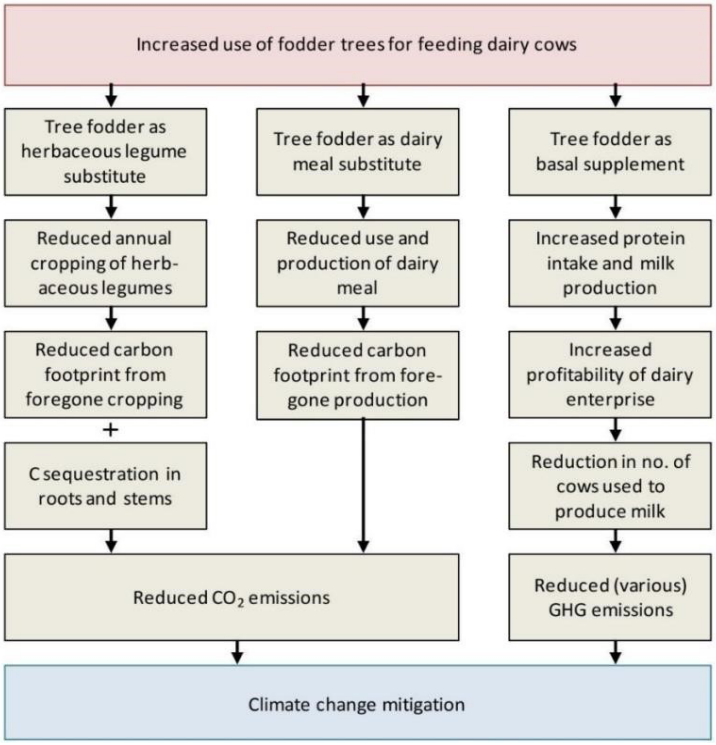

Figure 4. Possible scenarios for fodder trees to contribute to climate change mitigation in dairy farming *(Dawson et al., 2014)*

Globally, agriculture and livestock production are responsible for 70% of ground water withdrawals for the irrigation of livestock feed crops, contribute up to 26% of total GHG emissions and take up almost 50% of habitable land available (Castonguay et al., 2023). Habitable land is defined as land that is ice- and desert-free, encompassing various ecosystems such as forests, shrublands and grasslands (Our World in Data, 2024). While both herbaceous and woody leguminous plants have the potential to reduce GHG emissions in agriculture, improve biodiversity, increase production and sequester carbon, their effectiveness depends on soil conditions, particularly pH levels (Mahon et al., 2017; Tang & Yu, 1999). In suitable soil conditions, fodder trees can be more resilient to climate variability and drought than annual crops, presenting a potential adaptive response to climate change (Dawson et al., 2014). The use of high protein fodder shrubs and trees for these varied uses can be referred to as fodder tree technology (Hughes et al., 2022).

2.3.2 Tagasaste: classification and uses

Tagasaste is classified as an evergreen woody leguminous shrub or tree and is a member of the Fabaceae family. It is endemic to La Palma in the Canary Islands (Heuzè et al., 2017; Orwa et al., 2009; Snook, 1986), where it grows mostly in mediterranean or temperate climatic zones[2] (Orwa et al., 2009; González-Rodrıguez et al., 2005). It presents wide genomic variability as it can have an upright or prostate/weeping habit and grows to a height of up to 7m (Tozer et al., 2022; Heuzè et al., 2017). Some selections have been developed from specific tagasaste populations exhibiting favourable morphological traits, such as growth

[2] The climate of the Canary Islands archipelago varies from cold to semi-arid (Bechtel, 2016).

rate, habit or hardiness to different environmental conditions (Douglas et al., 1998). Leaves are grey-green and trifoliate, with trichomes (small hairs). It flowers indeterminately from mid-winter to early summer and produces white pea-like flowers in abundance (Heuzè et al., 2017; Orwa et al., 2009). Flowers can both cross- and self-pollinate (Cook et al., 2020; Tropical Forages, 2020). The seed pods ripen in summer and tend to burst open during high summer temperatures (Tropical Forages, 2020). Each pod is about 5cm in length and contains about six to ten small black seeds, with approximately 45,000 seeds per kilogram. Seeds are hard-coated and require scarification for successful germination (Heuzè et al., 2017). In nature, scarification can take a number of years to occur though processes of weathering, ingestion by animals or insects, or through microorganism activity. For agricultural or commercial seed production, artificial scarification methods are often used to break seed dormancy and achieve rapid, uniform germination rates (Orwa et al., 2009; Schmidt, 2000). These methods include acid treatment, hot water immersion, mechanical abrasion of the seed coat, or precise nicking of the seed coat using tools.

The scientific nomenclature for tagasaste is somewhat vague, and various sources have listed it as: *Chamaecytisus proliferus, Chamaecytisus prolifer, Cytisus palmensis* or *Cytisus proliferus*, with no obvious authoritative accuracy. In a literature review that looks at research on tagasaste from 1862 to 1991, Francesco-Ortega et al. (1991) describe tagasaste as forming part of a taxonomic complex of *Chamaecytisus proliferous*, and that its full botanical classification is *Chamaecytisus proliferous ssp. palmensis* (Christ) Kunkel, and this nomenclature is also listed on the Royal Botanic Gardens Plants of the World Online database (POWO, 2024). Common names include tagasaste, lucerne tree or tree lucerne, silky cytisus, false lucerne and boomlusern or lusernboom (South Africa), with tagasaste being the most internationally accepted common name (Francisco-Ortega et al., 1993). For this reason, the name tagasaste is used herein.

Tagasaste is considered a pioneer plant[3], and is therefore adaptable to a wide variety of conditions. It is tolerant to drought conditions and can survive dryland conditions in semi-arid areas with average annual rainfall as low as 200 mm yr^{-1}, but grows most actively with average annual rainfall of 600-1600 mm yr^{-1} (Tozer et al., 2022 ; Cook et al., 2020; Orwa et al., 2009). It grows at altitudes from sea level up to 3000 metres above sea level (Tozer et al., 2022; Bezabih & Mekonnen, 2019; Orwa et al., 2009). Tagasaste thrives in pH ranging from 5 to 7, but it can withstand soil of pH 4 to pH 8.5. Plants grow most actively in temperatures ranging from 20°C to 36°C but can endure temperatures above 50°C and as cold as -15°C (Orwa et al., 2009). Seedlings and small plants are less tolerant to frost (Cook et al., 2020; Tozer et al., 2022 and Orwa et al., 2009). Tagasaste prefers well drained soils, because it is susceptible to fungal infections caused by *Fusarium* and *Phytophthora*, particularly in poorly drained soils where waterlogging creates anaerobic conditions (Orwa et al., 2009). The longevity of plants can be up to sixty to eighty years (Heuzè et al., 2017), however, in waterlogged plants live up to eight to ten years (Tozer et al., 2021). Stem borer insects can negatively affect mature plants and decrease their longevity, particularly under harsh

[3] Pioneer plants are the first to colonise areas that have been disturbed by human-induced or natural disruptions and play an important role in regenerating ecological processes (Ye et al., 2021).

conditions. While capable of naturalising in suitable environments, particularly disturbed sites with adequate rainfall, tagasaste is not considered a major invasive threat (Randall, 2017). Its spread is generally limited by specific soil and climate requirements, and it primarily establishes near intentional plantings (Richardson & Rejmánek, 2011; Meyer, 2000).

The foliage, stems and small branches contain 17-22% crude protein, whereas actively growing young regrowth has crude protein levels of 25-30% (dry matter) (Tozer et al., 2022; Orwa et al., 2009). Annual yields of 15 to 20 tonnes edible dry matter can be achieved at a planting density of 1000 plants ha^{-1}, and 10 tonnes ha^{-1} yr^{-1} under dryland farming systems (Orwa et al., 2009). In New Zealand this can be up to 27 tonnes have been reported under favourable conditions with good management (Tozer et al., 2022). Drought conditions can decrease the nutritive value of leaves as well as cause leaf shedding. Tagasaste is considered to be a valuable source of minerals, in particular calcium and trace elements such as copper, iron, manganese and zinc. Most of the minerals that are essential to support a lactating ewe with one lamb can be obtained in excess from tagasaste (Tozer et al., 2022). Conversely, the Tropical Forages database (Cook et al., 2020) recommends that mineral supplements should be given to livestock due to the poor mineral content in the leaves. Unlike *Medicago sativa* (lucerne or alfalfa) and other grazing options (Azad et al., 2019), tagasaste does not cause bloat[4] in livestock (Tropical Forages, 2020). Its relatively long flowering period makes it a good apiculture plant, also because flowering starts at a time when there is often not much other available bee fodder.

Figure 5. Characteristics of tagasaste *(Chamaecytisus palmensis): 1) woody shrub or tree grows as a hedge when grazed, 2) nitrogen fixation through hosting beneficial bacteria in nodules on roots, 3) abundance of pea-like flowers turn into pods containing seed (own photos)*.

The foliage of tagasaste is not toxic (Orwa et al., 2009), however there is an overall increase of phenolic compounds (tannins) during summer and autumn as a response to heat and drought stress in winter rainfall areas (Moore et al., 2006). Phenolic compounds can disrupt the rumen microbiomes of livestock and can act as an antifeedant (feed intake is reduced) because increased tannins result in the foliage being less palatable (bitter) and decrease the digestibility of nitrogen and fibre (Moore et al., 2006; and Jeronimo et al., 2020). It was found that supplementing the diet with lupins, barley and/or urea restores rumen function

[4] Bloat is a digestive symptom that can occur in livestock grazing on pasture. Bloat is often fatal, and is a major limiting factor in conventional pasture systems (Azad et al., 2019).

in livestock (Tudor et al., 2016). On the other hand, Jeronimo et al. (2020) argue that tannins can have beneficial properties, including preventing bloat, aiding in the control of internal parasites, enhanced protein digestion and increased performance in growth, as well as milk and wool production. A rare syndrome called 'tagasaste staggers' has been observed in cattle and goats browsing tagasaste (Tudor et al., 2016). Affected livestock show signs of trembling or twitching and in severe cases may collapse and convulse, but these symptoms usually pass within 30 minutes. It is unclear what the cause of this is, but Tudor et al. (2016) suggest it could be due to certain phytotoxins that increase glucose and L-lactate, causing the tremors.

Tagasaste is known to be highly palatable and readily grazed or browsed once livestock or wildlife have become familiar with it (Wiley, 2006; and Jeronimo et al., 2020). If there is little other grazing available and livestock or wildlife gain access to young plants, it is probable that these plants would be overgrazed, causing plant mortalities due to the high palatability and nutritional value of their tender shoots, stems and leaves. Despite this, at first introduction, livestock may not readily take to feeding on tagasaste. In the 1918 Royal Botanic Gardens Bulletin, Hutchinson says that "[...] they must first of all be taught to eat it, if necessary, by a little starvation" (Hutchinson, 1918). Other approaches to encourage livestock to eat it could include simple tactics like mixing tagasaste with familiar feed or drizzling molasses on freshly cut branches (Jeronimo et al., 2020). Tagasaste can be established by direct sowing of seed or by planting seedlings (Tudor et al., 2016; and Lefroy et al., 2001).

Tagasaste was first introduced to South Africa in 1879 (Fransisco-Ortega et al., 1991), but its adoption has not been widespread, nor has it been extensively researched under South African conditions. It has, however, been determined that tagasaste grows well in both the summer and winter rainfall regions of South Africa (Lindeque and Rethman, 1998).

CHAPTER 3: MATERIAL AND METHODS

3.1 METHODOLOGY

Due to the complex nature of the research topic, a sequential data collection strategy within an integrated mixed methods approach was employed. This design enables researchers to strategically build upon results to illustrate integration of data sources and variables (Fetters et al., 2022). In a mixed methods approach, both qualitative and quantitative data are included.

A qualitative approach is generally used as an exploratory and investigative tool to gain a deeper understanding of a subject. It often consists of detailed and specific information collected from a small sampling of people through in-person engagements, interviews or surveys (Leavy, 2023). Qualitative research gathers subjective views and perspectives from a specific social group, which can be defined and targeted according to the research requirements. This approach is useful for gathering data for the research herein, because, to the researcher's knowledge at the time of writing, farmers' perspectives and experiences with tagasaste in South Africa had not been recorded formally (see literature earlier). This first-hand, subjective information can be interrogated and integrated with more linear and objective methods of data collection to provide a holistic result.

Quantitative research approaches, on the other hand, are objective and deductive, and involve collecting and analysing data from a broader sample to obtain a more statistical result on a topic (Leavy, 2023; Taherdoost, 2022). This approach can be useful to evaluate data and to add rational credence to an existing knowledge base, or to prove or disprove a theory. In this case, the approach is applied to allow the researcher to gather statistics on the main uses of tagasaste and its current adoption in South Africa, farmers' perspectives on climate change and the role of agriculture, how they make decisions of what and how to farm, and whether they think tagasaste could be used for mitigation and/or adaptation. Having these statistics helps to assess the likelihood of farmers to adopt practices or technologies in line with climate change mitigation and/or adaptation, in this case fodder tree technology.

Employing mixed methodologies enables researchers to collect rich data that would not be possible using either method alone. This helps minimise the limits of quantitative and qualitative methodologies when applied in isolation (Almeida et al, 2018). In addition, data can be presented as a combination of narrative text, tables and infographics to enable a more comprehensive understanding of its meaning. Choosing to use this approach herein is intended to provide meaningful and synergistic information (Ahmad et al., 2019) to holistically evaluate tagasaste, and its boundaries to sequester carbon and sustainably increase agricultural production in South Africa, while reducing GHG emissions and some of the negative environmental impacts associated with agriculture.

3.2 DATA

To provide a holistic and thorough study to achieve the objectives and to answer the research question posed, three data sources were used in this research, namely 1) an online survey, 2) personal communications obtained through the author's professional network and 3) secondary data. Combining these different datasets was particularly beneficial given the author's positionality to the research topic. Since 2012, the author has been cultivating tagasaste near Malmesbury in the Western Cape for their own agricultural interests and producing seeds and seedlings for sale both locally and internationally. This led to working with other farmers, private enterprises and aid organisations to provide technical assistance on the establishment and use of the crop. The survey results influenced the decision to incorporate relevant personal communications because many of the farmers expressed challenges propagating and establishing tagasaste. It was decided, together with the supervisor of this dissertation, that the feedback from clients and other farmers could add value to some of the findings. The survey and secondary data, on the other hand, allowed the author to view the topic from an unbiased perspective, which led to a more objective and comprehensive understanding.

3.2.1 Primary data

3.2.1.1 Targeted online survey

Primary data was collected via a semi-structured online survey, as set out in Annexure 1. The author targeted participants who are farmers and have either planted tagasaste or know about it and would like to plant it. The participants were identified through social media sites with agriculture as their primary focus, as well as through the author's professional network. The author's network comprises farmers with whom they have interacted during their twelve-year involvement with tagasaste. Participants were expressly requested to answer questions honestly and without personal bias. As respondents were given anonymity and only added their name or email address if they expressed an interest in receiving feedback on this research, it is difficult to gauge how many were reached specifically via the author's own network, and how many were reached through social media.

Ethical considerations were integral to the survey design to ensure compliance with ethical standards and respect for participants' rights. Participants were provided with detailed information about the study's purpose, scope, and voluntary nature at the start of the survey. Consent was obtained through a check-box mechanism, confirming their agreement to participate and allowing the use of their responses for research purposes. No personally identifiable information was collected unless participants voluntarily provided their email addresses for feedback. The survey's structure and anonymity measures ensured confidentiality.

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The survey was designed to have a combination of closed questions to provide specific quantitative data, and open-ended questions to provide qualitative data. It started with a description of the research, how the

questionnaire was laid out and the time it would take to complete. The relevant University of Cape Town contact details, as well the authors, were provided for any questions. The questions were divided into the following main themes:

Questions 1 to 8: profile of farm/farmer and their experience with tagasaste (relating to Objective 1: Determine the existing adoption and success of tagasaste use in South Africa). This section forms the bulk of the questionnaire. These questions record whether farmers planted tagasaste successfully and are still utilising it, or unsuccessfully and have stopped, or whether they still want to plant it but are hesitant. It also establishes the province in which the farm is located, the farmer's specific purpose of planting tagasaste, whether they grew it from seed, seedlings or young trees in pots and if they found it easy or difficult to grow. In addition, farmers are also asked to ascribe a category for their farming enterprise: whether they are intensive, extensive, rural community farmers or homesteaders, with an open-ended option to describe their farming in more detail.

Questions 9 to 13: farmers' perspectives of sustainable agriculture practices and climate change (relating to Objective 2: Examine the characteristics of tagasaste relevant to its potential role in mitigating and adapting to climate change). The motivation behind these questions is to explore whether there is a link between the adoption of tagasaste and alternative farming methods and a changing climate. These questions investigate what farmers perceive as good or bad agricultural practices and whether they think climate change poses a threat to the environment and humanity. Respondents were also asked whether or not they think tagasaste could be used for on-farm climate change adaptation and/or mitigation efforts.

Questions 14 and 15: relationship between how farmers decide what to cultivate and their perspective of consumer choice (relating to Objective 2: Analyse the parameters of tagasaste in terms of agricultural intensification, carbon sequestration and adaptation to climate change). The aim of these questions was to explore the potential of added benefits of marketing products as being sustainably produced, and in turn motivate farmers to adopt sustainable agricultural practices. These questions were included to gain insight into how farmers decide what to grow and how they grow it, as well as whether they think consumers drive the market. The latter question was open-ended to allow respondents freedom to respond without being guided into a specific direction.

Questions 16 to 18: invasive potential of tagasaste and water use (indirectly related to Objectives 1 and 2, to evaluate possible trade-offs/ maladaptation potential). From an ethical point of view, the capacity of tagasaste to become an invasive species in sensitive areas and to negatively impact surface and groundwater reserves needed to be explored. Farmers were asked if they were aware that tagasaste is considered an invasive species under some conditions in some countries, and whether they have experienced it becoming invasive in their area or think it could do so. Additionally, respondents were asked about their experience regarding the water requirements of tagasaste, and to compare its water use to other trees used in agriculture.

Question 19: overall perspective of tagasaste and its potential use (related to Objectives 1 and 2 to gain an insight into the likelihood of farmers utilising tagasaste for on-farm mitigation and adaptation options). To conclude the survey questions, respondents were asked for their overall impression of the possible uses of tagasaste, to establish if it is considered a multi-purpose plant (utilised to fulfil more than one purpose at the same time, for example providing livestock fodder and sequestering carbon simultaneously), and to what degree.

Question 20: option to receive feedback on the research, and to provide their email address for the feedback.

The respondents were targeted through social media sites on Facebook, including *Sustainable Sufficiency and Sustainable Living South Africa*; *Kom Ons Boer*; *Landbou Sosiaal Suid Africa;* as well as *Damara Farm.* Facebook's 'Sponsored Ad' feature was also utilised, using the keywords: sustainable agriculture; farm, agriculture and industry: farming, fishing and forestry; beekeeping; climate; rural area; biodynamic agriculture; and organic farming to target farmers who may have had experience with tagasaste. The survey was first sent out in English, to which thirty-two farmers responded between mid-December 2022 to February 2023. In mid-January it was translated into Afrikaans in an attempt to reach a wider audience of farmers. It was sent out for the month of February and received ten additional responses. This makes a total of forty-two responses to the online survey. Of the forty-two survey respondents, thirty-six are from South Africa, while six are from elsewhere (Canada, Jaipur India, Chad, Kenya, and two from Namibia). The data collected from those farmers not based in South Africa was excluded from the main data. Of the thirty-six respondents in South Africa, eleven had not planted tagasaste before, but are planning to or would like to.

3.2.1.2 Personal communication

In addition to gathering data directly from farmers through the online survey, additional primary data sources beyond the general academic data collection were gathered for this research.

The data included consist mainly of photographs received by email and via WhatsApp messages from farmers who sought guidance or encountered challenges in propagating and establishing tagasaste. Some of these farmers received plant material (seeds or bare-root seedlings) from the author's farm nursery, while others acquired plant material from other sources and were unknown to the author prior to their queries.

3.2.2 Secondary data

To further investigate and add perspective to some of the key questions this research intends to address, secondary data were collected and analysed. The secondary data draw upon and enhance the primary data, as well as providing an unbiased insight to answer the research question. The secondary data are

especially valuable in this research given the author's positionality to the topic (as explained earlier in 3.2 Data).

Considering the limited adoption of tagasaste in South Africa, drawing upon research conducted in other countries where farmers and researchers are more familiar with its application provided valuable insights. On searching for literature specifically on the potential of tagasaste to sequester carbon, it was found that very little research has been conducted to date anywhere in the world, with only one peer reviewed study from Australia by Wochesländer et al. (2016). To explore the appropriateness of using tagasaste to sequester carbon in the context of South Africa, a comparative study was undertaken. The research by Wochesländer et al. (2016) *Tagasaste Reforestation as an Option for Carbon Mitigation in Dryland Farming Systems* was studied and compared to research by Mills & Cowling (2006) on the *Rate of Carbon Sequestration at Two Thicket Restoration Sites in the Eastern Cape, South Africa*. The Mills & Cowling (2006) research is based on a different plant, *Portulacaria afra* (spekboom), a succulent shrub currently being used in carbon offsetting projects in South Africa. While tagasaste is a leguminous shrub and spekboom a succulent shrub, and they have distinct biophysical differences, for the purposes herein, spekboom serves as a reference point for carbon offsetting projects as a mitigation pathway in South Africa and possible co-benefits. Table 2 (section 4.2.3 Tagasaste: mitigation and adaptation to climate change) presents the results of the two primary studies chosen for the comparison, as they are set out in each study.

Table 2 presents both primary and secondary data together, comparatively looking at signs of stress and possible causes of challenges experienced establishing tagasaste. Firstly, key findings were drawn from the survey responses and put into themes, which then influenced the secondary data used to supplement and strengthen the overall result of challenges experienced by the farmers. A total of six sources were selected for use in Table 1 (section 4.1.4 Tagasaste adoption in South Africa: limitations and potential), four of which are peer-reviewed journal articles, one is a chapter from a book, and the other is a full book.

1.3 DATA ANALYSIS

A hybrid inductive/deductive thematic analysis design (Proudfoot, 2023) was used to synthesise the different datasets. This approach was chosen because the research questions presented a layered and multifaceted problem that required a versatile way to enforce a diligent and rigorous research process. The primary data were first analysed inductively (bottom-up) to define three themes 1) farmers plant tagasaste because they are looking for more sustainable and climate resilient alternatives; 2) there is a divide between farmers succeeding or failing to establish tagasaste and 3) farmers think that the adoption of sustainable agricultural practices would repair ecosystem services and reduce their carbon footprint. To build on this, the secondary data were analysed deductively (top-down) to present themes 1) farmers and multi-stakeholder institutions are also exploring ways to generate secondary incomes and co-benefits through carbon offsetting schemes; 2) with knowledge and support it is easy and economical to establish tagasaste; and 3) even though

tagasaste has been found to become invasive in other countries, its eradication has not been implemented due to its economic value.

The two research papers looked at in the comparative study (4.2.2.1 Mitigation) used different units of measurement of carbon to present their results. To allow for direct comparison, the units needed to be standardised to carbon dioxide equivalent (CO_2e)[5] (see 4.2.3 Tagasaste: agricultural intensification, carbon sequestration and adaptation to climate change. For carbon stock and sequestration calculations, this conversion is based on the molecular mass ratio of CO_2 to C (IPCC, 2006). The conversion factor of 44/12 (or 3.67) represents the ratio of the molecular weight of carbon dioxide (44) to that of carbon (12) (Thomas et al., 2015; IPCC, 2006). When measuring carbon stocks in biomass (above and below ground) and soil carbon pools (leaf litter and organic constituents), each unit of carbon is multiplied by 3.67 to derive the equivalent mass in CO_2e (Cardinael et al., 2021; Roy, 2019; IPCC, 2006).

$$(TOTAL\ CARBON \times 3.67) = CO_2e$$

Quantitative data derived from the survey results were imported into Microsoft Excel, and then transferred into the design platform Canva[6] to generate Figures 1 – 8, 13; and Tables 1 - 4. Figure 12 was generated using the data visualisation tool Flourish[7].

The inductive and deductive results were integrated, interpreted and discussed per topic in Chapter 4: Results and Discussion within the following subsections: 4.1 Adoption, Utilisation and Propagation; and 4.2 Mitigation and Adaptation Potential. Finally, in Chapter 5: Conclusion, an overall summary of the key findings is presented, along with recommendations, as well as outlining the limitations and relevance of this research.

[5] The weight is generally shown in megagrams (Mg), which is equivalent to 1 tonne, or 1000 kilograms.
[6] An online graphic design studio available at: https://www.canva.com
[7] An online data visualisation tool available at: https://www.flourish.studio

CHAPTER 4: RESULTS AND DISCUSSION

4.1 ADOPTION, UTILISATION AND PROPAGATION

Establishing the current status of tagasaste in South Africa was imperative to address the research question regarding its potential role in shaping on-farm adaptation and mitigation pathways. The online survey results provide quantifiable evidence through perspectives and experiences directly from farmers. The key quantitative data are combined and presented Figure 7. Data obtained through personal communication with farmers over the last twelve years add emphasis and context to some of the establishment challenges experienced by the respondents. The secondary data draw on scientific and grey (i.e. not academically peer-reviewed) literature from South Africa and elsewhere to provide a more comprehensive understanding of the establishment of tagasaste systems in general and to what extent farmers are likely to adopt fodder tree technology. Finally, these three datasets are integrated and discussed to gain a holistic understanding of the limitations and potential in regards to the adoption, utilisation and propagation of tagasaste in South Africa.

To present a comprehensive evaluation of tagasaste, the possible negative consequences also need to be explored. A concern regarding exotic plants in South Africa is that they can encroach on areas of indigenous vegetation or other sensitive areas, and/or threaten water resources, as experienced with some eucalyptus species and Port Jackson (Acacia saligna), for instance. Tagasaste is not listed in
South Africa's National List of Invasive Species (National List of Invasive Species, 2020) under the National Environmental Management: Biodiversity Act 10 of 2004 (NEMBA) as an invasive species and is not considered a threat to the author's knowledge at the time of writing. However, the potential of this occurrence happening in the future needed to be assessed because it has been found to naturalise in parts of Australia, New Zealand, Canada, and the United States.

4.1.1 Survey results

The survey was directed at any farmers in South Africa with experience growing tagasaste, or with a keen interest in utilising it in their farming systems. The primary focus was directed towards the viability of tagasaste cultivation in South Africa and the level of interest among farmers regarding its adoption, irrespective of their location or the scale of their agricultural activities. As they were not selected for specific geographical locations, their farms are randomly and unevenly distributed throughout the country, as seen below in Figure 6. The farmers who responded varied in their farming approaches/models and described their practices from intensive (seven) and extensive (seven) to rural community farming (four), small-scale (three) and homesteading (nine) (refer to Figure 7). Other farmers described their activities as self-sufficient (one), permaculture (one), hobby farmer (one) and micro-farming (one). One farmer planted tagasaste as an experiment, and one planted as part of academic research.

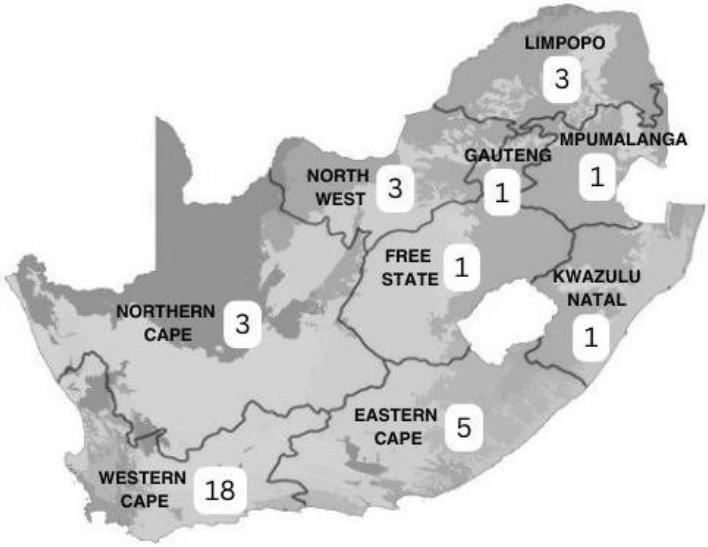

Figure 6. Location of survey participants by province *(adapted from Beck et al., 2018).*

Among the thirty-six responses included in the research, the main purpose for planting tagasaste was for livestock fodder (foliage), followed by soil rehabilitation (roots) and beekeeping (flowers). Overall, the majority of respondents grew tagasaste for livestock fodder. The next most common purpose was for soil rehabilitation, followed by beekeeping; planted by ten and nine respondents, respectively. Only four respondents planted as a windbreak, and one for its nitrogen fixing abilities in a permaculture system. One respondent planted as part of their MSc (Agric) dissertation at the University of Pretoria in 1997. Half of the respondents planted tagasaste for more than one purpose, i.e. a combination of two or more of the following: fodder for cattle and/or small ruminants, soil rehabilitation, windbreak, and apiculture, with the remaining 50% planting tagasaste for a single purpose only (refer to Figure 7).

Respondents were asked where they learned about tagasaste. Twenty reported that they learned about tagasaste through something they had read, nine through other farmers and three stated they had known about it for a long time. The remaining three mentioned specific people: one person's father planted it many years ago; one heard about it through the work of Geoff Lawton[8]; and another through Bill Mollison's[10] work. Additional feedback included discovering tagasaste through an article they found on the internet, and another that it was a 'misfortune' (translated from Afrikaans 'mislukking') that they came across through something they read. One respondent added that most research on tagasaste comes from Australia with some from the southern Cape. Respondents were asked if they could find useful information on tagasaste based on South African research and conditions, or based on other farmers' experiences to help guide them. Thirteen responded that they had found useful information, nineteen reported that they had not and four did not respond.

[8] Geoff Lawton is a permaculture designer, teacher and consultant (Permaculture Research Institute, 2024)
[10] Bill Mollison (1928 - 2016) was an Australian researcher and scientist and pioneered the principles and practices of permaculture design in the 1970s and 1980s (Permaculture College Australia, 2024).

Of the twenty-five respondents who had experience with planting tagasaste, only four said that it was easy to grow, and one said they experienced a 'relatively good' success rate, with twelve saying it was not easy or very difficult to establish (see Figure 7). Eight farmers planted seed, eight from seedlings and four planted young trees in pots. Five planted a combination of seed and seedlings, and one planted seed, seedlings and trees in pots. One farmer, who planted from both seed and seedlings, said that his plants suffered from 'root rot' when they were around 1 to 1.5 meters in height. Another farmer planted from seed and said that only some of the seed germinated and that soil is an important factor. One farmer noted challenges in establishing the seedlings, citing information suggesting that tagasaste requires no watering. On the other hand, another farmer who had successfully planted seedlings said that their plants needed to be watered for the first two years, after which the mature plants became hardy to dryland conditions. The latter farmer said that when the plants were between five and six years old, the hot Cape summers caused mortality in about 10% of their mature dryland plants.

"It was difficult. Some of the seeds emerged and some of them didn't."

One farmer commented that the leaves of his one-year-old plants had begun yellowing, which he thought might be due to a lack of nutrients. He then fertilised using superphosphate ($CaH_6O_8P_2^{+2}$) but is unsure if it could be due to another factor because the fertiliser did not solve the problem. Three farmers stated that their plants took longer than expected to grow actively, but once established the growth rate increased; two of those had planted from seed, and one from both seed and seedlings.

"To get started is difficult, once they are growing it's easy to maintain."

One farmer said their plants grew well for some time, but that harvester ants caused severe damage causing the plants to die. Three farmers expressed that they experienced difficulty establishing tagasaste due to livestock or wildlife gaining access to the plants before they could reach maturity, resulting in plant mortalities.

"Not that easy, everything likes to eat it."

Only five had planted trees in pots, all of whom reported difficulties with establishment. One of the respondents who planted potted trees commented that his trees died due to frost.

"Easy to establish, impossible to survive the winters."

Another farmer responded that tagasaste just doesn't grow, two did not elaborate beyond that establishing tagasaste is 'very difficult' and the fifth that the growth of his plants had been very slow.

"Difficult to grow from seed, but seedlings transplanted gently have established easily."

When asked if they knew that tagasaste is considered an invasive species in some countries, only six respondents said yes, while twenty-nine said they did not know this, and one did not respond. Twenty-eight respondents said they didn't think it had the potential to become invasive in South Africa, while some of them commented that it is too difficult to grow. Reasons given were that the climate is too dry in their area, that it is too susceptible to *phytophthora* rot and that much attention is already paid to limit the spread of exotic species in the country. One farmer said that they have had it growing on their farm for thirty years and have not experienced it becoming invasive, and that even though an abundance of seed is produced, very few seedlings survive. Five respondents commented that tagasaste is too palatable to wildlife and livestock for it to become an invasive issue. On the other hand, five said that they do think it has the potential to become invasive, with one comment that large numbers of seedlings germinate readily and another that it could become invasive if there is a lack of knowledge and skill in management practices.

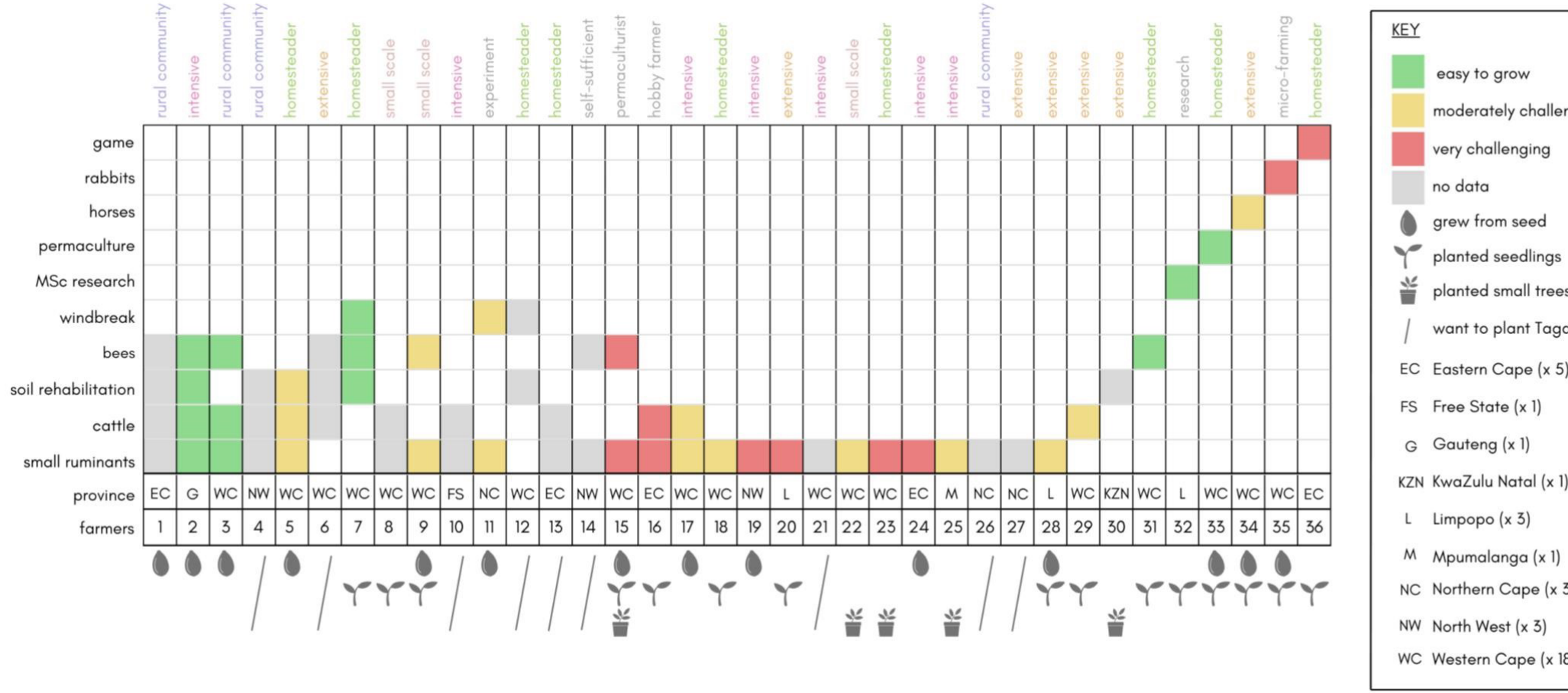

Figure 7. *The key quantitative findings on the adoption, utilisation and propagation of tagasaste.*

4.1.2 Personal communication

Several challenges encountered by the survey participants during the establishment of tagasaste exhibit similarities to inquiries the author received over the past twelve years from farmers who have sourced seed or bare-root seedlings either from her farm nursery or from other suppliers.

An email from one farmer expressed concern about having healthy and unhealthy plants next to each other. He said that the unhealthy plants' leaves turn yellow and then fall off, leaving just twigs, and then the plants die. He propagated seeds in bags and transplanted them into well-drained sandy soil when they were about 20 to 40 cm tall. He reported that they grew well initially but then started to die; only two plants looked very healthy. He included photos of what the dying plants looked like, as well as the roots of a dead plant as seen below in Figure 8.

Figure 8. Signs of stress in tagasaste*: 1) yellowing leaves, 2) leaves fall off, 3) roots of a dead tagasaste plant (personal communication, 2022).*

Similarly, another farmer sent a WhatsApp asking why her plants grow well for a short time and produce leaves, which then shrink, followed by the plants slowly dying. She planted seeds in bags (Figure 9.1 below), and of the fifty plants she transplanted, only one survived. She wondered if it could be the weather conditions. Another farmer asked me to come to his farm to help diagnose why his plants were losing their leaves and dying. These plants were propagated in bags and then transplanted into heavy loam soil. As the plants were dead, we pulled them out to inspect the root ball and planting depth and took photos. The soil was moist but not waterlogged, and it appeared that the seedlings were planted too deep (Figure 9.2), while the root development was restricted with a ‘root-bound’ formation (Figure 9.3).

Figure 9. Root development issues*: 1) potted seedlings and heavy soil can stunt root growth of seedlings and decrease longevity (personal communication); 2) incorrect planting depth and waterlogging cause mortality from fungal infections; and 3) seedlings propagated in pots become root bound and planting in compacted soil prevents effective root development, causing plant mortality.*

Over the years, the author also received inquiries asking about damage caused by pests. Several farmers reported evidence of wood borer insects on mature tagasaste plants. The same wood boring beetles are present on the author's farm and cause some damage to mature plants; however, the plants do not generally die as a result under normal conditions. The damage can only be seen by looking closely at woody stems or branches for the small characteristic holes, or when mature plants are heavily pruned or cut down (Figure 10.1). Mature beetles can also be observed on tagasaste plants during late spring. During extreme conditions, such as the 2015 - 2018 Western Cape drought, some plant mortalities were observed. As the tap roots of tagasaste reach below ground water level on the farm, it was assumed that the plants were weakened by the wood borer damage and were therefore less resilient to survive adverse conditions. The insect (Figure 10.2) has been identified as the Cape longhorn beetle (Ceroplesis aethiops, also known as the Rooibos Longhorn Beetle).

Figure 10. Pests*: 1) typical wood borer damage to the core of tagasaste stems decreases plant longevity, especially under challenging conditions; 2) mature Cape longhorn beetle, Ceroplesis aethiops; and 3) insect damage to young seedling (personal communication).*

Another farmer sent a photo on WhatsApp asking what was attacking the leaves of his young tagasaste seedlings. He said that only about 10% of his plants were affected but wanted to prevent the issue from spreading (Figure 10.3). He then sprayed all the seedlings with a weak dishwashing liquid and water

mixture as an insecticide, applied a single superphosphate treatment, and later reported that the problem went away.

Farmers also contacted the author regarding growing and environmental conditions. One farmer asked the author to visit his farm because he was concerned that some of his plants were becoming chlorotic[9] (Figure 11.1). He planted bare-root seedlings into heavy clay soil, and the plants grew well initially. Figure 11.1 below shows healthy plants next to chlorotic plants, with dense weed growth. The following season he planted in the same soil type but chose different fields with a distinct slope to ensure the free drainage of surface water and prevent waterlogging. He said he took the same approach to establishing the tagasaste seedlings as he did establishing a vineyard — he was a wine farmer — and adjusted macro- and micro-nutrients, as well as practising weed control. The seedlings grew well, and he asked me to visit the following year (Figure 11.2). Many farmers ask if tagasaste can withstand frost conditions because they have read that it cannot. Figure 11.3 shows densely planted two-month-old seedlings covered with frost. While seedling growth slowed down, there were no mortalities due to the frost.

Figure 11. Growing conditions*: 1) weed competition causes stunted growth (personal communication); 2) nutrient deficiency and waterlogging causing chlorosis of leaves; and 3) young tagasaste seedlings can withstand frost in some conditions.*

4.1.3 Secondary data

In a 1918 Royal Botanic Gardens Bulletin, it was noted that tagasaste was not popular with farmers in South Africa and its adoption was therefore low. The reason for this was thought to be *"due partly to faulty cultural methods*" (Hutchinson, 1918). The popularity of tagasaste remained low until the 1980s and 1990s, when there was some interest surrounding the use of tagasaste mainly as a source of fodder (Farmer's Weekly magazine, 12 February 1988; 21 April 1989 and Landbou Weekblad magazine, 1 April 1988; 19 May 1989). Access to tagasaste remained limited at that time, because plant material was only available from one nursery in the Western Cape and it was recommended to plant it only in winter rainfall areas such as the coastal regions of the Western Cape. tagasaste regained some popularity in 2012, but this was short-lived, because farmers reported that they had very little to no success in establishing tagasaste

[9] Yellowing of plant leaves is referred to as chlorosis, and can be a symptom of pests, nutrient deficiency, waterlogged conditions, disease or virus, soil compaction, drought conditions, cold or hot temperatures etc. Disease, virus and nutrient deficiencies are also referred to as necrosis (RHS, 2024).

(Farmer's Weekly magazine, 11 December 2012 and Landbou Weekblad magazine, 24 January 2012; 9 March 2012; 26 March 2012; 24 May 2012; and Die Pad Saam magazine, June 2012 Vol 13, page 13).

This trend is echoed elsewhere in Africa, according to Hughs et al. (2022). Adoption in Malawi remains relatively low, even with their promotion by NGOs such as World Agroforestry (ICRAF) and the Shrubs for Change Project. Their research revealed that where tagasaste was introduced in Malawi, farmers have limited knowledge of how to utilise or maintain it. Agricultural practices that incorporate perennials often involve greater levels of maintenance than farming systems based mainly on annual crops (Pannell & Ewing, 2006). Many farmers do not have the financial and/or managerial capacity to achieve the necessary maintenance requirements to ensure long-term productivity. The adoption of tagasaste also remains low in Ethiopia, where it was introduced in 1984 (Bezabih, & Mekonnen, 2019; Kebede et al., 2021; and Hughes et al. 2022). Hughes et al. (2022) report that a major constraint for adoption in Malawi is the lack of plant material (seed and seedlings) as well as limited knowledge. They concluded that the adoption of innovations such as fodder tree technology is multifaceted and challenging. Some of the reported issues included low germination rates, insufficient watering and heavy rainfall (Hughes et al., 2022). Similarly, a major hurdle to the widespread adoption in Ethiopia is that young tagasaste plants were not fenced off and were destroyed by livestock before the plants could become established, according to Bezabih and Mekonnen (2019).

By contrast, a 2001 report by the Department of Agriculture in Western Australia recorded that over 100 000 hectares of farmland had been planted with tagasaste in Australia, and that the potential area suited to tagasaste production was around 1.5 million hectares (Pannell & Ewing, 2006). According to Pannel and Erwing (2006) the main factor leading to its widespread adoption in Australia is the ability of tagasaste to cycle water and nutrients from deep, infertile soils with inadequate water retention capacity. This water and nutrient cycling ability makes tagasaste more efficient in harsh environments than crops with shallower root systems. The report also noted other aspects that contributed to its adoption, including the introduction of inexpensive direct-sowing methods and using cattle to graze systematically, eliminating the need for expensive pruning equipment for shrub maintenance. By browsing on the tagasaste, cattle sustain a good ratio between woody stems and branches and the more nutritious green growth, thus keeping the trees growing actively at the right height for direct grazing.

Propagation methods vary depending on source, intended scale, and whether for on-farm establishment or for the purpose of selling plant material. Soil nutrient deficiencies should be corrected prior to planting and seedlings should be inoculated with an appropriate nitrogen-fixing rhizobium bacterium to ensure optimum growth (Tudor et al., 2016; Lefroy et al., 2001). Tagasaste is, however, considered promiscuous, which means that it can develop effective nitrogen-fixing nodules on its roots by colonising wild strains of rhizobium inherent in healthy soils.

Once planted out, weed control needs to be carefully monitored and young plants should be protected from predation by insects, wildlife and livestock. A New Zealand farmer interviewed for the Growing Tagasaste

in New Zealand handbook (Tozer et al., 2022) reported that, to allow newly planted tagasaste to mature, he withheld livestock from the field for three years. This resulted in blackberry brambles taking over, which took years to control. The next field he planted, he protected the young plants individually with tree guards, but this increased input costs. He added that both strategies require detailed management throughout the establishment phase. Plant spacing varies to suit the intended purpose and environmental conditions. The farmer further explained that plantation management is required where tagasaste is used for livestock feed, whether it is grazed directly or harvested. This ensures that plants produce edible green growth rather than woody material, and correct pruning and/or grazing encourages more active regrowth. Where plants are grazed directly, rotational or strip grazing methods should be employed to avoid overgrazing and debarking by small ruminants (Moore et al., 2006).

In the Growing Tagasaste in New Zealand handbook, Tozer et al. (2022) write that the naturalisation of tagasaste is limited to areas that are relatively dry with well-drained soil and do not experience heavy frosts. The Tropical Forages database (Cook et al., 2020) states that tagasaste has become naturalised in areas with insufficient numbers of animals to control its encroachment and has become a significant issue in some cases. According to a 1988 article written by Ben Viljoen in the Farmer's Weekly magazine, tagasaste only persists in fenced areas in South Africa. Viljoen (1988) argues that the only reason tagasaste had not naturalized in wild areas is because it was readily grazed by wild and domestic animals and was therefore unable to thrive. The author further explains that the palatability of tagasaste presents a challenge establishing young plants where wildlife such as rodents and small buck gain access to the seedlings. For this reason, tagasaste cannot be set-stocked (permanent pasture) with small ruminants because of high plant mortalities by removing new growth points and debarking (Wiley, 2006; Lindeque & Rethman, 1998). Cattle, on the other hand, can be set-stocked on tagasaste, but overgrazing can cause 'broccoli' shaped plants (Wiley, 2006).

This theory can be supported by the images below in Figure 12 taken in 2023 near Masterton in New Zealand. tagasaste can be seen naturalising along a riverbank, which appears to consist of well drained sand with stones and rocks. The tagasaste plants on the near bank appear to be grazed by livestock or wildlife, and do not show signs of flowering or producing seed. On the other hand, the plants on the far bank appear to be ungrazed and are in full flower, which will result in multitudes of seed.

Figure 12. Invasive conditions near Masterton, New Zealand*: 1) young volunteer tagasaste trees that appear to have been grazed, 2) mature tagasaste in full flower on the far side of the riverbank 3) grazed tagasaste on the near bank and ungrazed on the far bank (personal communication, 2023).*

In the late 1990s, tagasaste was found to be susceptible to a biocontrol agent that was considered to control the spread of the plant Scotch broom (Cytisus scoparius), which is considered an invasive weed in Australia, New Zealand, the USA and Canada (Morin et al., 2000). As a result of tagasaste's vulnerability to the biocontrol agent, the release of the biocontrol was withheld because of the economic significance of tagasaste as a high protein livestock feed.

The NEMBA definition of an invasive species is any species whose introduction and proliferation beyond its native range poses a threat to habitats, ecosystems or other species, or exhibits demonstrable potential to do so, and which may cause environmental, economic or human health repercussions (NEMBA, 2020). In the case of tagasaste, it would be considered invasive if it encroached on indigenous ecosystems or invaded waterways.

4.1.4 Tagasaste Adoption in South Africa: Limitations and Potential

The survey results indicate that the farmers who planted tagasaste in South Africa did so predominantly for livestock fodder, soil rehabilitation, beekeeping and as a windbreak, in that order of importance. Many of the farmers experienced difficulties establishing tagasaste successfully (see Table 1 below), and on the whole agreed that they lacked access to practical information on its establishment and use, based on conditions in South Africa. This is echoed in the research/ secondary data from two other African countries, Malawi and Ethiopia. Conversely, the data from Australia and New Zealand, where tagasaste is widely grown, shows that farmers have access to comprehensive and practical information and guides on its use, establishment and multiplication based on scientific research as well as firsthand experience from other farmers. The contrast between countries where farmers struggle to grow tagasaste, and countries where it is grown successfully and commercially, highlights that tagasaste has specific propagation and establishment requirements, which are crucial to its successful establishment. Table 1 draws on the specific feedback from farmers who experienced challenges establishing tagasaste and integrates this with the secondary data results to provide a comprehensive summary. It suggests that the survey participants who indicated that they had difficulties growing tagasaste did not have the required knowledge or experience.

Accordingly, with the appropriate support, knowledge and resources, more farmers in South Africa would be able to establish tagasaste plantations successfully. Furthermore, Table 1 could serve as a foundational framework to produce a guide for farmers to successfully grow tagasaste, including functioning as a diagnostic instrument for addressing the key establishment challenges encountered by the farmers.

While being largely driven by the farmers themselves, most of the research on tagasaste from Australia and New Zealand is funded and supported through government agencies, such as The Commonwealth Scientific and Industrial Research Organisation (CSIRO) (Wochesländer et al., 2016), the Department of Primary Industries (Unkovich et al., 2000; Dann et al., 2003; Moore et al., 2006) in Australia, and New Zealand's Ministry for Primary Industries (MPI) Sustainable Farming Fund (Tozer et al., 2021). The successful use and management of tagasaste in these examples, suggests that developing localspecific research in South Africa, with financial backing and support from local organisations and institutions, would equip farmers with knowledge and tools that are appropriate to local practices and cultures. This, in turn, would enable them to harness some of the advantages associated with the utilisation of tagasaste in their agricultural systems.

In terms of the possible negative consequences that could result from increased adoption of tagasaste, the survey data indicate that, on the whole, farmers do not think that tagasaste has the potential to become invasive in South Africa. On the other hand, the secondary data indicate that tagasaste has become naturalised in areas of Australia and New Zealand that present the right climatic conditions (for example well drained soil, no frost) and only in the absence of predation by wildlife and/ or livestock. Its eradication in those areas, however, has not been implemented due to its contribution to livestock husbandry and therefore the economy. This indicates that the economic value of tagasaste outweighs the need to eliminate its use. The value of tagasaste estimated in the Growing Tagasaste in New Zealand Handbook (Tozer et al. 2022) indicates that tagasaste increases carrying capacity and livestock performance, as well as saving on input costs, and can also generate a secondary income for farmers, for example from beekeeping (Tozer et al. 2022) or carbon offsetting schemes (Thomas et al., 2015).

Table 1. *Summary of challenges experienced by survey respondents and literature on establishment requirements of tagasaste.*

Problem	No. of participants	Propagation method	Participants comments	Possible reasons	Source
Yellow leaves	1	Seedlings	Occurred at 1 year, added superphosphate but may need something else	Chlorosis; micro/ macro nutrient deficiency; waterlogging; high temperatures; not enough water	1. Wiley, T., 2006 2. Dann, P. et al, 2003 3. Douglas, G. B. et al., 1998 4. Snook, L., 1986
Temperature: too hot or cold	2	Trees in pots; seedlings	Easy to establish, but died due to Highveld frost.; 1 in 10 mature plants die during hot Cape summers.	Becomes dormant in extreme temperatures; young seedlings intolerant to frost	1. Wiley, T., 2006 2. Dann, P. et al, 2003 3. Douglas, G. B. et al., 1998
Difficult to grow from seed	3	Seed; seed and seedlings	Not all of the seed germinated; seedlings transplanted gently establish easily.	Seed requires scarification to germinate successfully; weed competition	1. Dann, P. et al, 2003 2. Douglas, G. B. et al., 1998 3. Snook, L., 1986 4. Assefa. G., et al., 2012
Root-rot	1	Seed and seedlings	Plants were about 1 to 1.5m tall when problem began.	Susceptible to stem and root disease; intolerant to waterlogging	1. Dann, P. et al, 2003 2. Snook, L., 1986 3. Assefa. G., et al., 2012
Everything likes to eat it	3	Seed; seed and seedlings; trees in pots	Rabbits (hare) and duiker damage plants, sheep broke in, baboon pulled them out	Highly palatable	1. Wiley. T., 2. Snook, L., 1986 3. Jeronimo et al., 2020
Water: too little or too much	3	Seedlings; trees in pots	Literature says does not need to be watered; needs water for first 2 years; I probably haven't watered enough.	Requires water for establishment; intolerant to waterlogging	1. Wiley, T., 2. Snook, L., 1986 3. Assefa. G., et al., 2012
Slow to get establishded	4	Seedlings; seed; trees in pots	I probably haven't watered enough; took longer than expected, once growing easy to maintain.	Nutrient deficiency; not enough water; planted during wrong season; unfavorable conditions	1. Dann, P. et al, 2003 2. Snook, L., 1986 3. Assefa. G., et al., 2012

4.2 MITIGATION AND ADAPTATION POTENTIAL

In countries such as South Africa, where there is limited access to financial and intellectual support from the government for the majority of farmers (Gwiriri et al., 2019 and Cloete et al., 2022), assessing farmers' perspectives is an important step towards understanding the adoption of agricultural practices with

mitigation and/or adaptation potential. This approach could encourage agricultural practices that contribute to mitigation and adaptation pathways, rather than being a driver of GHG emissions and climate change.

The online survey results provide opinions and insights directly from South African farmers, as well as quantitative data on respondents' views related to agricultural practices, climate change and tagasaste's potential for mitigation and adaptation. The quantitative data are analysed and combined, as presented in Figure 13. The secondary data refers to research on the mitigation and adaptation capacity of tagasaste. At the time of writing, no specific research had been conducted on the carbon sequestration potential of tagasaste from South Africa. For this reason, an existing carbon sequestration project using a different shrub, *Portulacaria afra* (spekboom), was taken as a comparative approach to explore the potential for tagasaste to play a role in such initiatives (see 3.2.2 Secondary data). The primary and secondary data were then integrated and discussed to assess the parameters of tagasaste to sequester carbon and adapt to climate change.

4.2.1 Survey results

To gauge farmers' perspectives as to what degree they think the agricultural sector in South Africa is open to the development of mitigation and adaptation pathways, the first introductory question to this theme was to establish whether they think that climate change poses a threat to the environment and humanity in the first place. Three respondents did not reply to this question, and of the thirty-three who did, 80% agreed and 20% did not agree or said they don't believe in climate change (refer to Figure 13). Of those that agreed, some of the feedback was that the threat primarily affects humans, since nature can adapt and evolve more quickly; that natural resources are depleting; and food is becoming limited in more nations than ever before.

" Not so much a threat to Gaia, but to human survival."

One farmer said that climate change can result in big issues for the environment in its extreme forms, but that farmers have adapted well over time. Another respondent said that farmers can be part of the solution through practising regenerative farming techniques (refer to 2.2.2 Farming systems for a description on sustainable farming techniques).

" Regenerative farming is a good way to reduce carbon footprint."

Of those who disagreed, some of the comments were that the climate has always changed and that it occurs naturally over time, but that the main problems are pollution and wasteful lifestyles. One person said that climate change is propaganda but added that some forms of agriculture have negative consequences on soil fertility, water resources and biodiversity.

" Climate change hype detracts from the true state of seasonal changes."

Farmers were then asked if they think some agricultural practices can: harm the environment, decrease soil fertility, pollute underground water and rivers, cause biodiversity loss, increase carbon footprint, cause land degradation or decrease production over time. Options were given in multiple-choice format with space at the end for additional comments. Overall, there was general agreement that this is the case, with three farmers saying that poor agricultural practices cause land degradation only, and four farmers did not respond to this question. As depicted in Figure 13, no distinct correlation emerges between farmers' beliefs in climate change and their perceptions of the adverse impacts of conventional agricultural practices.

When asked if they think farmers should practise more sustainable farming methods, almost 95% agreed. Two did not select either 'yes' or 'no', but one of them said in another section that they farm organically and regeneratively. Some of the other comments included concerns that monocropping and the use of chemicals such as synthetic fertilisers, herbicides and pesticides have negative impacts on the soil, and that soil biodiversity should be repaired. Regenerative agriculture, conservation agriculture and no-till practices were also themes that came across strongly, and one farmer said that livestock should be incorporated to regenerate soil through rotational grazing.

"Regenerative agriculture is a great way to reduce the carbon footprint, no-till farming and cover cropping are great examples for a better future."

In response to being asked whether, in their experience, tagasaste improves soil fertility due to the virtue that it is a legume, 25 farmers replied that it does, and the remainder did not select either 'yes' or 'no'. One farmer commented that they were unsure, because they used many methods congruently. Another said that the shallow root system can be a problem in a vegetable garden, because they compete for food, but does think that tagasaste can improve soil condition.

To establish farmers' experiences regarding the water use of tagasaste, respondents were asked if their trees have a high water demand in comparison to other trees they have grown. Around 47% said no, and some comments include that the water demand is low once the plants are established; water use could be comparable with fruit and nut trees, while another commented that water use would be much less than citrus or pecan nut trees. Respondents were undecided in 42% of cases, with some commenting that it is too soon to tell.

According to the sample of farmers represented by the survey results, crop selection and livestock choice are most frequently decided upon by how well it is suited to the specific conditions on their farm. Crop and livestock choices are also determined by enabling the best profit margins and followed by being the most environmentally responsible action (see more in Figure 13). Farmers were asked to give their opinion on the degree to which consumers play a role in directing their decisions on what and how they farm. This was an open-ended question, and the majority explained that consumers do play a role in their decisions,

because farming is market driven. Further comments included: consumers are concerned about price and guided by the media; that the food industry influences consumer choices and that farmers are most likely to make decisions based on what is most cost-effective. Three said that consumers have no influence on their decisions, because the market is controlled by standards and capitalism, and that consumers merely buy what is available or fashionable. One farmer said that the organic consumer group is and will always be small. One person said they believe that consumers are largely responsible for GMO produce because they want food that is bigger, lasts longer and has more flavour and colour, and that this has contributed to many varieties being lost. There were a few comments suggesting that consumers are easily influenced by media as well as their capacity to spend on quality produce.

"Ignorance of agriculture needs to be addressed."

When asked if tagasaste could be a potential option for on-farm climate change mitigation and adaptation efforts, responses were mixed. The question explained that there are two approaches to addressing climate change issues: mitigation, which involves limiting or removing carbon from the atmosphere; and adaptation, which involves minimising damage caused by climate-related events, such as severe droughts and floods. Twenty-two said they thought it could assist in both mitigation and adaptation measures; four said only adaptation; two only mitigation; two said neither adaptation or mitigation and the remaining six did not select an option. Of these, one commented that they did not know enough about the topic to offer an opinion, and another said that the scale would be too small to have an effect. The overall impressions of what farmers think tagasaste can be used for can be seen in Figure 13 below, with the most prevalent use being for livestock fodder, followed by soil improvement, beekeeping, land rehabilitation, windbreaks, mulching and pelleting for bagged feed.

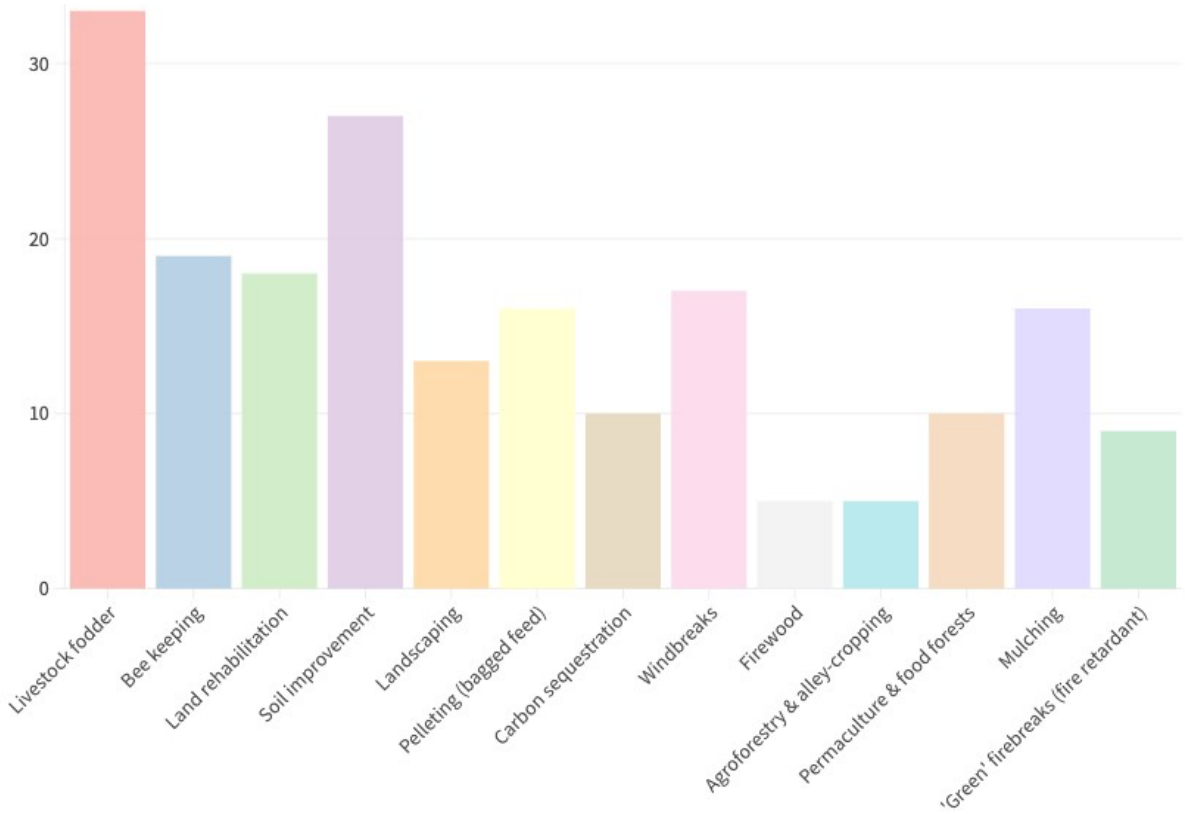

Figure 13. Farmers' overall impression of what tagasaste can be used for (further analysed in ***Table 4***).

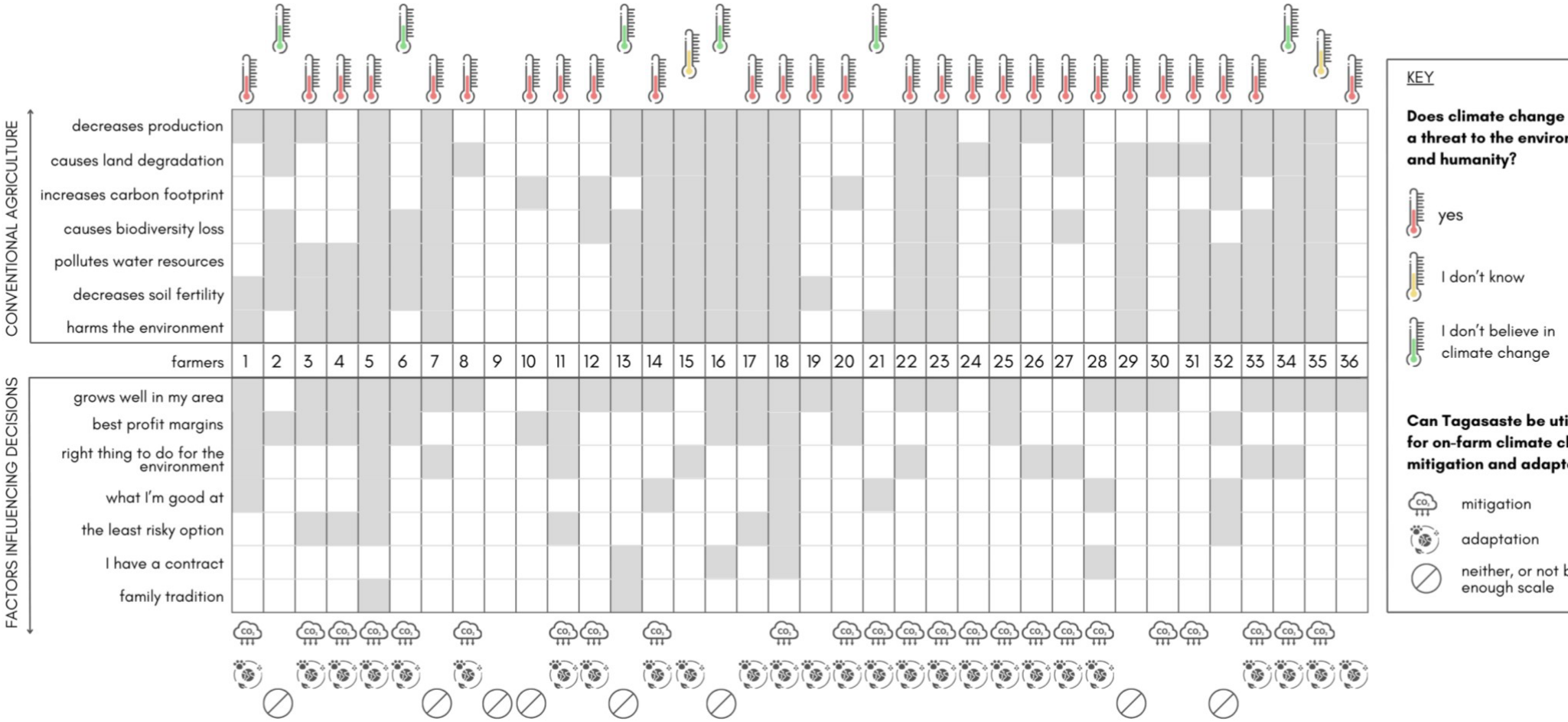

Figure 14. *The key quantitative findings on respondents' perspectives regarding agricultural practices, climate change, and tagasaste's potential for mitigation and adaptation.*

4.2.2 Secondary data

4.2.2.1 Mitigation

At the time of writing, only one primary study, originating from Australia, had been conducted to establish the carbon sequestration potential of tagasaste, entitled *Tagasaste (Cytisus proliferus) reforestation as an option for carbon mitigation in dryland farming systems.* In this study, Wochesländer et al. (2016) demonstrated that tagasaste, cultivated at a site in Australia with suboptimal conditions for conventional pasture cultivation, exhibited the capacity to sequester more than 20 metric tonnes of soil organic C ha^{-1}, along with an additional 35 metric tonnes of above and below ground biomass Cn ha^{-1} yr^{-1} over a twenty-two-year period. This is equivalent to a mean annual carbon sequestration rate of 2.5 Mg C ha^{-1} yr^{-1}, which equals 9.2 Mg CO_2e ha^{-1} yr^{-1} (Wochesländer et al., 2016). These results are based on an alley cropping system, with 30 m spacing between rows of tagasaste and 0.7 m between plants within the row, an overall planting density of 550 plants ha^{-1} [10].

An Australian multi-stakeholder collaboration (between the Commonwealth Scientific and Industrial Research Organization, New South Wales Department of Primary Industries, the Department of Agriculture and Food and Murdoch University, funded by the Commonwealth Department of Agriculture and the Future Farm Industries Cooperative Research Centre) called EverCrop Carbon Plus (Thomas et al, 2015) carried out an economic analysis based on the research by Wochesländer et al. (2016). The analysis modelled four scenarios to explore the economic impact of incorporating emissions abatement into tagasaste farming systems. The analysis found that while unmanaged, densely planted tagasaste plantations sequestered the most amount of carbon, and the inclusion of cattle within the system increased the economic value more than twofold. The cattle grazing system was calculated taking into account the methane emissions associated with cattle, as well as costs associated with a cattle enterprise.

To put the carbon sequestration potential of tagasaste into context under South African conditions, it can be compared to spekboom. Spekboom has been used in carbon sequestration projects for a number of years through the restoration of indigenous spekboom thickets in the Eastern Cape (Blignaut et al., 2009). Tagasaste and spekboom are similar, in that they are both well adapted to drought conditions (through different mechanisms) and can be used as fodder for livestock. However, they have some important physiological differences, which need to be taken into consideration. Tagasaste is a woody legume from the Fabaceae family (Snook, L. C., 1986), whereas spekboom is a succulent shrub from the Didiereaceae family (Mills & Cowling, 2014). Spekboom is known as a “CAM” plant, meaning that it has a photosynthetic adaptation called crassulacean acid metabolism (CAM) and can switch between “normal” C3 photosynthetic pathways and CAM pathways. CAM plants are considered more adaptable to drought conditions than non-CAM plants (Leveret & Borland, 2023). In terms of feed value, tagasaste has 17-30%

[10] Wochesländer et al. (2016) studied two sets of tagasaste plantings, where the block type had a plant density of 2300 trees ha^{-1}, and the alley planting had a density of 550 plants ha^{-1} yr^{-1}.Due to access issues, the researchers were unable to measure the total biomass of the block plantings. For this reason, only the results from the alley plantings have been used in this study.

crude protein (Orwa et al., 2009 and Tozer et al., 2022), while spekboom contains 0.57g/100g (or 5.7%) crude protein (Mahlanza, Z., et al., 2023).

Spekboom occurs naturally in the Eastern Cape and is well adapted to arid conditions, but vast natural thickets have been degraded due to overgrazing by domestic livestock (Mills & Cowling, 2006). According to Mills and Cowling (2006), spekboom is highly palatable, and these natural thickets have been used as grazing for goats since the 1900s, resulting in the degradation of almost half of South Africa's natural subtropical thickets (van Luijk et al., 2012). Research shows that spekboom can sequester up to a maximum of 15.4 Mg CO_2e ha^{-1} yr^{-1} (Mills & Cowling, 2014). This figure is based on the scaling up of the results of a 2006 study (Mills & Cowling, 2006) to 100% canopy cover, where the trial site[11] had 93% canopy cover. The primary results showed that a particular spekboom genotype, known locally as 'berg spekboom', sequestered 110 metric tons of soil and biomass C ha^{-1} over a twenty-seven-year period (Mills & Cowling, 2006).

As explained in 3.2 Data Analysis, the two studies presented their findings using different units. Where the value of the results differed, the available data were extrapolated using established standard calculation methods to allow for ease of comparison (refer to Table 2). Where Mills and Cowling (2006) calculated that 11 kgC per square meter (m^2) was sequestered over twenty-seven years, Wochesländer et al. (2016) calculated a sequestration rate of 55.4Mg C ha^{-1} over twenty-two years, which they calculated to be 9.2 Mg CO_2e ha^{-1} per year (9.2 Mg CO_2e ha^{-1} yr^{-1}). Therefore, to convert the Mills and Cowling (2006) units into the equivalent value, the following calculation can be applied:

$$11\ kg\ C/m^2 \times 1000 = 111\ Mg\ ha^{-1}$$ Then:

$$111\ Mg \div 27\ years = 4.07\ Mg\ carbon\ average\ per\ year \times 3.67 = 14.9\ Mg\ CO_2e\ ha^{-1}\ yr^{-1}$$

The results of Mills and Cowling (2006) study was based on a measurement of 93% canopy cover, which Mills and Cowling (2014) later scaled up to give a total of 15.4 Mg CO_2e ha^{-1} yr^{-1} at 100% cover in their paper entitled *How Fast can Carbon be Sequestered When Restoring Degraded Subtropical Thicket?* In comparison, the canopy cover in the Wochesländer et al. (2016) study was measured at 39%. To enable direct comparison with the Mills and Cowling (2014) calculations, the Wochesländer et al. (2016) results can similarly be scaled to 100% cover. Therefore, their measured rate of 9.2 Mg CO_2e ha^{-1} yr^{-1} at 39% cover would equate to 24.5 Mg CO_2e ha^{-1} yr^{-1} at 100% canopy cover.

4.2.2.2 Adaptation

Tagasaste has long been associated with agricultural practices that are considered 'alternative', as opposed to conventional farming associated with high chemical use in the form of fertilisers and pest, disease and

[11] Mills and Cowling (2006) included two study sites, only one of which was included in this paper, namely the site at Krompoort Farm. The reason for this is because the results from Mills and Cowling (2014) are based on the same data from Krompoort Farm.

weed control. Methods often associated with tagasaste include agroforestry, silvopasture, alley cropping and intercropping, agroecology, syntropic agriculture, permaculture and apiculture (Orwa et al., 2009). For the purposes herein, they are referred to collectively as agroforestry, within the margins of sustainable agriculture.

Perennial fodder trees are valuable sources of feed for livestock in low rainfall areas and have deep root systems that access ground water in the dry season or during droughts when other high-quality feed is scarce (Dawson et al., 2014). Tagasaste has a dimorphic root system which allows the plant to access moisture close to the surface as well as access deep ground water (Lefroy, et al, 2001). During times of extended drought, the lateral feeding roots near the surface can become senescent, allowing the plant to adjust its active growth according to water availability. However, according to Lefroy et al. (2001), tagasaste was observed to be capable of hydraulic lift during the dry season, bringing water from deeper ground reserves to the surface to maintain the integrity of its fine lateral feeding roots in preparation for rain. The authors explain that tagasaste sheds leaves under conditions of heightened temperature and water stress as an adaptive strategy to minimise water loss through transpiration, and that it demonstrates prompt responsiveness to out of season rainfall. Nitrogen fixing nodules have been found on tagasaste roots to a depth of 2.5 to 3.5m (Lefroy, et al, 2001), suggesting that nitrogen fixation continues during the dry season or periods of drought when nodules on lateral feeding roots have become senescent (dormant) (Unkovich et al., 2000).

In terms of tagasaste's water use efficiency, Lefroy et al. (2001) found that tagasaste can double its biomass in a year and only marginally increase its water use. The average water use efficiency over three years was 247 litres per kilogram of dry matter. Compared with alfalfa (Medicago sativa, also known as lucerne)[12], which has a similar nutritional value to tagasaste, this is a productive efficiency ratio. According to Singh et al. (2014), alfalfa requires just over 713 litres of water to produce one kilogram of dry matter. Furthermore, Lefroy et al. (2001) found that tagasaste can help address increased rates of dryland salinity[13] by restoring hydrological balance in areas where natural vegetation had been replaced by cropland and pasture. Tagasaste remains relatively productive during the dry season or mild drought conditions (González-Rodrıguez, 2005), and maintains a proportional ratio of roots to shoots after being coppiced, suggesting that water use is regulated according to demand (Lefroy et al., 2001).

The planting of trees or shrubs as part of a farming system can significantly reduce heat stress and mortalities in livestock, as well as reduce wind speed and erosion and increase crop and livestock production (Bird et al., 1992; Hassen et al., 2017 and Edwards-Callaway et al., 2021). One of the farmers interviewed for the Tagasaste Handbook (Tozer et al., 2022) said that his farm in Marlborough, New Zealand, reaches temperatures of over 50°C. He adds that because woody shrubs effectively cool the

[12] Alfalfa is widely utilized as livestock feed in South Africa as pasture, hay, or silage. Like tagasaste, it is also leguminous and part of the Fabaceae family (Solontsi et al., 2022).
[13] Dryland salinity occurs as a result of natural vegetation clearing in areas with brackish (salty) groundwater, often in preference for agriculture leading to water levels rising (Pannell & Erwing, 2006).

surface of the ground, increasing the area of marginal land planted to tagasaste is a positive way to respond to climate change in areas that experience extreme heat and/or drought. This alludes to the process whereby erosion and land degradation increase albedo and therefore heating of the atmosphere; and conversely that the planting or restoration of vegetation reduces albedo. Utilizing leguminous fodder trees, including tagasaste, can increase the carrying capacity of degraded or marginal agricultural land and improve livestock production due to their high feed value (Dawson et al., 2014). Furthermore, tagasaste is considered a fire retardant and is planted around pine forests as a green fire break in parts of Western Australia (Hèuze et al., 2017).

The Growing Tagasaste in New Zealand handbook (Tozer et al., 2022) estimates that establishment costs in New Zealand are NZD 860 ha^{-1} (which equates to just under ZAR 10000[14]) and that the economic benefits solely for agricultural application and soil erosion prevention is estimated at NZD 726 (around ZAR 8400) ha^{-1} yr^{-1}. Establishment costs were based on the purchase of seedlings for NZD 1.70 each (about ZAR 20 per seedling[15]) from a nursery and planting at a sparse density of 156 plants ha^{-1}, without the use of tree guards. It also includes soil preparation costs and labour for planting and assumes that weed control is carried out using chemicals. The income benefits were broken down into the following components:

1. Nitrogen fixation: NZD 62 (rounded to ZAR 690) ha^{-1} yr^{-1}.This was calculated using a low planting density of 156 plants ha^{-1}, which fixes 25 kg N ha^{-1} yr^{-1}.

2. Feed value: NZD 114 (about ZAR 1270) ha^{-1} yr^{-1}. This was also based on 156 plants ha^{-1} and the price attributed to tagasaste was the same as alfalfa (Medicago sativa) hay. tagasaste and alfalfa are comparable because they have similar nutritional values.

3. Soil conservation: NZD 250 (rounded to ZAR 2800) ha^{-1} yr^{-1}. This calculation was based on the prevention of estimated soil erosion through the planting of tagasaste and included pre- and post-harvest sedimentary loss.

4. Honey production: NZD 300 (rounded to ZAR 3350) ha^{-1} yr^{-1}. This was based on an apiary of 15 hives located near 1ha of tagasaste planted at a low density of 156 plants ha^{-1}.

While these figures are not directly applicable to South Africa due to differences in local market conditions, and other factors such as government support programs, logistics and transportation costs, they provide an insight into the various ways in which tagasaste can add economic value to farming enterprises.

4.2.3 Tagasaste: mitigation and adaptation to climate change

Overall, the respondents agreed that sustainable agricultural practices should become more mainstream to curb the negative effects of conventional farming and the use of agrichemicals. The majority also said that consumers drive the market, and therefore play a role in what and how they farm. This suggests an increased awareness within the agricultural sector and amongst consumers of the connection between

[14] Based on exchange rate: NZD 1 = ZAR 11.14 (Forbes Currency Converter, March 2024).
[15] To the authors knowledge at the time of writing, tagasaste plants can be purchased for approximately ZAR 25 each in South Africa.

human activities and the fate of the environment. The data illustrates that farmers in South Africa are already practising sustainable agricultural methods, such as regenerative agriculture, conservation agriculture, organic farming, permaculture and no-till, in response to current agricultural challenges and societal trends. While the majority of respondents said they think that tagasaste could be used for both mitigation and adaptation purposes, the secondary data provide more quantifiable evidence regarding the parameters of such.

The comparative study to explore carbon sequestration opportunities indicates that tagasaste is capable of sequestering significant amounts of carbon in comparison to spekboom, a shrub currently being used in environmental restoration and carbon offsetting projects in South Africa. It must be noted however, that the application and use of spekboom and tagasaste are not directly interchangeable. For example, it would be inappropriate to plant tagasaste in natural spekboom thicket restoration sites because tagasaste is an exotic species. Similarly, spekboom may be less suited for use as livestock fodder in commercial agricultural operations due to its lower protein content. Table 2 shows more detail about the two studies, how the research was conducted, the main findings, as well as further analysis conducted by the author as described in 4.2.2.1 Mitigation.

The significance of these values should be considered within the constraints of applicability. For example, while it might be realistic that a natural spekboom thicket could have up to 100% canopy cover in the absence of livestock or dense wildlife populations, tagasaste plantations are generally established for the purposes of feeding livestock, and would therefore have much less canopy cover, even if planted more densely than the alley planting in the Wochesländer et al. (2016) study. Furthermore, the calculations are limited to the confines of only two studies, and do not take into consideration that carbon sequestration rates are influenced by several other factors, such as management practices and environmental conditions (Tiefenbacher et al., 2021). In addition, different soils can hold differing quantities of soil organic carbon, with depleted soils having the highest capacity to store carbon (Tiefenbacher et al., 2021). Tiefenbacher et al. (2021) explain that this is based on the carbon saturation capacity concept, where the mineral composition and the size of the particles of soil determine the stability of the carbon stored.

Table 2. Comparative study *summary between spekboom and tagasaste. Where the value of results was not the same, the available results were extrapolated using accepted standard calculations (shown in green).*

	Spekboom	Tagasaste
Source	Mills, A.J. and Cowling, R.M., 2006	Wocheslander, R., et al., 2016
Sampling	Soil carbon: to a depth of 0.5m, total of 30 pits Root carbon: wet sieved then dried, including stones Aboveground biomass: plants adjacent and above soil pit included	Soil carbon: to a depth of 2m (2 test plots and 2 control plots, 5 samples per plot) Biomass: Subplots containing 3 trees each, tangled tree branches from neighboring trees excluded Above-ground biomass: crown, branches, stem, dead attached, dead detached Below-ground biomass: relevant root material up to 1.5m included, sand excluded
Data analysis	Unistat 5.5	IBM SPSSStatistics Verion 21
Study site	Krompoort Farm near Kirkwood, Eastern Cape South Africa Climate: Warm Temperate, average annual rainfall of 250 - 350mm Soil profile: Bokkeveld shale, sandstone, siltstone with Calcaric cambisols, Calic Luvisols, Rhodic Luvisols, Calcaric regosols	A plot near Moora, Western Australia Climate: Mediterranean, average annual rainfall of 498mm Soil profile: Yellow-orthic Tenosol (deep yellow sand)
Canopy cover/ plant density	**93% canopy cover** plant density per hectare unknown. Plant layout was not systematic, resulting in constrained statistical analysis.	**37.5% canopy cover** 550 plants per hectare, planted in alley strips 30m apart with a spacing of 0.7m between plants. Average canopy per plant sampled: length 6.51m x width 10.8m
C sequestration	Total for 27 year trial site: 11 kg C/m2 OR 111 Mg C ha Average per annum: 0.42kg C -2 yr-1 OR **4.07 Mg C ha-1 yr-1 OR 14.9 CO2e ha-1 yr-1**	Total for 22 year trial site: 55.4 Mg C ha -1 Average per annum: **2.5 Mg C ha-1 yr-1 OR 9.2 Mg CO2e ha-1 yr-1**
CO2e at 100% canopy cover	**15.4 Mg CO2e ha-1 yr-1**	**24.5 Mg CO2e ha-1 yr-1**
Co-benefits/ adaptation (taken directly from corresponding paper)	• better rainfall infiltration • reduced erosion • increased biodiversity • income via carbon credits • enhanced tourism potential • increased wildlife carrying capacity • browse for livestock • employment (restoration projects)	• potential bioenergy and biofuel • increased sustainability of farming systems • mitigate CO2 emissions • livestock fodder • reduced erosion • fix atmospheric nitrogen • extract nitrogen from soil if available • increase production of mixed planting systems • soil microbial activity increases retention of relatively stable soil organic carbon

Further to the biophysical carbon sequestration potential of tagasaste as a mitigation pathway, its adoption in livestock husbandry can create additional mitigation benefits. Methane emissions per livestock unit are reduced through improved enteric fermentation as well as a reduction in the input of manufactured animal feed (Dawson et al., 2014). In addition, methane emissions from livestock can be reduced by up to 20% with increased tannins in their diet, provided the diet is not deficient in protein (Min et al., 2020). This implies that incorporating tagasaste into livestock diets may lower the overall methane output of meat and dairy production, given tagasaste's relatively high tannin and protein content.

In terms of adaptation pathways through the use of tagasaste, the survey data shows varied results. While some farmers said that tagasaste's water requirements are comparable to commercially grown trees such as fruit or nut trees, others said that tagasaste's requirements are less than the requirements of fruit and nut trees. On the whole, farmers' experiences are that tagasaste benefits from irrigation during the dry season, but that, once established, water requirements are relatively low. The secondary data indicate that tagasaste can withstand mild drought conditions and has a favourable water use efficiency compared to commercially grown alfalfa. In a water-scarce country such as South Africa, this presents an attractive alternative feed source in livestock enterprises. The risk that tagasaste could threaten water resources would likely be influenced by its potential to naturalise along water courses or in water-sensitive areas. According to literature, the prevention of this occurrence would require monitoring and management (as discussed in 4.1.4 Tagasaste Adoption in South Africa: Limitations and Potential).

The results indicate that tagasaste can aid in the repair or enhancement of soil productivity through its ability to fix nitrogen into the soil and increase below ground biodiversity, as well as rehabilitate soil erosion. Furthermore, the data indicates that the planting of perennial plants such as tagasaste in degraded agricultural lands can cool the surface of the soil, reduce albedo, and improve livestock performance and welfare by providing shade and shelter. With an increase in more frequent and intense heat waves (Roberts & Craig, 2022), there is a growing imperative to investigate strategies for generating cooling mechanisms to alleviate the adverse impacts of elevated temperatures on livestock, crops, and soil. Implementing agroforestry practices such as planting deep rooted perennial plants enrich subsoil organic carbon, enhance nutrient and water cycling, sequester carbon and can decrease the use of fossil fuels (Tiefenbacher et al, 2021). Incorporating fodder trees/woody legumes into farming systems can increase yields and simultaneously enhance ecosystem services (Mbow et al., 2013). There are several ways in which the use of agroforestry methods such as fodder tree technology can be considered a method of mitigating and adapting to climate change, directly (primary) and indirectly (secondary). Mbow et al. (2014) argue that agroforestry practices present a viable avenue to achieve climate change and sustainable livelihood objectives. While Mbow et al. (2014) refer specifically to agroforestry, the theory could also be applied to other sustainable agricultural practices that incorporate trees/shrubs, for example integrated crop-livestock models where fodder tree technology has been implemented. Table 3 shows the impact that the inclusion of trees can have on agroecosystems. Sustainable agricultural practices that increase soil organic carbon repair or enhance the environment and have positive economic, societal and ethical implications (Tiefenbacher et al., 2021).

Table 3. *Impacts of implementing agroforestry practices (Source: adapted from Mbow et al., 2014).*

		LIVELIHOOD	MITIGATION	ADAPTATION
AGROFORESTRY	Carbon benefit	(Income)	+++	+
	Wood energy	(Asset)	+++	++
	Bufer climate risks/ water recycling	(Asset)	++	+++
	Improve ecosystem resilience/microclimate soil fertility	(Asset-Income)	+	+++
	Ecosystem services: Food/fruits/medicine	(Asset-Income)	-	+++
	Reduce pressure on natural forest	(Asset-Income)	+++	+

+++: high positive impact; ++: positive impact; +: limited positive impact; -: zero positive or potential negative impact

In terms of nutritional deficits in areas experiencing food insecurity, vitamin A deficiency is one of the four major nutritional deficiencies in humans and is considered the second most prevalent contributor to the global burden of disease (Zhao et al., 2022). Tagasaste is reported to have a high carotenoid and vitamin A content, which has been shown to improve chicken egg quality and yolk colour when given as part of a ration to layer chickens (Cook et al., 2020; Sindeke et al., 2021 and Rajan et al., 2019). According to Gutierrez et al. (1996), the nutritive composition of eggs is directly linked to chickens' dietary intake. This suggests that eggs produced by hens fed tagasaste could help alleviate vitamin A deficiencies in affected populations. According to the most recent IPCC report (IPCC, 2023), balanced and environmentally sustainable dietary patterns (and the reduction of food loss and waste) offer significant prospects for adaptation and mitigation pathways, while at the same time yielding co-benefits such as supporting biodiversity, ecosystem services and human well-being.

According to Locatelli et al. (2015), synergistic design of mitigation and adaptation initiatives are more effective than initiatives where only one outcome is prioritised. The mutual reinforcement of both outcomes enhances their effectiveness, and the comprehensive analysis of multiple factors diminishes the likelihood of adverse outcomes. Therefore, to build upon the responses in Figure 13 *Farmers' overall impressions of what tagasaste can be used for,* Table 4 below was developed to explore possible mitigation and adaptation strategies that could be employed through the use of tagasaste.

Table 4. *Potential mitigation and adaptation benefits of tagasaste (the mitigation and adaptation benefits are extrapolated and synthesised from: Cusworth et al., 2022; Nayak et al., 2022; Cardinael et al., 2021; EdwardsCallaway et al., 2021; Climate Positive Design, 2020; Ramankutty et al., 2018; Myers et al., 2017; Locatelli et al., 2015; Dawson et al., 2014; Mbow et al., 2014; Wambugu et al., 2011; Brussaard et al., 2010; Orwa et al., 2009).*

Tagasaste uses	Mitigation	Adaptation
Livestock fodder	direct grazing, reduces need for transporting feed from elsewhere	food security, enhanced livestock well-being, increased production, reduced land use change
Bee keeping	enhanced above-ground carbon stocks - plants not pruned/ grazed to allow flowering	increased biodiversity and enhanced pollination of food crops
Land rehabilitation	enhanced carbon sequestration, reduced albedo, repair ecosystem services	can be designed to provide shade and windbreaks, 'green' firebreaks, enhanced ecosystem resilience
Soil improvement	reduced GHG emissions due to decreased fertiliser use	improve naturally poor soils or damaged soils to increase productivity
Landscaping	carbon sequestration, design to repair ecosystem services including biodiversity	design to provide shade and windbreaks, 'green' firebreaks
Pelleting (bagged feed)	carbon sequestration, reduced GHG emissions if pelleting achieved on-farm	fodder banking for dry season or times of drought, enhanced food security
Carbon sequestration	avenue to attract funding for carbon offsetting projects	design projects to have adaptation co-benefits such as improved livestock fodder
Windbreaks	carbon sequestration, soil preservation	shade, cooling of soil, wildlife corridors
Firewood	reduction of harvesting indigenous trees for fuel	provision of fuel for cooking where other trees are not available
Agroforestry & alleycropping	carbon sequestration, less GHG emissions, reduced albedo, ecosystem services including biodiversity	agri diversification can reduce risks caused by climate change, food security
Permaculture and food forests	carbon sequestration, less GHG emissions, reduced albedo, ecosystem services including biodiversity	agri diversification can reduce risks caused by climate change, food security
Mulching	increased soil carbon stocks, reduced albedo	improved soil biology, cooling of soil, weed suppression, enhanced water retention
"Green" firebreaks	carbon sequestration, soil preservation	help prevent wildfires, shade, cooling of soil, wildlife corridors

CHAPTER 5: CONCLUSION

This research has set out to identify solutions to certain negative consequences of conventional agriculture, as well as to investigate alternatives that accommodate existing farming practices. The literature review presents an overview of the global food system and a perspective on the agricultural landscape in South Africa. The use of woody leguminous plants offers a potential strategy for reducing land use change, enhancing agricultural output and building resilience in rural communities, while also supporting climate change mitigation in agriculture. The main purpose of this study has been to evaluate the potential agricultural benefits offered by tagasaste to contribute towards mitigation and/or adaptation strategies within the context of South Africa, with a focus on improving food and nutritional security, enhancing rural livelihoods and supporting healthy ecosystems.

The results indicate that farmers in South Africa are currently exploring ways to respond to on-farm challenges, such as soil degradation and climate change. On the whole, crop and/or livestock choices are determined by their suitability to local conditions, as well as their economic value. Interest in tagasaste has persisted in South Africa for more than forty years, mainly for use as livestock fodder, soil rehabilitation and apiculture. Its adoption, however, has remained low, predominantly due to lack of knowledge about its successful establishment. The data indicate that the primary establishment challenges experienced by farmers in South Africa are associated with unfamiliarity with the soil, nutrient and environmental growing requirements of tagasaste.

In terms of climate change mitigation, this research confirms that tagasaste has a high carbon sequestration capacity. Considering this, tagasaste presents the potential to be included in carbon trading projects in rural areas in South Africa. Tagasaste's characteristics are conducive to soil rehabilitation and erosion control, making it particularly suitable for use on degraded agricultural lands. Additionally, through nitrogen fixation and the high protein content of edible matter, it can sustainably increase the productivity and carrying capacity of depleted soils. Incorporating tagasaste into farming systems also reduces secondary emissions through tagasaste's nitrogen-fixing capabilities, and its water and nutrient cycling attributes, as well as indirectly reducing the GHG emissions associated with the production and transport of feed and agricultural chemicals. This research further suggests that feeding tagasaste to ruminants enhances enteric fermentation, thus reducing methane emissions through improved grazing that is higher in tannins and protein.

This study indicates that tagasaste can also function as an adaptation pathway. The characteristics of tagasaste make it suitable for the reclamation of degraded land, enhancing ecosystem services, and improving livestock productivity through the provision of shade and high-quality feed (improved feed conversion ratio). Furthermore, as tagasaste is drought tolerant and responds well to minimal irrigation or rainfall, the overall water requirements to produce livestock feed are less than those of conventional crops with a similar nutritional value. The results suggest that including tagasaste in farming systems offers an

opportunity for agricultural diversification, thus reducing some of the economic risks associated with climate change. In South Africa, where up to a quarter of the population experiences food insecurity or undernutrition – particularly among previously disadvantaged small-scale farmers and their families - tagasaste can offer options to improve food security and enhance livelihoods. This can be achieved both directly through increased production of meat and dairy products and indirectly through carbon offsetting projects. In relation to tagasaste's nutritional aspects, further studies may determine whether animal-derived products, such as meat and eggs, exhibit elevated levels of vitamin A when livestock and poultry are supplemented with tagasaste as a component of their dietary intake.

In South Africa, where farmers often have constrained financial capacity and increasingly struggle with limited water resources and drought conditions, tagasaste offers practical opportunities to respond to the effects of climate change. Farmers could utilise tagasaste to diversify their agricultural activities, increase livestock carrying capacity and add value through carbon offsetting and/ or carbon trading. Although the findings herein raise challenges to consider, including the potential of tagasaste to encroach on native vegetation and, conversely, the possibility of its failure to become established, its potential economic value deserves to be assessed in more detail and balanced against these risks. The author proposes that the implementation of a strategy to facilitate the monitoring of the possible risks of tagasaste encroachment would help prevent negative consequences and pave the way for farmers to deal with the challenges and to benefit from its versatile characteristics. While tagasaste has not been found to be invasive in South Africa and is not listed on the National List of Invasive Species, the Department of Forestry, Fisheries and the Environment (DFFE) could periodically assess tagasaste's potential to naturalise on farms where tagasaste has already been planted. Thus, if tagasaste's adoption accelerated and its economic contribution outweighed the risks, the Department of Agriculture, Land Reform and Rural Development (DALRAD) would be able to make an informed decision to allow for its use in areas found to be less conducive to the naturalisation of tagasaste and enforce appropriate management practices or restrictions. The 2001 Conservation of Agricultural Resources Act (Act 43 of 1983) or CARA Regulations, operating under DALRAD, makes allowances for some exotic plant species that have demonstrated invasive tendencies in specific areas and has set conditions where applicable. To facilitate the successful establishment of tagasaste, a comprehensive and accessible South African handbook should be developed. This handbook ought to provide detailed guidance for farmers on the successful establishment of tagasaste, as well as the different methods of incorporating fodder tree technology into their farming systems.

The deductions made as a result of this research are constrained to a small sample of farmers and the limited scientific research based specifically on the mitigation and adaptation potential of tagasaste under South African conditions. The parameters for tagasaste's carbon sequestration potential under different growing and environmental conditions should be established in more detailed studies. Similarly, the use of tagasaste in agricultural adaptation applications would require localised studies to establish the needs of the specific target community and/or region.

With due attention to the abovementioned considerations, this study provides evidence that the use of tagasaste could present a cost-effective option to boost agricultural production without the need to increase land use change. The use of tagasaste has the potential to support a growing population and contribute positively towards biodiversity and environmental services, as well as offer rural development options to enter a growing carbon trading market. The author proposes that tagasaste could be planted in marginal areas or areas with degraded agricultural land, where it is not appropriate and/or not feasible to restore the natural vegetation. Tagasaste would be suitable for planting, for example, in areas where rural communities should not be displaced in favour of rewilding and would benefit from having access to a sustainable and nutritious source of livestock feed. This approach would be beneficial to rural settings throughout the Global South, because the utilisation of fodder trees aligns with the principles of existing practices, such as agroforestry, agroecology, regenerative agriculture, and other traditional farming methods. Moreover, the implementation of 'payment for environmental services' schemes (Herrero et al., 2013), aimed at stimulating sustainable agricultural practices in such regions, may aid in the diversification of and increase in income streams. This would not only foster the adoption of sustainable agricultural methods and therefore the restoration or improvement of environmental services, but also potentially attracting international climate finance through established mechanisms such as the Green Climate Fund, the Least Developed Countries Fund and the Global Environment Facility (GCF 2023; GEF 2023), along with specialized forest conservation initiatives including the Forest Carbon Partnership Facility and the Reducing Emissions from Deforestation and Forest Degradation (REDD+) framework (UNFCCC 2023). These funding sources specifically support climate adaptation, sustainable agriculture and forest conservation projects in developing countries, particularly where interventions can demonstrate multiple benefits across environmental, social and economic dimensions.

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Annexure 1

THE USE OF TAGASASTE/ TREE LUCERNE: FARMERS EXPERIENCES AND PERSPECTIVES

Thank you for taking the time to participate, your input is valued and much appreciated![16]

[16] Anonymised survey data can be shared upon request from the authors.

Questionnaire:

Tagasaste is the most widely used common name for Chamaecytisus palmensis internationally. Tagasaste is also known as lucerne tree, or boomlusern in Afrikaans (South Africa).

Please answer the questions as fully and honestly as you can. If some of the questions don't apply to you, skip that question and move to the next one.

1. Are you currently growing tagasaste?
   - ❑ Yes, I've planted tagasaste on my farm
   - ❑ Not anymore
   - ❑ No, but I want to
   - ❑ Yes, as part of a project for rural development or research

2. Where is your farm/project?
   - ❑ Eastern Cape
   - ❑ Free State
   - ❑ Gauteng
   - ❑ KwaZulu-Natal
   - ❑ Limpopo
   - ❑ Mpumalanga
   - ❑ Northern Cape
   - ❑ North West
   - ❑ Western Cape
   - ❑ Other country

3. What did/would you plant tagasaste for?
   - ❑ Cattle
   - ❑ Sheep/goats
   - ❑ Game
   - ❑ Bees
   - ❑ Soil rehabilitation
   - ❑ Windbreak
   - ❑Other (please specify)_____

4. If you have grown tagasaste, how did you grow it?
   - ❑ from seed
   - ❑ seedlings
   - ❑ trees in pots

If you tried and failed, please describe what went wrong _____

5. What is easy or difficult to grow and establish tagasaste? Please describe your success and failures.

_____

6. Could you find useful, local information on tagasaste that was based on farmers' experiences?
   - ❑ Yes
   - ❑ No

Comments

_____

7. Where did you hear about tagasaste?
   - ❑ Another farmer
   - ❑ Something I read

❑ Can't remember, I've known about it for a long time
❑Other (please specify)_____

8. How would you describe your farm/project? ❑ Extensive farming
❑ Intensive farming
❑ Homesteader
❑ Rural community farming
❑ Other, please specify (e.g. beekeeper, permaculture gardener, food forest homesteader, combination of the above)_____

9. Do you think some agricultural practices...
❑ harm the environment
❑ decrease soil fertility
❑ pollute underground water and rivers
❑ cause biodiversity loss
❑ increase carbon footprint
❑ cause land degradation
❑ decrease production over time

Any other comments
_____

10. Do you think farmers should practice more sustainable farming methods?
❑ Yes
❑ No

Please elaborate (eg. less chemical use, no-till, regenerative agriculture, conservation agriculture, or don't believe chemicals are harmful to the environment)_____

11. Tagasaste is a leguminous plant, which means it can fix nitrogen into the soil via a beneficial relationship with rhizobium bacteria that live in nodules on its roots. Other examples include lupins, peas, clover, soybeans, peanuts and carob, amongst many others.

12. In your experience/opinion, does tagasaste increase soil fertility?
❑ Yes
❑ No

Any other comments
_____

13. Climate change is a topic increasingly featured in media today. Do you believe that climate change poses a threat to the environment and humanity?
❑ Yes
❑ No
❑ Don't believe in climate change

Please elaborate
_____

14. There are two approaches to addressing climate change issues: mitigation, which involves limiting or removing carbon from the atmosphere; and adaptation, which involves minimizing damage caused by climate-related events such as severe droughts and floods.

In your opinion, could tagasaste be a potential option for on-farm climate change mitigation and adaptation efforts?
❑ Only mitigation (carbon sequestration)
❑ Only adaptation (drought hardy, fixes nitrogen)
❑ Both
❑ Neither

Any further comments

_____

15. In your opinion, how much do consumers drive the market, and ultimately decide what farmers grow and how they grow it?

    _____

16. What factors influence how you decide what to farm/cultivate?
    - ❑ Family tradition
    - ❑ Grows well in my area
    - ❑ Best profit margins
    - ❑ It's what I'm good at
    - ❑ It's the least risky option
    - ❑ It's the right thing to do for the environment
    - ❑ I have a contract to grow for someone else
    - ❑ Other (please specify)_____

17. Did you know that tagasaste is listed as invasive under certain conditions in some countries, including New Zealand, Australia and Canada?
    - ❑ Yes
    - ❑ No

Any further comments

_____

18. Do you think there is potential for tagasaste to become invasive in your area?
    - ❑ Yes
    - ❑ No

Why?

_____

19. Once established, have you found tagasaste to have a high water demand in comparison to other trees you have planted?
    - ❑ Yes
    - ❑ No

Compared to which other trees (or any other comments) _____

20. In your opinion, which of the following uses do you think tagasaste could be utilized for?
    - ❑ Livestock fodder
    - ❑ Bee keeping
    - ❑ land rehabilitation
    - ❑ Soil improvement
    - ❑ Landscaping
    - ❑ For human consumption
    - ❑ For pelleting (animal feed)
    - ❑ Carbon sequestration
    - ❑ Windbreaks
    - ❑ Firewood
    - ❑ Agroforestry and alley cropping
    - ❑ Permaculture and food forests
    - ❑ Mulching
    - ❑ 'Green' firebreaks (fire retardant)
    - ❑ It's not really a useful plant

Any other comments

_____

20. Would you like to receive feedback on this research once it is complete?

- ❑ Yes
- ❑ No

Your email address:

_____

THAT'S IT, SURVEY DONE! THANK YOU FOR TAKING THE TIME TO PARTICIPATE!

PS. PLEASE PASS THIS ON TO ANY OTHER FARMERS/GROWERS THAT YOU THINK COULD CONTRIBUTE TO THIS RESEARCH!