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COMPLEX EVALUATION OF ECOSYSTEM SERVICES IN AGRICULTURAL LANDSCAPES

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CONTENTS

LIST OF ABBREVIATIONS AND ACRONYMS

AfSIS	African Soil Information Service
AfSP	Africa Soil Profiles
AfSS	AfSIS Sentinel Site
AGROTOPO	Hungary Agrotopographical Database
ARIES	Artificial Intelligence for Environment & Sustainability
BD	bulk density
CBA	Critical Biodiversity Area(s)
CICES	Common International Classification of Ecosystem Services
CFR	Cape Floristic Region
CLC	Corine Land Cover
CS	carbon stock(s)
CSIR	Council of Scientific & Industrial Research
CSV	comma separated values
CWDM	Cape Winelands District Municipality
DALRRD	Department of Agriculture, Land Reform and Rural Development (SA)
DEA	Department of Environmental Affairs (SA)
DEADP	Department of Environmental Affairs and Development Planning (WC)
DEM	digital elevation model
DFFE	Department of Forestry, Fisheries and the Environment (SA)
DoA	Department of Agriculture
DOSoReMI	Digital, Optimized, Soil Related Maps and Information in Hungary
DWAF	Department of Water Affairs and Forestry (SA)
DWS	Department of Water Affairs and Sanitation (SA)
EEA	European Environmental Agency
ES	ecosystem service(s)
ESA	Ecological Support Area(s)
ESDAC	European Soil Data Centre
ESRI	Environmental Systems Research Institute
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GDP	gross domestic product
GHG	greenhouse gas
GIS	geographic information system(s)
GlobalGAP	Global Good Agricultural Practices

GloSEM	Global Soil Erosion Modelling platform
GloREDa	Global Rainfall Erosivity Database
GPS	global positioning system
GSOCmap	Global Soil Organic Carbon Map
GSOCseq	Global Soil Sequestration Potential (FAO map)
HU	Hungary
INDCs	independent nationally determined contributions
InVEST	Integrated Valuation of Ecosystem Services and Trade offs
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IPM	integrated pest management
IPW	Integrated Production of Wine
ISRIC	International Soil Reference and Information Centre
ITPS	Intergovernmental Technical Panel on Soils
KSH	Központi Statisztikai Hivatal (Hungarian Central Statistical Office)
LULC	land use (and) land cover
MEA	Millennium Ecosystem Assessment
MODIS	Moderate Resolution Imaging Spectroradiometer
MS	Microsoft
NASA	National Aeronautics and Space Administration
NRM	Natural resource management
OECD	Organisation for Economic Co-operation and Development
OM	organic matter
PSDF	Provincial Spatial Development Framework
RQ	research question(s)
RUSLE	Revised Universal Soil Loss Equation
SA	South Africa
SANBI	South African National Biodiversity Institute
SANLC	South African National Landcover
SCS	soil carbon stock(s)
SDGs	Sustainable Development Goals
SDR	Sediment Delivery Ratio
SEP	Science for Environment Policy
SOC	soil organic carbon

SOM	soil organic matter
SOTER	Soil and Terrain Digital Database(s)
SOTWIS	SOTER-based soil parameter estimates
SPLUMA	Spatial Planning and Land Use Management Act
SRMT	Shuttle Radar Topography Mission
Stats SA	Statistics South Africa
SWAT	Soil and Water Assessment Tool
TAKI	Agrártudományi Kutatóközpont Talajtani Intézet (Hungarian Agricultural Science Research Centre Institute of Soils)
TEEB	The economics of ecosystems & biodiversity
UNEP	United Nations Environment Programme
UNFCC	United Nations Framework Convention on Climate Change
USA	United States of America
USD	United States Dollar ($)
USGS	United States Geological Survey
WC	Western Cape
WCDM	West Coast District Municipality
WCG	Western Cape Government
WWF-SA	Worldwide Fund for Nature South Africa
ZAR	South African Rand (R)

1. INTRODUCTION

Ecosystem services (ES) are the benefits that people receive from nature (MEA, 2005). They play a critical role in ensuring human well-being (Grunewald & Bastian, 2015; IPBES, 2019). Fundamentally, humankind and all living creatures are dependent on the flow of ES (Daily, 2013). ES both directly and indirectly provide major inputs into various economic sectors and support the survival and flourishing of all life on earth that takes part in natural environmental processes (IPBES, 2019). This dependence on ES has led to unprecedented changes in the natural environment.

Over the last century, humans have altered landscapes on various scales more quickly and extensively than during any other comparable period in history. This extensive land use land cover (LULC) change happened largely to meet growing demands for food, fresh water, timber, fibre and fuel (IPBES, 2019; MEA, 2005). The changes in land use have significantly contributed to net improvements in human well-being and economic development. However, these gains have been achieved with costly hidden trade-offs in the form of loss of biodiversity, degradation of ecosystems and natural resources, and loss of ES (IPBES, 2019; MEA, 2005). One prominent example for change in land use is the expansion of cultivated areas. Between 1950 and 1980, more land was converted to farmland than in the 150 years from 1700 to 1850, illustrating the rapid pace of agricultural expansion (IPBES, 2019).

These changes in LULC not only affect local ecosystems but also push global environmental systems towards critical thresholds. Predictive earth-systems research have identified critical thresholds or gradients of increasing global environmental risk that is directly linked to the well-being of humans. The Planetary Boundaries concept identifies nine critical natural threshold limits, revealing human activity as the main driver of environmental change, with four of these limits having already been exceeded, most notably land-system change and loss of biosphere integrity (Rockström et al., 2009; Steffen et al., 2015).

In response to these challenges, spatial development planning is essential for aligning human needs with ecological health. It aims to guide sustainable changes in LULC, ensuring the responsible management of natural resources, enhancing ecosystem functions, and reducing environmental stress. This approach supports ecological resilience and stability, crucial for maintaining ES (Goodenough & Hart, 2017). Identifying the long-term trends of LULC conversion supports planning for sustainable spatial development (Metzger et al., 2006).

Agricultural ecosystems, or agroecosystems, are a significant source of ES essential for human survival and societal welfare (Garbach et al., 2014; Power, 2010). Agroecosystems are the largest terrestrial ecosystems in the world, occupying around 34% of the surface of all land on the planet

(IPBES, 2019; MEA, 2005). Agriculture itself is dependent on the healthy functioning of several ES on multiple scales, such as on the farm, in a landscape, and across a region. Natural resources on farms subsume ES, e.g., crop production, clean water, flood control and nutrient cycling (Grunewald et al., 2015; Power, 2010).

Humans are an integral part of ecosystems, benefitting from them and managing these systems to maximise the production of selected ES, e.g., food, feed and fibre (Grunewald et al., 2015). A dynamic interaction occurs between people and components of ecosystems in areas where natural resource management is practiced, such as with farmers in agricultural landscapes. This farmland management drives direct and indirect changes in ecological conditions and ES (Power, 2010). Studies show that LULC change and management decisions have multiple impacts on the structures, processes, and functions of ecosystems in agricultural areas (Hasan et al., 2020; Zhan, 2015).

As environmental degradation in high-value agricultural production landscapes becomes a growing concern, the use of ES assessment and mapping tools can help determine the status and condition of these services and benefits (Jacobs et al., 2017). The resulting maps can inform land managers, spatial planners, and researchers on potential scenarios to reverse ecosystem degradation while meeting the increasing demand for ES (Gemmill-Herren et al., 2019). These tools can also aid in the development of policies focused on climate change resilience and protecting regional agricultural production over the long-term (Schulze, 2017).

Problem Statement and Justification

Agricultural production has had hidden costs, it has come with the trade-offs between ‘provisioning’ and ‘regulation and maintenance’ ES in economically productive areas (Elmqvist et al., 2011; Foley et al., 2005; Matson et al., 1997). The global environmental impact of agriculture includes land degradation that has reduced productivity in 23% of terrestrial areas, and in some areas, crop output is threatened by pollinator loss (IPBES, 2019). Many countries throughout the world are facing challenges with ensuring food security due to the degradation of natural and agricultural land. Some can be attributed to unsustainable land use management decisions, and others to current climatic conditions and climate change impacts (Bakker et al., 2005; Koch et al., 2013; Steiner, 1996; Tengberg & Torheim, 2007).

The transformation of natural landscapes into agricultural land is a significant trend in South Africa. Between 2001 and 2019, the country experienced continuous LULC changes, characterized by an increase in croplands and a decline in natural vegetation. These shifts were further intensified by climate change-related events, such as droughts (Abd Elbasit et al., 2021; Egoh et al., 2009). While only less than 3% of South Africa's land (36,600 km^2) is deemed high-potential agricultural land, a substantial 37% (464,000 km²) is nonetheless cultivated or utilized for farming systems (IPBES, 2018; Stats SA, 2020; WWF-SA, 2014). This illustrates how much area is being treated to boost agricultural production capacity through some form, highlighting the potential significance of how farming inputs may be impacting the provisioning and regulation of ES (Horak et al., 2021; Quinn et al., 2011; Van Niekerk et al., 2018).

In the Western Cape (WC) province of South Africa, a region distinguished by the biodiversity-rich Cape Floristic Region, a concerning trend has emerged over the past two decades: a steady decline in the ‘provisioning’ and ‘regulation and maintenance’ ES, coupled with escalating land degradation (Abd Elbasit et al., 2021). This situation underscores the urgent need for research to safeguard the resilience of this ecologically vital region, aiming to balance human demands on natural resources with maintaining ecological integrity (Giliomee, 2006; Goodness & Anderson, 2013).

Key research gaps identified include insufficient localized ES maps/models and data, a gap in understanding the impacts of regional spatial development trends on ES, and a limited understanding of the drivers of farm management decision-making that impact ES in the WC (Choruma & Odume, 2019; Goodness et al., 2013; Pasquini & Cowling, 2015). Addressing these gaps is essential for informing regional spatial planning frameworks, making them more robust tools for researchers, spatial planners, and policymakers to ensure ES-supported development (Sitas et al., 2014b).

Various assessments of ES have been done in South Africa, including both biophysical and economic valuations. These assessments are mostly generalised and do not provide useful contextual information on ES in high-value agricultural landscapes to regional spatial planners (Abd Elbasit et al., 2021; Egoh et al., 2009, 2008; Malherbe et al., 2019). Presently, there are limited ES maps and models specifically tailored to the WC's agricultural landscapes for landscape level planning. The existing maps do not incorporate localized, field-specific data, which can lead to inaccuracies (WCG, 2014, 2019). As the ES scientific field is relatively new, there is a lack of localised data on ES for the WC, South Africa. Generalised data are regularly used as input into ES models which result in generalised and imprecise ES maps (FAO, 2018a, 2022). This reliance on generalized data compromises the accuracy of ES assessments. As all ES valuation is locally and contextually specific, particularly in high-intensity land use landscapes, in-field samples and observations should be combined with publicly available ES data to improve data quality and increase the accuracy of localised ES maps of agricultural landscapes (Petrokofsky et al., 2012).

The influence of spatial development trends on the region's ES has not been thoroughly examined (Abd Elbasit et al., 2021). Gaining a deeper insight into the impacts of LULC changes on ES occurrence is imperative for shaping effective spatial planning strategies in the WC (Pasquini et al., 2015).

The factors driving farmers' land management decisions in the WC, including both external and internal influences, are poorly understood. Exploring the relationship between farming practices and ES, especially the role of sustainable practices, is crucial for the inclusion of data-driven recommendations for regional spatial development planning (Bourne et al., 2016; Findlater et al., 2018; Smith & Sullivan, 2014). There is a need for actionable, research-driven recommendations to improve ES-support in land use planning, grounded in region-specific insights. Consequently, this would result in improved agricultural spatial development guidelines for the mitigation and adaptation to climate change impacts and improved natural resource management. This knowledge can reduce short-sighted failures by decision-makers who trade off long-term provision against short-term gain, maximising one ES at the expense of others (SEP, 2015). Current planning frameworks fail to integrate socio-ecological factors, undermining their capacity to foster sustainable agricultural practices across the landscape level (DALRRD, 2023; WCG, 2014).

Research Objectives and Questions

This study aims to strengthen evidence-based ES support in environmental management, and spatial planning and development, by assessing key ES and identifying key factors influencing agricultural landscapes in the WC. The three key ES selected for this research are global atmospheric regulation, soil erosion control, and crop production, as they have a shared ES interaction caused by the same drivers (Bennett et al., 2009).

Objective 1. Model and assess 3 key ecosystem services in the agricultural study areas with the Integrated Valuation of Ecosystem Services and Trade offs (InVEST) tool, on the landscape-scale to quantify ecosystem service provisioning in the Western Cape.

(i) How can in-field sampled data be integrated into the modelling methodology of assessing soil carbon storage (for global atmospheric regulation) to improve the quality of data inputs? (Pilot study in Hungary)

(ii) What is the status of the three ecosystem services' provisioning and functioning in the agricultural landscape study areas, based on the combined public databases and in-field sampled data?

Objective 2. Determine the recent spatial development trends in land use land cover in the agricultural landscape study areas that impact ecosystem service provisioning.

(iii) What are the major spatial development trends in land use land cover in the agricultural landscape study areas that impact ES provisioning at the landscape-scale?

Objective 3. Determine how farmers impact ecosystem services in agricultural landscapes in the Western Cape.

(iv) What are the drivers of farmer decision-making in the Western Cape that have an impact on ecosystem services in the agricultural landscape study areas?

(v) What specific impacts do farmers have on ES on their farms?

(vi) What environmentally sustainable practices do farmers implement on their farms that support ES provisioning and functioning?

(vii) What impacts do influencers have on farmer decision-making that affect ES?

Objective 4. Develop policy proposals on evidence-based additions (resulting from Objectives 1-3) to Western Cape municipal spatial planning and development frameworks to include consideration of ecosystem services in local government spatial planning for agricultural landscapes.

(viii) How are ecosystem services integrated into spatial planning processes, and what gaps exist?

(ix) How can InVEST ecosystem service models be used to improve the current spatial planning and development of agricultural landscapes of the Western Cape?

2. LITERATURE REVIEW

2.1. Ecosystem Services

First being used in the formal scientific literature in 1983, the meaning of ES has transformed over 40 years (see definitions in Table 1) (Daily, 1997; Danley & Widmark, 2016; Ehrlich & Mooney, 1983; Gómez-Baggethun et al., 2010). The term developed as scientists reframed debates within natural science and conservation. Then, the term was reworded when scientists played a larger role in influencing policymakers and contributing to sustainability and resource economics fields (Daily, 1997; Lamarque et al., 2011). It was found that a generalized definition of ES that describes society's dependency on nature is more useful for communicating with the public and policymakers, on the need for environmental conservation (Lamarque et al., 2011).

Table 1. A selection of ecosystem service definitions proposed by various scientific literature sources between 1997 and 2018.

Literature Reference	Definitions
Daily (1997)	"The conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfil human life."
Daily & Dasgupta (2001)	"The wide array of conditions and processes through which ecosystems, and their biodiversity, confer benefits on humanity; these include the production of goods, life-supports functions, life-fulfilling conditions, and preservation of options."
De Groot et al. (2002)	"The capacity of natural processes and components to provide the goods and services that satisfy human needs, directly or indirectly."
MEA (2005)	"The benefits people obtain from ecosystems."
Haines-Young & Potschin (2013)	"The contributions that ecosystems make to human well-being... The outputs of ecosystems that most directly affect the well-being of people... they retain a connection to the underlying ecosystem functions, processes and structures that generate them."
Grunewald et al. (2015)	"The services rendered by nature and used by humankind."
Burkhard & Maes (2017)	"The contributions of ecosystem structure and function (in combination with other inputs) to human well-being."

The ability of the ES term to hold different definitions and meanings to different stakeholders, as a boundary object, makes it a versatile policy advocacy tool. Since 2010, it has been used as a boundary object (with interpretive flexibility) for sustainability and transdisciplinary collaboration between natural scientists and economists, as the concept appeals to scientists, policy-makers, land users, and others (Abson et al., 2014; Steger et al., 2018).

The ES approach provides a useful framework for analysing and evaluating the relationship between people and the environment (Grunewald et al., 2015; Haines-Young & Potschin, 2010). This relationship can be identified through the elements in the ecosystem-human continuum, e.g. status, capacity, continuity of ecosystem goods and services, and the beneficiaries (Jørgensen, 2009). Based on the ES concept, it is a type of analytical lens to allow natural systems to be viewed in a different way, specifically as the source for a variety of public goods and services (FAO, 2014; Grunewald et al., 2015). From transdisciplinary efforts, the ES approach has been formulated to mainstream the value of nature, in terms of economic, ecological, and social aspects, into society's activities.

The ES approach aligns the valuing of nature more closely to the economic science paradigm, with the aim of improving natural resource management and addressing environmental damage. It also emphasizes the role of incentives in shaping economic behaviour (Costanza et al., 1997, 2014; UNEP, 2010). Public ecosystem goods and services underpin large industries such as the agriculture sector (Dwyer et al., 2015; OECD, 2015; Power, 2010). Within this paradigm, farmers prioritize profit in their agricultural practices, which can lead to detrimental impacts on the environment and ultimately cause degradation of ES, resulting in reduced productivity of their farms in the long-term (FAO, 2014).

Cascade Model

The Cascade Model described by Haines-Young and Potschin (2010), a conceptual framework, illustrates how ecosystem functions translate into services and benefits for humans, and describes how changes in ecological conditions can affect the provision of ES (Figure 1).

The Cascade Model provides a framework that connects the ES flow to ecological structures and processes, functions, services, benefits and values. The chain starts with biophysical structures that, together with fundamental processes of nature, create the capacity or potential for ecosystem functioning (Haines-Young et al., 2010). The potential for the delivery of ES exist in functioning ecosystems. From functioning ecosystems, potential for the delivery of ES emerges, and benefits are obtained by extracting a share from the entire pool of ES potential, and values are assigned to these benefits provided (Haines-Young et al., 2010; Potschin & Haines-Young, 2016).

This model indicates that soil functions, such as carbon storage, are usually on the 1st level (the ecosystem condition). Services that depend on soil such as erosion control, food provision, and carbon sequestration in the soil as indicator for global atmospheric climate regulation are on the 2nd and 3rd levels (Czúcz et al., 2020). Role-players such as the beneficiaries and users of final products, and those that impact the potential of an ecosystem to provide goods and services, are important considerations for environmental management and policy development (Rounsevell et al., 2010).

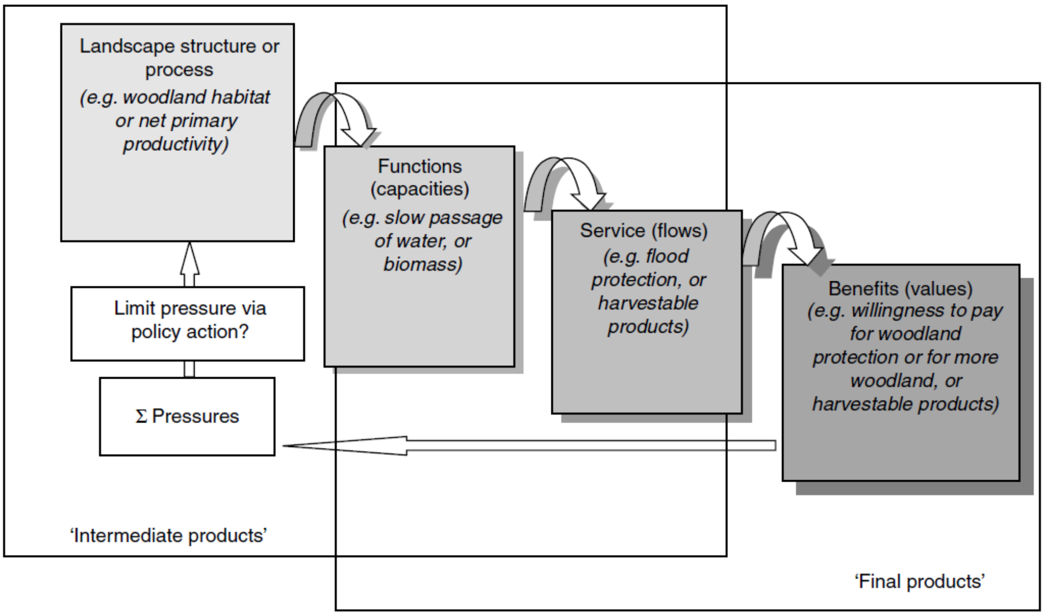


Figure 1. The ecosystem service Cascade Model (Haines-Young et al., 2010).

Ecosystem Services in Landscapes

The European Landscape Convention defines landscape as "an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors", which includes urban, peri-urban, rural, natural land, and water areas (Council of Europe, 2002). The term has been difficult to characterize within environmental science as it is a social construct of a unit of spatial extent, commonly associated with social and cultural factors (Gergel & Turner, 2017; von Haaren et al., 2019). The term is multifunctional, and it has spatial range (extent and scale), social perception, is composed of elements and components, its spatial management and organisation is largely impacted by humans, it's dynamic, and naturally experiences spatial fluxes (Antrop, 2005). A landscape describes a medium-scale excerpt of the globe's surface, typically anywhere between 1-10^4 km^2 (Wratten et al., 2013). Core themes of landscape ecology include the spatial pattern or structure of landscapes, the relationship between pattern and process in landscapes, the relationship of human activity to landscape pattern, process and change, and the effect of scale and disturbance on the landscape (Gergel et al., 2017).

The elements and components, like soil and vegetation, that make up landscape structure play a central role in the provisioning of ES (Frank et al., 2012; Gergel et al., 2017). Landscape pattern is determined by LULC size, spatial arrangement, shape, and distribution of landscape elements, such as rivers and mountains (Figure 2). Landscape patterns are linked to underlying ecological gradients and processes (von Haaren et al., 2019). Ecological processes, such as competition, dispersal, disturbance, and the flux of energy and matter, impact on and are affected by landscape patterns and structure (Gergel et al., 2017).

Figure 2. An agricultural landscape with a mosaic of varying land use land cover, including agroecosystems, in the Western Cape, South Africa (Jacobs, 2022).

Agroecosystems across large spatial extents with large areas of continuous farmland create agricultural landscapes (Eichler Inwood et al., 2018; Gliessman, 2014). Much like the term landscape, the agricultural landscape is a social perception where large areas are characterised by expansive farmland across it (Antrop, 2005; Benson & Roe, 2007; Wratten et al., 2013). These intensely managed ecosystems have been engineered to maximise specific provisioning ES, such as food and textile production, as they have high value in international and regional commodity markets (Dwyer et al., 2015; Sandhu & Wratten, 2013).

Classification

The MEA (2005) offered a simplified classification of ES that has been widely adopted in research, categorizing them into provisioning, regulating, cultural, and supporting services. Examples include, but are not limited to, provisioning services such as the production of food, fibre and clean water; regulating services including atmospheric concentrations and flood protection; cultural services including recreational activities in nature; and supporting services including all the processes that support the condition and potential for ES creation (MEA, 2005).

In this research, the Common International Classification of Ecosystem Services (CICES) version 5.1 is used as a standardised classification and categorisation framework of ES (EEA, 2018; Haines-Young et al., 2013). CICES presents the most current and authoritative version of ES classification, as it is regularly updated after reviewing of relevant literature and widespread consultation with experts (Haines-Young & Potschin-Young, 2018). It was developed as part of the revision of the United Nations Statistical Division's System of Environmental and Economic Accounting and is used in economic and policy sectors (Haines-Young et al., 2013). CICES classifies ES in a *sensu stricto* hierarchical structure, with no overlap between individually labelled ES (so each ES identified is unique and is considered a single ES). The definitional structure has three broad sections, similar to MEA (2005), classified as provisioning, regulation and maintenance, and cultural ES, see Table 2. These are further classified within divisions and groups, and a total of 90 individual ES are detailed (EEA, 2018; Haines-Young et al., 2018).

Table 2. Simplified categorisation of ecosystem services by the Common International Classification of Ecosystem Services relevant to agricultural production (Haines-Young et al., 2018).

CICES Section (Biotic & Abiotic)	**Ecosystem Service examples**
Provisioning	Harvested crop produced energy and seed for commercial sale.
Regulation and Maintenance	Flood mitigation, pest damage reduction in crops, sustaining population of ES-related species.
Cultural	Ecotourism, recreation, local identity, artistic inspiration.

Table 3 shows the full CICES framework classification of the three ES assessed in this study. It describes the section, division, group, class, code, class type, simple descriptor, ecological and use clauses, example services, goods and products, and the IPBES name equivalency (EEA, 2018).

2.1.1. Global atmospheric regulation

Global atmospheric regulation is the regulation and maintaining ES describing one of the most fundamental life-sustaining services provided by nature (Costanza et al., 1997; IPCC, 2014; MEA, 2005). The ability of ecosystems to absorb and emit chemicals, at various scales, makes it an important factor in the global reduction of global greenhouse gases (Foster et al., 2017; Reichle, 2019).

Table 3. Full classification of the three ES assessed in this study extracted directly from the Common International Classification of Ecosystem Services (CICES) v5.1. framework (EEA, 2018).

Selected Ecosystem Service	**Global atmospheric regulation**	**Soil erosion control**	**Crop production**
Section	Regulation & Maintenance (Biotic)	Regulation & Maintenance (Biotic)	Provisioning (Biotic)
Division	Regulation of physical, chemical biological conditions	Regulation of physical, chemical, biological conditions	Biomass
Group	Atmospheric composition conditions	Regulation of baseline flows and extreme events	Cultivated terrestrial plants for nutrition, materials or energy
Class	Regulation of chemical composition of atmosphere and oceans	Control of erosion rates	Cultivated terrestrial plants grown for nutritional purposes
CICES v5.1 Code	2.2.6.1	2.2.1.1	1.1.1.1
Class Type	By contribution of type of living system to amount, concentration or climatic parameter (Global climate regulation by reduction of greenhouse gas concentrations)	By reduction in risk, area protected (Stabilisation and control of erosion rates)	Crops by amount, type (e.g. cereals, root crops, soft fruit, etc.)
Simple descriptor	Regulating our global climate	Controlling or preventing soil loss	Any crops and fruits grown by humans for food; food crops
Ecological clause	Regulation of the concentrations of gases in the atmosphere...	The reduction in the loss of material by virtue of the stabilising effects of the presence of plants and animals…	The ecological contribution to the growth of cultivated, land-based crops…
Use clause	…that improves living conditions for people	…that mitigates or prevents potential damage to human use of the environment or human health and safety	…that can be harvested and used as raw material for the production of food
Example service	Sequestration of carbon in forests	The capacity of vegetation to prevent or reduce the incidence of soil erosion	Standing wheat crop before harvest (Proxy for: ecosystem contribution to growth of harvestable wheat)
Example goods or service	Climate regulation resulting in avoided damage costs Or Mitigation of impacts of ocean acidification	Reduction of damage (and associated costs) of topsoil loss in farmland	Harvested crop; fruits and nuts in farmer's store; fruit-derived products like juice
IPBES Name	Regulation of air quality	Formation, protection and decontamination of soils and sediments	Food and feed

Anthropogenic climate change, due to the historical emissions of enormous amounts of carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and fluorinated gases, has been identified as the greatest threat facing global populations due to the harsh impacts felt when the global atmospheric service is destabilized. The continued release of greenhouse gases into the atmosphere throughout the Anthropocene has changed the chemical constituency of the earth's atmosphere and has resulted in global changes to the climate (Foster et al., 2017; IPCC, 2014; Lewis & Maslin, 2015).

One method of addressing the stabilisation of CO_2 emissions in global atmospheric climate regulation is leveraging the environmental management of terrestrial ecosystems to maintain currently stored carbon and enhance organic carbon capture and sequestration, i.e., conserving carbon pools (Bhattacharyya et al., 2008; Gorshkov et al., 2000). Soils are responsible for the atmospheric recycling of half of all carbon globally. It has been estimated that soils contain approximately 80% of carbon found in all terrestrial systems, about 2500 gigatons of carbon of which 1550 Gt is organic carbon and 950 Gt is inorganic carbon, within the top 1 meter depth worldwide (Lal, 2008; Reichle, 2019). Above and below-ground biomass, such as plants and root systems, are vital for carbon sequestration, storing substantial amounts of carbon and contributing to the overall carbon balance in terrestrial ecosystems. Long-term soil carbon sequestration contributes to the global regulation of the carbon cycle, aiding our need to decrease dangerous levels of gaseous carbon (Bhattacharyya et al., 2008; Smith et al., 2020).

2.1.2. Soil erosion control

Soil erosion control is a crucial ES provided by terrestrial ecosystems that plays an essential role in protecting soil from water or wind erosion (Coleman et al., 2017; Lal, 2022; SEP, 2015). Erosion poses a significant threat to soil functioning globally, reducing the land's ability to support vegetation and crop production, ultimately leading to land degradation and loss of ES (Borrelli et al., 2017; Costantini et al., 2018; Eekhout & de Vente, 2022). Soil erosion control is critical for maintaining soil health and productivity, which supports food production, water regulation, and carbon sequestration, among other ES (Lal, 2022; Nasir Ahmad et al., 2020; Steiner, 1996).

Human activities, such as deforestation, agriculture, and urbanization, and land mismanagement have damaged the natural processes that control erosion, such as plant cover, soil structure, and topography (Dale & Polasky, 2007; El-Swaify, 2022; Hasan et al., 2020; Zhan, 2015). Furthermore, it disrupts the supply of soil-related ES, leading to compaction, salinity and the loss of topsoil thickness, nutrients, structure and carbon (Almagro et al., 2016; Steiner, 1996; Zhang et al., 2007). Additionally, the anticipated effects of climate change on soil erosion are expected to have negative implications on ES and human well-being, especially in semi-arid regions, such as the WC (Borrelli et al., 2017; Lal, 2004; Schulze, 2017). These challenges have a negative impact by reducing agricultural production in general and its efficiency (Bakker et al., 2005; Costantini et al., 2018; Lal, 2001, 2022). Therefore, human intervention is often necessary to restore the land's natural erosion control (Kumarasinghe, 2021; Nasir Ahmad et al., 2020).

2.1.3. Food production

Food production is a crucial provisioning ES that supports human survival and wellbeing by providing essential nutrients required for human health (FAO, 2014). With the global population projected to reach 9.7 billion by 2050, increasing food demand is driving the need for sustainable food production (FAO, 2014). Commercial agriculture, as a primary financial income of farmers, has been a driving force in the global food industry, supplying the majority of the world's food (Matson et al., 1997; Power, 2010). The shift towards commercial agriculture began in the 20th century to meet the demands of growing populations and urbanization, characterized by large-scale production utilizing modern farming technologies. However, commercial agriculture's expansion has led to the conversion of natural ecosystems into agricultural land, resulting in soil erosion, loss of biodiversity, and water resource degradation (Hasan et al., 2020; Matson et al., 1997; WWF-SA, 2014; Zhan, 2015).

2.2. Mapping and assessing ecosystem services

ES modelling and mapping present a cost-effective tool that supports decision-making in environmental management and spatial planning by producing visual representations of the spatial distribution of specific ES across an area which enables their assessment (Syrbe et al., 2017). ES modelling and mapping form part of the techniques used to assess ES (Grunewald et al., 2015). ES assessment is the systematic process of recording and using empirical data to measure (assess) the condition and flow of ES. It involves the process of identifying, measuring, and quantifying the various benefits that humans derive from nature to determine the state or condition of an ecosystem (Burkhard et al., 2017; Malinga et al., 2015).

While ES assessment provides a quantitative foundation by measuring the tangible benefits derived from ecosystems, ES evaluation delves deeper, integrating a more nuanced, multidisciplinary approach (Liu et al., 2010). It involves the process of analysing and comparing the costs and benefits of different environmental management options and impacts on human well-being, and whether certain management actions will lead to a net gain or loss in ES (Liu et al., 2010; von Haaren et al., 2019).

Developing predictive and forecasting models for future environmental scenarios provides a valuable tool to help inform management decisions (Jørgensen & Fath, 2011). Land use managers, environmental managers, and spatial planners use these spatially explicit maps as ecosystem management decision-support tools. For environmental professionals, ES mapping assists biodiversity monitoring, identification and evaluation of habitat development potentials, habitat capacity, evaluation of the landscape multifunctionality, and future prospects for landscape planning (Albert et al., 2017; Cowling et al., 2008; von Haaren et al., 2019).

Integrating these tools into environmental management decision-making supports better policy design to protect and enhance beneficial ES functioning in agricultural landscapes (IPBES, 2019; Maes et al., 2012; SEP, 2015). This holds relevance for environmental managers who work with complex trade-offs between land use development and conservation. ES mapping is a useful decision-supporting tool allowing for a participatory approach to planning and management that can involve a wide range of stakeholders and support integrated environmental planning (García-Nieto et al., 2015; Zulian et al., 2018). It has successfully been used as an advisory tool for governments to institute sound economic decisions that support sustainable development, and provide a framework within which sustainable management impact can be evaluated (Egoh et al., 2008; Maes et al., 2012; Reyers et al., 2009; Verutes et al., 2017). Verutes et al. (2017) detail the successful case-study of the Belizean government developing the country's first integrated coastal zone management plan based on ES modelling, stakeholder participation, and spatial planning design.

Mapping and modelling of ES, as part of assessment or evaluation, have limitations. Generally, ES valuation during an assessment is based on empirical data and calculations, and can partly include subjective valuations, that are constrained by our limited understanding of ecosystem structures and processes across scales (Chatzinikolaou, 2013; Jacobs et al., 2017; Syrbe et al., 2017). Additionally, ES modelling and mapping use statistics, biophysically sampled data, and dynamic mathematical models that inherently contain generalizations, bias and incomplete data to fully describe ecological complexity (Chatzinikolaou, 2013). For this reason, no model or map could project the exact and true state of ES. Theoretical models and maps do, however, provide useful generalized information to researchers and environmental practitioners, and have been shown to convey complex information in a simple manner within policy development and natural resource management (Cowling et al., 2008; Jørgensen et al., 2011).

Due to the high rates of ES loss and damage across the globe, much research on ES assessment and evaluation has been done and is being completed to provide contextual ES valuation (Czúcz et al., 2020; Martínez-Harms & Balvanera, 2012). Securing and promoting the functionality of ES in agricultural landscapes lies in our ability to determine their quantitative baseline and monitoring methods for accurate assessment (Antrop, 2005; von Haaren et al., 2019). ES status can be determined through measurement and collection of bioindicator data, and these can be evaluated through area comparison (Dale et al., 2007; Power, 2010).

Mapping ES involves identifying and locating the distribution and abundance of ES in an area. This involves using spatial data, such as geographic information systems (GIS), to create maps that show the spatial patterns of ES (Burkhard et al., 2012; Martínez-Harms et al., 2012; Syrbe et al., 2017). Ecological spatial modelling and ES mapping computer programs used in environmental management include well-known software such as Integrated Valuation of Ecosystem Services and Trade offs (InVEST), Soil and Water Assessment Tool (SWAT), and Artificial Intelligence for Environment & Sustainability (ARIES) (Ochoa & Urbina-Cardona, 2017).

2.2.1. Mapping inputs

Modelling inputs, comprising detailed environmental information and ecological indicators, are the core data used to construct representative ES maps. As with most modelling tools, the InVEST models use inputs such as LULC data and indicator data as proxies for ES to develop maps.

LULC is foundational for ES mapping, linking ES to specific land uses based on (1) the relationship between LULC and ES that has been established by published literature, and (2) the absence or presence of LULC classes tied to ES functionality (Burkhard et al., 2012). Published research on LULC details sound assumptions that can be made regarding ES, e.g., the presence of flowering natural vegetation is indicative of pollination services, while agricultural areas are associated with provisioning services like food production (Malinga et al., 2015; Zulian et al., 2013). Ongoing research aims to refine these associations and enhance the accuracy of the use of LULC data inputs through the integration of ecological indicators and field verification (Galbraith et al., 2015).

Indicators serve as measurable proxies for the condition of ecosystems and the flow of ES. They can be biophysical, economic or social (e.g. subjective preference) values selected to represent specific ES (Grunewald et al., 2015). Indicators are meant to provide quantifiable information, in an efficient way, to examine complex ES functioning (Heink & Kowarik, 2010). Ecological indicators must be credible and feasible to monitor, and the simpler it is to monitor, the better an ecosystem can be evaluated and managed (Cassatella & Peano, 2011). Using indicators for the assessment and evaluation of ecosystems forms an important part of monitoring ES for sustainable natural resource management.

Indicators allow land use managers to evaluate the condition of the environment as ES are not provided homogenously across an area and change over time (Goodenough et al., 2017). They are used as the main input for ecological modelling and other tools for environmental management

(Syrbe et al., 2017). The selection of suitable indicators is critical, requiring consideration of their representativeness, accuracy, and the spatio-temporal scale of the study (Affek et al., 2019; Czúcz et al., 2018, 2020; Heink et al., 2016, 2010; Pastor et al., 2022). Indicator selection can be varied depending on the ES being measured, and the purpose of assessment and diagnosis investigated (Dale et al., 2007; Heink et al., 2016; van Oudenhoven et al., 2018). Therefore, they can be seen as tools for communicating simplified information about complex socio-environmental systems. Indicators can directly or indirectly (as proxy) express both the condition and functioning ability of various related ES (Czúcz et al., 2018). Direct indicators provide quantifiable and feasible data on ES, based on measurements from studies. Indirect indicators assess the driving factors that influence the capacity of the ecosystem to provide a given service (Grunewald et al., 2015).

True representativeness of indicators for both biophysical assessment and economic valuation has been difficult to achieve in ES modelling without using generalizations, data extrapolation, and producing value estimates by benefit transfer (Martínez-Harms et al., 2012; Richardson et al., 2015; van Oudenhoven et al., 2018). For these reasons, the ES approach faces some challenges in producing truly accurate and fully representative ecosystems and ES maps and models for effective sustainable natural resource management (Martínez-Harms et al., 2012; Pinke et al., 2022).

Global Atmospheric Regulation

Assessing global atmospheric climate regulation is underpinned by a variety of biophysical and socioeconomic indicators that assess the capacity of ecosystems to modulate climate. These indicators range from greenhouse gas fluxes to vegetation cover, each providing unique insights into how ecosystems contribute to climate stabilization (Reichle, 2019). Soil organic carbon (SOC) is considered a meaningful indirect indicator to monitor atmospheric regulation as an ES (Foster et al., 2017; Heink et al., 2016). SOC can be categorized into stabilized organic matter (OM), living OM, fresh residue, and decomposing OM. SOC and soil organic matter (SOM) are often used interchangeably (Weil & Brady, 2016). It is well-known that the use of SOC measurements is a contentious topic in science (Lehmann & Kleber, 2015; Roper et al., 2019). Studying the nature of SOM within and between soils is complex due to the high variability of the mineral matrix, microbial ecology, fine-scale redox environment, temperature and moisture content, and interactions of mineral surfaces across space and time (Coleman et al., 2017; Dignac et al., 2017; Nayak et al., 2019). SOM has even been called the “most complex biomaterial on earth” because of this difficulty in understanding it (Masoom et al., 2016). Though SOC can be variable and difficult to measure accurately, it is considered one of the most important ecological indicators within earth and agricultural sciences (Balkovič et al., 2020; Dignac et al., 2017; FAO, 2018b; Schütte et al., 2019).

Soil carbon measurement became standard practice when soil sample analyses were introduced as a crop fertility management tool (Kaleeswari et al., 2013; Rowe, 1993). SOM plays a crucial role in soil fertility for agricultural production and has been measured in agricultural systems for the past 50 years (Allison, 1973). The FAO has now established a global soil carbon monitoring program for SOC (Global Soil Organic Carbon Map, GSOCmap) and soil carbon sequestration (Global Soil Sequestration Potential (GSOCseq) Map) through a consultative and participatory process involving several countries, contributing to the further development of global soil carbon stock (SCS) indices to be used for monitoring purposes (FAO, 2018a). These carbon stock (CS) inventories have been developed to support countries in their reporting of their independent nationally determined contributions (INDCs), in terms of carbon sequestration, reducing emissions and soil carbon loss mitigation, for the 2015 United Nations Framework Convention on Climate Change (UNFCC) climate treaty (Beasley et al., 2019; Kinley, 2017). These INDCs form part of the Natural Capital Accounting efforts of South Africa and require comprehensive valuation and estimation of terrestrial carbon sinks and sources in agricultural landscapes (FAO, 2016; SANBI & Stats SA, 2018). Natural capital refers to the stock of natural resources, incorporating ES that provide direct and indirect contributions to human well-being and economic activity, such as clean air, water, food, and materials (Costanza et al., 1997).

The African Soil Information Service (AfSIS) database of predictive models provides the national SCS data for South Africa (Hengl et al., 2015). The database maps soil properties such as SOC and soil bulk density (BD) across the country. The database was created by combining two-point data sets of soil property data from Africa: the Africa Soil Profiles (AfSP) database and the AfSIS Sentinel Site (AfSS) database. The AfSP database is a collection of over 18,000 legacy soil profiles from various international and national public and governmental organizations and research groups, collected in the last 25+ years. The AfSS database contains data from about 9,000 locations collected by the AfSIS project between 2008 and 2012.

Soil Erosion Control

Soil erosion can be measured using various methods, including direct measurements and modelling approaches (Fu et al., 2011; Kumar K.V.G. & Barik, 2018). Common indicators used to assess soil erosion control include soil organic matter content, which reflects soil health; vegetation cover, acting as a protective barrier against erosive forces; soil aggregate stability, indicating the soil's resistance to breakdown; and runoff and sedimentation rates, quantifying the movement of water and soil particles (FAO and ITPS, 2015).

The Revised Universal Soil Loss Equation (RUSLE) is used in ES modelling assessing soil erosion control, providing a quantitative framework to estimate soil loss. It considers several key indicators, including rainfall erosivity (R factor), soil erodibility (K factor), topographic slope length and steepness (LS factor), crop and vegetation cover management (C factor), and support practices (P factor) (Patil, 2018). Each of these indicators reflects different aspects of the environmental and management conditions that influence soil erosion potential. Rainfall erosivity (R) captures the impact of raindrop energy and runoff on soil detachment, while soil erodibility assesses the inherent susceptibility of soil particles to be dislodged (Benavidez et al., 2018). The topographic factor evaluates how terrain features affect the accumulation and velocity of runoff, exacerbating or mitigating erosion. The cover management factor (C) reflects the protective role of vegetation or crop residues in shielding soil from erosive forces, and support practices represent human-implemented measures (Benavidez et al., 2018). The integration of these factors in ES modelling allows for a comprehensive assessment of soil loss potential, guiding land use planning and the implementation of effective soil conservation strategies (Bakker et al., 2005; Costantini et al., 2018).

Food production

Crop yield is used as a primary indicator of food production as an ES, reflecting the health and productivity of the ecosystem and the efficiency and profitability of agriculture (Dale et al., 2007; Demestihas et al., 2017). In South Africa, as in many parts of the world, crop yield values published in reports by farmer organizations or agribusinesses are typically calculated based on a combination of field data collection, technological tools, and statistical analysis (GreenCape, 2016; Stats SA, 2020).

Crop yield estimation involves a comprehensive approach starting from field data collection, which can be manual or use technology like yield monitors on harvesting machinery. Precision agriculture tools, such as GPS-equipped machinery and drones, are increasingly used to gather detailed data on crop health and growth stages (Shaheb et al., 2022). For more precise measurements, especially in market research, sample plots are designated and closely monitored. The collected data is then analysed and extrapolated to estimate the yield for larger areas, taking into account field variability due to different factors like soil type and weather conditions (GreenCape, 2016). Yield data from various sources might be aggregated for regional or crop-specific estimates, and these figures typically undergo verification and validation (Shaheb et al., 2022). Crop yield can also be used as a measure of sustainability, with sustainable agriculture practices aiming to increase crop yield by improving soil health, reducing pest and disease pressure, and conserving water and other resources (Altieri, 2018; Gemmill-Herren et al., 2019; Solen et al., 2018).

2.2.2. Integrated Valuation of Ecosystem Services and Trade-offs (InVEST)

The Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) ES spatial modelling suite, developed by The Natural Capital Project Partnership, is a spatial assessment toolset that includes models for quantifying, mapping, and valuing the benefits provided by nature (Natural Capital Project, 2022). It is used as a standalone software in conjunction with GIS software to prepare inputs and view outputs. The InVEST modelling tool was specifically developed for a wide range of users, such as land use managers, environmental researchers and policy-impact analysts (Natural Capital Project, 2022). It provides an effective tool for leveraging economic goals with environmental conservation to address diverse natural resource management interests (He et al., 2016).

Most researchers do not have the resources available to collect data from all the factors that can influence environmental variables when mapping ES, e.g., organic carbon mineralization, vegetation cover, land use management, water, and soil parent material all impact SCS (Vos et al., 2019; Wiesmeier et al., 2019). Therefore, modelling tools such as InVEST, using a suitable resource-efficient method, is used to map ecological indicators and infer ES provision. Remote sensing-based data may be too generalised in specific research contexts, so in-field samples and observation data can be used in combination with remotely sensed data to improve the quality and accuracy of resulting ES maps (Balkovič et al., 2020; Lescourret et al., 2015).

GIS map and attribute data (in the form of GIS layers and rasters), and MS Excel files, are prepared as inputs for the various InVEST models that map ES indicators (Figure 3). The InVEST models produce ES indicator maps as outputs with some additional valuation in text format, in either biophysical or economic terms depending on the model (Figure 4, see Appendix 1 for descriptions of how the InVEST models used in this research work) (Natural Capital Project, 2022).

2.2.2.1. Global atmospheric regulation in the InVEST model

The InVEST Carbon Storage and Sequestration model estimates SCS and can project carbon sequestered over time, to investigate the ES flow of global atmospheric climate regulation.

This model has been used to map the mineral SCS of large landscapes, display soil carbon pools and sources, project policy impacts on croplands, evaluate alternative management scenarios in forestry, and estimate blue carbon storage in large-scale coastal reclamation areas (Dida et al., 2021; He et al., 2016; Imran & Din, 2021; Kumar K.V.G. et al., 2018).

Several studies have used this model to analyse soil carbon dynamics across different landscapes (Dida et al., 2021; Imran et al., 2021; Li et al., 2022; Nelson et al., 2010; Piyathilake et al., 2022).

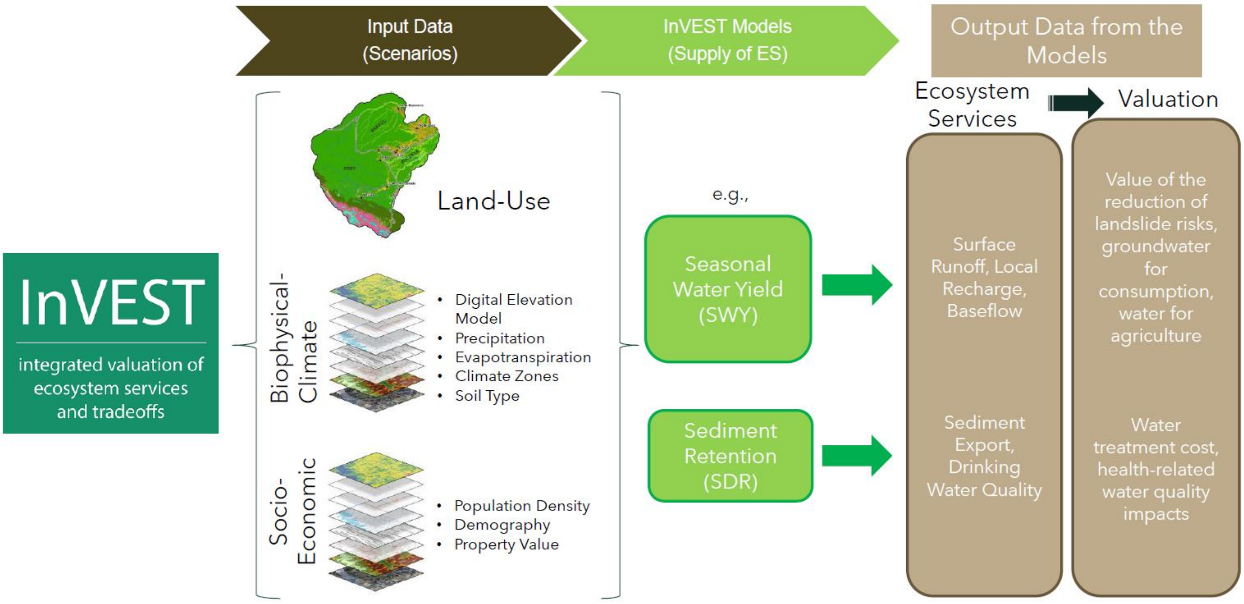


Figure 3. The InVEST software uses the process of data input, model processing, and output data (NASA Applied Sciences, 2022).

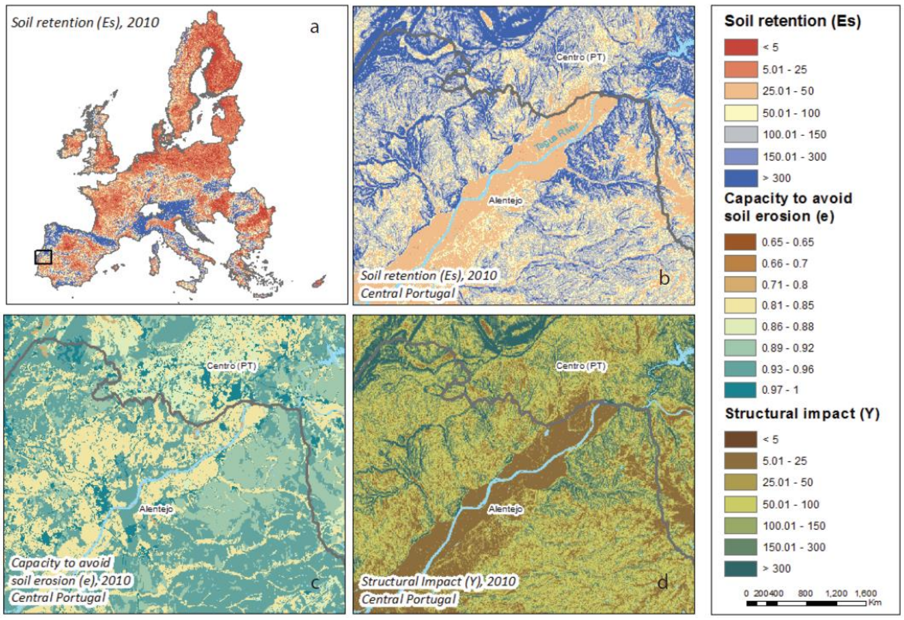


Figure 4. Examples of soil-related ecosystem service maps as outputs from various InVEST modelling done in environmental research in Europe and Portugal (Maes et al., 2017).

Li et al. (2022) focused on the Heilongjiang Province in Northeast China, a region characterized by significant forest cover. They estimated static carbon storage and dynamic sequestration across various LULC types, considering factors like soil carbon and biomass carbon density. The research observed significant changes in LULC where SCS was assessed to investigate the relationship between land use, climatic factors, and carbon dynamics (Li et al., 2022). Piyathilake et al. (2022)

used the model to estimate the CS of the Uva province of Sri Lanka, which is 50% covered by forests and scrublands.

Results highlighted the importance of natural forests for carbon storage and suggested that these outcomes could be effectively used in the preparation of environmental management plans (Piyathilake et al., 2022). Nelson et al. (2010) studied the effects of global land use change on ES and biodiversity. Their scenario-based research assessed urban and farmland expansion and impacts on the provision of crop production, water availability, carbon storage, and habitat for species. Results showed a large decrease in soil carbon storage, with scale-dependent impacts such as lower trade-off rates at the country level compared to the regional level (Nelson et al., 2010).

Soil carbon models present limitations to investigating the ES flow of global atmospheric climate regulation. However, they are widely used in open-market carbon credit exchange programs, and to make land management and spatial development decisions (Conant et al., 2011; Diop et al., 2022; Ellili-Bargaoui et al., 2021; FAO, 2022). In particular, these types of models are used by South Africa in determining specific regional spatial development targets for their independent nationally determined contributions (INDCs) towards carbon emissions under the 2015 climate treaty (DEA, 2015; SANBI et al., 2018).

2.2.2.2. Soil erosion control in the InVEST model

The InVEST Sediment Delivery Ratio (SDR) model estimates and maps soil sediment generation overland and sediment loss due to water movement, e.g., during precipitation or flooding, through sheet and overland erosion (excludes wind erosion). This model is used to map the spatial distribution of sediment sinks and sources, considering hydrological connectivity in the landscape, and is of particular interest in landscapes that have had large natural areas converted to farmland (Natural Capital Project, 2022).

Anesetee et al. (2020) examined the impact of land use changes on soil erosion and sediment delivery in Ethiopia's Winike watershed from 1988 to 2018 using this model and satellite imagery. It identified the main sources of soil loss and sediment export, linking them to increased cultivation and the decline of forests, grazing, and shrublands. The findings highlighted the need for immediate conservation efforts to mitigate further soil degradation (Aneseyee et al., 2020). Marques et al. (2021) used the model to assess the changes in sediment retention and soil erosion in mainland Portugal from 1990 to 2018 to understand the effects of land use changes on soil and water conservation. Their results showed change in some areas, while most areas had little or no change in sediment retention. These findings helped inform land use planning strategies and identify knowledge gaps (Marques et al., 2021).

The strengths of this model include the quantification of topsoil loss across landscapes, locations of concern and the benefits provided by soil covers. Delivering information that land managers can use to develop soil erosion control management strategies. The model only maps overland sediment loss and does not consider gully, bank or mass erosion, usually due to the small-scale of these structures when compared with the landscape level (Natural Capital Project, 2022).

2.2.2.3. Food production in the InVEST model

Crop yield is one of the indicators used in the InVEST suite to investigate the ES flow of food production. This model can be used as a tool in large-scale spatial development decision-making by municipalities to understand the impacts of various LULC matrix scenarios and to determine how cropping arrangements and crop types compare to the current farming systems in terms of total production (Li et al., 2020). This model could be used to calculate which cropping arrangement produces the highest economic returns within a specific agricultural landscape. As well as to evaluate different strategies for addressing forecasted food demand while decreasing farmland size to increase natural capital infrastructure.

Rayner et al. (2021) investigated how the spatial and thematic resolution of LULC maps affects the estimation of ES provision of crop production in an agricultural landscape. Using this model, they found that crop production increased with coarser resolution datasets, due to the aggregation of different LULC types, and differentiating between crop types is an important factor for this modelling (Rayner et al., 2021). Adelisardou et al. (2021) investigated the spatiotemporal variation of LULC changes and their impacts on soil-dependent ES, including crop production, in the Jiroft plain, Iran, from 1996 to 2016 using this model. Results showed that crop production increased significantly due to the expansion of cropland and irrigation, but at the cost of reducing other ES, especially water yield and carbon storage (Adelisardou et al., 2021).

The strengths of this model include the straightforward data inputs to deliver summarized data on crop production. A major weakness of this model includes its main consideration of climate on crop yield and less on farm location or agricultural management practices. Yield results of crops across different landforms, like river valleys and slopes, would be the same if they share the same climate category. Therefore, it cannot convey nuanced information on variation in productivity across landscapes, nor create a map of “hotspots” or “cold spots” where farming is most or least destructive (Natural Capital Project, 2022).

2.2.3. Ecosystem services research in South Africa

South Africa has a wealth of natural resources and ecosystems that provide various ‘provisioning’ and ‘regulating and maintaining’ ES (Abd Elbasit et al., 2021; Egoh et al., 2008). The country's unique position at the southern end of the African continent has created a diverse range of biomes, including fynbos, succulent and Nama-karoo, grasslands, forests, savannas, thicket, deserts, and wetlands (Rutherford et al., 2006). A few studies have attempted to value ES on a national scale, all using various assessment methodologies (Abd Elbasit et al., 2021; Anderson et al., 2017; Turpie et al., 2017). Anderson et al. (2017) conducted a study to estimate the values of ES in South Africa using global and national datasets and the benefit transfer method, based on LULC assigned values from The Economics of Ecosystems & Biodiversity (TEEB) (de Groot, 2010). They calculated ES valuation at USD 497 billion/annum (in 2015) for the global dataset, and USD 610 billion/annum for the finer resolution national dataset (Anderson et al., 2017).

Abd Elbasit et al. (2021) mapped and evaluated national and regional-scale LULC change and associated ES across South Africa from 2001 to 2019. They used MODIS satellite data and published LULC valuations as proxies for ES, based on Costanza et al. (1997). The study calculated the total ES value for South Africa to be USD 437 billion in 2019, about 125% of GDP. It was suggested that different approaches must be undertaken in order to characterize the real, functional values that local ecosystems have across landscapes (Abd Elbasit et al., 2021).

Egoh et al. (2008) mapped the production of five ES in South Africa: surface water supply, water flow regulation, soil accumulation, soil retention, and carbon storage. Using biophysical databases and assessment techniques, they published national-scale maps of ES richness and congruence. The results revealed that a large portion of the country's land surface is vital for supplying at least one ES, albeit with low congruence. This implies that the heterogeneity of the country’s landscapes and the provision of ES has significant implications for environmental and ecosystem-based management. The management of ES will require significant resource and land investments, and focusing conservation efforts on small areas that deliver multiple ES may be challenging (Egoh et al., 2008). Further analyses indicated that certain biodiversity facets co-occur with ES. Hotspots of water flow regulation and soil accumulation showed higher species richness than expected by chance, with varying levels of congruence with overall biodiversity richness (Egoh et al., 2009). This highlights the importance of environmental management in water catchments.

Turpie et al. (2017) used spatial datasets on ecosystem characteristics, human geography, ecosystem capacity for supply and demand for 11 selected ES (provisioning, regulating and cultural services), to value terrestrial, freshwater and estuarine habitats. Their initial approximations indicate that the habitats are valued at a minimum of ZAR 275 billion annually (USD 44.65 billion, in 2016), and their research proposes that carbon sequestration holds significant worth for South Africans in mitigating local climate change impacts (Turpie et al., 2017).

2.3. Spatial development impacts on ecosystem services

In environmental management, spatial development planning guides the structured growth and organization of land use in landscapes, focusing on the arrangement of built-up environments, natural capital and economic activities across space (Milovanović et al., 2020; von Haaren et al., 2019). Spatial development strategies guide land use changes, aiming to balance economic growth with environmental sustainability (Schoeman, 2015). Effective spatial planning ensures that land use changes support desired development outcomes, such as improved living conditions, economic opportunities, and conservation of natural resources (Benson et al., 2007).

The sub-Saharan Africa region has experienced a reduction in forested areas, grasslands and wetlands and an increase in urban and agricultural areas, driven by population growth, urbanization, and the need for agricultural extensification (Chiaka & Zhen, 2021). Similarly, for South Africa and the WC province, trends in farmland and urban expansion increased since the 1990s, with an increase in agroforestry and high-value commodity farmland and a decrease in natural grassland and shrubland areas (Halpern & Meadows, 2013; Niedertscheider et al., 2012).

LULC changes impact ES by altering the state of ecosystems, affecting services like atmospheric climate regulation, flood regulation, pollination, etc. Hasan et al. (2020) reviewed the general relationship between LULC change and provisioning, supporting, regulating, and cultural ES and concluded that impacts are predominantly negative with major implications on human well-being (Hasan et al., 2020). A similar review by Metzger et al. (2006) concluded with a more nuanced outlook that while LULC changes can be detrimental for some ES provisioning and functioning, others could benefit, depending on the type of LULC change (Metzger et al., 2006).

When examined individually, studies focusing on LULC change and its effects on individual ES provide nuanced insights critical for informed spatial planning. Borrelli et al. (2013) studied the impact of global LULC changes on soil erosion and found that LULC change and land management affected spatial variation and magnitude of soil erosion. An average yearly potential soil erosion amount of 35 Pg was modelled for 2001 globally, with a projected annual increase of 2.5% caused by LULC changes (Borrelli et al., 2017). For crop production, changes in LULC such as farmland expanding across natural grasslands in the WC, have led to an increase in food production (Halpern et al., 2013). However, these gains in food production can come with significant trade-offs, including the loss of biodiversity and degradation of other ES essential for long-term environmental sustainability (Macchi et al., 2020; Power, 2010). Power et al. (2010) detailed the principal trade-offs in agricultural landscapes, highlighting conflicts between provisioning ES and biodiversity-related services (such as habitat provisioning and genetic resource availability), as well as trade-offs between agricultural output, income, ecosystem functioning, and biodiversity conservation.

Nelson et al. (2009) used InVEST models to assess the trade-offs among ES, biodiversity conservation, and agricultural commodity production across different LULC change scenarios in Oregon, USA. Their analysis revealed that a scenario prioritizing ecosystem protection and restoration delivered superior outcomes in providing ES and conserving biodiversity. Moreover, this scenario demonstrated a higher market value, particularly when factoring in payments for carbon sequestration. This study highlights the importance of quantifying ES and understanding their trade-offs to inform natural resource management and to develop policies that effectively enhance ES and biodiversity conservation (Nelson et al., 2009).

Reyers et al. (2009) showed that land cover changes significantly affected ES in the Little Karoo, a semiarid, intermontane basin situated in the WC, resulting in a decline of ES levels ranging from 18% to 44%, corresponding with the loss of biodiversity in the area. The study assessed five ES-related factors: carbon storage, freshwater flow regulation, erosion control, production of forage for domestic livestock, and tourism. Results showed a decrease in water-flow regulating ES and soil erosion control, with the largest ES losses observed in lowland and foothill regions that have undergone transformation to cultivated agricultural areas or have been overgrazed, subsequently leading to severe degradation (Reyers et al., 2009).

2.4. Land use and management drivers that impact ecosystem services

Within the socio-ecological systems of agricultural landscapes, the intricate balance between food production and the conservation of ES is influenced by a complex interplay of internal and external drivers (FAO, 2014; Haines-Young, 2009; IPBES, 2019). Internal drivers, including crop selection, farm management practices, and the specificities of the local climate (which encompasses the condition and availability of essential natural resources for farming) originate from within the agricultural system (FAO, 2014). Conversely, external drivers emerge from broader societal, economic, environmental, and policy contexts, shaping the framework within which agricultural practices are devised and implemented (Nelson et al., 2006; Von Bormann, 2019). Understanding these drivers is crucial for developing effective spatial planning strategies that harmonize the demands of agricultural production with the need to conserve the ES that underpin environmental sustainability and human well-being (von Haaren et al., 2019).

Internal drivers directly influence ES by affecting the availability of natural resources, as well as shaping land use and management practices across landscapes, creating mosaics of various LULC types (Zhan, 2015). These internal factors play a pivotal role in determining how agricultural landscapes are utilized and managed, both on the farm and landscape level, thereby exerting a significant impact on the sustainability and efficiency of ES provision. Agricultural intensification, characterized by practices such as precision agriculture, the use of chemical inputs, efficient irrigation, high-yield varieties, and monoculture cultivation, primarily aims to enhance food provisioning services. Impacts on ES are determined by the intensity of cultivation, the effectiveness of management of production inputs and waste materials, and the type and amount of applied inputs, like water, nitrogen, phosphorus, and pesticides (Matson et al., 1997).

Intensive farming practices can significantly impact ecosystems, reducing the ecosystem's resilience and ability to offer diverse services (Tscharntke et al., 2005). These practices may also degrade soil quality, affecting essential functions such as water regulation and carbon storage. Moreover, the simplification of agricultural landscapes (landscape homogenisation) can disrupt natural water flow, increasing the likelihood of flooding or intensifying water scarcity. Farmers and farm managers (also termed land use managers) act as land use decision-makers, and their management decisions have environmental impacts at various scales (Brady et al., 2019; Choruma et al., 2019; Solen et al., 2018; Vignola et al., 2010).

The cumulative impact of land use management in agricultural landscapes emerges from individual decisions made at the farm-level, which, while tailored to the specific needs of their crop production units, often overlook the broader environmental implications and interconnectivity with neighbouring management practices, leading to varied and widespread ecological effects (Heege, 2013; Lescourret et al., 2015; Sandhu et al., 2008; von Haaren et al., 2019).

Global environmental and natural resource destruction, increases in farming input costs, and higher external costs of modern agriculture have piqued interest in using ES-supporting approaches on farms for improved sustainable production and management (von Haaren et al., 2019). In South Africa, the detrimental cumulative effects of conventional farming practices on ES has become increasingly evident, and as South African farmers face challenges such as soil fertility loss and droughts, there is a growing recognition locally of the need for sustainable farm management (Gemmill-Herren et al., 2019; IPBES, 2018). An analysis by WWF-SA (2019) highlights that current methods of food production in South Africa threaten the environment and human health, and that change in farm management practices is urgently required. The report evaluates agricultural food systems in the country, reporting them as highly productive, vital to supporting local economies and crucial to food security, and implicates these systems as the largest contributor to biodiversity loss, deforestation, desertification, soil degradation, water scarcity, declining water quality and degradation to marine ecosystems (Von Bormann, 2019).

Sustainable agricultural management has emerged as a pivotal strategy for securing food provision over the long-term by improving landscape multifunctionality (Huang et al., 2015). This approach includes strategic decisions regarding the utilization and conservation of critical natural resources on farms, like water for irrigation, soil fertility for crop growth, and leveraging animals for pollination and soil formation (Altieri, 2018). Such farm management decisions not only influence ES directly on the farms but also extend to the surrounding areas across landscapes (Power, 2010; Zhang et al., 2007). Bommarco et al. (2013) detail using ecological intensification, a process of enhancing crop productivity through ecological principles, where agricultural land can increase capacity to provide several agriculture-related ES (provisioning and regulating and maintaining) thus promoting global sustainable food security. According to Matson et al. (1997) and Lescourret et al. (2015), the principles of environmental sustainability must be based on ES on which humans depend, and those ES that support the proper functioning of agroecosystems.

Adopting practices from ecosystem-based farm management, including planting cover crops, preserving natural habitats, and minimizing the use of harmful chemicals, plays a crucial role. This approach views agricultural systems as integral components of broader ecological systems, aiming to manage them in a manner that promotes sustainability and bolsters beneficial ES like pollination and soil health (Agula et al., 2018; Vignola et al., 2010). The sustainability of farm management practices is closely linked to the capacity of agroecosystems to deliver ES. Emphasizing the protection of natural resources and ES is crucial for sustainable agriculture (FAO, 2014). According to the FAO (2014), sustainable agricultural development involves managing and conserving natural resources in a way that ensures the ongoing fulfilment of human needs for current and future generations. Sustainable practices aim to conserve land, water, and genetic resources, ensuring environmental sustainability, and economic viability (Dong et al., 2022; Gliessman, 2014). This includes adopting practices like minimal soil tillage, planting cover crops for soil stabilization and protection, and utilizing green manure and mulching to enhance soil fertility (FAO, 2014).

In agricultural landscapes, the interplay of external drivers such as economic policies, socio-cultural norms, climate change, and land conversion critically shapes farming practices and ecosystem sustainability (Nelson et al., 2006; Petschel-Held et al., 2005). Market forces and policy decisions drive land expansion and intensification, often compromising ES (Bengochea Paz et al., 2020). Socio-cultural influences and environmental awareness guide agricultural stewardship, while climate change demands adaptive farming strategies to maintain resilience (Macchi et al., 2020; Nelson et al., 2006).

Economic and policy drivers serve as pivotal external forces that significantly shape agricultural practices and priorities, thereby influencing the provisioning of ES. As the societal demand for food, feed, and fibre has increased, farmers have responded by expanding the area of cultivated land and intensifying production (Dasgupta, 2021; IPBES, 2019). This expansion and intensification, primarily driven by the focus on maximizing financial returns, underscore the profound impact of market demands on agricultural practices (Choruma et al., 2019). Farmers' pursuit of commercial gains has resulted in the reduced ability to supply other vital ES, e.g., crop production has been prioritised over clean water provisioning due to the leaching effects of applied chemicals (Power, 2010).

The intricate web of economic actors within the food production system, including small-scale and commercial farmers, agribusinesses, and consumers, plays a critical role in shaping the sustainability and equity of the food system (Choruma et al., 2019; Vignola et al., 2010). Each stakeholder group contributes uniquely to the production, demand, and consumption nexus, highlighting the need for an integrated approach to ensure the sustainable management of agricultural landscapes (Choruma et al., 2019; FAO, 2014; García-Nieto et al., 2015; Reed, 2008; Reyers et al., 2009). Consumers' preferences and demands hold the power to steer the agricultural sector toward more sustainable and equitable production systems. However, this consumer influence is often modulated by factors such as affordability, accessibility, and convenience, presenting a nuanced challenge in aligning market demands with sustainable practices (Dasgupta, 2021; de Groot, 2010; Hannon, 2001; Jovanović et al., 2015).

The global food market is an important driver of food production, with international trade allowing countries like South Africa to increase their efficiency and competitiveness in the agricultural sector (Schulze, 2017; WWF-SA, 2014). While this global integration brings about economic benefits and efficiencies through economies of scale, it also introduces environmental challenges, including the resource-intensive nature of food production and the carbon footprint associated with transportation (Dale et al., 2007). Furthermore, the sustainable management of agricultural landscapes is under threat from a progressively rising global demand for natural resources (IPBES, 2019).

Agricultural practices encompass a wide array of cultural values, traditions, and community management strategies that are reflective of the unique socio-environmental composition of agricultural landscapes (Bengochea Paz et al., 2020). The intricate relationship between farmers, as key stakeholders, and their surrounding environment underscores the significance of socio-cultural dynamics in spatial development patterns across agricultural landscapes (Foley et al., 2005; Hasan et al., 2020; Solen et al., 2018).

Amidst these socio-cultural intricacies, the growing societal awareness concerning health and environmental issues related to agriculture emerges as a critical factor (FAO, 2014). This heightened consciousness influences cultural practices, fostering a shift towards more environmentally responsible farming practices (Agula et al., 2018). Sources of information and the dissemination of knowledge in agricultural landscapes play a crucial role in this. Farmers often have a deep understanding of local ecosystems and their agricultural practices can support biodiversity conservation and ecosystem health (Findlater et al., 2018; Smith et al., 2014; Vignola et al., 2010).

Dissemination of scientific research, environmental awareness, and educational outreach forms an essential driver in transforming agricultural landscapes (Assefa et al., 2014). Through the effective dissemination of research findings and the promotion of sustainable practices, farmers are empowered to make informed decisions, thereby enhancing the sustainability of agricultural systems (Ha et al., 2008; Smith et al., 2014). Misinformed land management decisions on farms can result in land degradation where the supply of ES is disrupted and, sometimes, permanently destroyed (Bengochea Paz et al., 2020). The knowledge and interests of farmers, as the primary land use decision-makers, form an integral part of effective and efficient management in agricultural landscapes (Brady et al., 2019). Therefore, understanding the beliefs, production interests, management decisions, and risk perceptions of farmers is crucial in evaluating and mitigating the impacts of agricultural practices on ES (Blanco et al., 2022; Petschel-Held et al., 2005).

The impact of climate change on agricultural landscapes extends far beyond the immediate boundaries of individual farms, affecting agricultural productivity and the provision of ES on a global scale (Pörtner et al., 2022). The transformation in climate patterns in South Africa, characterized by changes in temperature, precipitation, and extreme weather events, necessitates a recalibration of agricultural practices to maintain productivity and ecosystem integrity (Schulze, 2017). Compounding the challenge are specific environmental degradation issues—such as water supply vulnerability, increased flooding risk, escalated heat stress, and more frequent and severe droughts—that are intricately linked to and exacerbated by climate change (DFFE, 2020). These challenges underscore the urgency for adaptive management strategies within the agricultural sector, aimed at bolstering resilience and ensuring the sustainability of farming practices in the face of an unpredictable climate (Petersen & Holness, 2013; Schulze, 2017)

Farmers and agricultural stakeholders are increasingly recognizing the necessity to adapt to these changes, not merely as a response to immediate threats but as a strategic approach to safeguarding the long-term viability of agricultural systems (Findlater et al., 2018; Vignola et al., 2010).

Adaptation strategies include a broad spectrum of practices, from modifying crop varieties and adjusting planting schedules to implementing water conservation techniques and soil management practices designed to enhance resilience against climate variability (DFFE, 2020). These pressures compel a re-evaluation of traditional farming practices, pushing for innovation and the adoption of more sustainable and climate-resilient agricultural methods (Altieri, 2018; FAO, 2014; Gemmill-Herren et al., 2019; Shaheb et al., 2022).

The conversion of natural habitats into agricultural land, driven by the escalating demand for agricultural products and the pressures of urbanization, poses challenges to ecosystem integrity (Guerrero-Pineda et al., 2022; Nelson et al., 2006). As previously discussed, this land use change, while instrumental in meeting the growing food demands of a growing global population, often results in significant losses of ES, undermining the ecological balance and biodiversity that underpin these services (Hasan et al., 2020). The transition from natural landscapes to cultivated fields leads to the immediate local loss of flora and fauna and has consequential implications for soil health, water cycles, and carbon sequestration capacities (Frank et al., 2014; Zhan, 2015). Recognizing and mitigating the adverse impacts of land conversion on ES are essential for ensuring the sustainability of agricultural practices and environmental resilience (Dong et al., 2022; Macchi et al., 2020).

Research shows that there is a pressing need to better understand the direct and indirect drivers that impact ES in agricultural landscapes, particularly at the local level (Mertz & Mertens, 2017; Tengberg et al., 2007). Many new environmental problems demand a better understanding of landscape functioning and demand rapid solutions at an appropriate scale of research and actions (von Haaren et al., 2019).

2.5. Spatial planning to support ecosystem services in Western Cape and South Africa

In South Africa, the management of natural resources and agricultural land is underpinned by a comprehensive framework of policies, regulations, and monitoring programs aimed at promoting sustainable agricultural practices and mitigating environmental degradation stemming from historical natural resource extraction (Nel & Alberts, 2018). The Department of Agriculture, Land Reform, and Rural Development (DALRRD) plays a pivotal role in this regard, implementing national policies and programs that emphasize soil conservation, water management, and conservation agriculture to bolster agricultural productivity, ensure food security, and support local economies while minimizing environmental impacts (DALRRD, 2023; Schulze, 2017). The country has also responded to the environmental challenges posed by international agricultural trade by advancing policies and initiatives that enhance sustainable agriculture (Von Bormann, 2019; WWF-SA, 2014). These include efforts to improve water and energy efficiency on farms, promote conservation agriculture, and minimize waste along the food supply chain (Schulze, 2017). The global push towards sustainable land management practices, particularly in farmland, presents an opportunity for significant contributions to carbon sequestration and climate change mitigation (FAO, 2014, 2016).

The integration of ES into spatial planning (also known as ES mainstreaming) remains crucial for addressing food security comprehensively. Effective environmental management, which includes the protection and conservation of ecosystems and their services, is instrumental in mitigating negative human impacts and promoting the sustainable use of natural resources (Hessburg et al., 2014; von Haaren et al., 2019). This often involves the collaboration of various stakeholders, including government, land owners and managers, businesses, and local communities (García-Nieto et al., 2015; Reed, 2008; Reyers et al., 2009). Regions where environmental management is efficiently applied often witness stable and abundant ES, contributing significantly to human well-being (Grunewald et al., 2015).

In South Africa, legislative instruments like the National Environmental Management Act and the Biodiversity Act form the backbone of guiding environmental management (Nel et al., 2018). The National Spatial Development Framework and the Spatial Planning and Land Use Management Act (SPLUMA) guide the integration of urban, rural, and agricultural land uses (DALRRD, 2023; Schoeman, 2015). SPLUMA provides the framework to govern planning permissions and approvals, sets parameters for new developments and provides for different lawful land uses through zoning, which directly determines LULC changes and, consequently, the provisioning of ES (Nel, 2016). Despite these frameworks, the integration of ecosystem-based environmental management and ES management into environmental planning and spatial frameworks is still evolving (Nel et al., 2018; WCG, 2014). Often, environmental management plans and development policies lack the necessary tools or frameworks to incorporate ecosystem-based information, leading to the oversight of ES in managed areas (Roberts et al., 2012; Sitas et al., 2014a, 2014b). To bridge this gap, toolkits have been developed to facilitate the integration of ES into decision-making processes, particularly within the government's integrated natural resource management plans (Cowling et al., 2008; Johnson et al., 2019; Reyers et al., 2009). There is no indication as to the extent of these toolkits being used by the government.

On the local level, the Western Cape Provincial Spatial Development Framework (PSDF) (2014), and its 2020 amendment, serves as a crucial spatial planning and land use management instrument that visually represents the province's spatial priorities and guides policies and directives for regional environmental management (WCG, 2014, 2020). Regional governments, such as the WC government, enact the strongest influence on the allocation of land use rights for urban, rural, agricultural and other LULC, through zoning measures guided by the Western Cape Biodiversity Spatial Plan, which directly impacts the provisioning of ES (Hasan et al., 2020; Siebritz & Coetzee, 2022). The WC provincial government employs a variety of policies, regulations, and monitoring programs to manage the environment, natural resources, and agricultural and natural areas (Locke, 2016; WCG, 2014). Additionally, the Cape Winelands District Spatial Development Framework 2021/2026 (2022), West Coast District Spatial Development Framework (2020) and Western Cape Land Use Planning Guidelines for Rural Areas (2019) guide the local spatial development of the agricultural landscapes on the municipal level of the central WC, where the study areas are located (CWDM, 2022; WCDM, 2020; WCG, 2019).

The cultural and economic diversity of communities in the WC, coupled with conflicting perspectives on natural resource management, adds complexity to local environmental management (Locke, 2016). The increasing societal demand for natural resources necessitates adaptive water planning and management strategies to meet forecasted demands and mitigate climate change impacts (Callaway et al., 2012; WCG, 2014). Conservation efforts, such as establishing "green" belts and buffer strips, play a crucial role in biodiversity conservation and reducing pesticide impacts, contributing to the creation of multifunctional agricultural landscapes that promote ES (Frank et al., 2014; Giliomee, 2006). Challenges such as constrained natural resources and environmental emergencies like wildfires and flooding heighten the urgency for effective environmental management (Botai et al., 2017; Callaway et al., 2012; DFFE, 2020). Wildfire management of fire-dependent biodiversity hotspots in the fynbos biome is a crucial aspect of the regional and local governments' engagement with landowners (Van Wilgen, 2013).

Case studies, such as those by Goodness and Anderson (2013) and Wilkinson et al. (2013), highlight the emerging concept of ES value in environmental management globally and the challenges of integrating ES into strategic spatial planning due to institutional and legal barriers (Goodness et al., 2013; Wilkinson et al., 2013). Longato et al. (2021) further emphasize the widespread gap between ES research and its practical application in spatial planning, underscoring the need for more policy-relevant case studies and identifying enabling factors for ES integration, such as data availability and science-policy collaboration (Longato et al., 2021).

3. MATERIALS AND METHODS

3.1. Study design & development

This study takes a mixed-method approach to evaluating key ES in agricultural landscapes, that results in recommendations on improving ES support in spatial planning and development. The study design framework shown in Figure 5 outlines the dual approach this research took to evaluate ES in agricultural landscapes, integrating both natural and social science methodologies (Biggs et al., 2021; Drury et al., 2011). The use of this mixed-method approach aimed to create holistic management recommendations to support ES in natural and socially dynamic systems, leveraging the understanding of social dynamics in farm management to enrich the evaluation of their impacts on ES within agricultural landscapes. This methodology enhances the precision of data interpretation and analysis, leading to improved insights (Drury et al., 2011).

In the natural sciences study design, a pilot study conducted in Hungary helped the preparations and informed the primary ES assessments in the WC, which focused on assessing SCS, soil erosion, crop production, and land use change trends in agricultural landscapes. It aimed to improve model reliability by integrating in-field sampled and observed (primary) data with remote sensing-derived (secondary) data (Ellili-Bargaoui et al., 2021; Syrbe et al., 2017). The social science study design involved interviews with WC farmers to understand the impact of their management decisions on ES and reviewing ES-related content in regional spatial planning frameworks to determine policy gaps.

The parameters of this research were limited to the assessment of the three selected ES in farmland and natural LULC types within the study areas, and focused on commercial agriculture farm owners and managers as primary land use managers impacting ES on farmland. It included consideration of ‘provisioning’ and ‘regulation and maintenance’ ES for the social science assessment. The following fell outside the scope; forestry industry, subsistence farming, wild food and medicinal foraging, built-up industrial, commercial and urban LULC, linear infrastructure (roads and railways), and cultural ES services.

Pilot Study

The research design of the preliminary (pilot) study in Hungary was developed as an exploratory approach to outlining the methods for the natural science study in the WC. The preparatory work during the pilot study in Hungary was instrumental in revealing the necessity for varied sampling depths in contrast to South Africa, due to sampling differences in regional SCS inventories.

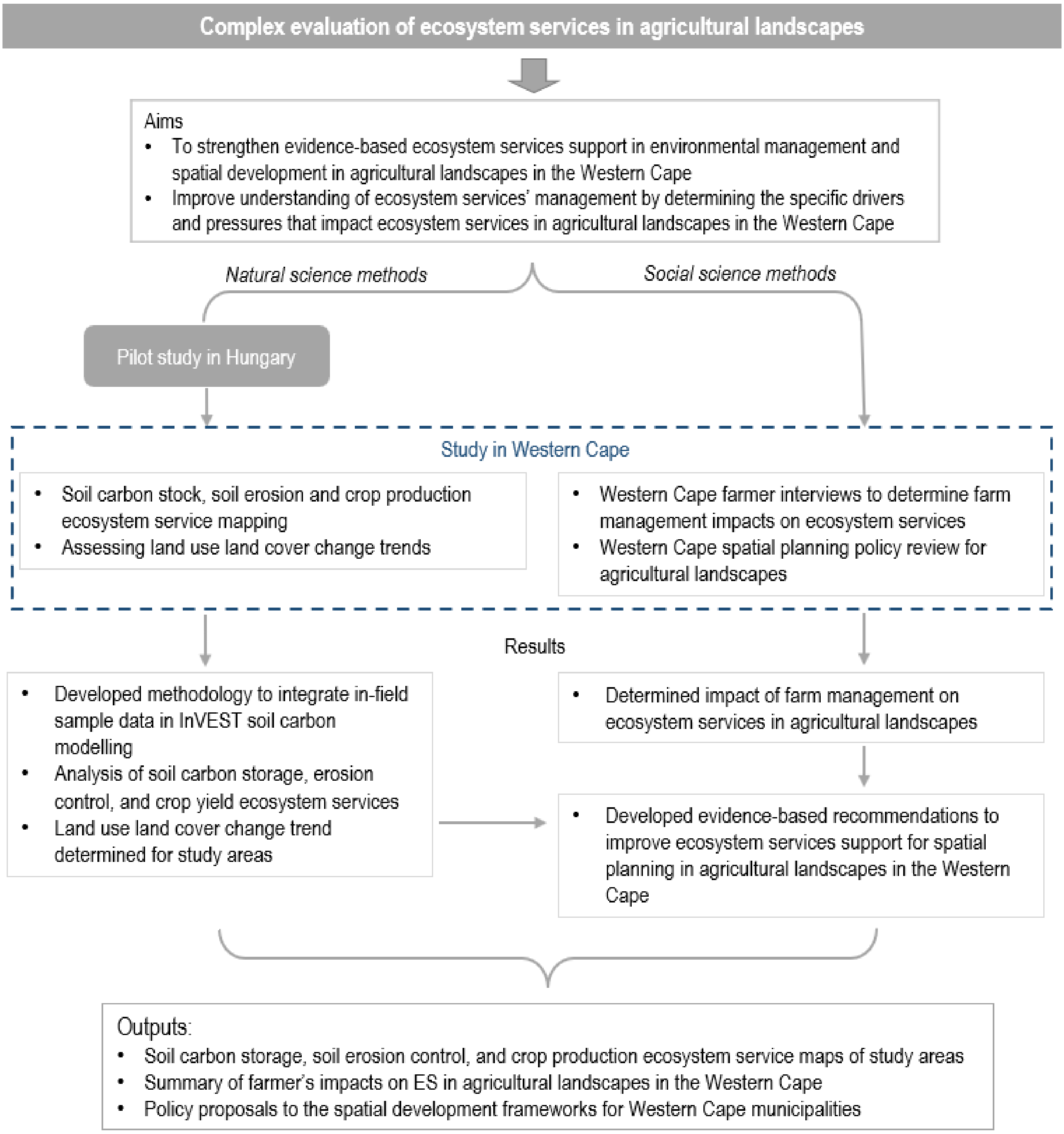


Figure 5. Design framework of this study on the complex evaluation of ecosystem services in agricultural landscapes of the Western Cape, South Africa, undertaken from 2019 to 2022 (author's deductions).

While Hungary's SCS inventory had samples taken from 0-30 cm and 30-60 cm depths, the South African inventory incorporated sample depths of 0–20 cm and 20–40 cm, reflecting the distinct soil profiles and following the methodology of national SCS assessments for each country (Agrártudományi Kutatóközpont, 1992; ISRIC, 2015).

Selecting Ecosystem Services

ES selected for this study were informed by Zhang et al. (2007) and Power (2010) which reviewed key ES in agricultural landscapes, and following the selection guidelines of Bennet et al. (2009) and Crossman et al. (2013). Criteria used in the ES selection considered consistency in valuation and mapping methods so that it may have broader application within natural resource management, policy development, and national natural capital accounts. The three ES of global atmospheric climate regulation, soil erosion control and crop production were selected for this research due to their research popularity, relevance to current natural resource management challenges on the landscape level, data relevance linked to map resolution at the landscape-scale, and inter-connected relationships when examined as an ES bundle (Crossman et al., 2013). Indicators were selected as proxies to quantify the provisioning and functioning of the selected ES. In this case, indicators were selected for the three ES evaluated based on their feasibility for in-field sampling/observation, availability from public access GIS data repositories, measurability within the given time frame and given resources, and analysis methods done within the scope of this research (Bennett et al., 2009; Crossman et al., 2013).

3.2. Description of the study areas

The pilot study in Hungary (total area: 93,030 km^2) and the agricultural landscape study areas in the WC province (total area: 129,462 km^2), South Africa (Figure 6) were selected based on several criteria; medium-sized regions (± 500-3000 km^2) with mixed LULC (two study areas were selected for result comparisons); the presence of farmland, grassland, and forested LULC class types; shared crop types such as fruit (i.e., wine, apples, cherries), grains (i.e., wheat, canola, sorghum), and vegetables (i.e., pumpkin and tomatoes); vast areas of farmland with intensive commercial agricultural management; similar elevation of around 100-300 meters; and time constraints related to crop production time, data collection, stakeholder engagement, lab analysis time, data analyses, and research write-up.

3.2.1. Pilot study in Hungary

In Hungary, the agricultural landscape pilot study areas selected were the Vác-Pest-Danube Valley (Vác-Pesti-Duna-völgy) microregion, within the Dunamenti-plain (Danube) mesoregion, and the South-Zselic (Dél-Zselic) microregion, within the Mecsek and Tolna-Baranya hills mesoregion, see Figure 7.

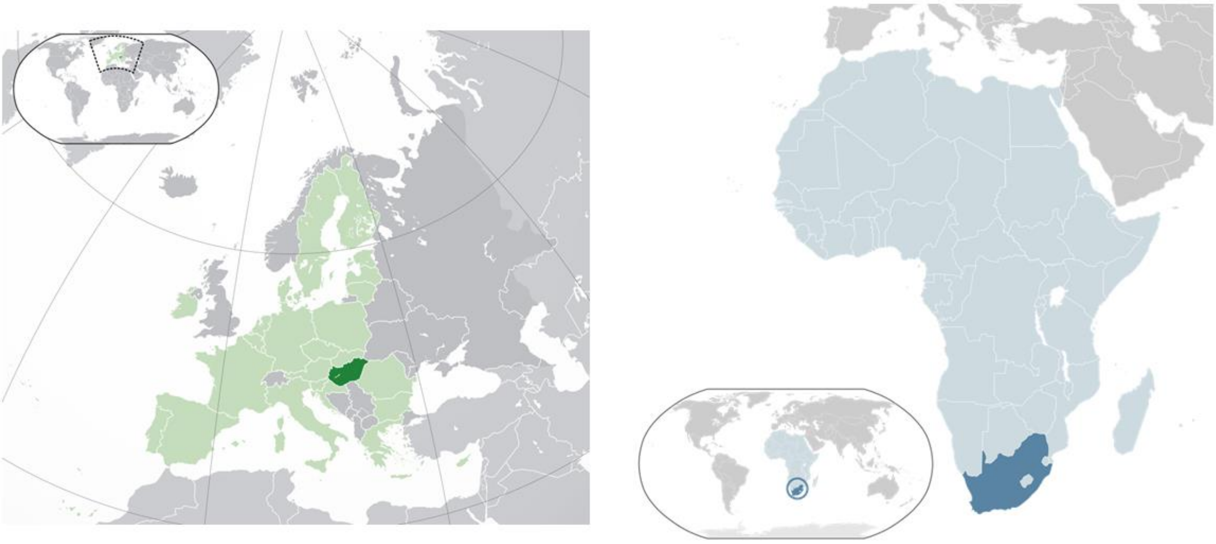


Figure 6. (left) Hungary, in green, located within Europe where the pilot study was done, and (right) South Africa, in blue, located in Africa where the primary study was conducted (WikiMedia Commons, 2009a, 2009b).

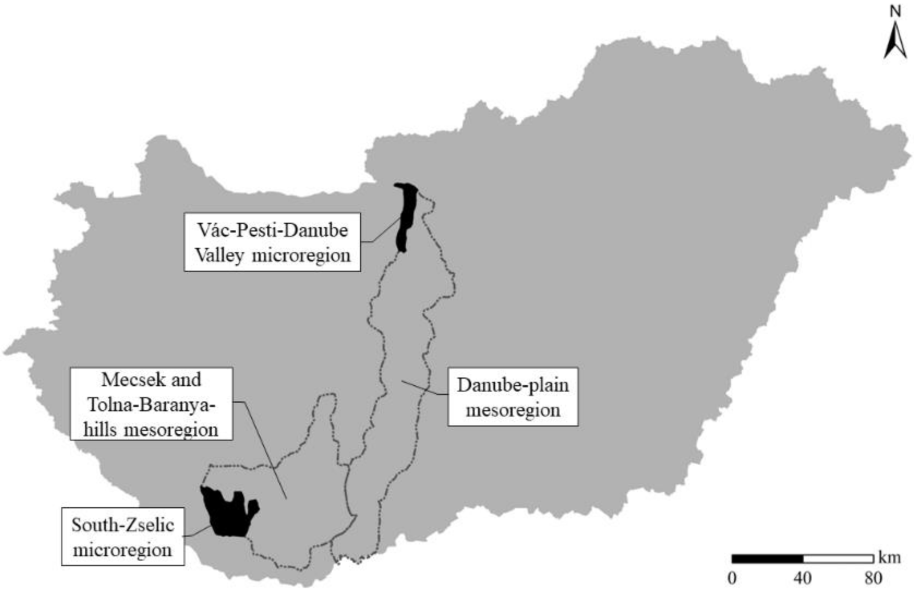


Figure 7. The locations of the pilot study areas in Hungary; Vác-Pest-Danube Valley (north) and South-Zselic (south) microregions.

Ecological mesoregions and microregions in Hungary are defined areas that share geo-ecological and biome characteristics, with microregions representing the smallest mapped units for shared biological and geological traits (Agrártudományi Kutatóközpont, 1992; Sándor et al., 1990; TAKI, 2022). In Hungarian landscapes, land use has generally shifted, with a decrease in agricultural land and an increase in uncultivated land cover and forestry (Cegielska et al., 2018).

Pilot Study Area 1

The Vác-Pest-Danube Valley microregion (208 km^2), the northern study area (47°43'14.2"N, 19°06'31.4"E), within the Dunamenti-plain (Danube) mesoregion, stretches from northern Pest County south into the Budapest metropolis. It includes towns such as Szentendre and Vác along the Danube River, and smaller settlements like Kisoroszi, Tahitótfalu, Pócsmegyer, and Szigetmonostor on Szentendre Island (hereafter Island).

The Island (73 km^2) extends 42 km along the Danube River and is home to about 10,000 permanent residents divided into four settlements (Orosz et al., 2015).

A portion of the Island is part of the Danube-Ipoly National Park and hosts several Natura 2000 ecological network areas (EEA, 2012; Gergely, 2011). Agricultural activities have been practiced on the Island since the Neolithic Age 5–4000 BC, intensifying after the 17th century, with modern commercial farming appearing from the 1960's (Dinnyés et al., 1993; Gergely, 2011; Mari, 2002). The present homogenous agricultural landscape primarily produces a variety of crops, including sunflower, corn, alfalfa, potatoes, and other vegetables. It also includes orchards, strawberries, other fruits, vineyards, and cereals as key agricultural outputs (EEA, 2019). The area is characterized by wooded-steppe vegetation and wetland habitats along the Danube banks, with extensive agricultural areas (TAKI, 2022). In 2018, land use included forested areas (28.04 km^2), farmland (32.74 km^2), grasslands (21.68 km^2), industrial, commercial and urban areas (97.68 km^2), and water bodies (28.19 km^2), see Figure 8.

The area falls within the 'Plain on unconsolidated deposits, with brown earth' genetic landscape type (Csorba et al., 2018). The elevation ranges from 103 to 122 m above sea level (Mari, 2002; Pécsi, 1953). The soil types are predominantly alluvial, comprising brown (forest) earth, alluvial meadow, and humus sandy soils. Soil textures range from sand and sandy loam to loam, clay loam, and clay (Figure 9) (Agrártudományi Kutatóközpont, 1992).

Previous environmental monitoring studies have been done on and around the Island in the Danube River, north of Budapest, Hungary. Csereklye (2010) evaluated pollution levels through plant samples and Nagy-Kovács et al. (2019) monitored water quality changes along the riverbank. Vegetation species on the Island have been recorded since 1943, with more recent plant surveys to update species indexes (Kevey & Bőhm, 2017; Zsolt, 1943). However, Gergely (2011) is one of few studies that evaluate land class types on the Island. He notes the degradation of sandy grassland and increasing patch fragmentation through vegetation monitoring done for the Natura 2000 ecological network project.

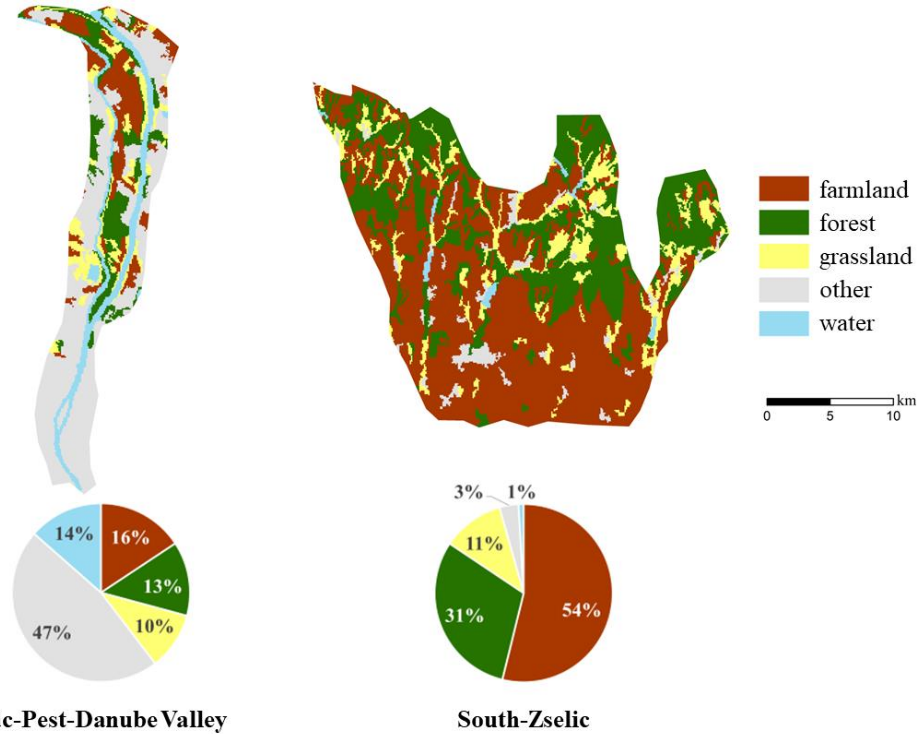


Figure 8. Land use land cover maps, with a % summary of total land cover, of the (left) Vác-Pest-Danube Valley and (right) South-Zselic agricultural landscapes, the microregion study areas in Hungary (author's calculations based on EEA (2019)).

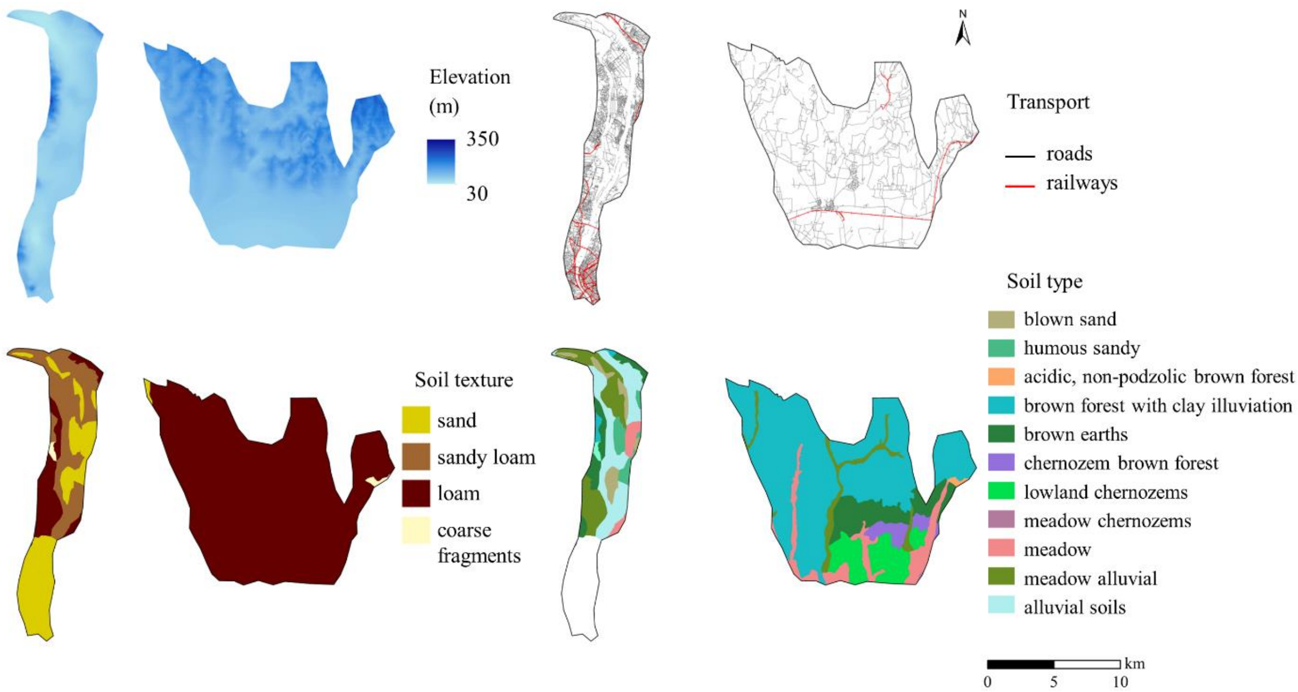


Figure 9. Elevation, transport network, soil texture and soil type maps describing biophysical features of the Vác-Pest-Danube Valley (left) and South-Zselic (right) microregion pilot study areas in Hungary (Agrártudományi Kutatóközpont, 1992; OpenStreetMap contributors, 2018).

Residents of the Island, a part of the EU's Natura 2000 conservation network, have expressed interest in developing an eco-island. This makes soil carbon storage data invaluable for the Island's spatial and environmental managers (EEA, 2012; Orosz et al., 2015). Recent analyses indicate that the climate vulnerability of the Island, or its propensity to be adversely affected by climate change, ranges from low-medium to high, while the variability in land use/land cover (LULC) between 1990 and 2012 was low (Buzási & Dajka, 2019; Csorba et al., 2018; Szilassi, 2017).

Pilot Study Area 2

The South-Zselic microregion (511 km^2), the southern study site (46°5'11.62"N, 17°51'23.81"E), within the Mecsek and Tolna-Baranya-hills mesoregion, is found in the southern part of the Transdanubian hills (Dél-Dunántúl), see Figure 7. The total population for the Southern Transdanubia administrative area is 879,596, which includes the Baranya, Somogy and Tolna counties (KSH, 2019). This study area was limited to the Magyarlukafa village, Visnyeszéplak (about 3 km was added to the study area delineation to include this village) and Gyűrűfű eco-villages. In 2018, land use included forested areas (1588 km^2), farmland (280 km^2), grasslands (59 km^2), industrial, commercial and urban areas (18 km^2), and water bodies (5 km^2) (Figure 8) (EEA, 2019). Known for its hilly landscapes (98 to 250 m above sea level), a variety of agricultural practices take place in this area, including commercial, organic and biodynamic farming activities, and eco-villages that have set environmentally conscience land use practices (Borsos, 2013; Szabó et al., 2021). Crops farmed include vegetables, grains, fruit and orchards. Unlike pilot study area 1, this landscape covers a variety of genetic landscape types including low, erosional and dissected hills, with small areas of plains on unconsolidated deposits and in high floodplain positions, including alluvial fan plains (Csorba et al., 2018). Soil types include brown (forest) earth, brown forest soils with clay illuviation, and a smaller mix of lowland chernozems combined with brown forest and meadow soils (Figure 9). The parent material for soils in both Hungarian pilot study areas consists of glacial and alluvial deposits, as well as loess and loess-like deposits. The soil texture is predominantly loam, with a generally uniform distribution, though there are small areas containing coarse fragments such as gravel and partially weathered rocks (Agrártudományi Kutatóközpont, 1992).

Environmental and spatial research has been done in this area for the past 50 years. A well-known recreational hunting and tourism area, studies on the forests, insect communities, and settlement developments within Southern Transdanubia are common and present a multi-land use area (Farkas, 2016; János, 2000; Morschhauser et al., 2009; Prohászka et al., 2020; Slachta, 2009; Tóth, 2002). Of particular interest are the eco-village communities enforcing landscape-scale land use management to create sustainable settlements, mostly concerning natural resource use. These close-knit communities faced depopulation and repopulation in the past decades and family-led land ownership has increased the average farm unit size for agricultural production (Borsos, 2013; Farkas, 2017; Hajnal et al., 2009; Szabó et al., 2021).

3.2.2. Western Cape, South Africa

For the WC, the two agricultural landscape study areas selected were Swartland-Tulbagh-Slanghoek and Helderberg-Grabouw-Breede Valley, see Figure 10. These research sites were delineated based on grouping basic-unit polygon mesozones, produced by the Council of Scientific & Industrial Research (CSIR), into a landscape-scale size (± 3000 km^2) that represented a comprehensive, representative "agricultural landscape" that features a variety of LULC classes, environmental features (i.e., rivers, mountains) and anthropogenic factors (i.e., roads, farms and artificial areas). The study areas shared a similar surface area and presented a complex mix of diverse land uses. Mesozones are approximately 50 km^2 in size, which incorporate notable administrative and physiographic boundaries (CSIR, 2007).

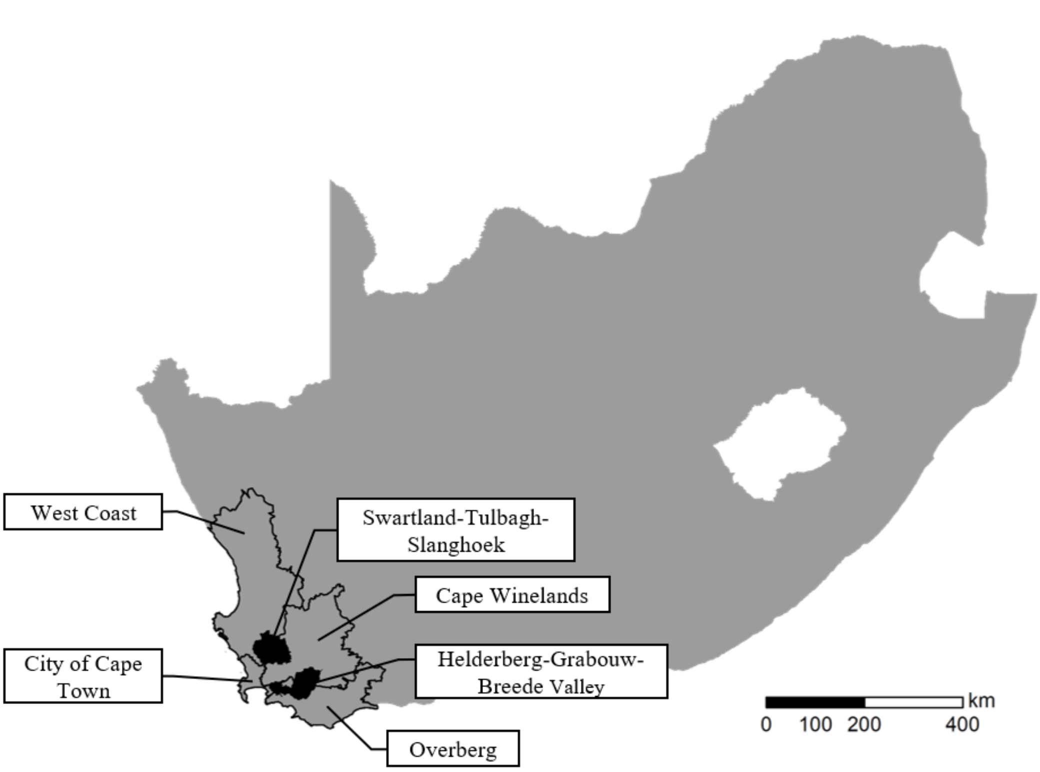


Figure 10. Location of the Swartland-Tulbagh-Slanghoek (study area 1) and Helderberg-Grabouw-Breede Valley (study area 2) agricultural landscape areas in the Western Cape, South Africa. District Municipal boundaries of the West Coast, City of Cape Town, Cape Winelands and Overberg are shown in black outline (Municipal Demarcation Board, 2018).

One of nine provinces of the Republic of South Africa, the WC is situated at the south-western tip of the African continent. It features a dry Mediterranean climate, characterized by warm, dry summers and cold, wet winters, with an annual average temperature range between 5° and 28°C and a mean annual rainfall of 515 mm (Tyson & Preston-Whyte, 2000). Because of the proximate confluence of the cold Atlantic and warm Indian oceans, ecological and geographical isolation, and topographic diversity, unique macro- and microclimates exist across the province, particularly from low-lying areas to the high-elevation Cape Fold mountain ranges (Rutherford et al., 2006).

This gave rise to one of the 6 globally recognised floral kingdoms, the notable Cape Floristic Region (CFR) that occurs across the region. The CFR spans about 90,000 km^2 and boasts an extraordinary amount of plant (app. 9000 vascular plants) and animal diversity with high levels of endemism (about 70%) (Linder, 2003).

In terms of botanical diversity, it is one of the world's richest regions and in 1992 had the highest known concentration of endangered and threatened Red Data Book plant species in the world (Rebelo, 1992). The valleys between the mountain ranges, with 1000 to 2300 m elevation, generally have fertile weathered loamy soils, which gave rise to increased agricultural production and expansion creating a mosaic of LULC across large landscapes (DWAF, 2003). Future climate change impacts are forecasted to increase overall temperatures and the variability and intensity of rainfall across the province, with water availability being of particular concern for the population and industries that it supports, such as agriculture (DFFE, 2020).

This biodiversity hotspot is covered mostly by the fynbos biomes, including strandveld and renosterveld. Fynbos, the most extensive natural vegetation type in the WC, is a fire-driven Mediterranean-type shrubland with plants adapted to favour nutrient-poor, shallow soils (Rutherford et al., 2006). Renosterveld is a grassy shrubland occurring on rich, basic coastal shale soils, dominated by the grey-coloured renosterbos (*Elytropappus rhinocerotis*) plant species that gave Swartland ("black land") its name (Linder, 2003).

The WC has a strong export-oriented horticultural industry and is a major contributor to agricultural production in South Africa by crop export value. In 2020, ZAR 78.68 billion (USD 11.28 billion) worth of combined agricultural and agri-processing products were exported from the WC (Partridge et al., 2022). Large-scale grain crops and fruit growing, including wine grapes and citrus, in the WC started around the 17th Century with the growth of seafaring trading between Europe and the East (Mabin, 2017). The agricultural industry has grown and diversified, and in recent decades has established itself as an international agricultural trade partner to Europe and other countries. Agricultural production in the region contributes meaningfully to the country's export earnings, providing thousands of jobs (about 200,000 in 2019) across the agricultural value chain, and wine farming is directly linked to the growth in attracting international and domestic tourism throughout the province (Demhardt, 2013; Partridge et al., 2022). Crop production in the province is diversified and approximately 2 million hectares of farmland was recorded in 2017, with extensive monocultures of grain (wheat, barley, oats and sorghum covering about 530,000 hectares) and fruit crops (wine grapes, apples, table grapes, pears, citrus covering about 180,000 hectares) produced by commercial agricultural businesses (Partridge et al., 2022).

3.2.2.1. Study Area 1: Swartland-Tulbagh-Slanghoek

The Swartland-Tulbagh-Slanghoek agricultural landscape study area (total area: 3138 km^2; 33°23'37.50"S, 18°56'46.91"E) transverses the Breede Valley, Drakenstein and Witzenberg Local Municipalities in the Cape Winelands District Municipality; and the Bergrivier and Swartland Local Municipalities in the West Coast District Municipality (Municipal Demarcation Board, 2018). In 2011, the population in the study area was approximately 118,000 (Stats SA, 2011).

Figure 11 shows both study areas' elevation, towns nearby, roads, railways and major rivers. The elevation across the area varies from the low-lying Berg River at 20 m to 1580 m at the highest Klein-Wellington-Sneeukop mountain peak in the Boland Mountains. Two major water sources for farming cross the area; the Berg River flows from the Franschhoek Mountains in a north-westerly direction, stretching about 95 km across the study area, and the Breede River, with its source in the Skurweberg mountain range close to Ceres, flows in a south-easterly direction for roughly 33 km across the area. Multiple tributaries join the rivers as they flow from the mountains, across the plains, to the Atlantic Ocean for the Berg, and the Indian Ocean for the Breede River (Le Maitre et al., 2018). Malmesbury is the only town within the study area, and Paarl and Ceres are nearby (Figure 11).

Recently in 2017/18, the WC experienced a significant water shortage crisis, severely affecting water availability and quality, which in turn disrupted agricultural production, destabilized local economies, and impacted human welfare (Botai et al., 2017). Key threats to river water quality include agricultural encroachment, agricultural runoff, polluted stormwater runoff from urban settlements, invasive alien species, and inadequately treated wastewater effluent (Locke, 2016; Tererai et al., 2013). Further habitat degradation is caused by various land use activities such as urban development, industrial operations, mining, access roads, river encroachment, and agriculture (DEADP, 2012; McLean et al., 2017). The Berg River, the second-largest in the WC province, stretches approximately 285 km with a catchment area of 8980 km^2. Flowing north from Franschhoek to Velddrif, it is a vital water source for the agricultural sector and provides drinking water for the City of Cape Town, which serves about 4.52 million residents (DWS, 2016).

The study area falls mostly within the temperate, dry, hot and warm summer (Csa & Csb) Köppen-Geiger present climate classifications (Beck et al., 2018). Mean annual rainfall varies between 200 and 600 mm across the lowlands, and up between 700 and 1000 mm in the mountain ranges that supply the water catchment areas (Schulze, 2009).

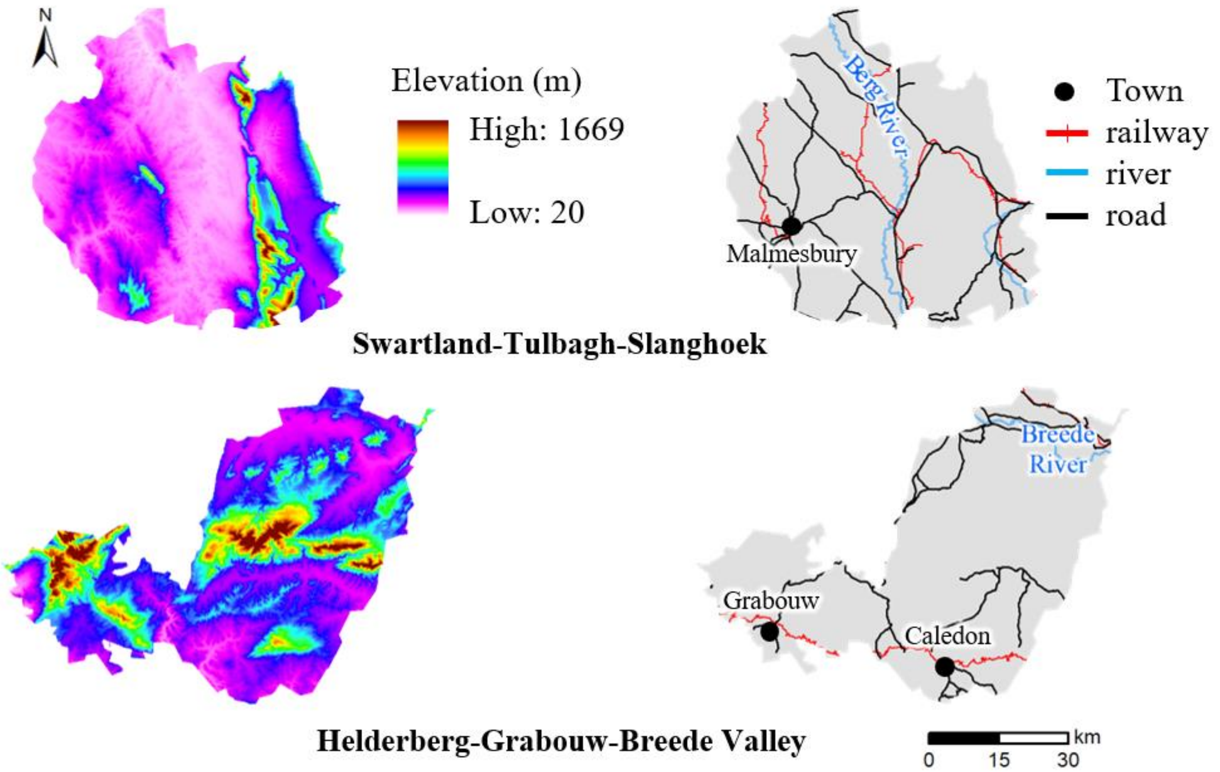


Figure 11. (left) Elevation (m), and (right) towns, major rivers, roads and railways within the Swartland-Tulbagh-Slanghoek and Helderberg-Grabouw-Breede Valley study areas (OpenStreetMap contributors, 2019; USGS EROS, 2015).

Figure 12 shows the LULC of the study areas. In 2018, generalized LULC was distributed between barren land (1%), built-up and other LULC like commercial, industrial and urban areas (1%), farmland (62%), forested areas (4%), grasslands (4%), shrublands (25%), and water bodies and wetlands (3%) (SANBI, 2018).

The dominant soils in distribution are Eutric Regosols, Eutric Planosols, Lithic Leptosols, Haplic Luvisols, Eutric Leptosols. The rest occur in less than 200 km^2 within the area. The Berg River features a variety of soil types, from sandy sediments in the lower catchments to distinct clay accumulations in the middle catchment (Clark & Ratcliffe, 2007). The nutrient-rich clay soils in these areas have spurred agricultural development, resulting in significant alteration of riparian habitats along the river (Kamish, 2008). Over the past 50 years, the conversion of natural vegetation to other land uses along both the Berg and Breede Rivers has negatively impacted biodiversity and substantially decreased the extent of natural vegetation (DWAF, 2003, 2004).

The study area intercepts with the Cape Winelands and Cape West Coast Biosphere Reserves and protected areas are situated mostly on and around the mountain ranges, such as the Winterhoek and Hawequas Mountain Catchment Areas. Speciated vegetation types of fynbos, renosterveld, and strandveld are characteristic of this region, the most widely distributed type being the Swartland Shale Renosterveld (Rutherford et al., 2006).

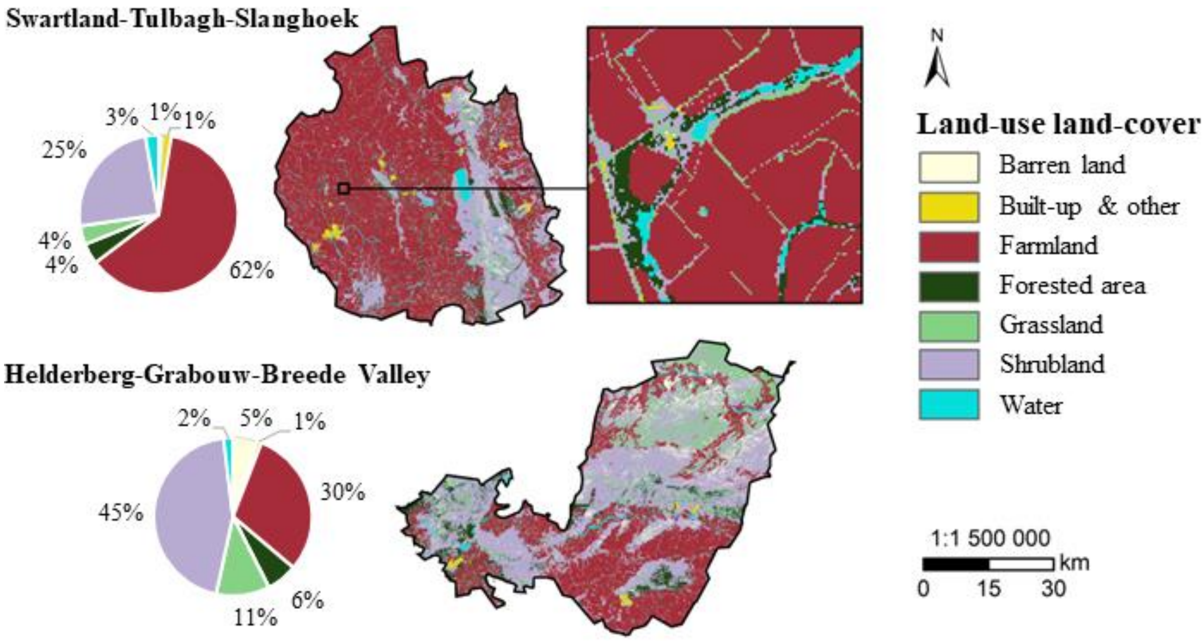


Figure 12. Generalized land use land cover map of the two agricultural study areas showing % coverage of each LULC in both areas, and a close-up of an area that shows LULC variation. LULC types; barren land, built-up and other types, farmland, forested area, grasslands, shrublands, and waterbodies and wetlands (1:1,500,000) (SANBI (2018), with author's calculations).

3.2.2.2. Study Area 2: Helderberg-Grabouw-Breede Valley

The Helderberg-Grabouw-Breede Valley agricultural landscape study area (total area: 3025 km^2; 34° 6'34.92"S, 19°26'49.48"E) traverses parts of the City of Cape Town Metropolitan; the Stellenbosch, Breede Valley, and Langeberg Local Municipalities in the Cape Winelands District Municipality; and the Theewaterskloof Local Municipality in the Overberg District Municipality (Municipal Demarcation Board, 2018). In 2011, the population in the study area was approximately 177,000 (Stats SA, 2011).

Figure 11 shows the elevation across the area varying from the low-lying Breede River Valley at 55 m to 1662 m at the highest mountain peak on Jonaskop, Riviersonderend Mountains. The Breede River is a major water source for farming, with 66% of all water use in this catchment used as irrigation water, including groundwater abstractions (DWAF, 2003). Other rivers include the Riviersonderend River, a semi-seasonal water source. The towns of Grabouw and Caledon fall within the study area.

This area falls largely within temperate, dry, hot and warm summer (Csa & Csb) and arid, steppe, cold (BSk, on the eastern boundary) Köppen-Geiger present climate classifications (Beck et al., 2018). It has a mean annual rainfall between 100 and 600 mm across the lowlands, and up to 2000 mm in the highest mountain ranges (Schulze, 2009). Figure 12 shows the generalized LULC distribution in 2018; barren land (5%), built-up and other (1%), farmland (30%), forested areas (6%), grasslands (11%), shrublands (45%), and water bodies and wetlands (2%) (SANBI, 2018).

The dominant soils across the area are Lithic Leptosols, Albic Arenosols, Eutric Regosols, and Eutric Leptosols. The study area intercepts with the Kogelberg and Cape Winelands Biosphere Reserves and protected areas are situated mostly on and around the mountain ranges and a few rivers, such as the Jonkershoek, Hottentots Holland, Groenlandberg, Riviersonderend and Theewaters Nature Reserves, including the Riviersonderend Mountain Catchment Area. The most widely distributed vegetation type is various shale renosterveld with succulent karoo pockets (SANBI, 2018).

3.3. Data collection & analyses

Data were collected from remote sensing-derived GIS maps, in-field sampling and observations, and interviews with farmers in the WC.

3.3.1. Remote sensing data

Biological and geophysical digital GIS map datasets were collected for the pilot and primary study for the ES modelling and LULC change summary of the WC. Data collection was done by downloading GIS datasets and maps from online sources or requesting them directly from publishers, all data products were developed from remote sensing-derived data. Most of the maps were available online in an open-access format, accompanied by metadata reports. Maps were stored, viewed, edited and analysed with ArcGIS (ESRI version 10.4.1). The maps collected for the pilot study in Hungary and the primary study in the WC are listed in Table 4.

The Hungarian Soil Information and Monitoring System (also known as the AGROTOPO 1992) was received from the Institute for Soil Sciences recently belonging to the Hungarian Centre for Agricultural Research (Agrártudományi Kutatóközpont, 1992; TAKI, 2022). Within each mesoregion in Hungary, SCS was classified into ranges (0–20, 20–40, 40–60, 60–80, 80–100, 100–120, 120–140, and 140–160 Mg) for farmland, forest, and grassland LULC classes per area hectare. DOSoReMI.hu (Digital, Optimized, Soil Related Maps and Information in Hungary), inspired by the GlobalSoilMap initiative, was started intentionally for the renewal of the national spatial soil data infrastructure in Hungary. The primary outcome of DOSoReMI.hu is a compilation of spatial soil information presented as unique digital soil map products. These maps have been developed to regionalize specific soil features effectively. A significant part had never been mapped before, even nationally with high (~1 ha) spatial resolution. Through the https://dosoremi.hu/en/ portal, nationwide digital soil property and more general soil-related maps are published in a structured way (TAKI, 2022).

Table 4. The digital GIS-based maps of environmental and geophysical datasets were collected for the pilot study in Hungary and the primary study in the Western Cape, South Africa.

Dataset Name, Year	Description	Type, Scale	Source
Hungary			
Corine Land Cover (CLC), 2018	Land use land cover map of Hungary	Raster, 100 m^2	(EEA, 2019)
Hungary Agrotopographical Database (AGROTOPO), 1991	Soil spatial data, properties and details map of Hungary	Vector, 1:100000	(Agrártudományi Kutatóközpont, 1992)
Digital, Optimized, Soil Related Maps and Information in Hungary (DOSoReMI.hu), 2018	Renewed Hungarian Soil Spatial Data at the national level	Raster, 100 m^2	(TAKI, 2022)
HU DEM, 2013	Digital Elevation Model of Hungary	Raster, 100 m^2	(EEA, 2013)
Cadastre of the small regions of Hungary, 1990	Mezo- and Micro-regions descriptions in Hungary	Vector, 1:1000000	(TAKI, 2009)
South Africa			
South African National Landcover (SANLC), 2018	Land use land cover map of South Africa	Raster, 20 m^2	(DEA, 2019b)
SANLC Change, 2018	South African National Land Cover Change Assessments between 1990–2014-2018	Raster, 20 m^2	(DEA, 2019a)
Soil and Terrain Database for Southern Africa (SOTER/SOTWIS), 2004	Soil spatial data, properties and details map of SA	Vector, 1:2000000	(Batjes, 2004)
Africa Soil Profiles database: Africa Soil Grids, 2015	Soil organic carbon (SOC)	Raster, 250 m^2	(ISRIC, 2015)
South Africa SRMT, 2014	Digital Terrain Elevation Data	Raster, 30 m^2	(USGS EROS, 2015)
Crop Census 2017/18, 2016	Crop field boundaries mapped during the 2017/18 Western Cape commodity census	Vector, 1:9244649	(WC DoA, 2018)
Global Rainfall Erosivity, 2010	Global Rainfall Erosivity Database (GloREDa)	Raster, 894 m^2	(ESDAC, 2017)
Global Soil Erodibility, 2012	Global Soil Erosion Modelling platform (GloSEM)	Raster, 25 km^2	(ESDAC, 2019)

Geospatial Analysis Platform – Mesoframe, 2007	Mesozone demarcation of South Africa	Vector, various	(CSIR, 2007)

The SANLC Change spatial dataset maps change in LULC between 1990 and 2018 based on the comparison of the historical Landsat-generated 1990 SANLC dataset versus the Sentinel-generated 2018 SANLC dataset (30m cell matrix) (DEA, 2019a).

3.3.2. Field work (soil sampling) and laboratory analysis

Soil samples were collected from the pilot study areas in Hungary between 2019 and 2020. Based on this field work experience, soil samples and observational data were collected from sampling sites across the agricultural landscape study areas in the WC in 2021 for ES modelling. In both countries, sampling sites were selected based on purposive sampling, a non-probability sampling method that is most effective when investigating a specific knowledge domain. Locations were selected based on the observed representativeness of a LULC class, environmental conditions, and good spatial coverage (Zhu et al., 2008). For example, farmland sample sites were selected based on the occurrence of commercial agricultural production and relative coverage of crops, and forests and bush- or grasslands were selected based on the appearance of naturalness (i.e., no human disturbances) and occurrence of variation of vegetation growth (e.g., mixed vegetation, bushes, trees, flowering plants, and grasses). LULC maps were first previewed to identify target areas to explore in selecting sampling sites as described above.

3.3.2.1. Soil sampling in the pilot study areas, Hungary

Between October and December 2019, fifteen soil samples were collected from the northern Vác-Pest-Danube Valley microregion study area. Five samples were each taken from farmland, forest and grassland LULC classes. Between September and October 2020, sixty samples were collected from the southern South-Zselic microregion study area, focussed on Magyarlukafa, Visnyeszéplak, and Gyűrűfű. Five samples were collected in forests, 5 in grasslands, and 10 from farmland (including 5 residential gardens and 5 orchards) within each town boundary. The farmland sampled ranged from 0.2 to 1.5 hectares of commercial and horticultural farming, the majority with haplic soils, where samples were taken from organic, permaculture and non-organic farms. A total of 75 soil samples were collected from the two pilot study areas (Figure 13).

Samples were taken from 0-30 and 30-60 cm depths, based on the sampling depth of the national Hungarian SCS inventory (Agrártudományi Kutatóközpont, 1992). A Dutch soil auger was used to collect soil cores from three holes made 1 meter apart, from 0 to 30 cm depth, at each site. The samples were collected in a bucket, mixed and 1 kg of the mixed sample was collected in plastic, marked soil sample bags.

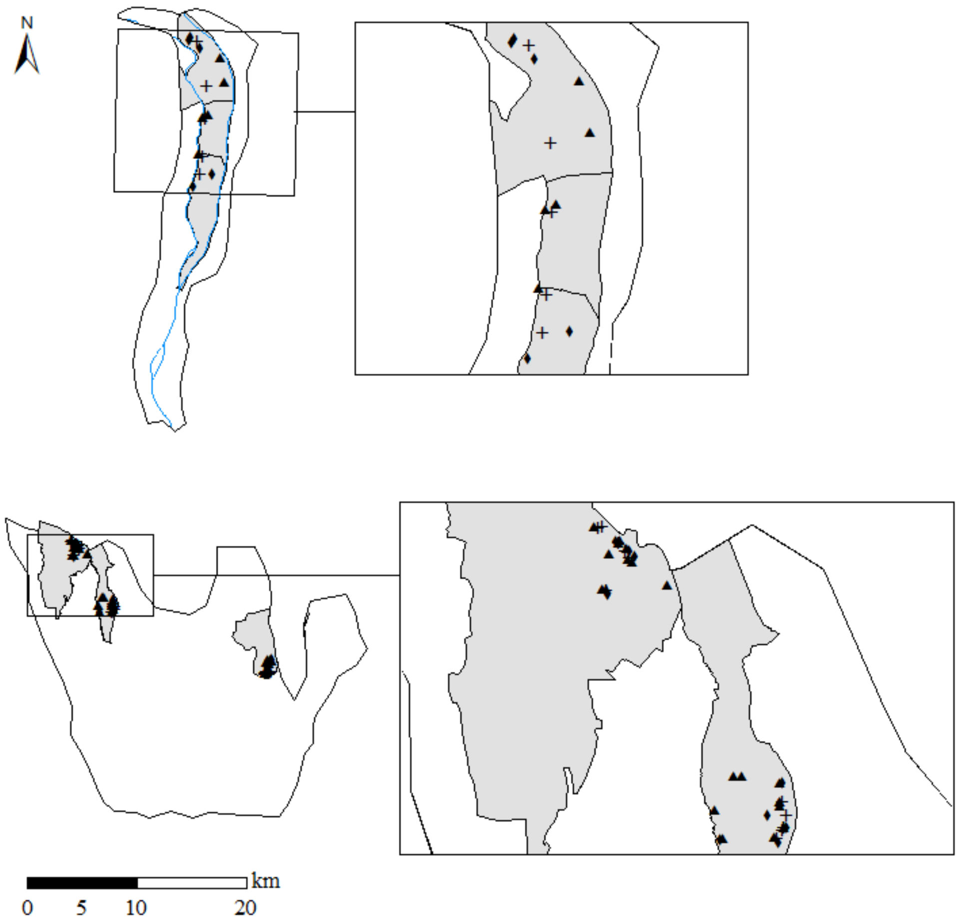


Figure 13. Soil sampling sites across the (top) Vác-Pest-Danube Valley and (south) South-Zselic pilot study areas in Hungary, showing the LULC sampled; forested areas (▲), grassland (♦), and farmland (+). Sampled settlements are shown in grey, and rivers as blue lines.

This procedure was repeated with soil cores from 30 to 60 cm depth (or however deep the soil was) from the same holes and collected separately. The soil samples were packaged and sent to a certified soil laboratory in Hungary for analysis. SOC was analysed using the Turin wet oxidation method (1931), measured as a percentage of humus (m/m) (FAO, 2018b).

The primary study's research protocol was developed during the pilot study, where modifications were made to the planning and implementation of research done in South Africa, namely increasing the size of the agricultural landscape demarcation to allow for larger areas to be mapped, more detailed and better-defined soil sampling protocols, steps outlined in developing the SCS inventories, and developing the methodology of reporting ranges of SCS based on InVEST ES maps.

3.3.2.2. Soil sampling in Western Cape, South Africa

Based on the procedure developed during the pilot study, soil sampling was done in both agricultural landscape study areas in the WC between January and March 2021. Twenty soil samples were collected from each area, totalling 40 samples, see Figure 14. Samples were taken from 0–20 and 20–40 cm depths (or however deep the soil was), following the sampling depth of the national South African SCS inventory (ISRIC, 2015). In each landscape, for depths of 0–20 cm and 20–40 cm, five samples were collected in shrubland areas, 5 in grasslands, 5 from commercial farmland, and 5 from commercial orchards. The soil samples were packaged and sent to a certified soil laboratory in South Africa for analysis. SOC was analysed using the Walkley Black method, measured as C % (FAO, 2018b).

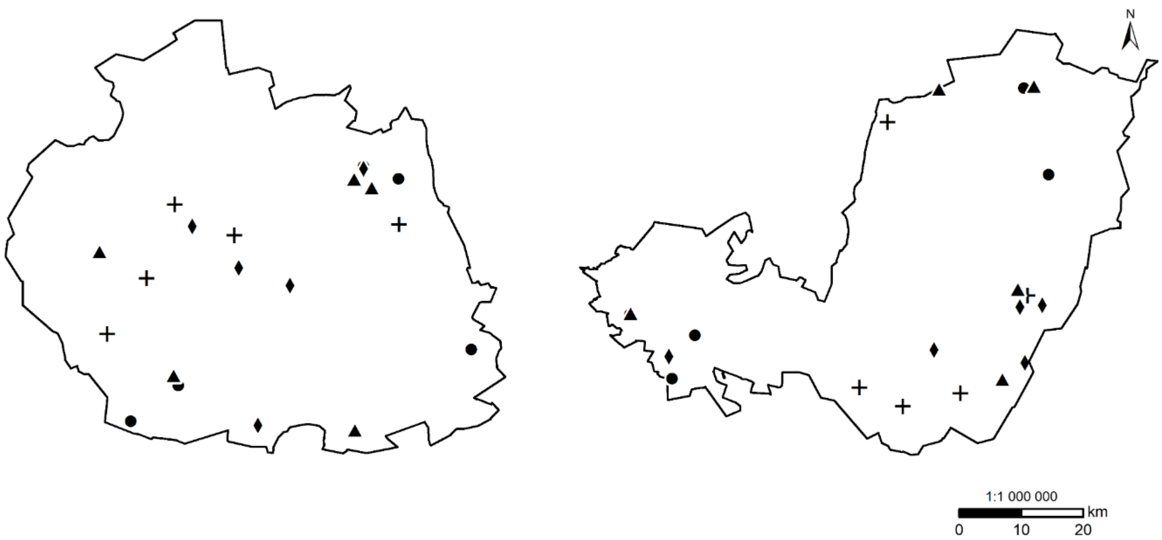


Figure 14. Soil sampling sites across the (left) Swartland-Tulbagh-Slanghoek and (right) Helderberg-Grabouw-Breede Valley agricultural landscape study areas, showing the LULC sampled; shrubland (▲), grassland (♦), farmland (+), and orchards (●).

3.3.3. Western Cape farmer interviews

The social science study part was exploratory to determine the cause-effect relationship between farmers and ES functioning on farmland and understand the social complexities around it (Biggs et al., 2021; Clayton, 2012). Semi-structured interviews (Newing et al. 2011) were conducted with 15-15 local farmers from each study area to add depth, detail and meaning to the ES assessments (Drury et al., 2011).

In preparation for developing and designing the interview questions, informational consultations were held with five professionals working in the WC who have had experience working with farmers, see Table 5. These specialists were consulted on their experiences of working with farmers, how to approach local farmers to better understand their impacts on the environment and collect factual information, key considerations about environmental law and compliance, and suggested local farmers' contacts. Following the consultations, it was determined that a semi-structured interview would be most appropriate for capturing comprehensive and nuanced insights, and would facilitate in-depth discussions, allowing for the exploration of diverse perspectives and experiences within the research questions (Newing et al., 2011).

Table 5. Professionals consulted in the Western Cape to gain insights on local farmers, applicable environmental law and farmer contacts.

Date Consulted	Person/s Consulted	Affiliation, Unit
20 May 2020	Francois Koegelenberg	Western Cape Department of Agriculture, GIS Services Manager
20 May 2020	Cor van der Walt	Western Cape Department of Agriculture, Land use Management Officer
2 July 2020	Anneliza Collet	Department of Agriculture, Land Reform and Rural Development, Directorate: Land Use and Soil Management
15 January 2021	Joan Isham & Shelly Fuller	WWF South Africa, Wine & Fruit Team
22 January 2021	Francis Steyn & Rudolph Roscher	Western Cape Department of Agriculture, Program: Sustainable Resource Management

Literature was reviewed on farmers' impacts on ES and their perspectives, particularly studies that involved interviews, see Findlater et al. (2018), Logsdon et al. (2015), Mattila et al. (2022), Smith et al. (2014), Xun et al. (2017). Considering the background information of the consultations and published literature, 20 interview questions were developed, see Table 27 in Appendix 1, following the strategic themes; to investigate drivers of land use management decision-making that impact ES (Research Question iv), farmers' perspectives on their role and impact on ES provisioning and functioning in a landscape (Research Question v), sustainable practices that are implemented to support ES (Research Question vi), and social influences (internal/external) that impact ES on their farms (Research Question vii).

Following a similar purposeful sampling approach of Patton (2002), farmer interviewees were contacted from two farmer contact lists supplied by the WC Department of Agriculture (DoA) and WWF-SA. A focus was placed on selecting interviewees from the different municipalities and farming various crops for broader data collection. Of 30 farmers contacted, 19 replied and interviews were set up with them. A further 11 farmers were identified using the snowball approach by asking farmers to name others who could be contacted, and interviews were arranged afterward (Newing et al., 2011; Patton, 2002).

Interviews were conducted with 14 farmers in-person on farms and 16 farmers through online video conferencing (due to Covid-19 pandemic precautions) between 1 February to 24 March 2021. A total of 18 farmer landowners and 12 farm managers were interviewed. Interview responses were recorded except for four farmers who did not consent to being recorded. In these cases, detailed notes were made on their responses. Interviews lasted an average of 39 minutes (median= 37, min.= 23, max.= 63), dependent on the time interviewees had available (interviews were done during harvest season which restricted scheduling times). Basic background information was collected during the interviews for summary statistics; age, education, years of farming experience, farm size, natural area size, and descriptive farm business information. Ethical principles of social research were followed (Babbie, 2013; Patton, 2002). Interviewees signed an informed consent and privacy statement notification to indicate understanding and agreement. Interview responses were anonymised.

Interview recordings and notes were transcribed. The transcriptions were analysed with qualitative content analysis assisted by the MAXQDA qualitative content analysis software (VERBI GmbH Berlin, Release 22.6.1). Analysis of qualitative data collected from the farmer interviews included reducing the volume of raw information, sifting trivia from significance, identifying significant patterns through coding words and full/part sentences from responses, and allowing the frequency and relationships across topics to be analysed (Mayring, 2020, 2022). In this assessment, 4212 sentences containing a total of 53,000 words were analysed. A coding system (with six codes) was developed to analyse content according to the four main research questions, see Table 6. ES disservices, such as crop pests and disease, were not further considered as they fall outside the scope of this study. Qualitative content analysis was done, where word analysis and summaries through systematic text analysis of major themes and trends were identified related to the research questions (RQ); (iv) drivers of farmer decision making, (v) impacts of farmers on ES in agricultural landscapes, (vi) agricultural practices supporting and damaging ES on farms, and (vii) influences of other landscape actors and stakeholders. Data were extrapolated from the individual interviewees at the farm level to farmer groups at the landscape level to answer the research questions.

Table 6. The coding system used during the qualitative analysis of the Western Cape farmer interviews, detailing the six codes' anchor examples and related research questions (RQ).

Code System	**Memo/Anchor Example**
Drivers & source of disturbance	RQ (iv): the drivers of farmer decision-making in the WC that have an impact on ecosystem service provisioning in the agricultural landscape study areas
Impacts	RQ (v): specific impacts farmers have on ES provisioning on their farms; results/outcomes of management practices, such as pollution, water use, depopulation, impacts on wildlife, transforming natural vegetation, etc.
Practices & actions	RQ (vi): practices farmers implement on their farms that support ES provisioning and functioning; management and farming actions irrigation, no-till, less spraying, cover crops, rehabilitation of vegetation, replanting; chemical spraying, synthetic fertilizer

Code System	Memo/Anchor Example
Influences & info sources	RQ (vii): stakeholders that influence farmer decision-making on land management that impacts ES on farms
ES mentioned	farmers mentioning ES directly or indirectly, actions, impacts, association: mulching, no-till, soil sampling, soil health, fire; erosion, steep ground, gabions; yield, tonnage, pests & disease, farming inputs; wild plants and animals, natural area, etc.
Sustainability definition	what farmers think of "sustainability"; mixed, economic, environmental and social; how farmers think, what is important to them, what controls their decision-making on farming practices and land use.

3.4. InVEST ecosystem service mapping and modelling

Three ES (global atmospheric regulation, soil erosion control and crop production) were assessed in the agricultural landscape study areas (the pilot study only investigated one ES; global climate change) by using three InVEST models. Global atmospheric climate regulation was assessed by using the InVEST Carbon Storage and Sequestration model, soil erosion control was assessed by using the InVEST SDR model, and crop production was assessed by using the InVEST Crop Production Percentile model (InVEST software version 3.12.0). ArcMap (version 10.4.1) and MS Excel (Windows 10) were used to prepare all model inputs and produce outputs.

3.4.1. Global atmospheric regulation

Soil carbon storage, as an ES indicator, was assessed in two agricultural landscape study areas in both Hungary (as a pilot study) and the WC, South Africa. For this study, only the projected functional condition of organic carbon stored in mineral soils between the sampled depths was considered.

3.4.1.1. Soil carbon stock mapping in the pilot study areas in Hungary

SCS of the study areas were mapped using the InVEST Carbon Storage and Sequestration model, based on data from the national CS inventories and soil sample CS data. Five InVEST SCS maps were produced for each study area based on the generalised national CS inventory data at the (a) country-wide and (b) mesoregion-level, and from the (c) minimum, (d) mean, and (e) maximum values measured from the collated soil sample data. The CLC2018 LULC raster map was used as input, and 23 LULC types were reclassed into the LULC types that were sampled (i.e., farmland, grassland, and forested areas), water and other (such as built-up, non-natural areas). Farmland included vineyards, arable land, orchards, plantations and cultivated areas. Meadows, pastures and natural grasslands were classed as grasslands. Coniferous, broad-leaf, mixed forest and woodland were classed as forested areas. Commercial, industrial, built-up areas, urban and other categories were classed as ‘other’ and were excluded from analyses as it is outside the scope of this study.

SCS inventories for forested areas, farmland and grassland classes were created from the 1992 national AGROTOPO soil organic CS dataset, and soil sampled CS data (Agrártudományi Kutatóközpont, 1992). For the five maps for each of the study areas, the SCS for each LULC was based on the country-wide national CS data, meso-region CS data, and the soil samples' minimum, mean, and maximum values. The total CS for all LULC of Hungary was calculated by summing the median values of each range to develop the first inventory. This total was then divided by the area categorized under each LULC type, for the national and mesoregion-levels. To develop the inventory based on the soil sample data, humus (%) measurements were converted to SOC and a simplified FAO formula was used to determine SOC stock for mineral soils,

$$SOC = d \times bulk\ density \times C_{org} \qquad \text{(FAO, 2018b)}$$

where SOC = soil organic carbon content ($kg \cdot m^2$); d = depth of horizon/sample (m); bulk density ($kg \cdot m^3$); and C_{org} = organic carbon [$g \cdot g^{-1}$].

A CSV file detailing the SCS lookup values for the LULC classes was created for each map. Five SCS maps and the total aggregated CS value per landscape (and per km^2) were produced and reported. When excluding 'other' non-target LULC; for the Vác-Pest-Danube Valley area, 82 km^2 were mapped, and for the South-Zselic area, 497 km^2 were mapped.

3.4.1.2. Soil carbon stock mapping in the Western Cape

The soil carbon mapping of the two agricultural landscape study areas in the WC followed the SCS mapping procedure established during the pilot study done in Hungary. Similarly, five InVEST SCS maps were produced of both study areas, based on five differently sourced CS inventories. The South African National LULC raster map was used as input. LULC was reclassed into shrubland, grassland, farmland, orchards, water and others. Shrubland included naturally vegetated areas with woody bush and tree plant species (>10% canopy cover, with low to >2.5m canopy height), typical of the woodlands and shrublands of the fynbos and karoo shrub biomes (forested areas are not widespread in the WC, do not occur in large spatially continuous areas, and where they occur, they are distributed in areas <2 km^2). Grassland included naturally vegetated areas dominated by indigenous grass plant species, which may include sparsely wooded grasslands (5–10% canopy cover) and typically representative of grassland, and savanna biomes. Farmland included all commercial agricultural land that excludes LULC classes associated with the orchards class. Orchards included cultivated commercial orchards and vines that produce citrus, apples, olives or wine grapes typically grown in the study areas. Water included all waterbodies and flooded wetlands. Other included all bare ground, industrial, commercial and urban LULC classes that fall outside the scope of this study.

SCS inventories for shrubland, grassland, farmland, and orchards were developed from national soil organic CS datasets, and soil sampled CS data. To develop the first inventory, CS values for these LULC were collected from ISRIC datasets and accompanying published literature on national soil organic CS datasets (Batjes, 2004; ISRIC, 2015). To develop the second inventory, total carbon % measurements of the soil samples were converted to SOC and the above FAO formula was used to determine SOC stock (FAO, 2018b).

As above, CSV files detailing SCS lookup values for the LULC classes were created for each map as model inputs; based on the country-wide national CS data, provincial CS data, and the minimum, mean, and maximum values of the soil samples. SCS maps and the total aggregated CS value per landscape (and per km^2) were produced and reported.

3.4.2. Soil erosion control

Avoided soil erosion and avoided export, as ES indicators, were investigated in the two study areas in the WC. Input data were prepared for the InVEST SDR model; soil erodibility (K factor), rainfall erosivity (R factor), digital elevation model, support practice factor (P) and cover-management factor (C) coefficients, LULC raster maps, biophysical tables, watershed boundaries and several calibration parameters, based on 2018 data. The Rainfall Erosivity Index is input as a raster file that provides the index for each pixel or watershed, indicating the erosive power of rainfall, based on its intensity and duration (ESDAC, 2017). Soil Erodibility (K) is input as a raster file that provides the factor for each pixel or watershed, indicating the susceptibility of soil particles to detachment and transport by water (ESDAC, 2019). The P and C Coefficients are input as a table file that provides values for each LULC type. The P factor reflects the effect of soil conservation practices on erosion, while the C factor reflects the effect of vegetation cover and management on erosion (Natural Capital Project, 2022). Calibration parameters are input as a table file that is set by the InVEST SDR model instructions. These are; Borselli K: 2, threshold flow accumulation: 1000, Borselli IC0: 0.5, Max. L: 122 and Max. SDR: 0.8, which defines the shape of the modelling relationship between the connectivity index (IC) and the SDR (Natural Capital Project, 2022).

The InVEST SDR model uses the Revised Universal Soil Loss Equation (RUSLE) in its methodology:

$$usle = R \times K \times LS \times C \times P \qquad \text{(Renard et al., 1997)}$$

where R = rainfall erosivity (units: MJ·mm (ha·hr·yr)$^{-1}$); K = soil erodibility (units: ton·ha·hr (MJ·ha·mm)$^{-1}$); LS = a slope length-gradient factor (unitless); C is a cover-management factor (unitless); and P = a support practice factor (unitless) (Bhattarai & Dutta, 2007; Renard et al., 1997).

The equation is used to estimate the annual amount of overland soil erosion. The model then calculates sediment export from each pixel by considering the hydrological connectivity of the landscape. The SDR model enhances the RUSLE by considering additional factors such as hydrological connectivity and sediment delivery to streams (Natural Capital Project, 2022). Following the input data preparation instructions for the InVEST model, inputs were prepared for watersheds that cover the study areas, which extend beyond the delineated areas. This was done to create more accurate outputs that consider entire drainage pathways throughout watersheds that impact soil erosion modelling of landscapes.

The model was run twice for both study areas to model avoided topsoil erosion in the landscapes where orchards and arable land had no soil erosion control measures applied and where erosion control measures were applied. To model these two scenarios, two CSV files with biophysical data of the LULC classes were set up and, through ratio coefficients, detailed the soil cover management (C coefficient, the cover management factor, values near 0 mean erosion is less likely and values near 1 mean erosion is more likely) and erosion-reduction practices (P coefficient, the support practice factor, indicating planting direction, minimum tillage and mulching practices, values near 0 mean management practices are done to reduce erosion and values near 1 mean no erosion-reducing practices), see Table 7.

Table 7. P and C coefficients used for the biophysical tables as input, and their literature references, to model landscape level soil erosion under the two no erosion and erosion control measures scenarios for the two study areas in the Western Cape. * indicates unchanged values.

	No erosion control		**Erosion control**		**Reference**
LULC	**usle_c**	**usle_p**	**usle_c**	**usle_p**	
Arable cropland	0.35	1	0.09	0.75	(McKague, 2023; Panagos et al., 2015)
Bare surface	0.4	1	*	*	(Panagos et al., 2015)
Forest plantation	0.13	1	*	*	(Panagos et al., 2015)
Forested areas	0.003	1	*	*	(Panagos et al., 2015)
Grassland	0.07	1	*	*	(Panagos et al., 2015; Rozos et al., 2013)
Orchards	0.45	1	0.15	0.5	(McKague, 2023; Panagos et al., 2015)
Shrubland	0.1	1	*	*	(Panagos et al., 2015)

Three model outputs were produced for both landscapes, for the two scenarios; models that display the total amounts of potential soil loss (RUSLE total potential soil loss), sediment retained (avoided erosion by vegetation), and overall sediment deposited (avoided soil export by vegetation). Sediment retained refers to the amount of soil erosion that is prevented due to the presence of vegetation. Vegetation can mitigate soil erosion and sediment transport by flowing water. It does so by reducing runoff volume, slowing water velocity, and shielding the soil surface from direct impact (Weil et al., 2016)

The model estimates this by using information on climate, geomorphology, vegetative coverage, and management practices. Overall sediment deposited refers to the amount of sediment that is prevented from being exported to the streams due to the current management practices and vegetation cover. It is calculated as the difference between the potential sediment export (without current vegetation) and the actual sediment export (with current vegetation) (Natural Capital Project, 2022). Results were summarised and reported as landscape-scale soil erosion models and sediment retention data tables.

3.4.3. Food production

Crop yield, as an ES indicator, was investigated in the two agricultural landscape study areas in the WC. Crop census data for 2012/2013 and 2017/2018 (from the winter season) were obtained for both study areas from the WC DoA (WC DoA, 2014, 2018). Census data were summarised, analysed and displayed in tables and charts to show total cultivated and cropland extent (ha) for all data, including grains and oilseeds, animal feed (i.e., planted grazing pastures, lucerne and medics), fruit, fallow, vegetables, flowers, nuts, herbs and other LULC classes.

The crop census maps of both study areas, for both production years, were transformed into raster maps of 34 crop types; almonds, apples, apricots, barley, beetroot, blueberries, cabbage, canola (rapeseed), carrots, citrus, figs, garlic, grapes (table and wine), lemons (and limes), lupines (pea), maize, mango, other nuts, oats, olives, onions, oranges, peaches/nectarines, pears, plums, potatoes, pumpkins (and butternuts), strawberries, sweet potatoes, tea (rooibos and honeybush), tomatoes, triticale, walnuts and wheat. Farmland for animal feed, flowers, herbs, and unidentified crop types were not mapped. A CSV crop-type lookup table was set up. The InVEST Crop Production model parses the input data by clipping the study area extents from the global climate bin maps per crop and interpolating input maps resolutions, referencing the observed yield per crop. The model produced a crop yield map for each crop type per study area (north and south) and production year (2012/2013 and 2017/2018). The top five crop types by extent (with >10,000 ha planted area) were displayed, including wheat, grapes, canola (rapeseed), apple and barley. Total crop yields (ha) are reported in tables and graphs per study area for the 2012/2013 and 2017/2018 production years.

Total crop planted area (ha) per study area was summarised to indicate area change between the production years to analyse crop change over the four years, reported in tables. The top five crop types by extent were displayed to show differences in the agricultural composition between the study areas. Total distinct farm and field counts were summarised per crop and year, indicating the extent of change per average field size to analyse the farm-level change in crops, reported in Table 32 in Appendix 2.

3.5. Land use land cover change mapping

The remote sensing-derived South African National Landcover (SANLC) Change 1990–2018 GIS dataset was used as the primary source of assessment to summarise major LULC changes, serving as a key source for evaluating environmental shifts impacting ES (Research Objective 2) (DEA, 2019a). LULC types were reclassed into the below-listed classes and specific land conversion categories, to enable a streamlined analysis of generalised spatial development trends. LULC were reclassed into the following categories: agro-forestry (commercially planted forest), arable cropland, bare and eroded area, built-up environments (urban, commercial and industrial), bush and shrubland (fynbos, renosterbos and karoo), forested area (forest and woodland), grassland, orchards (incl. fruit orchards and vineyards), waterbodies, and wetlands. The LULC change data were processed and analysed to produce LULC change maps of each study area in ArcMap (10.4.1). Only LULC changes of above 5 km^2 between 1990 and 2018 were considered. Attribute data were assessed in MS Excel with pivot tables to summarise large-scale spatio-temporal change in each study area and results were reported on LULC change and spatial development trends.

3.6. Developing ecosystem service-supporting recommendations

To refine ES recommendations for the WC's spatial development frameworks (i.e., Western Cape Provincial Spatial Development Framework (2014), Cape Winelands District Spatial Development Framework 2021/2026 (2022), West Coast District Spatial Development Framework (2020), and Western Cape Land Use Planning Guidelines for Rural Areas (2019)), a brief analysis was done to first assess how these current frameworks address ecosystems, their functions, and services (CWDM, 2022; WCDM, 2020; WCG, 2014, 2019). This involved a review of the frameworks' content related to ES (identification of ES), their integration into planning processes (methods used for mapping and assessing ES), and the potential impact on decision-making (existing approach to understanding land use impacts on ES). The review aimed to identify gaps in how ES are currently incorporated. Results are reported, offering recommendations that bolster the frameworks' capacity for supporting ES-centric spatial planning.

Afterward, priority areas for local landscape level spatial planning and development were evaluated for the study areas, based on maps of farms, protected areas (Critical Biodiversity Areas (CBA) and Ecological Support Areas (ESA)), and soil carbon and avoided erosion data as InVEST models' outputs. Data were processed and analysed in ArcMap (10.4.1). The following data maps were used for both landscape study areas: topsoil carbon storage maps, 0–20 cm depth (of the InVEST Carbon Storage model output map based on the mean of the soil samples from the study areas), were used as it has the best descriptive data to determine high topsoil carbon storage (>50 $Mg \cdot ha^{-1}$); avoided erosion maps (of the InVEST SDR model output map) were used to determine high annual avoided erosion areas (>30 $Mg \cdot ha^{-1}$); farms; and WC CBA and ESA maps (CapeNature, 2017; WC DoA, 2018). Maps were assessed to identify priority management areas for spatial planning. Priority Areas 1 were delineated from farmland occurring within CBA and ESA sites, and overlapping areas of high topsoil carbon storage and avoided erosion values. Priority Areas 2 were delineated from non-overlapping areas of high topsoil carbon storage and avoided erosion. Priority Areas 3 were delineated from farmland where soil carbon storage and avoided erosion took place. Policy proposals were made to integrate these spatially explicit priority areas into localised spatial planning and development to better support ES in the WC agricultural landscapes.

4. RESULTS AND DISCUSSION

4.1. Integrating sampled data into soil carbon stock ecosystem service assessment

Research Question (i): How can in-field sampled data be integrated into the modelling methodology of assessing soil carbon storage (for global atmospheric regulation) to improve the quality of data inputs?

To address this question, the data summary and integration methodology for SCS developed during the pilot study in Hungary are first shown, and thereafter the methodology is applied to the South African soil carbon data. The national SCS and soil sample data are summarised and SCS inventory datasets are presented. SCS spatial models based on these datasets are shown in the ES evaluation section hereafter, where the aggregated SCS per landscape is also reported.

Pilot Study in Hungary

The national SCS data for Hungary (with 1015 data points), and specifically for the Dunamenti Plain (29 data points) and Mecsek and Tolna-Baranya-hills (29 data points) Mesoregions, are shown in Figure 15. For Hungary, the majority (3,499,531 ha) of farmland, forested areas (forest), and grassland are categorised by soil with 40–60 $Mg \cdot ha^{-1}$ of CS, with less distribution across soils with high CS values between 80 and 160 $Mg \cdot ha^{-1}$. The Dunamenti Plain Mesoregion shows LULC on soils with higher CS of 60–80 $Mg \cdot ha^{-1}$, whereas the Tolna-Baranya-hills Mesoregion LULC has soils with generally lower CS of 20–40 and 40–60 $Mg \cdot ha^{-1}$.

The SCS based on the soil sampling data for both study areas is shown in Table 8, with the minimum, mean, and maximum CS ($Mg \cdot ha^{-1}$), standard deviation, and variance, also shown in Figure 16.

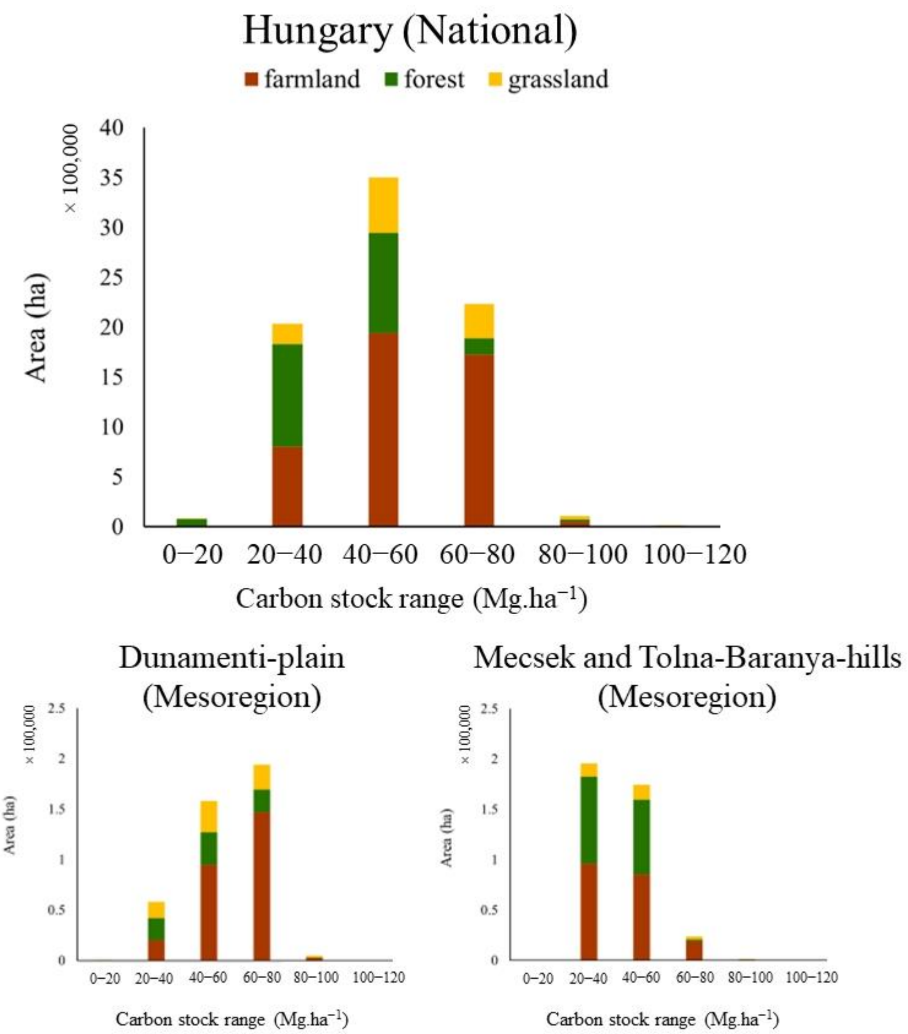


Figure 15. Total amount of area (ha) categorised under soil carbon stock ranges (Mg·ha^{-1}) for farmland, forested areas (forest), and grassland land use land cover classes for Hungary (top) according to the national soil database, also showing the Dunamenti Plain and Mecsek and Tolna-Baranya Hills Mesoregions individually (below) in which the northern and southern study areas are situated, respectively (TAKI, 2022).

Table 8. Soil carbon stock statistics from soil samples collected from the Vác-Pest-Danube Valley and South-Zselic Microregion study areas in Hungary, between 2019 and 2020, 0–30 cm depth.

		Soil Carbon Stock (Mg·ha^{-1})				
Land Use Land Cover (LULC) Class	**No. of Samples (*n*)**	**Min.**	**Mean**	**Max.**	**St. Dev.**	**Var.**
Farmland	35	30.48	60.40	100.67	17.15	293.96
Forested areas	20	39.72	64.21	91.44	14.15	200.29
Grasslands	20	18.88	52.75	92.41	18.38	337.79
Vác-Pest-Danube Valley Microregion (north)						
Farmland	5	35.69	48.26	57.33	9.76	95.30

		Soil Carbon Stock (Mg·ha^{-1})				
Land Use Land Cover (LULC) Class	**No. of Samples (*n*)**	**Min.**	**Mean**	**Max.**	**St. Dev.**	**Var.**
Forested areas	5	56.04	63.91	67.18	4.62	21.37
Grasslands	5	18.88	39.37	69.76	21.44	459.52
South-Zselic Microregion (south)						
Farmland	30	30.48	62.30	100.67	17.37	301.58
Forested areas	15	39.72	64.32	91.44	16.45	270.70
Grasslands	15	28.28	57.20	92.41	15.55	241.95

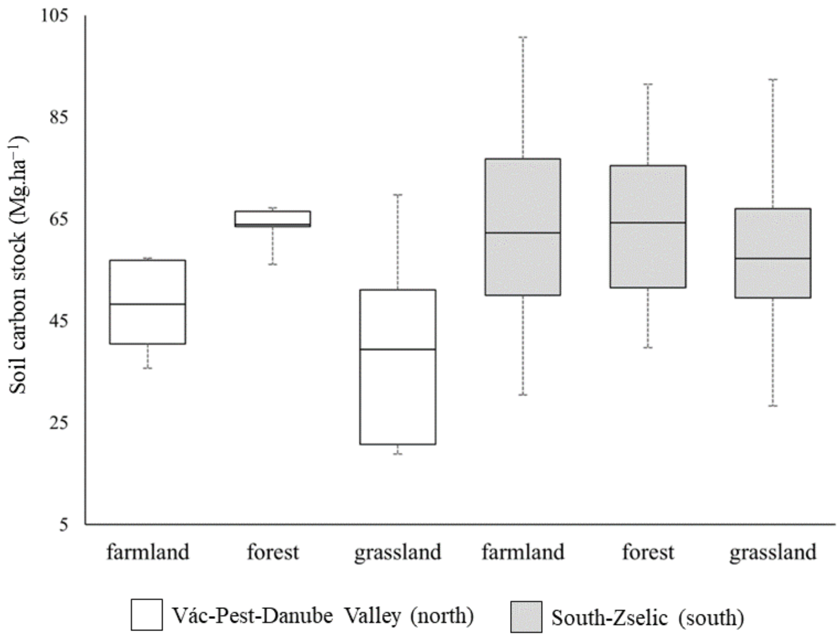


Figure 16. Box plots of soil carbon stock measured from soil samples taken from farmland, forested areas (forest), and grassland LULC in the Vác-Pest-Danube Valley and South-Zselic Microregion study areas, Hungary, in 2019 and 2020. The upper, middle and lower lines show the third quartile, mean, and first quartile, respectively, where the error bars indicate maximum and minimum.

Methodology to develop Carbon Stock Inventories

SCS inventories for farmland, forested areas (forest), and grassland are reported in Table 9 and shown on a graph in Figure 17, developed from the national Hungarian CS data and soil sample CS datasets. Five SCS inventory datasets are shown: (a) the country-wide CS for Hungary based on the complete national soil data; (b) mesoregion-specific CS, in which the study areas are situated, based on that specific mesoregions' data in the national soil dataset (namely the Danube plain for the northern Vác-Pest-Danube Valley and the Mecsek and Tolna-Baranya Hills for the

South-Zselic study area); and then the soil sample data is used to show the (c) minimum, (d) mean, and (e) maximum of both areas.

Table 9. Soil carbon stock inventories for farmland, forested areas, and grassland LULC classes based on five carbon stock datasets, shown for Hungary, and the north and south study areas. The (a) national soil carbon data show country-wide carbon stock for Hungary and the (b) two mesoregions in which the study areas are situated. The soil sample data show the (c) minimum, (d) mean, and (e) maximum carbon stock values.

Datasets	**Carbon Stock ($Mg \cdot ha^{-1}$)/LULC**		
	Farmland	**Forested Area**	**Grassland**
(a) National Soil Data - Hungary	54.45	41.87	53.58
Vác-Pest-Danube Valley Microregion (north)			
(b) National Soil Data - Danube plain mesoregion	60.01	50.22	53.2
(c) Min. soil sample value	35.69	56.04	18.88
(d) Mean of soil samples	48.26	63.91	39.37
(e) Max. soil sample value	57.33	67.18	69.76
South-Zselic Microregion (south)			
(b) National Soil Data - Mecsek and Tolna-Baranya hills mesoregion	42.5	39.6	43.76
(c) Min. soil sample value	30.48	39.72	28.28
(d) Mean of soil samples	62.3	64.32	57.2
(e) Max. soil sample value	100.67	91.44	92.41

The Danube plain (north) mesoregion has higher carbon stock for farmland and forested areas, and the Mecsek and Tolna-Baranya hills (south) mesoregion has lower CS for farmland and grassland compared to the national soil data of Hungary (Figure 17).

Both mean soil samples' CS differ largely from farmland and grassland, but forested areas' CS are nearly identical and generally higher than the national data. The national soil data of Hungary has similar or lower CS compared to the other datasets, where soil samples show higher CS for forested areas.

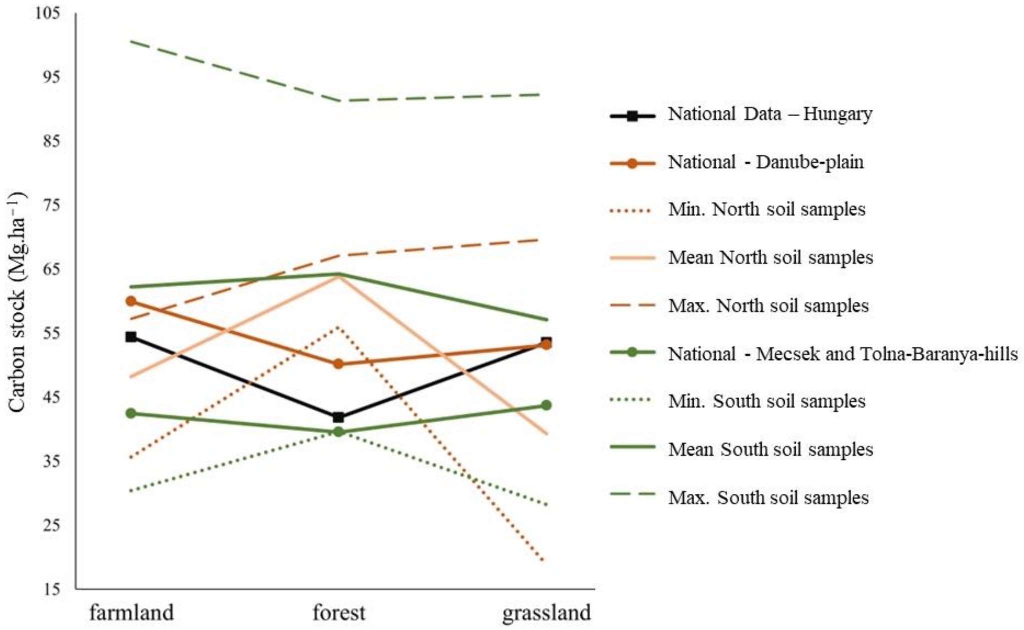


Figure 17. Variation of the carbon stock values for farmland, forested areas (forest), and grassland LULC classes shown for Hungary and the Vác-Pest-Danube Valley (north) and South-Zselic (south) agricultural landscape study areas. Based on separate datasets, the national soil database and soil sample data (TAKI, 2022).

Soil Carbon Stocks in the Western Cape, South Africa

The AfSIS SOC map of South Africa (predictive models based on > 653 data points) presents millions of data points for SOC nationally. When cross-referenced with a LULC map it shows all three LULC SCS are predicted mostly between 1 and 90 $Mg{\cdot}ha^{-1}$ across the country, with grasslands and shrublands showing more area with low soil carbon (2–10 $Mg{\cdot}ha^{-1}$) and farmland showing greater area with 10–20 $Mg{\cdot}ha^{-1}$ of CS.

The SCS based on the soil sampling data (at 0–20 and 20–40 cm depth) for both study areas are shown in Table 10, with the minimum, mean, and maximum CS ($Mg{\cdot}ha^{-1}$), standard deviation, and variance of all sample data combined, as well as of the data from each Swartland-Tulbagh-Slanghoek (North) and Helderberg-Grabouw-Breede Valley (South) study areas, see Figure 18.

Table 10. Soil organic carbon stock statistics from soil samples collected in 2021 from the Swartland-Tulbagh-Slanghoek (North) and Helderberg-Grabouw-Breede Valley (South) study areas in the Western Cape, South Africa, 0–20 and 20–40 cm depth.

		Soil Carbon Stock ($Mg{\cdot}ha^{-1}$)				
Land Use Land Cover (LULC) Class	**No. of Samples (*n*)**	**Min.**	**Mean**	**Max.**	**St. Dev.**	**Var.**
			Both Study Areas			
0–20 cm depth						
Shrubland	10	13.78	36.43	58.73	17.02	289.81
Grassland	10	30.11	58.57	113.69	25.87	669.48
Farmland	10	20.17	39.25	102.38	25.48	649.25
Orchard	10	7.94	61.03	143.08	37.52	1407.85
20–40 cm depth						
Shrubland	10	11.51	28.75	53.41	14.16	200.58
Grassland	10	13.61	47.45	98.36	27.37	749.14
Farmland	7	8.18	35.08	86.15	26.59	707.01
Orchard	6	18.89	35.67	72.96	20.04	401.52
			Swartland-Tulbagh-Slanghoek (north)			
0–20 cm depth						
Shrubland	5	26.21	42.22	52.74	12.19	148.55
Grassland	5	41.98	66.09	113.69	28.94	837.30
Farmland	5	20.54	38.43	59.89	14.92	222.63
Orchard	5	32.23	57.88	90.27	26.26	689.78
20–40 cm depth						
Shrubland	5	15.72	35.28	53.41	15.25	232.69
Grassland	5	21.17	52.23	98.36	33.04	1091.77
Farmland	5	8.18	26.79	54.40	17.30	299.22
Orchard	4	23.69	38.16	72.96	23.49	551.66
			Helderberg-Grabouw-Breede Valley (south)			
0–20 cm depth						
Shrubland	5	13.78	30.64	58.73	20.49	419.72
Grassland	5	30.11	51.04	88.40	22.97	527.51
Farmland	5	20.17	40.07	102.38	35.16	1236.52

Land Use Land Cover (LULC) Class	No. of Samples (n)	Soil Carbon Stock ($Mg \cdot ha^{-1}$)				
		Min.	**Mean**	**Max.**	**St. Dev.**	**Var.**
Orchard	5	7.94	64.18	143.08	49.53	2453.08
20–40 cm depth						
Shrubland	5	11.51	22.22	36.41	10.58	112.03
Grassland	5	13.61	42.67	77.44	23.16	536.62
Farmland	2	25.41	55.78	86.15	42.95	1844.55
Orchard	2	18.89	30.67	42.46	16.67	277.77

Carbon Stock Inventories of Western Cape Study Areas

SCS inventories for shrubland, grassland, farmland, and orchard LULC are reported in Table 11 for 0–20 cm depth, Table 12 for 20–40 cm depth, and both shown on graphs in Figure 19, developed from the national South African CS data and soil sample CS datasets. Six SCS inventory datasets are shown: (a) the country-wide CS for South Africa based on the complete national soil data; (b) WC province-specific CS, in which the study areas are situated, based on that specific provinces' data in the national soil dataset; (c) total aggregated soil sample data show the mean of samples from both study areas, and the (d) minimum, (e) mean, and (f) maximum CS values for the Swartland-Tulbagh-Slanghoek (north) and Helderberg-Grabouw-Breede Valley (south) study areas individually.

Overall, the soil samples have higher CS for all LULC by about 20 to 30 $Mg \cdot ha^{-1}$ compared to the national soil data of South Africa for 0–20 cm depth, and a difference of about 10 to 20 $Mg \cdot ha^{-1}$ for 20 to 40 cm depth compared to national data (Figure 19). Soil samples have higher overall CS for both depths for all LULC, with orchard and grassland CS exceeding 100 $Mg \cdot ha^{-1}$ in the maximum CS. National data and the sample's minimum values were all relatively low (<40 $Mg \cdot ha^{-1}$) for all LULC. Interestingly, for 0–20 cm, the sample's CS show a similar pattern with all having higher orchard and grassland CS than farmland and shrubland. This pattern is different for 20–40 cm where farmland has the highest mean CS for the south soil samples.

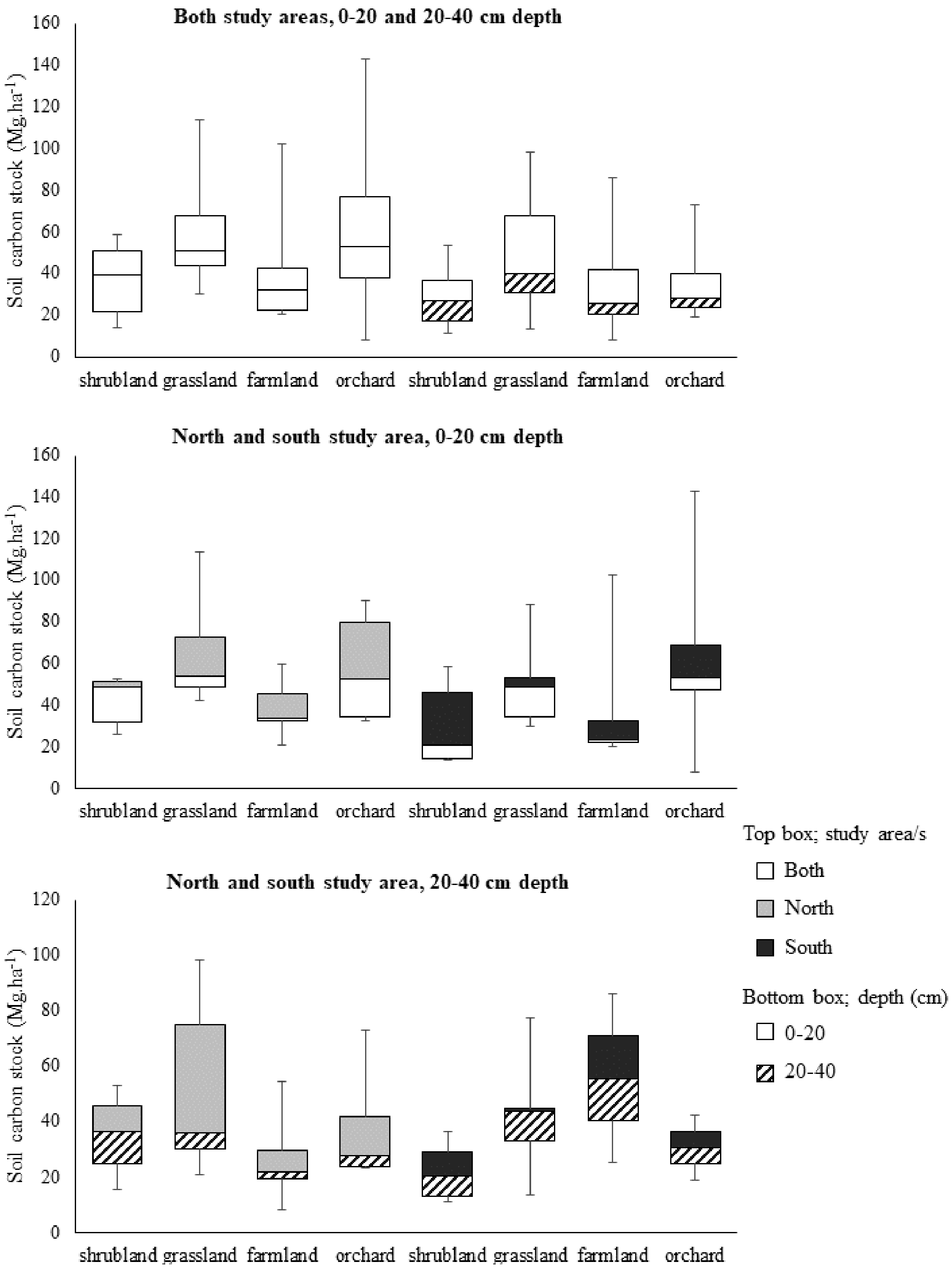


Figure 18. Box plots of soil carbon stock measured from soil samples taken from farmland, forested areas (forest), and grassland LULC in the Swartland-Tulbagh-Slanghoek (North) and Helderberg-Grabouw-Breede Valley (South) agricultural landscape study areas in South Africa, 2021. The upper, middle and lower lines show the third quartile, mean, and first quartile, respectively, where the error bars indicate maximum and minimum.

Table 11. Soil carbon stock inventories for shrubland, grassland, farmland, and orchard LULC classes based on five carbon stock datasets for 0–20 cm depth, shown for South Africa, Western Cape, and the north and south study areas. The (a) national soil carbon data show country-wide carbon stock for South Africa and the (b) Western Cape province, where the study areas are situated. The soil sample data show the (c) mean of samples from both study areas, and the (d) minimum, (e) mean, and (f) maximum carbon stock values for the north and south study areas individually.

Datasets	**Carbon Stock ($Mg \cdot ha^{-1}$)/LULC**			
	Shrubland	**Grassland**	**Farmland**	**Orchard**
(a) National Soil Data - South Africa	14.87	20.82	23.69	23.69
(b) National Soil Data - Western Cape	19.92	13.04	22.65	22.65
(c) Samples' Soil Data - mean of both sites	36.43	58.57	39.25	61.03
Swartland-Tulbagh-Slanghoek (north)				
(d) Min. soil sample value	26.21	41.98	20.54	32.23
(e) Mean of soil samples	42.22	66.09	38.43	57.88
(f) Max. soil sample value	52.74	113.69	59.89	90.27
Helderberg-Grabouw-Breede Valley (south)				
(d) Min. soil sample value	13.78	30.11	20.17	7.94
(e) Mean of soil samples	30.64	51.04	40.07	64.18
(f) Max. soil sample value	58.73	88.40	102.38	143.08

Table 12. Soil carbon stock inventories for shrubland, grassland, farmland, and orchard LULC classes based on five carbon stock datasets for 20–40 cm depth, shown for South Africa, Western Cape, and the north and south study areas. The (a) national soil carbon data show country-wide carbon stock for South Africa and the (b) Western Cape province, where the study areas are situated. The soil sample data show the (c) mean of samples from both study areas, and the (d) minimum, (e) mean, and (f) maximum carbon stock values for the north and south study areas individually.

Datasets	**Carbon Stock ($Mg \cdot ha^{-1}$)/LULC**			
	Shrubland	**Grassland**	**Farmland**	**Orchard**
(a) National Soil Data - South Africa	11.50	16.28	17.11	17.11
(b) National Soil Data - Western Cape	14.72	9.07	14.06	14.06
(c) Samples' Soil Data - mean of both sites	28.75	47.45	35.08	35.67
Swartland-Tulbagh-Slanghoek (north)				
(d) Min. soil sample value	15.72	21.17	8.18	23.69
(e) Mean of soil samples	35.28	52.23	26.79	38.16

Datasets	Carbon Stock (Mg·ha^{-1})/LULC			
	Shrubland	Grassland	Farmland	Orchard
(f) Max. soil sample value	53.41	98.36	54.40	72.96
Helderberg-Grabouw-Breede Valley (south)				
(d) Min. soil sample value	11.51	13.61	25.41	18.89
(e) Mean of soil samples	22.22	42.67	55.78	30.67
(f) Max. soil sample value	36.41	77.44	86.15	42.46

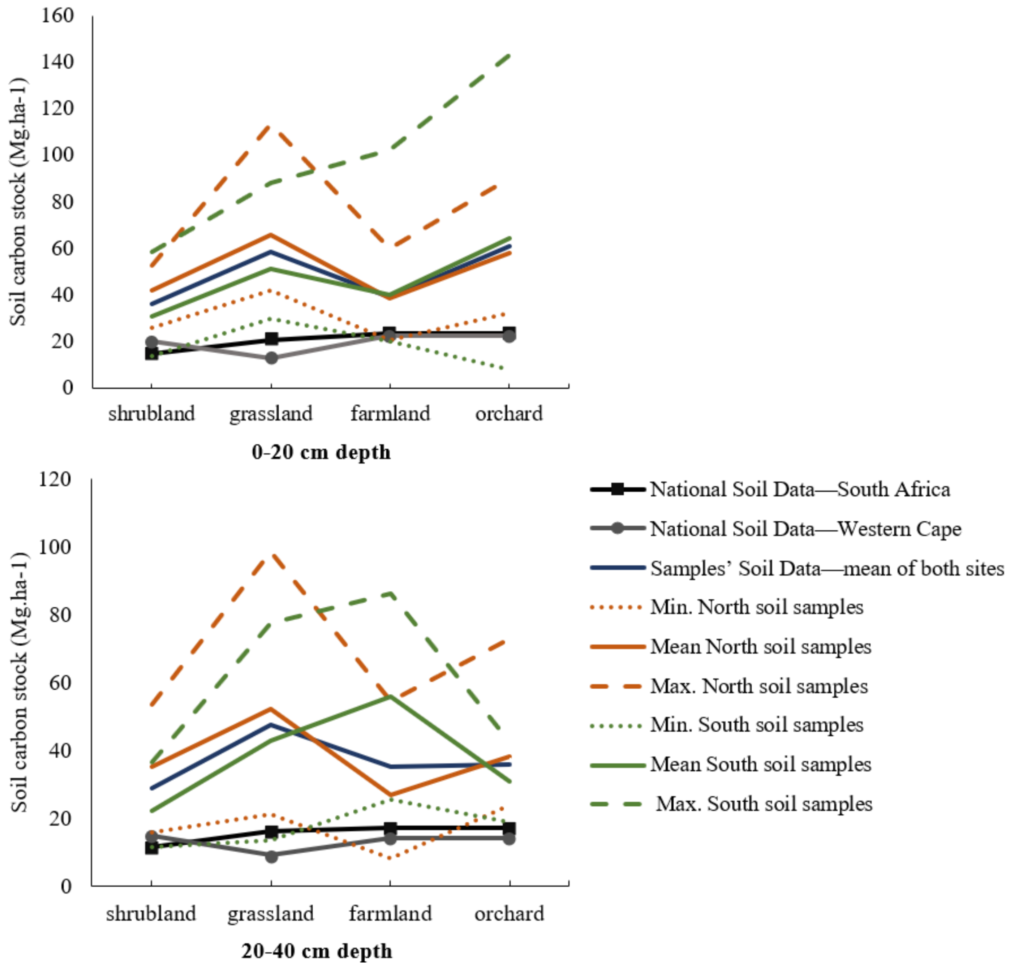


Figure 19. Variation of the carbon stock values for shrubland, grassland, farmland, and orchard LULC classes shown for South Africa (National Soil Data), Western Cape (National Soil Data), study areas combined sampling data, and the Swartland-Tulbagh-Slanghoek (North) and Helderberg-Grabouw-Breede Valley (South) agricultural landscape study areas. Based on separate datasets, the national soil database and soil sample data (ISRIC, 2015).

4.2. Assessment and evaluation of ecosystem services in agricultural landscapes

Research Question (ii): What is the status of the three ES' provisioning and functioning in the agricultural landscape study areas, based on the combined public databases and in-field sampled data?

4.2.1. Global atmospheric regulation

4.2.1.1. Pilot study - Hungary

The SCS map results of the InVEST soil carbon models of the two study areas in Hungary are shown in Figure 20, based on the five SCS inventories shown in Table 9. The (a) country-wide SCS for Hungary shows the same carbon range across both models, making it impossible to discern differences in LULC. In contrast, the (b) mesoregion-specific CS exhibit variation across LULC in both maps. The (c) minimum CS based on soil samples reveals greater variation between LULC in the north study area and no differences in the south. The (d) mean CS, based on soil samples, show the most variation in carbon between LULC classes, ranging from low to high CS. The (e) maximum carbon based on soil samples indicates very high carbon levels for all LULC, with little variation.

Figure 21 reports the total aggregated SCS for the 0 to 30 cm depth in each landscape study area. For the Vác-Pest-Danube Valley microregion (north), the calculated total potential CS values for the 8246 ha mapped area are as follows; national soil data for Hungary: 410,243 Mg; Danube plain mesoregion: 450,878 Mg; north soil sample's minimum: 313,700 Mg; north soil sample's mean: 420,928 Mg; and north soil sample's maximum: 525,273 Mg. The total aggregated SCS mean for the north study area is estimated at 424,204 Mg.

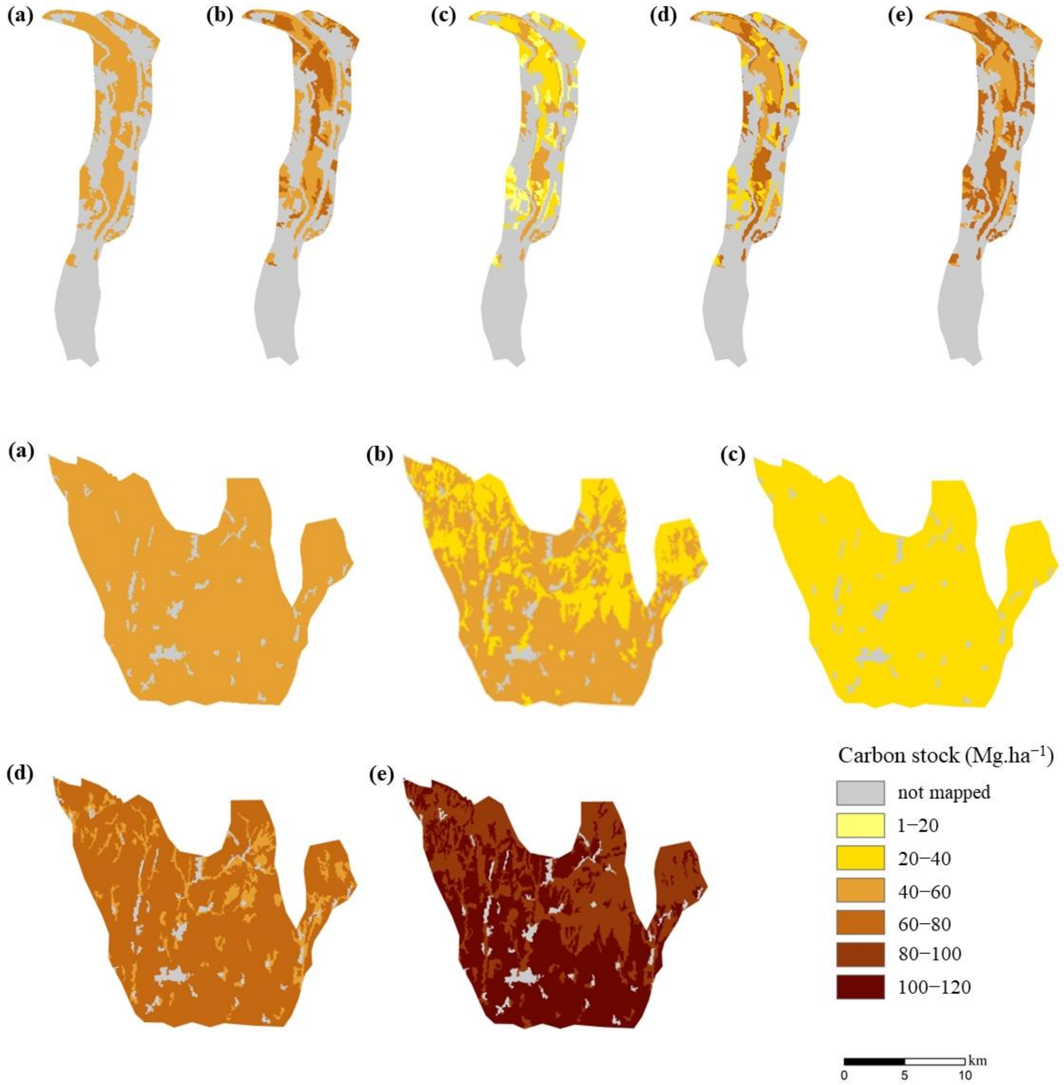


Figure 20. Soil carbon stock (Mg·ha^{-1}) maps of the northern Vác-Pest-Danube Valley (top) and southern South-Zselic (below) study areas in Hungary, based on the soil (0–30 cm) carbon values from the (a) national soil carbon data, (b) mesoregion soil carbon data, and the (c) minimum, (d) mean, and (e) maximum values of the soil samples (1:250,000).

For the South-Zselic microregion (south), the calculated total potential CS values for the 49,747 ha mapped area are as follows; national soil data for Hungary: 2,488,350 Mg; national soil data for the Mecsek and Tolna-Baranya hills mesoregion: 2,062,493 Mg; south soil sample's minimum: 1,639,510 Mg; south soil sample's mean: 3,081,877 Mg; south soil sample's maximum: 4,783,027 Mg. The total aggregated SCS mean for the south study area is estimated at 2,811,051 Mg.

Figure 21 also shows the mean aggregated CS per hectare for both study areas. Table 13 compares the differences in the calculated total potential aggregated SCS (Mg) for both Hungarian landscape study areas between the different CS inventories. The greatest difference in total stored carbon is predictably seen between the minimum and maximum CS from the soil samples in both landscapes.

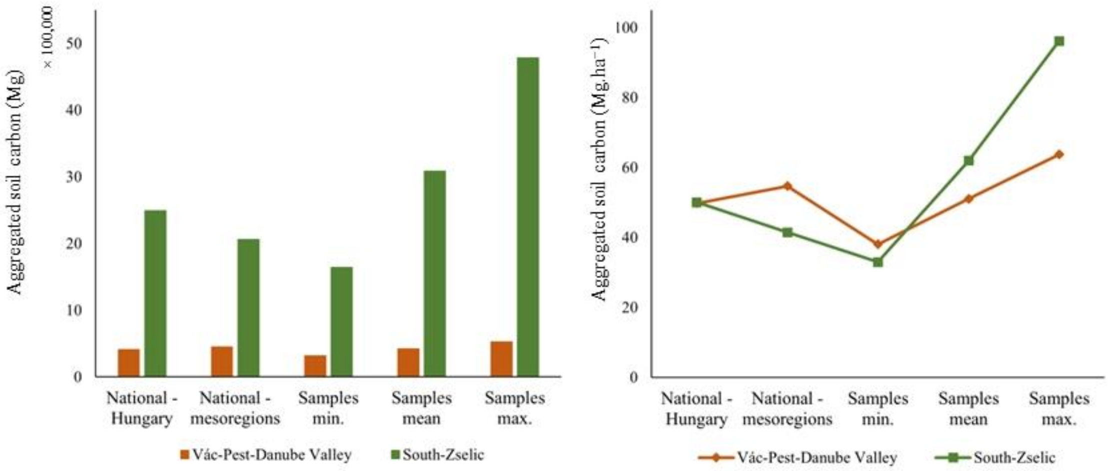


Figure 21. (left) Total potential aggregated soil carbon stock (Mg) stored between 0 and 30 cm soil depth in the Vác-Pest-Danube Valley and South-Zselic study area landscapes, Hungary, and the (right) mean potential aggregated soil carbon per mapped hectare for both study areas, calculated from each carbon stock inventory dataset, for 0–30 cm depth.

Table 13. The differences in the individually calculated total potential aggregated topsoil carbon stock (Mg), 0–30 cm, for the Vác-Pest-Danube Valley and South-Zselic study area landscapes, Hungary, based on the five carbon-stock inventories.

	National—Mesoregion	**Samples Min.**	**Samples Mean**	**Samples Max.**
	Vác-Pest-Danube Valley (North)			
National - Hungary	−40,635	96,543	−10,685	−115,030
National - mesoregion		137,178	29,950	−74,395
Samples min.			−107,228	−211,573
Samples mean				−104,345
	South-Zselic (South)			
National - Hungary	425,857	848,840	−593,527	−229,4677
National - mesoregion		422,983	−1,019,384	−2,720,534
Samples min.			−1,442,367	−3,143,517
Samples mean				−1,701,150

The InVEST SCS spatial models demonstrate significant variation based on the CS inventory used, highlighting the models' sensitivity to input data. By mapping these models with different datasets, a clearer and more detailed valuation range of topsoil carbon storage in the agricultural landscape study areas (0-30 cm depth) was established. This methodology presents a distinct potential range of landscape-level SCS, offering a novel approach to evaluating and reporting SCS on this scale.

Integrating soil sample data with national CS data shows promise for assessing the potential soil CS currently stored in these agricultural landscapes. This approach can provide more accurate information for decision-making about the impacts of policies and the trade-offs involved in creating financial incentives linked to environmental and climate change mitigation programs for farmers and land managers.

While national CS data is useful for viewing general spatial trends over large areas (>500 km^2), soil sample-based CS inventories are more effective for medium to large scales (approximately 80 to 500 km^2). In agricultural landscape study areas, these inventories offer a more detailed and meaningful view of soil CS ranges. They provide greater detail on CS inventories and enhance our understanding of SCS realities in these specific landscapes. The total aggregated SCS for both landscape study areas shows large differences, and it would be useful for land management decision-makers to better understand the root causes in SCS variation within LULC classes for the mapped landscape for improved understanding of bio-physical variation which would lead to improved decision-making.

4.2.1.2. Western Cape, South Africa

Study Area 1: Swartland-Tulbagh-Slanghoek

Based on the six SCS inventories and four LULC classes, shown in Table 11 and Table 12, InVEST SCS spatial models of the Swartland-Tulbagh-Slanghoek (north) study area in the WC, for 0–20 and 20–40 cm soil depths, are shown in Figure 22. The (a) country-wide national SCS of South Africa shows lower carbon ranges (<40 $Mg \cdot ha^{-1}$) for all LULC across both depths compared to other CS inventories. The (b) WC province-wide national SCS of South Africa shows identical CS variation compared to national SA CS for both depths. The (c) mean of samples from both study areas shows generally higher CS (by 20 $Mg \cdot ha^{-1}$) compared to both national CS for both depths, with 20–40 cm depth showing the second highest CS. The (d) minimum, (e) mean, and (f) maximum CS maps of the north study area show equivalently lower, medium and higher CS for both depths. The (d) minimum map shows generally higher CS than the (a) national SA CS. The (f) maximum CS map shows the highest spatial distribution of CS across the area for both depths.

Figure 22 and model outputs present these three main results; the sampled CS inventories (maps c-f) present higher CS spatial distribution across the north study area for both depths and all 20–40 cm soil depth maps show marginally lower CS compared to 0–20 cm depth, and the national SCS data of South Africa and the WC province subset data (of the national SA data) do not display substantial differences in CS.

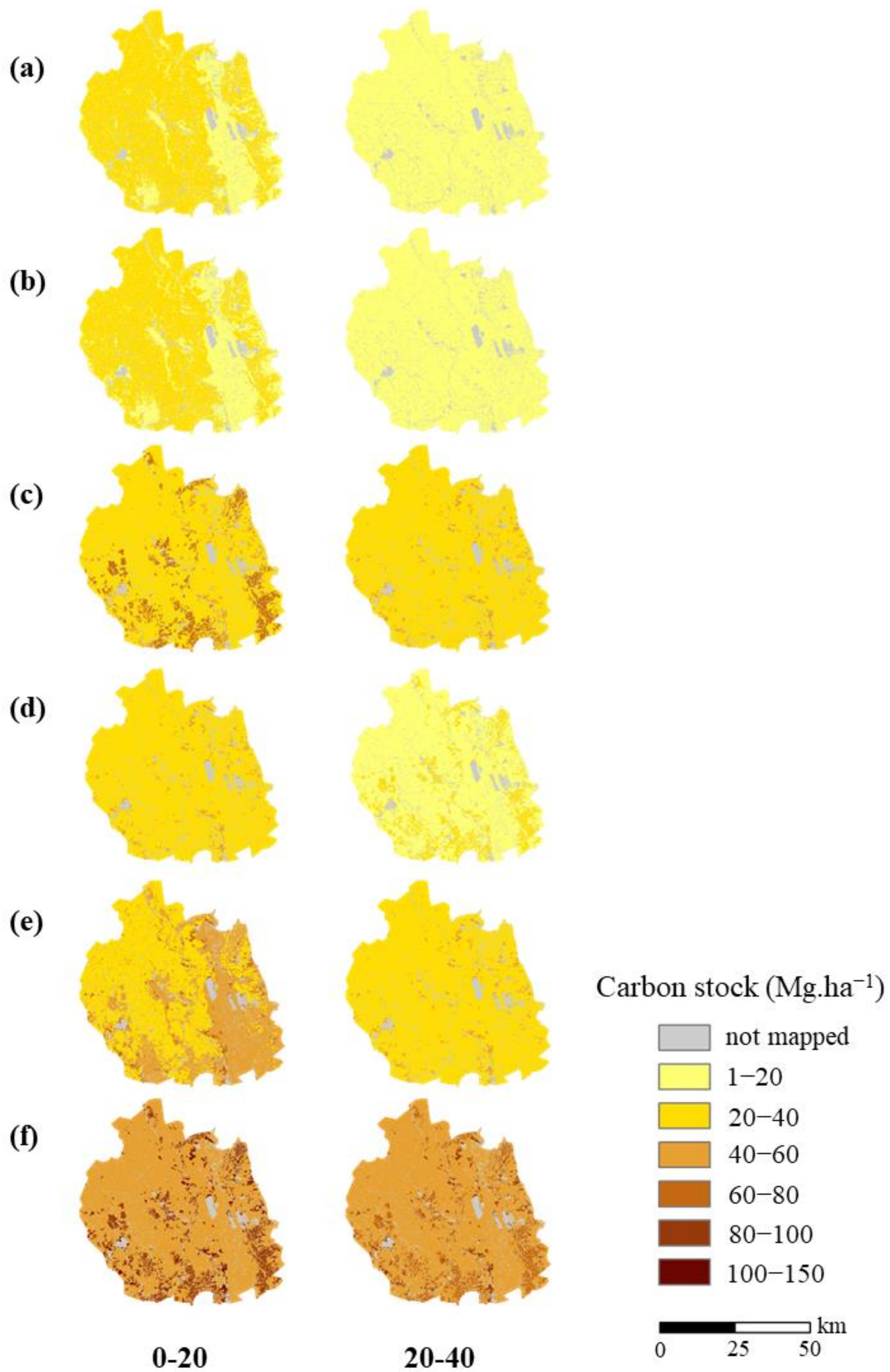


Figure 22. InVEST soil organic carbon stock (Mg·ha^{-1}) spatial models of the Swartland-Tulbagh-Slanghoek (north) study area in the Western Cape, based on the soil (0–20 and 20–40 cm) carbon values from the (a) national soil carbon data of South Africa, (b) Western Cape province-wide national soil data, and soil sample data of the (c) mean of samples from both study areas, and the (d) minimum, (e) mean, and (f) maximum carbon stock values for the north and south study areas individually (1:1,600,000).

Study Area 2: Helderberg-Grabouw-Breede Valley

Similarly, the InVEST SCS spatial models of the Helderberg-Grabouw-Breede Valley (south) study area in the WC, for 0–20 and 20–40 cm soil depths, based on the six SCS inventories and four LULC classes (Table 11 and Table 12), are shown in Figure 23. The (a) country-wide national SCS of SA shows lower carbon ranges (<40 $Mg \cdot ha^{-1}$), with 20–40 cm depth showing the lowest CS ranges across the study area (<20 $Mg \cdot ha^{-1}$). The (b) WC province-wide national SCS 0–20 cm shows slightly higher CS compared to the SA national CS, and similarly, very low CS ranges are shown for 20–40 cm depth.

The (c) mean of both area's soil samples 0–20 cm generally shows greater CS variation across the area (up to 60–80 $Mg \cdot ha^{-1}$), and slightly higher CS for 20–40 cm compared to the national data. The (d) minimum, (e) mean, and (f) maximum CS maps of the north study area show equivalently lower, medium and higher CS for both depths. The (d) minimum 0–20 cm map shows lower CS than the national SA and WC CS, and the 20–40 cm map shows higher CS than both national SA and WC CS. The (f) maximum CS map shows the highest spatial distribution of CS across the area for both depths (up to 80-150 $Mg \cdot ha^{-1}$).

The south study area CS maps present these three main results; the sampled CS inventories (maps c, e and f, excluding minimum map) present higher CS spatial distribution across the north study area for both depths, all 20–40 cm soil depth maps show noticeably lower CS compared to 0–20 cm depth (by about 20 $Mg \cdot ha^{-1}$), and the maximum CS maps at both depths show exceptionally high CS distribution across the study area (80–150 $Mg \cdot ha^{-1}$).

Based on the range of digitally mapped CS of the two agricultural landscape study areas in the WC, South Africa, several main points emerged for consideration in sustainable land use management. Firstly, the sampled CS inventories showed higher CS than the national CS data, indicating that the national and province-based CS data are not truly reflective of measured CS values for shrubland, grassland and farmland in the WC. As the national soil data for CS in South Africa and the WC are mostly identical, it could be assumed that national CS data presented by ISRIC (2015) are over-generalized and values broadly reflect low variation of low CS across the large country topsoil. Due to the fertile and productive soils of the WC, it is surprising for the WC subset data of the national CS data to reflect lower CS for the region. This shows the importance of local sampling when mapping CS and assessing soil carbon storage at the landscape scale.

Compared to levels in the Northern Hemisphere, soil carbon levels in South Africa are generally lower and can be non-existent in bare ground shallow soiled areas, particularly in the Western and Northern Cape provinces (Du Preez et al., 2011a, 2011b; Kucharik et al., 2000).

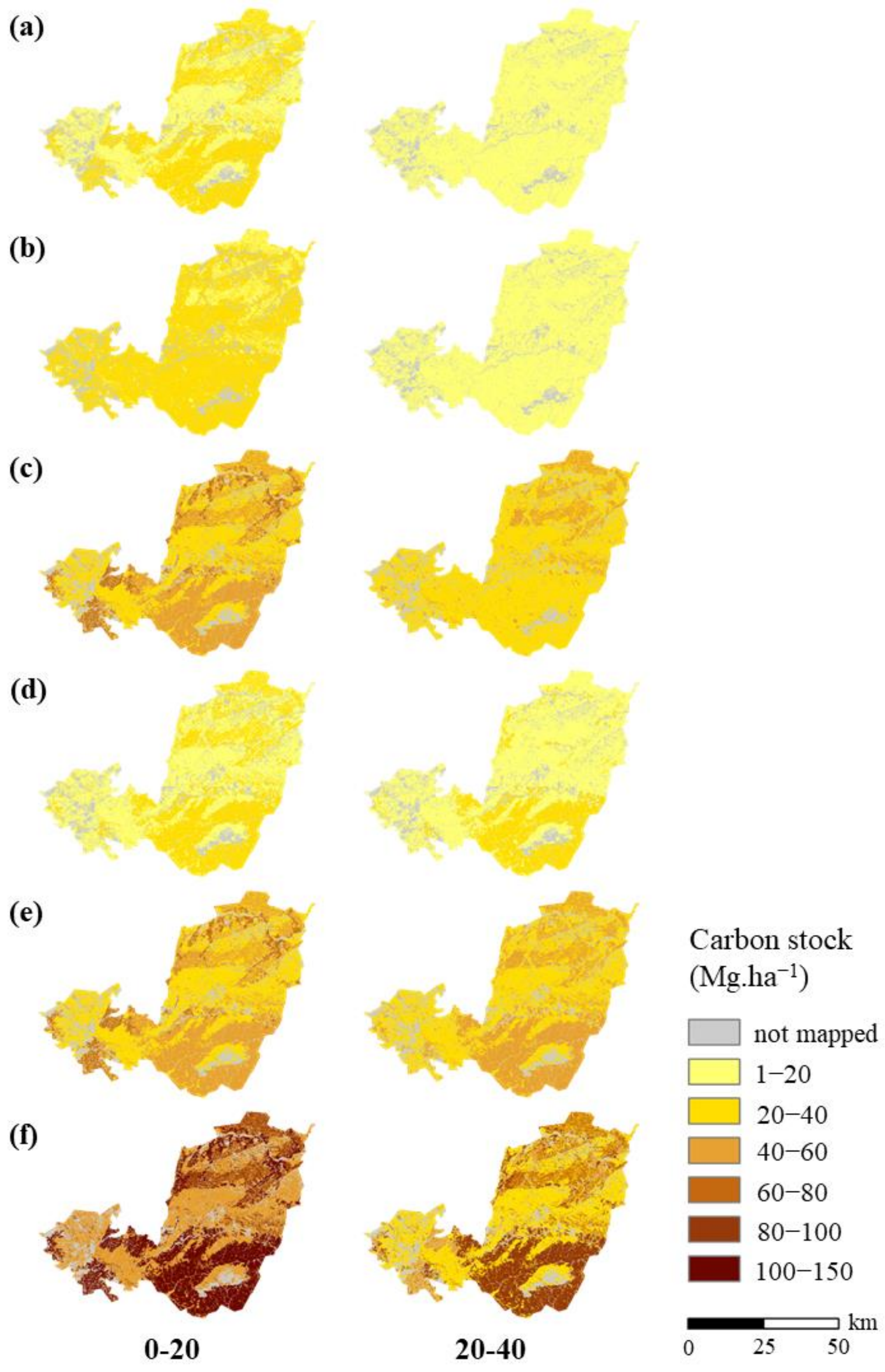


Figure 23. InVEST soil organic carbon stock (Mg·ha^{-1}) spatial models of the Helderberg-Grabouw-Breede Valley (south) study area in the Western Cape, based on the soil (0–20 and 20–40 cm) carbon values from the (a) national soil carbon data of South Africa, (b) Western Cape province-wide national soil data, and soil sample data of the (c) mean of samples from both study areas, and the (d) minimum, (e) mean, and (f) maximum carbon stock values for the north and south study areas individually (1:1,600,000).

Grasslands and savanna biomes, due to their large size, make the largest contribution to South Africa's terrestrial CS, whereas in the WC, most area falls under the shrubland of fynbos biomes (DEA, 2017; Venter et al., 2021b).

Large-scale nation-wide soil carbon mapping of South Africa has been done in the past decade (DEA, 2017; Schulze & Schütte, 2020; Schütte et al., 2019; Venter et al., 2021b). Both DEA (2017) and Schütte et al. (2019) identified and mapped soils rich in organic carbon, going as deep as 1 m, in South Africa as a climate change mitigation option.

These reports provide information on the extent of organic soils in SA and how CS data can be incorporated into greenhouse gas (GHG) inventories, which contributes to the government’s yearly national reporting of GHG emissions (Schütte et al., 2019).

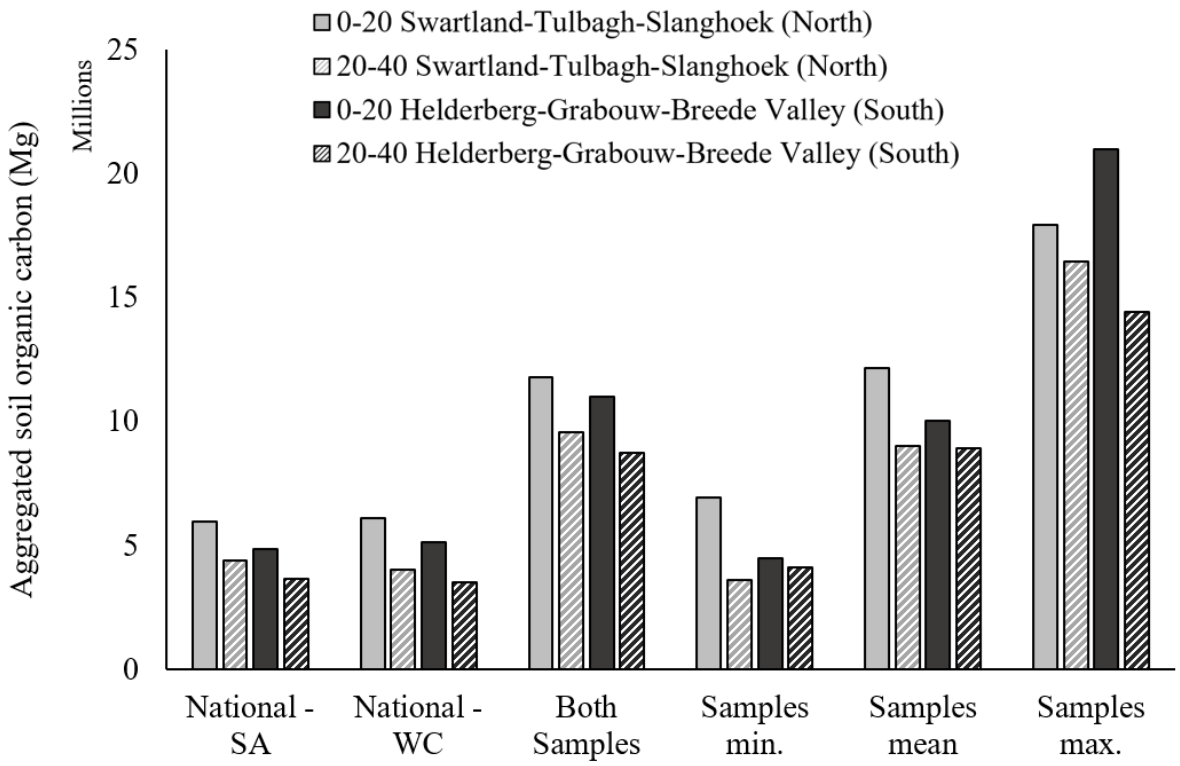
Details of WC soils and CS are largely missing from these reports as fynbos grow on comparatively nutrient-poor, acidic soils that are low in organic matter and have low water-holding capacity (SANBI, 2018). These soils, however, should not be dismissed for their soil carbon storage capacities. Fynbos soils can contain significant amounts of soil carbon due to root biomass, compared to crops, with recent studies showing that fynbos ecosystems may have some of the highest SCS in the world for similar soil types (Mills et al., 2012). Where this study calculated fynbos CS generally between 30–50 $Mg \cdot ha^{-1}$, Mills et al. (2012) measured much higher levels between 50–80 $Mg \cdot ha^{-1}$ for various fynbos biome types, suggesting that shrubland CS can be even higher than presented here and, once again, highlight the importance of active and efficient soil management by land managers.

Secondly, the 20–40 cm CS map showed slightly lower CS than the 0–20 cm CS map, in line with known results that deeper soils have lower CS compared to topsoil (FAO, 2022; Kaleeswari et al., 2013). However, the difference was only slight, suggesting that deeper soils are equally important in considerations of soil management in terms of managing soil carbon loss due to land use practices (Olsson et al., 2022; Schütte et al., 2019).

The highest CS mapped reflects the combination of the fertile soil of the Breede Valley featuring intensively managed commercial agricultural areas, producing apples and wine grapes. Commercial farming practices often include intense, active management of soil fertility and health, using several biological and mechanical methods to increase measured soil carbon, a common land management feature in the WC (Fourie, 2012; Heege, 2013; Power, 2010). The promotion of carbon sequestration in agricultural soils through improved soil management practices, such as conservation agriculture, cover cropping, and reduced tillage, has been well-established (FAO, 2014). These practices have the potential to enhance soil health, increase organic matter content, and reduce soil erosion, ultimately leading to increased carbon storage (Altieri, 2018; Lal, 2021).

Therefore, this result suggests various extents and areas of micro carbon sinks and sources, that may have an accumulative effect on total soil C loss or gain across the Breede Valley. Spatial planning can incorporate the management of micro carbon sinks and sources by identifying and prioritizing areas with high potential for carbon storage and sequestration (Olsson et al., 2022). This shows that CS maps help identify areas where the implementation of appropriate land management practices can promote carbon sequestration (Balkovič et al., 2020; Wang et al., 2020).

The total potential aggregated SCS (Mg) for 0–20 and 20–40 cm depths for both landscape study areas are reported in Figure 24. A comparison of the differences in the calculated total potential aggregated SCS (Mg) for both landscape study areas between the different CS inventories is reported in Table 28, Appendix 2.



	National - SA	National - WC	Both Samples	Samples min.	Samples mean	Samples max.
0-20 Swartland-Tulbagh-Slanghoek (North)	5 945 196	6 114 590	11 793 374	6 929 896	12 160 932	17 915 485
20-40 Swartland-Tulbagh-Slanghoek (North)	4 374 031	4 013 536	9 589 972	3 596 171	8 992 836	16 437 342
0-20 Helderberg-Grabouw-Breede Valley (South)	4 840 522	5 117 610	10 980 827	4 493 291	10 040 137	20 982 875
20-40 Helderberg-Grabouw-Breede Valley (South)	3 645 252	3 527 115	8 719 737	4 126 025	8 922 860	14 403 730

Figure 24. (left) Total potential aggregated soil organic carbon stock (Mg) stored between 0–20 and 20–40 cm soil depths in the Swartland-Tulbagh-Slanghoek (north) and Helderberg-Grabouw-Breede Valley (south) study area landscapes, Western Cape.

Both landscapes' 0–20 cm soil layer potentially store between 4–20 million SOC Mg, with a total average of 9–10 million SOC Mg (mean of 31 $Mg \cdot ha^{-1}$). The landscapes' 20–40 cm soil layer potentially store between 3–16 million SOC Mg, with a total average of 7 million SOC Mg (mean of 23 $Mg\cdot ha^{-1}$). Presenting both landscapes, at 0–40 cm depth, as sturdy CS sinks, potentially with a total of about 16–17 million SOC Mg (mean of 27 $Mg\cdot ha^{-1}$) for each of the two ±3000 km^2 agricultural landscapes. These features on the lower end scale for SOC are typically measured in thicket and grasslands biomes in South Africa and are equivalent to measured SOC (mean of 25–55 $Mg\cdot ha^{-1}$) in semi-arid biomes such as shrubland (incl. fynbos and karoo) in the WC (Mills & Fey, 2004; Mills et al., 2005; Snyman, 2003; Venter et al., 2021b).

Generally considering the aggregated CS for both landscapes, at both depths, national CS data calculates about half that of the sampled CS data (means and maximum), except where it is equivalent to the minimum values of sampled CS. This represents a serious limitation to the national CS dataset, as sampling data presents millions of unaccounted SOC across the landscapes. Spatial planning is most effective when based on accurate information and, in this case, would be incorrectly informed by using only the national CS data.

Results show both agricultural landscape study areas to be significant soil carbon sinks. Other national CS datasets are over-generalised, less or not-representative of real-world settings (Bellassen et al., 2022; Chen et al., 2023). Bellasen et al. (2022) reported on miscalculated CS monitoring in Europe, with possible under- and over-estimation of carbon dioxide emissions linked to croplands, forests and grasslands based on National inventories. It is estimated that only 33% of forest SCS is correctly assessed across the EU (Tóth et al., 2018). This misrepresentation has a direct impact on national policies addressing climate change mitigation (Bellassen et al., 2022; Conant et al., 2011).

This CS mapping methodology presents a practical, cost-efficient tool for landscape managers and regional spatial planners to determine baseline data and monitoring needs of important landscapes, such as these study areas, to promote continued functionality of soil carbon storage to contribute to the effective provisioning of the atmospheric climate regulation ES. Avoiding net carbon emissions through better land use change and management policies, and increased restoration efforts, is a feasible and achievable action in managed landscapes where the data is available (FAO, 2016; Jovanović et al., 2015; von Haaren et al., 2019).

4.2.2. Soil erosion control

InVEST SDR model outputs are reported for both study areas as spatially-explicit assessments of topsoil erosion (potential soil loss, sediment retention and trapping) with and without erosion control measures applied on agricultural LULC; Figure 25 shows the total amounts of topsoil loss (RUSLE total potential soil loss), and Figure 26 shows the sediment retained (avoided erosion by vegetation).

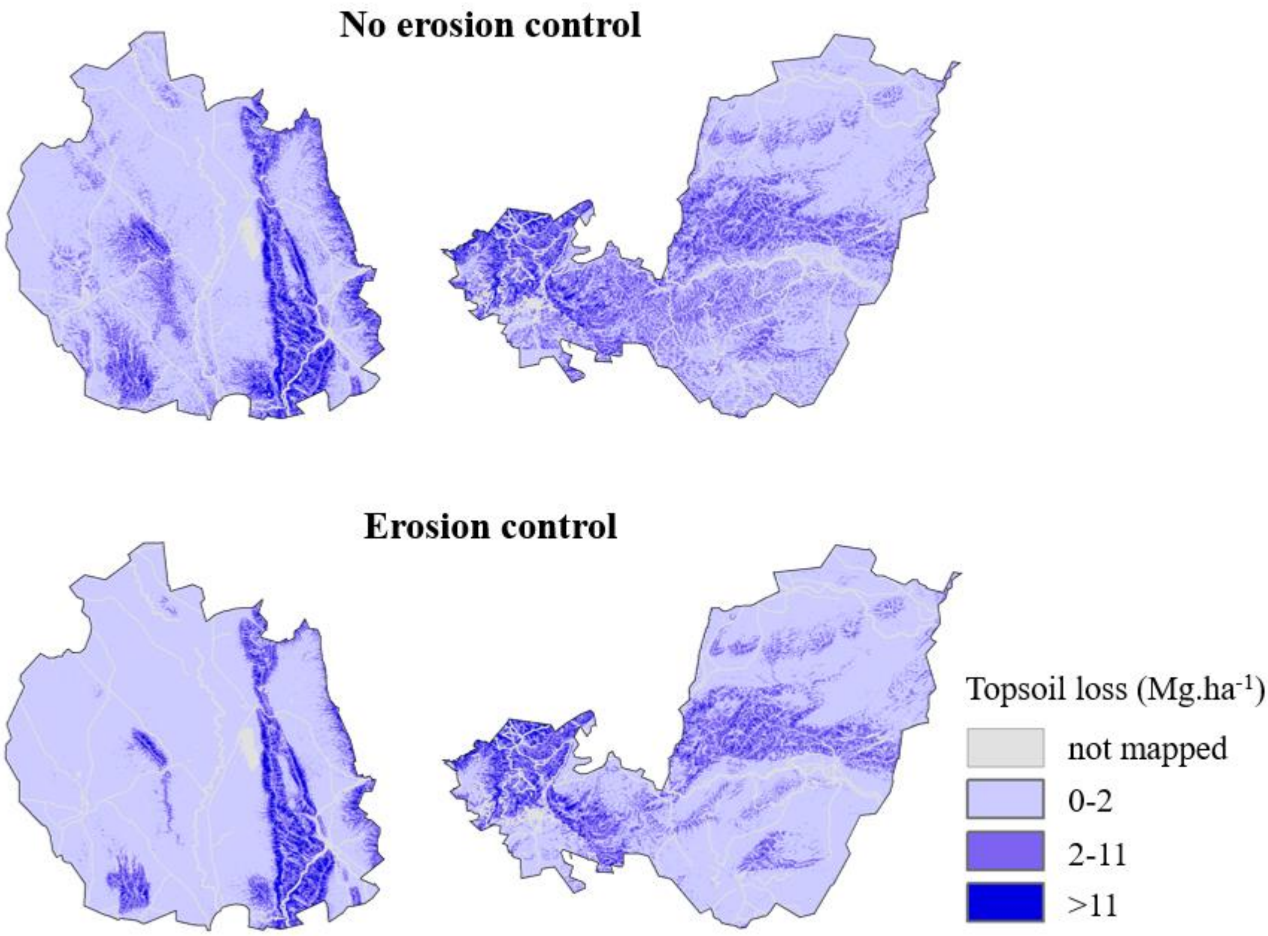


Figure 25. InVEST SDR model output of the total amounts of topsoil loss (Mg·ha^{-1}) annually across the (left) Swartland-Tulbagh-Slanghoek (north) and (right) Helderberg-Grabouw-Breede Valley (south) landscape study areas, under erosion control measures and none, calculated from the (R)USLE equation, excluding sediment retention (1:100,000).

Table 14 details the annual total sum of overall topsoil loss per study area and LULC classes modelled, with and without erosion control measures. Potential soil loss in the Swartland-Tulbagh-Slanghoek (north) study area was 9001 Mg without erosion control and 6072 Mg with erosion control measures, a 38% difference. In the Helderberg-Grabouw-Breede Valley (south) study area, the total potential soil loss was 9470 Mg without erosion control and 7577 Mg with erosion control measures, a 22% difference.

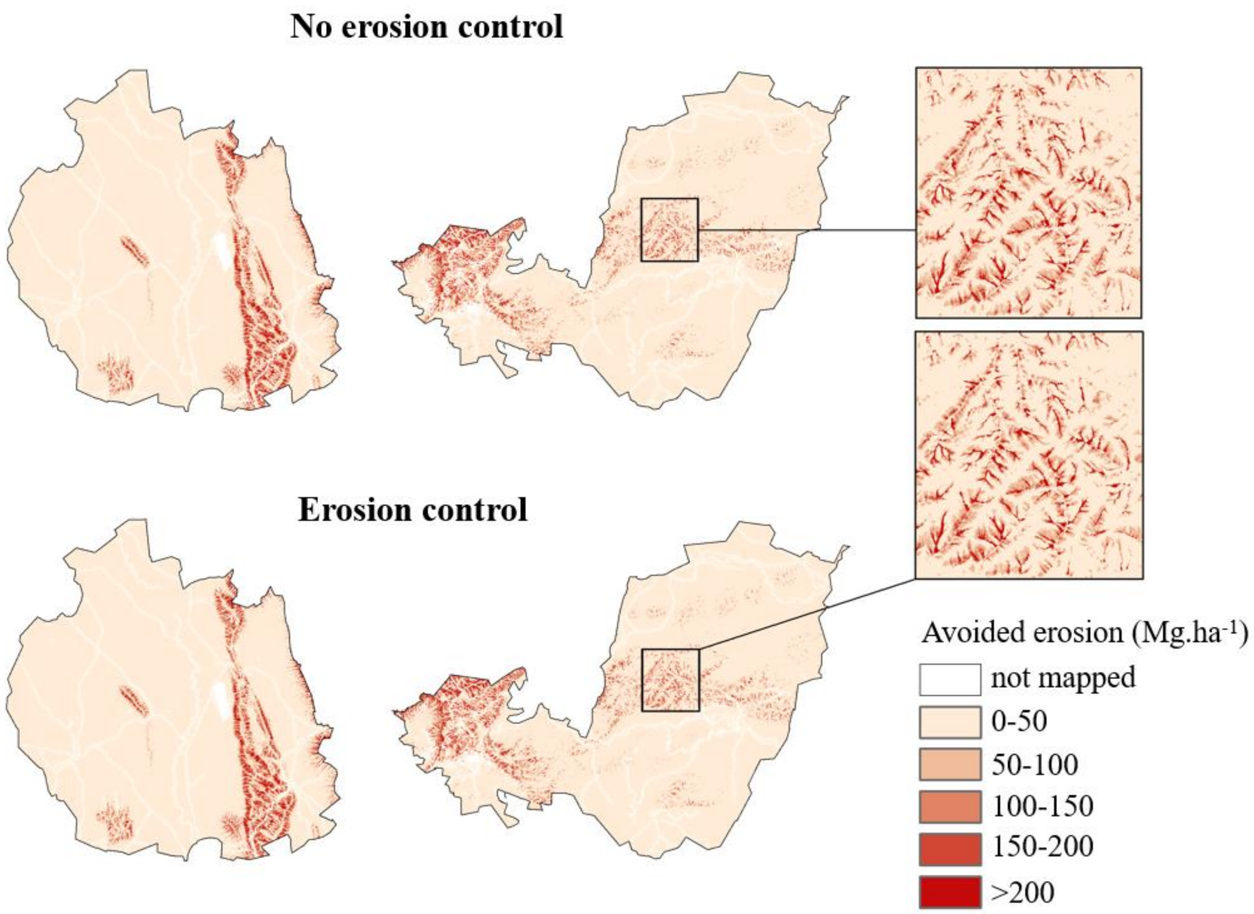


Figure 26. InVEST SDR model output of soil sediment retained annually via avoided erosion by vegetation (Mg·ha^{-1}), under erosion control and none, of the (left) Swartland-Tulbagh-Slanghoek (north) and (right) Helderberg-Grabouw-Breede Valley (south) landscape study areas (1:100,000), with enlarged areas (1:250,000).

Table 14. Total annual potential topsoil loss (Mg·ha^{-1}), excluding sediment retention, in the original land cover across the landscape study areas, calculated from the (R)USLE equation by the InVEST SDR model, under erosion control measures and none.

	No erosion control		**Erosion Control**	
LULC	Mean (Mg·ha^{-1})	Sum (Mg)	Mean (Mg·ha^{-1})	Sum (Mg)
North		*9 001*		*6 072*
Arable cropland	13	2 470	3	501
Bare surface	19	35	16	30
Forested areas	30	252	26	218
Forest plantation	35	150	33	141
Grassland	45	608	42	567
Orchards	25	818	5	151
Shrubland	53	4 667	51	4 464
South		*9 470*		*7 577*
Arable cropland	20	1 587	4	317
Bare surface	24	39	23	37
Forested areas	32	340	30	322
Forest plantation	61	277	61	274

	No erosion control		Erosion Control	
LULC	Mean (Mg·ha^{-1})	Sum (Mg)	Mean (Mg·ha^{-1})	Sum (Mg)
Grassland	25	922	24	904
Orchards	27	589	5	104
Shrubland	37	5 715	36	5 619

Table 15 details the annual potential avoided topsoil erosion, through sediment retained by vegetation (or the contribution of vegetation to keeping soil from eroding), per study area and LULC classes modelled, with and without erosion control measures. Total topsoil retained in the Swartland-Tulbagh-Slanghoek (north) study area was 61,676 Mg without erosion control and 64,604 Mg with erosion control measures, a difference of 5%. In the Helderberg-Grabouw-Breede Valley (south) study area, the total topsoil loss was 78,643 Mg without erosion control and 80,536 Mg with erosion control measures, a difference of 2%. Considering both total topsoil loss and soil retained, soil erosion control measures applied on agricultural LULC potentially reduce overall topsoil loss by 2636 Mg/annum in the north study area and by 1755 Mg/annum in the south study area. The largest reduction can be seen for arable cropland, where yearly soil tilling across vast land cover shows large soil erosion rates.

Table 15. Total annual avoided topsoil erosion (Mg·ha^{-1}) across the landscape study areas, calculated by the InVEST SDR model output of the soil sediment retained (avoided erosion), under erosion control measures and none.

	No erosion control		Erosion Control	
LULC	Mean (Mg·ha^{-1})	Sum (Mg)	Mean (Mg·ha^{-1})	Sum (Mg)
North		*61 676*		*64 604*
Arable cropland	27	4 913	37	6 882
Bare surface	54	102	57	107
Forested areas	545	4 544	549	4 579
Forest plantation	232	984	234	993
Grassland	528	7 207	532	7 249
Orchards	36	1 176	57	1 843
Shrubland	487	42 749	489	42 952
South		*78 643*		*80 536*
Arable cropland	39	3 079	55	4 349
Bare surface	64	105	66	107
Forested areas	734	7 802	735	7 820
Forest plantation	411	1 857	412	1 861
Grassland	316	11 693	316	11 711
Orchards	37	797	59	1 281
Shrubland	343	53 311	343	53 407

Table 16 details the annual avoided topsoil export, through sediment retained and trapped by vegetation (the contribution of vegetation to keeping erosion from entering a stream, combining local and upslope trapping), per study area and LULC classes modelled, with and without erosion control measures. Total avoided topsoil export in the Swartland-Tulbagh-Slanghoek (north) study area was 14,042 Mg without erosion control and 11,733 Mg with erosion control measures, an 18% difference. In the Helderberg-Grabouw-Breede Valley (south) study area, the total potential soil loss was 16,658 Mg without erosion control and 15,197 Mg with erosion control measures, a 9% difference.

Table 16. Total annual avoided topsoil export ($Mg \cdot ha^{-1}$) across the landscape study areas, calculated by the InVEST SDR model output of the soil sediment retained and trapped, under erosion control measures and none.

	No erosion control		**Erosion Control**	
LULC	Mean ($Mg \cdot ha^{-1}$)	Sum (Mg)	Mean ($Mg \cdot ha^{-1}$)	Sum (Mg)
North		*14 042*		*11 733*
Arable cropland	13	2 422	8	1 423
Bare surface	50	94	38	71
Forested areas	146	1 219	120	998
Forest plantation	85	361	79	336
Grassland	86	1 176	80	1 093
Orchards	31	1 013	22	698
Shrubland	88	7 758	81	7 113
South		*16 658*		*15 197*
Arable cropland	17	1 348	10	816
Bare surface	39	63	30	49
Forested areas	178	1 888	170	1 807
Forest plantation	89	403	85	382
Grassland	52	1 944	51	1 889
Orchards	32	683	22	470
Shrubland	66	10 328	63	9 784

Agricultural land, such as cropland and orchards, experience higher rates of soil erosion due to factors such as tillage, removal of vegetation cover, and irrigation practices (Borrelli et al., 2017). Erosion control measures, such as the use of cover crops and minimum tillage, can help reduce soil loss in these areas, as shown by these results (Nasir Ahmad et al., 2020). The fynbos shrubland occurs widely across mountainous areas with steep topography in these study areas, influenced by intense rainfall, low and sparse vegetation cover, and rugged topography, which experiences intense soil erosion (SANBI, 2018). Kiage (2013) argues that, in the rangelands of South Africa, biophysical factors sometimes interact among themselves to yield high soil erosion and degradation rates independent of anthropogenic impacts, such as can be seen in the shrublands of the study areas. The primary challenge lies in distinguishing between soil erosion that occurs naturally due to topographic, biophysical, geomorphic, and climatic factors, and that which is induced by human activities. Understanding of the anthropogenic causes of soil erosion and land degradation in sub-Saharan Africa may be incomplete (Kiage, 2013).

Results show that soil erosion control on agricultural land has a potential benefit of decreasing soil loss between 22 and 38%, and retaining and trapping between 9 to 18% more soil across landscapes per annum. This erosion control on farmland slightly impacted soil erosion control on bordering LULC classes, such as shrubland and grasslands, demonstrating the potential widespread effect of erosion control measures across a mosaic of multiple land use landscapes, particularly in agricultural landscapes within valleys. Implementing soil conservation measures to prevent land from becoming barren and losing topsoil, particularly in mountainous regions, in agricultural landscapes in the WC is an important land use management aspect, as this contributes significantly to soil erosion rates (Bakker et al., 2005; Diop et al., 2022; Lal, 2001).

4.2.3. Crop production

The total extent (ha) and proportion (%) of croplands in the study areas, based on the 2012/13 and 2017/18 crop censuses, are shown in Table 17. The total extent of cultivated area did not change significantly over the 4 years (<1.3%). The cropland extent in the south study area was less than 30%, while cropland extends approximately 60% across the north study area, indicating that the north site has a more extensive agricultural landscape than the south. This has implications for SCS, as previous research has shown that croplands can be a significant source of soil carbon loss due to intensive and extensive land use practices, such as tillage and monoculture cropping.

Table 17. Total planted area (ha) for croplands in the north and south study areas, % area extent in each study area with % change between years, based on the 2012/13 and 2017/18 Crop Censuses (WC DoA, 2014, 2018).

Study Area	**2012/2013**		**2017/2018**		**% Change**
	ha	**%**	**ha**	**%**	
North	186 369	59	188 596	60	0.7
South	85 328	28	88 901	29	1.2

Table 18 shows a summary of crop types of the two crop censuses, with Figure 27 displaying the proportional extent of the most extensive crop types (> 10,000 ha). Grains and oilseeds constitute 37–56% of croplands of the north study area, with an increase of about 6% over these 4 years. The south study area, on the other hand, has less grain and oilseed, making up less than 30% of croplands. The data also indicates that animal feed production, including feed and grazing, occupies 25–35% of the cropland area in both regions. The sharpest decrease in animal feed production is observed in the south study area, where it decreased by 10%. In terms of fruit crop extent, 15–24% of cropland is occupied by fruit crops where both study areas show a decrease (-2.3–3.1%), with the south study area showing the largest extent. Fallow cropland decreased in the north study area (-3.1%) but increased slightly in the south study area (4.7%). Vegetables are minimal in both areas, comprising only about 1%. Flowers, nuts, and herb croplands have the smallest extent in both areas (<1%), indicating low production of these crops.

Table 18. Total planted area (ha) of crop types in the north and south study areas, % of total croplands for each crop within the study area, with % change between years, based on the 2012/13 and 2017/18 Crop Censuses. (-) indicates <1 (WC DoA, 2014, 2018).

Crops	**2012/2013**		2017/2018		% Change
	ha	**%**	**ha**	**%**	
	Swartland-Tulbagh-Slanghoek (north)				
Grains & Oilseeds	93 975	50	105 730	56	5.6
Animal Feed	46 975	25	46 650	25	-
Fruit	32 931	18	27 502	15	-3.1
Fallow	11 928	6	6148	3	-3.1
Vegetables	313	-	1147	1	-
Other	177	-	634	0.3	-
Flowers	64	-	19	0.01	-
Nuts	6	-	101	0.1	-
Herbs	0	0	667	0.4	-
	Helderberg-Grabouw-Breede Valley (south)				
Grains & Oilseeds	31 184	37	38 508	43	6.8
Animal Feed	29 537	35	22 203	25	-9.6
Fruit	20 679	24	19 487	22	-2.3
Fallow	3370	4	7728	9	4.7
Vegetables	408	-	540	1	-
Flowers	138	-	190	-	-
Other	5	-	236	-	-
Nuts	3	-	8	-	-
Herbs	2	-	0	0	-

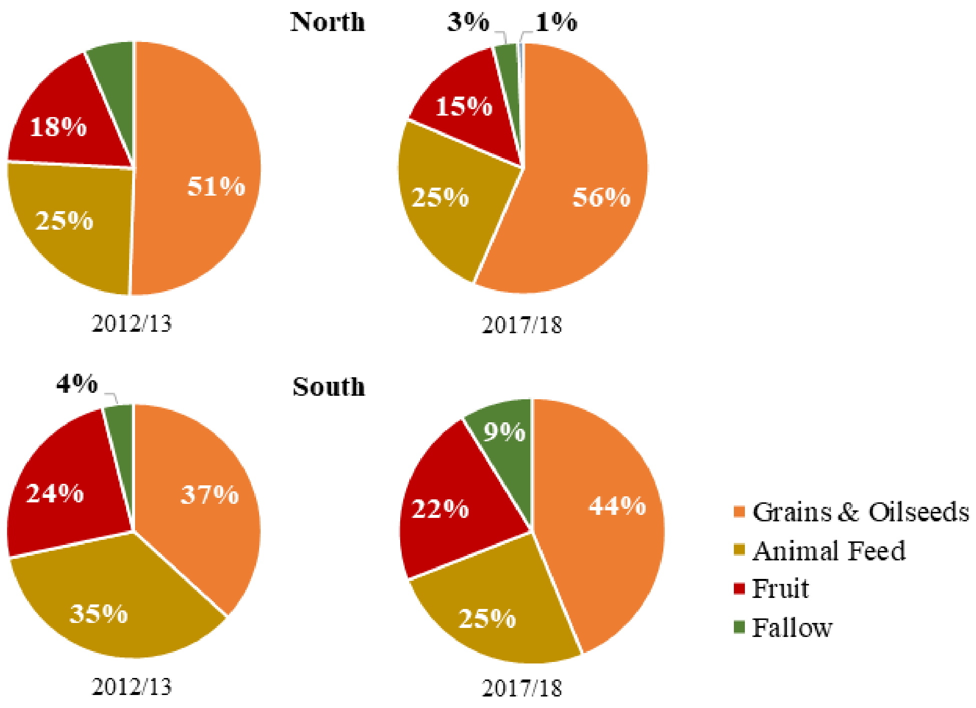


Figure 27. Proportional % of the most extensive cropland types (>10 000 ha) within the Swartland-Tulbagh-Slanghoek (north) and Helderberg-Grabouw-Breede Valley (south) landscape study areas for 2 years, based on the 2012/13 and 2017/18 Crop Censuses (WC DoA, 2014, 2018).

Figure 28 displays the spatial extent of 32 of the InVEST-mapped crops for the north and south study areas, based on the 2012/2013 and 2017/2018 crop censuses. In the north study area, the Swartland area to the west of the mountain range is dominated by grains and oilseed crops, with wheat being the predominant crop. Canola, barley and lupines are also interspersed throughout this area. Grape production is concentrated around the surrounding areas of Malmesbury and Paarl to the west of the mountain, as well as from Tulbagh to Slanghoek east of the mountain. Pear orchards can be observed in the Tulbagh basin, east of the mountain.

In the south study area, grapes are grown in the north part of the study area in the Breede Valley. Fruit crops, including apples and pears, are highly concentrated in the Elgin area, west of the study area. In the plains of the Overberg to the southeast of the study area, wheat, canola, barley, and lupines dominate. These observations provide insight into the crop distribution and concentration patterns in the study areas over the four years.

Based on the InVEST Crop Production model, the total crop yields of 2012/12 and 2017/18 are reported for both study areas (see the full version in Table 29 and Table 30, Appendix 2). In the north study area (Swartland-Tulbagh-Slanghoek) a total of 892,510 Mg crops were produced in 2012/13. Grapes had the highest total yield (389,982 Mg), followed by wheat (261,252 Mg), pears (67,616 Mg), peaches/nectarines (65,539 Mg), and plums (44,326 Mg).

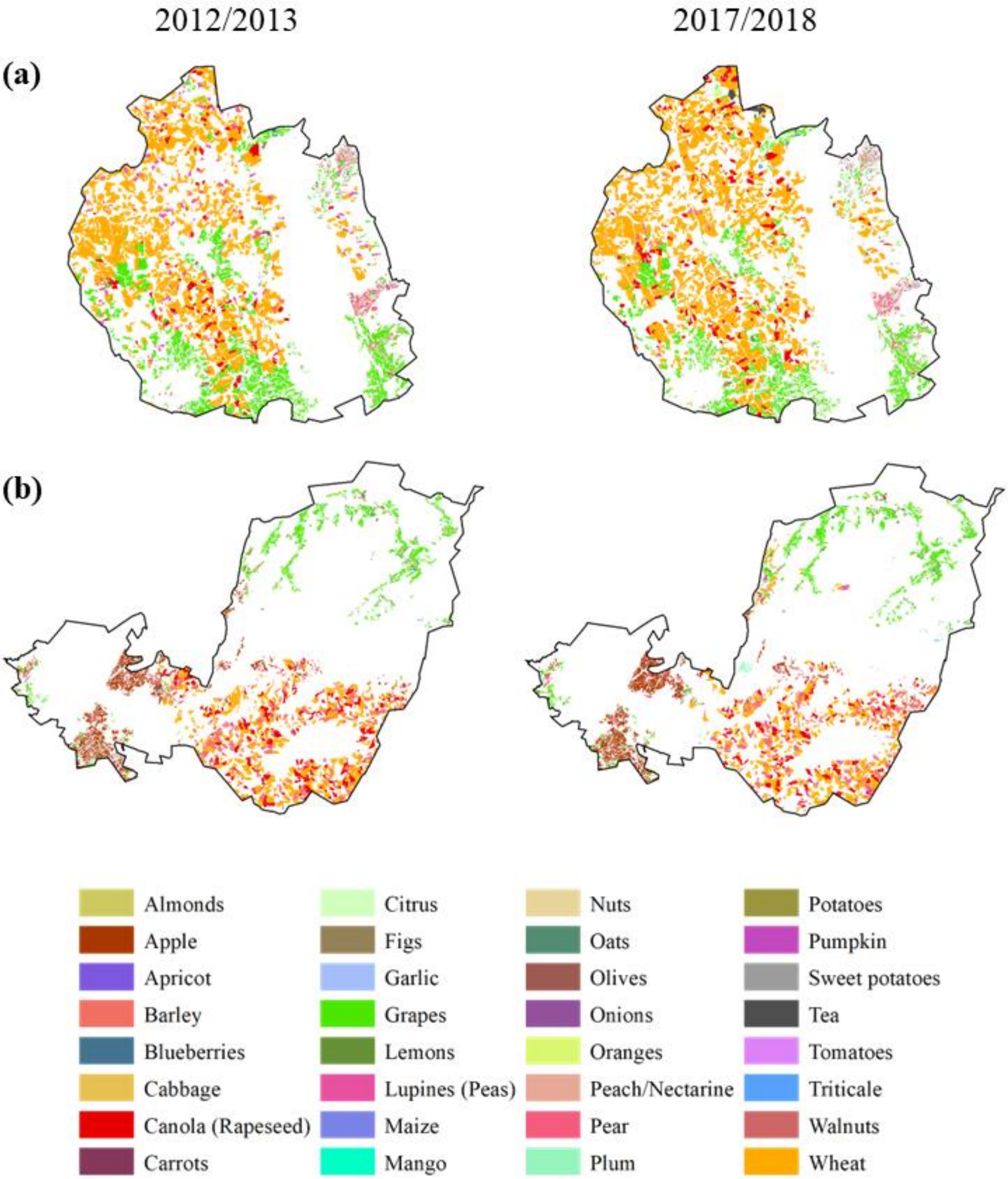


Figure 28. InVEST mapped crops for the (a) Swartland-Tulbagh-Slanghoek (north) and (b) Helderberg-Grabouw-Breede Valley (south) study areas for the winter seasons of 2012/2013 and 2017/2018 (1:1 000 000) (WC DoA, 2014, 2018).

Other crops with significant yields in this area include citrus (15,943 Mg) and canola (10,506 Mg). In the south study area (Helderberg-Grabouw-Breede Valley) a total of 863,747 Mg crops were produced in 2012/13. Apples had the highest total yield (485,978 Mg), followed by grapes

(150,906 Mg), pears (72,894 Mg) and wheat (68,042 Mg). Other crops with significant yields in this area include barley (22,051 Mg), plums (18,202 Mg) and canola (10,869 Mg).

In the north study area (Swartland-Tulbagh-Slanghoek) a total of 866,736 Mg crops were produced in 2017/18. Grapes had the highest total yield (324,325 Mg), followed by wheat (303,342 Mg), pears (63,976 Mg), peaches/nectarines (47,854 Mg), and plums (41,197 Mg). Other crops with significant yields in this area include citrus (28,594 Mg) and canola (18,318 Mg). In the south study area (Helderberg-Grabouw-Breede Valley) a total of 872,730 Mg crops were produced in 2017/18. Apples had the highest total yield (492,028 Mg), followed by grapes (133,754 Mg), pears (77,326 Mg) and wheat (70,745 Mg). Other crops with significant yields in this area include barley (29,182 Mg), peaches/nectarines (22,066 Mg) and canola (14,687 Mg).

Some general similarities include the crops with the highest total yields in both study areas. In the north study area, grapes and wheat consistently had the highest total yields in both 2012/13 and 2017/18. Similarly, in the south study area, apples and grapes consistently had the highest total yields in both years. Generally, study areas had the same pattern of highest-yielding crops between the years.

The top five crops by extent mapped by the InVEST Crop Production model are shown in Figure 29. The crop production overlaid ES maps define the spatial extent and yield intensity by location for wheat, grapes, canola (rapeseed), barley and apples in both study areas.

Table 19 shows detailed information on the yield (Mg) changes per crop in both study areas, between 2012/13 and 2017/18. One notable difference between the two tables is the total crop yield for each study area. In the north study area, the total crop yield decreased from 892,510 Mg in 2012/2013 to 866,736 Mg in 2017/2018, a change of -25,773 Mg. In contrast, in the south study area, the total crop yield increased from 863,747 Mg in 2012/2013 by 8984 Mg, to 872,730 Mg in 2017/2018. In the north study area, grapes' total yield decreased over time (-65,657 Mg). Wheat also had a high total yield in both years (261,252 Mg in 2012/2013 and 303,342 Mg in 2017/2018), with an increase in total yield over time (42,090 Mg). In the south study area, apples had a slight increase in total yield over time (6051 Mg). Grapes' total yield decreased by -17,152 Mg between years. Overall, the crops with high yields showed some changes in total yield between 2012/2013 and 2017/2018, with some crops experiencing slight increases or decreases in total yield.

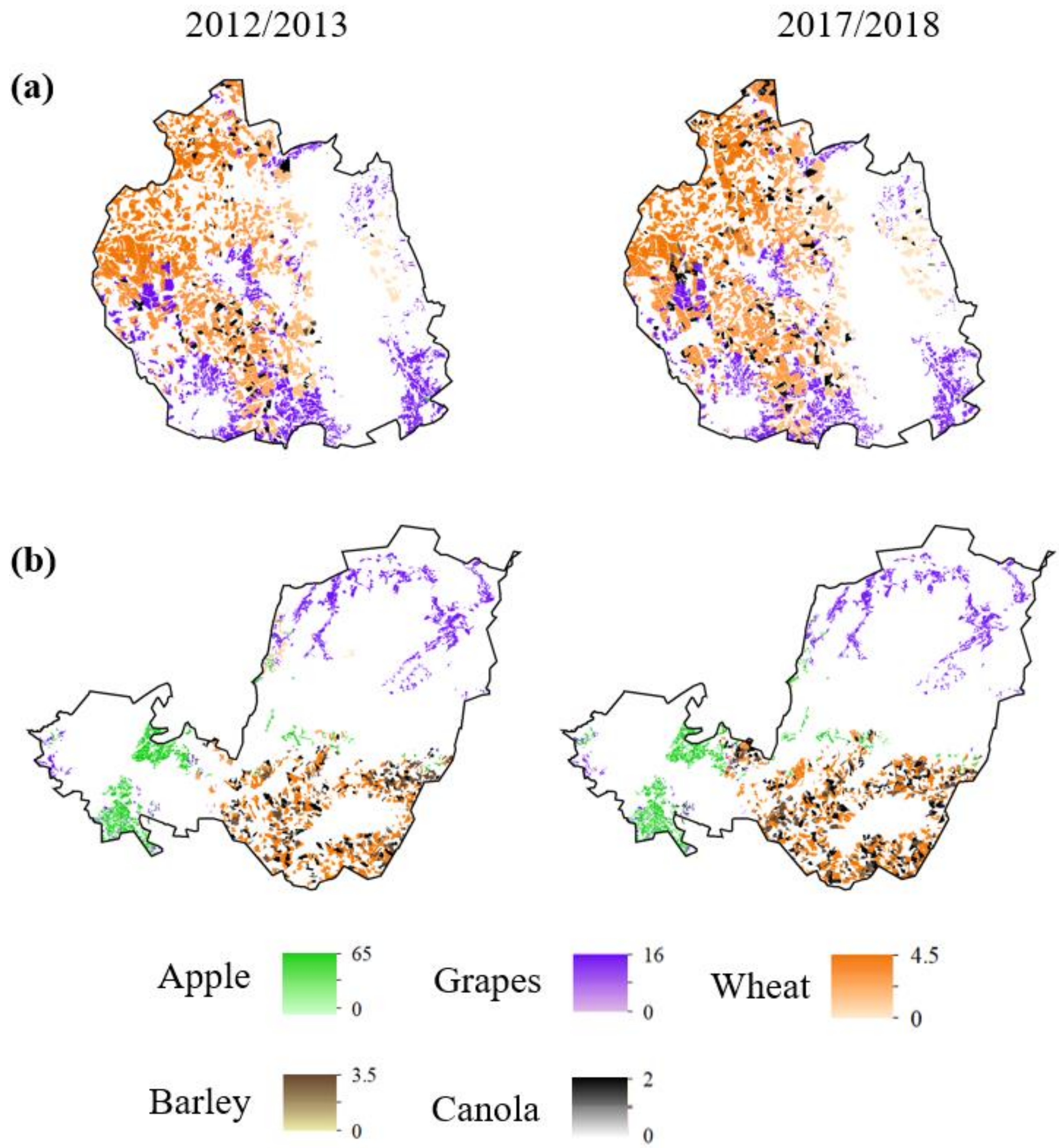


Figure 29. Crop yields (Mg) for the top five crops by extent of the (a) Swartland-Tulbagh-Slanghoek (north) and (b) Helderberg-Grabouw-Breede Valley (south) study areas mapped by the InVEST Crop Production model, based data from the 2012/13 and 2017/18 Crop Censuses.

Table 19. Total crop yield (Mg) of 2012/13 and 2017/18 of the Swartland-Tulbagh-Slanghoek (north) and Helderberg-Grabouw-Breede Valley (south) study areas, mapped by the InVEST Crop Production model, indicating yield (Mg) change for each study area over the 4 years.

	Swartland-Tulbagh-Slanghoek (north)			**Helderberg-Grabouw-Breede Valley (south)**		
	2012/2013	**2017/2018**	**Change**	**2012/2013**	**2017/2018**	**Change**
Total (Mg)	*892 510*	*866 736*	*-25 773*	*863 747*	*872 730*	*8 984*
Almonds	0	134	134	0	1	1
Apple	5 882	4 653	-1 228	485 978	492 028	6 051
Apricot	1 593	718	-875	5 202	5 547	344
Barley	1 106	2 522	1 415	22 051	29 182	7 131
Blueberries	849	820	-29	340	456	115

	Swartland-Tulbagh-Slanghoek (north)			Helderberg-Grabouw-Breede Valley (south)		
	2012/2013	**2017/2018**	**Change**	**2012/2013**	**2017/2018**	**Change**
Cabbage	130	337	207	1 578	1 228	-350
Canola (Rapeseed)	10 506	18 318	7 812	10 869	14 687	3 818
Carrots	2 172	0	-2 172	0	32	32
Citrus	15 943	28 594	12 651	3 197	8 135	4 938
Figs	529	232	-297	10	11	1
Garlic	231	270	39			
Grapes	389 982	324 325	-65 657	150 906	133 754	-17 152
Lemons	2 456	5 763	3 308	254	2 254	2 000
Lupines (Pea)	4 978	282	-4 695	1 959	813	-1 146
Maize	164	0	-164			
Mango	0	3	3			
Nuts	11	24	13	7	12	5
Oats	17	0	-17			
Olives	5 905	5 011	-895	2 098	1 920	-178
Onions	1 380	1 044	-336	1 122	278	-845
Oranges	7 130	12 981	5 851	758	2 098	1 340
Peach/Nectarine	65 539	47 854	-17 685	17 471	22 066	4 595
Pear	67 616	63 976	-3 639	72 894	77 326	4 432
Plum	44 326	41 197	-3 129	18 202	9 229	-8 974
Potatoes	526	0	-526	46	141	95
Pumpkin	2 108	2 355	247	558	89	-469
Sweet potatoes	0	160	160	0	33	33
Tea	0	1 308	1 308			
Tomatoes	80	176	96	203	530	327
Triticale	100	338	238	0	127	127
Walnuts				0	9	9
Wheat	261 252	303 342	42 090	68 042	70 745	2 702

The overall total planted area (ha) of the crops mapped by the InVEST Crop Production model, of the north and south study areas, in 2012/2013 and 2017/2018 is fully reported in Table 31, Appendix 2. The total planted area for both study areas increased from 152,490 hectares in 2012/2013 to 161,089 hectares in 2017/2018, an increase of 8599 hectares (5.48%). In the north study area, the total planted area increased from 102,361 hectares in 2012/2013 to 108,288 hectares in 2017/2018. In the south study area, the total planted area also increased, from 50,129 hectares in 2012/2013 to 52,800 hectares in 2017/2018. The table provides information on the change in planted area for each crop between 2012/2013 and 2017/2018. The largest change was seen in the planted area for wheat, which increased by 10,393 hectares, while the planted area for lupines and grapes decreased the most by -5616 and -5176 hectares, respectively.

The top five crop types by total extent across both study areas were wheat, wine grapes, canola (rapeseed), barley and apple, as presented in Figure 28. The north study area is characterised by extensive wheat fields (>50,000 ha), large areas of grapes (>17,000 ha), and some canola and barley for the winter seasons in 2013 and 2018. The south study area is characterised by a less homogenised crop extent mix, with the top five crops by extent totalling less than 20,000 ha in both years. Total farms and fields change, for both study areas, in 2012/13 and 2017/18, and the change in average field size over the four years are reported in Table 32, Appendix 2.

The commercial agriculture industry in South Africa is characterized by a high level of specialization among grain and fruit farmers, who employ large-scale, high-production farming systems (GreenCape, 2016; Partridge et al., 2022). These farmers use specialised equipment and commercial practices, and have access to crop production consultants to assist with their farming efficiency, to achieve maximum crop yields and good crop quality that will result in maximum profits (Choruma et al., 2019; Von Bormann, 2019).

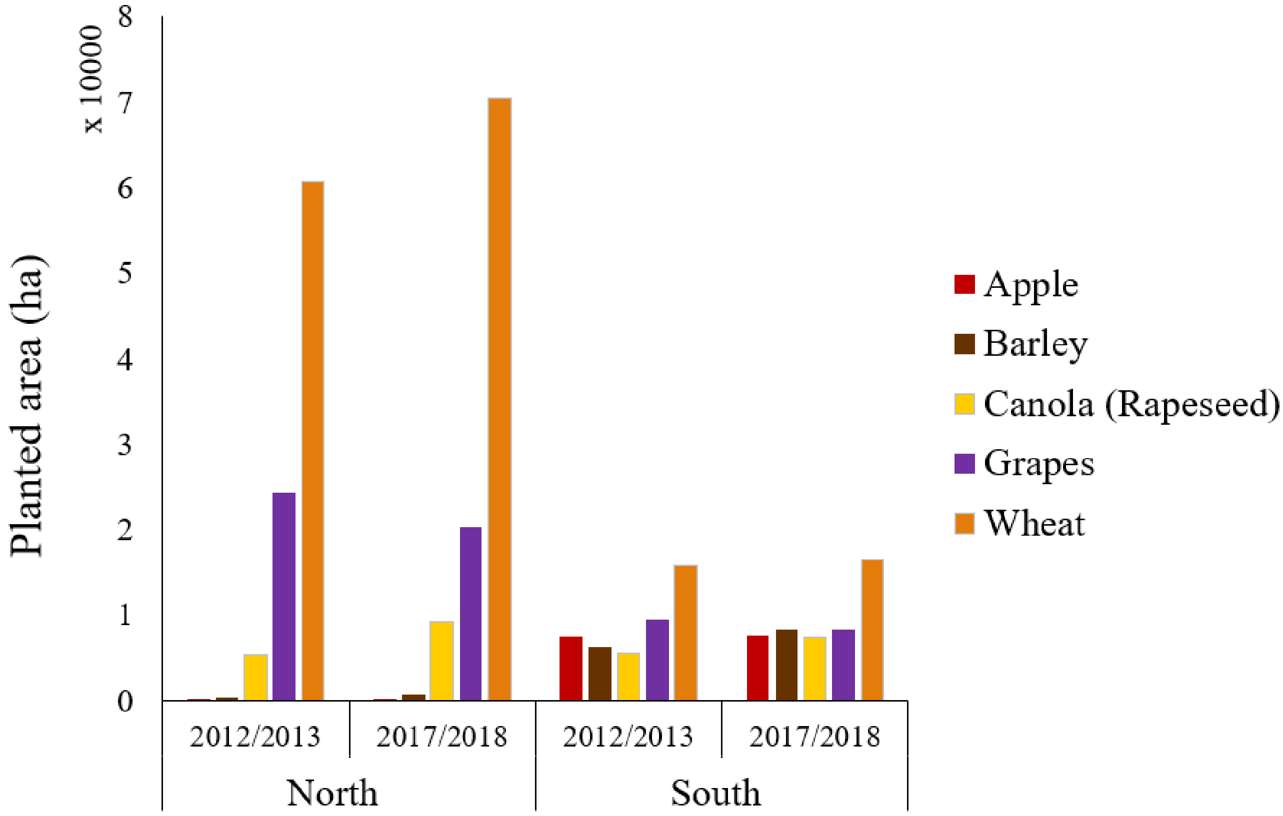


Figure 30. Planted area of the five most extensively grown crops (>1000 ha) in both study areas for the winter seasons of 2012/2013 and 2017/2018 (WC DoA, 2014, 2018).

Additionally, they benefit from well-established training institutions and often come from a farming background, which contributes to their success in the industry (Giliomee, 2006; WWF-SA, 2014). These factors collectively enable WC grain and fruit farmers to achieve high levels of productivity which is seen in the crop yield and cropland extent results.

Wheat and canola (rapeseed) are widespread crops in the Swartland (north) and Overberg (south) plains because they are well-suited to the climate and soil conditions of the WC province. In the WC, wheat farming is commonly practiced using conventional tillage methods, which involves ploughing and harrowing to prepare the soil for planting (Partridge et al., 2022). This method is often associated with soil erosion and degradation, loss of organic matter, and decreased soil fertility over time (Kaleeswari et al., 2013). In recent years, conservation tillage practices have been introduced as part of a broader conservation agriculture initiative, backed by the government and research institutions, which aims to reduce soil disturbance and maintain soil cover by leaving crop residues on the soil surface (Fourie, 2012; Nelson Havlin, 2016).

The sheltered valleys of the WC mountain belts provide ideal conditions for growing fruit such as grapes, apples and pears (du Plessis & Schloms, 2017; WCG, 2014). These crops are produced on a large scale due to favourable growing conditions and strong demand for these crops both domestically and internationally (Giliomee, 2006). Mountain areas in South Africa harbour unique ecosystems with distinct microclimates and fertile soils, often located in valleys surrounded by steep mountain slopes (Ngwenya et al., 2019). These topographical features create a diversity of microclimates and soil conditions, allowing for the growth of high-value crops such as apples, grapes, and pears. The circumscribing mountains can provide protection from harsh winds and excessive sunlight, source fresh water, while the fertile soils and well-drained terrain allow for optimal growing conditions. Mountains are known to provide a range of unique regulating and provisioning ES due to their distinct geological, topographical, and climatic characteristics (Mengist et al., 2020). The fruit-producing areas in the WC often have access to privately-stored fresh water that source from nearby mountains. Such as in the Elgin area, where apples are intensively farmed, the Eikenhof Dam Water Scheme is owned, operated and maintained by the Groenland Irrigation Board, which secures water for agricultural production even in drought conditions (Naudé et al., 2019).

Fruit farming in the WC utilizes integrated soil management practices, which involve soil analysis, nutrient management, and the use of cover crops to improve soil health and fertility (Partridge et al., 2022). Cover crops such as legumes and grasses are grown during fallow periods to improve soil structure, organic matter content, and nutrient availability (Fourie, 2012). Integrated pest management strategies are also commonly used, integrating chemical (synthetic and organic pesticides) and mechanical control (weeding and mulching) of disease and pest pressures (Röösli et al., 2022). Recently, more fruit farmers in the WC are reducing the unnecessary use of synthetic pesticides, and are advised to use chemicals categorised with low environmental hazard, and use natural pest controls, such as biocontrol (release of sterile insects) and natural repellents (using garlic and chili infused sprays) (Venter et al., 2021a).

The changes in crop yields between 2012/2013 and 2017/2018 in both study areas could be due to a variety of factors such as weather conditions, changes in farming practices or market demand for certain crops. Drought events that caused water scarcity could have impacted decision-making around crop planting. Changes in farming practices such as the adoption of new technologies or crop rotation strategies could also have impacted crop planting, particularly for grains, pulses and oilseeds. Market demand for certain crops influences farmers' decisions on which crops to grow and how much to produce. Climatic conditions, such as temperature, precipitation, and sunlight, determine crop growth and yield. The drought conditions of 2017/18 undeniably had an impact on crop yield that is not reflected in these results. An estimated 35% decrease in total agricultural output resulted from the drought event, with a total of -13% specifically seen for exported fruit volumes in 2017 (Pienaar & Boonzaaier, 2018).

Farm and field size changes indicate farm-level changes in crop production. The increase in the number of farms and fields for wheat and canola could be due to the high demand for these crops in the market. The decrease in the number of farms and fields for grapes and apples could be attributed to the decrease in demand for these crops or the difficulties faced by farmers in cultivating these crops, particularly due to drought conditions. However, it could signal a diversification to produce other fruits as there were slight increases for apples, pears, olives and citrus. The decrease in the mean field sizes for wheat and grapes could be attributed to the increasing cost of farming and the need to optimize resources, or this was directly due to the drought conditions at the time. Farmers adjusted their farming practices, to maintain profitability and maximise resource use efficiency, by reducing their farm sizes. The increase in mean field size for barley could be due to the increase in demand for the crop, leading to the cultivation of larger fields.

As a result of the severe water shortages during the drought, farmers were forced to cut back on irrigation, which led to reduced crop yields and livestock production. Some farmers were forced to abandon crops or reduce the size of their herds, resulting in lost income and reduced food availability (Naudé et al., 2019). While some farmers were able to adapt by investing in more drought-resistant crops or technologies, the overall impact of the drought highlights the vulnerability of agricultural systems to climate change and the need for adaptive strategies to ensure sustainable food production in the future (Partridge et al., 2022). Climate change is expected to increase the frequency and severity of extreme weather events, which will have significant implications for crop production (Botai et al., 2017).

These results highlight the complex and multifaceted nature of crop production systems in agricultural landscapes. Crop yields and cropland extent are influenced by a range of factors that interact in complex ways, and it is important to carefully consider these factors when managing sustainable spatial development and planning in these landscapes.

Crop production plays the lead role in securing regional food security in the WC and is intricately linked, directly and indirectly, to the local and national economy of South Africa. In order to ensure sustainable crop production in the future, it is essential to carefully consider the interactions between landscape factors that impact crop yield and cropland extent, as well as the potential impacts of other factors such as land use changes and spatial development policy decisions. This requires a holistic approach that takes into account both the ecological and socio-economic dimensions of crop production systems and seeks to balance the needs of food production and environmental sustainability.

4.3. Agricultural landscape's spatial development trends

Research Question (iii): What are the major spatial development trends in LULC in the agricultural landscape study areas that impact ES provisioning at the landscape-scale?

Total LULC spatial development trends of the Swartland-Tulbagh-Slanghoek (north) and Helderberg-Grabouw-Breede Valley (south) landscape study areas between 1990 and 2018 are detailed in Table 20 and the north and south LULC change maps shown in Figure 31 and Figure 32, respectively. Over the 28 years between 1990 and 2018, 877 km^2 of the north and 1141 km^2 of the south study areas changed LULC.

Table 20. Total land use land cover (LULC) spatial extent changes in the Swartland-Tulbagh-Slanghoek (north) and Helderberg-Grabouw-Breede Valley (south) landscape study areas, between 1990 and 2018 (DEA, 2019a).

	1990		**2018**		**Change**	
LULC	**km²**	**%**	**km²**	**%**	**km²**	**%**
			Swartland-Tulbagh-Slanghoek (north)			
Agro-forestry	49.24	1.6	38.36	1.2	-10.88	-0.3
Arable cropland	1507.57	48.1	1657.59	52.8	150.02	4.8
Bare & eroded	4.78	0.2	39.43	1.3	34.65	1.1
Built-up environments	19.03	0.6	40.67	1.3	21.64	0.7
Bush & shrubland	902.86	28.8	771.76	24.6	-131.10	-4.2
Forested area	16.04	0.5	93.82	3.0	77.77	2.5
Grassland	182.24	5.8	120.30	3.8	-61.94	-2.0
Orchards	342.10	10.9	291.22	9.3	-50.88	-1.6
Waterbodies	28.41	0.9	35.43	1.1	7.02	0.2
Wetlands	85.09	2.7	48.39	1.5	-36.70	-1.2
			Helderberg-Grabouw-Breede Valley (south)			
Agro-forestry	67.83	2.2	40.62	1.3	-27.21	-0.9
Arable cropland	628.67	20.8	709.15	23.5	80.47	2.7
Bare & eroded	13.55	0.4	150.01	5.0	136.46	4.5
Built-up environments	12.45	0.4	28.60	0.9	16.15	0.5
Bush & shrubland	1778.07	58.8	1351.98	44.7	-426.09	-14.1
Forested area	58.21	1.9	151.12	5.0	92.91	3.1
Grassland	152.86	5.1	330.97	10.9	178.11	5.9
Orchards	216.42	7.2	204.67	6.8	-11.75	-0.4

LULC	1990 km²	%	2018 km²	%	Change km²	%
Waterbodies	19.38	0.6	17.55	0.6	-1.83	-0.1
Wetlands	75.52	2.5	39.10	1.3	-36.42	-1.2

In the north study area, the largest increases were seen for arable cropland (150 km^2) and forested areas (78 km^2). The largest decreases were seen for bush and shrubland (131 km^2), grassland (62 km^2) and orchards (51 km^2). In the south study area, the largest increases were seen for grassland (178 km^2), bare and eroded (136 km^2), forested area (93 km^2) and arable cropland (80 km^2). The largest decreases were seen for bush and shrubland (426 km^2) and wetlands (36 km^2).

Figure 31 shows the spatial extent of the transition of various LULC classes between 1990 and 2018 of the north study area; 359 km^2 of bush and shrubland and wetlands to forested area and other natural vegetation cover, 158 km^2 of natural vegetation was converted into arable cropland (130 km^2) and orchards (28 km^2), and 163 km^2 of farmland was converted from arable croplands (118 km^2) and orchards (45 km^2) to natural vegetation, which is possibly used for natural grazing pastures.

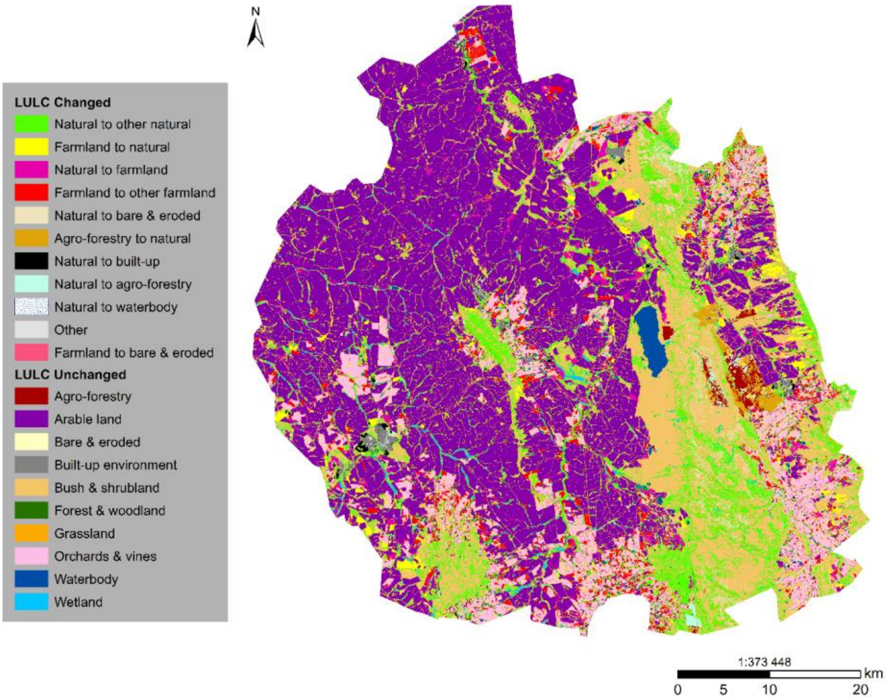


Figure 31. Land use land cover (LULC) spatial extent change map of the Swartland-Tulbagh-Slanghoek (north) landscape study area between 1990 and 2018, indicating changed and unchanged LULC (DEA, 2019a).

Figure 32 shows the spatial extent of the transition of various LULC classes between 1990 and 2018 of the south study area; 710 km^2 of bush and shrubland to grassland, forested area and other natural vegetation cover, 145 km^2 of natural vegetation transformed to become bare and eroded, 98 km^2 of natural vegetation was converted into arable cropland (70 km^2) and orchards (28 km^2), and 83 km^2 of farmland was converted from arable croplands (51 km^2) and orchards (32 km^2) to natural vegetation, which is possibly used for natural grazing pastures.

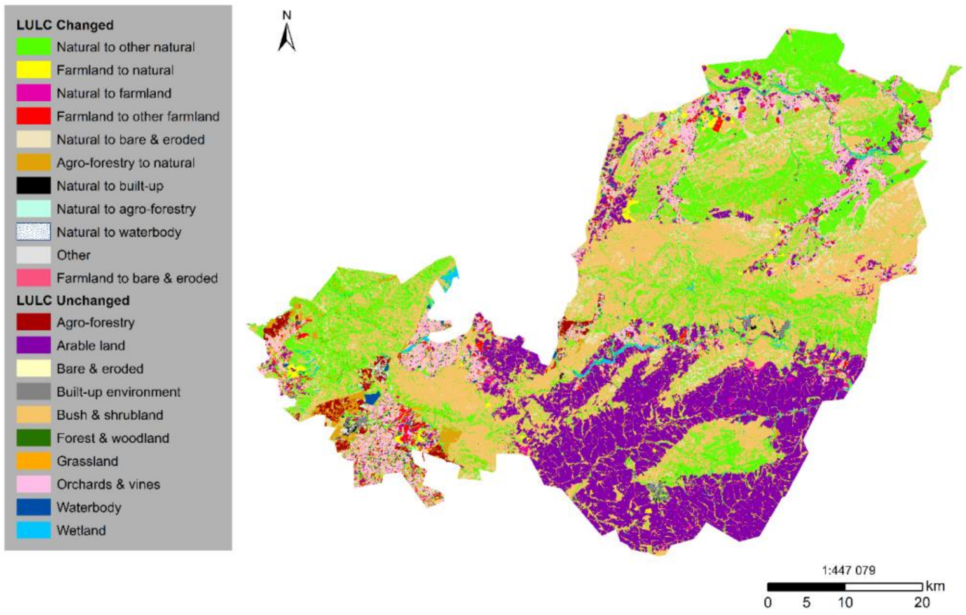


Figure 32. Land use land cover (LULC) spatial extent change map of the Helderberg-Grabouw-Breede Valley (south) landscape study area between 1990 and 2018, indicating changed and unchanged LULC (DEA, 2019a).

Both study areas show a trend of increased farmland, by decreasing natural vegetation, indicating a trend in land conversion for agriculture, with a combined total of 256 km^2. Transformation of natural vegetation cover was seen in both areas, with a combined total of 1069 km^2, were LULC transitioned between bush and shrubland, grassland and forested areas, indicating an ongoing trend of natural vegetation cover which may be linked to climatic changes experienced in both study areas. A trend of increased bare and eroded areas was shown for the south study area, which may be due to soil erosion or the drought conditions of 2018 in the drier climate of the south study area. These spatial LULC trends could impact ES provisioning and regulation throughout both the study areas (Metzger et al., 2006; Reyers et al., 2009; Schulze, 2017).

4.4. Farmers' impacts on ecosystem services on farmland

This section is split into four parts that address interview analyses for each of the four research questions stated for Research Objective 3; (iv) What are the drivers of farmer decision-making that impact ES?, (v) What specific impacts do farmers have on ES?, (vi) What environmentally sustainable farmer actions and agricultural practices support ES?, and (vii) What impacts do influencers have on farmer decision-making that affect ES?

The following summarises the backgrounds and descriptive business information of the 30 commercial farmers from the WC study areas, Swartland-Tulbagh-Slanghoek (study area 1) and Helderberg-Grabouw-Breede Valley (study area 2), that participated in the interviews. The average age of the interviewed farmers was 51, with a median age of 54 and a range of min. 28 to max. 71 years old. Most farmers (22) possessed tertiary education, while 5 had secondary schooling and 3 had attended college. Notably, 16 farmers had specialized agricultural education, demonstrating their expertise in the field. On average, the interviewed farmers had 22 years of farming experience, with a median of 21 and a range of 3 to 42 years. Between all participants, 28 farmers operated commercial agricultural businesses engaged in crop production and/or livestock farming, while 2 specialized in agro-tourism enterprises. Family farms constituted the working environment for 24 interviewees, with the majority managing their own farms. In contrast, 6 interviewees worked on farms that were operated as part of private companies with a board of directors. Of all the farmers, 17 worked on farms that exported crops and products internationally and traded nationally, while the remaining 13 focused on producing for only regional or national markets.

Regarding farming systems, 19 interviewees were engaged in intensive farming practices, 7 in extensive farming systems, and 4 utilized specific farming practices of organic, regenerative, or biodynamic methods. Fruit cultivation exclusively occupied the activities of 10 farmers, encompassing soft and stone fruits, pome fruits, citrus, and other orchard crops such as olives. Additionally, 4 farmers solely concentrated on livestock (cattle, sheep and chickens) farming and grazing pastures. A total of 15 farmers implemented mixed farming, incorporating the cultivation of fruits, vegetables, and livestock. One farmer specialized in the production of ornamental wildflowers. Farmers reported owning or managing land within and outside of the delineated two agricultural landscape study areas. The average size of all the 30 interviewees' farms was 1264 hectares, with a median size of 383 hectares and a range of min. 23 to max. 10,000 ha. Notably, 28 farmers reported having natural areas on their land, averaging 1020 hectares in size, with a median size of 73 hectares and a range of min. 5 to max. 2234 ha. These natural areas served various purposes, including potential grazing grounds for livestock or wildlife. However, this was only applicable to 19 farms, while in two cases, wildlife management was specifically mentioned (as part of wildlife breeding or agro-tourism activities). Furthermore, 12 farmers indicated active soil erosion management practices throughout the year, whereas 18 farmers reported no significant issues requiring soil erosion management.

4.4.1. Drivers of farmer decision-making

Research Question (iv): What are the drivers of farmer decision-making in the WC that have an impact on ES in the agricultural landscape study areas?

In the context of the landscape study areas in the WC, farmers consistently emphasized three broad categories of drivers that significantly influence their decision-making: economic factors, risk and uncertainty, and policy and regulations, summarised in Table 21.

Table 21. Summary of drivers that influence farmer decision-making, which were directly or indirectly mentioned during the farmer interviews in the Western Cape.

Categories of Drivers	Description
Economic Factors	• Profitability is the primary consideration, impacting crop/livestock selection, natural resource management, and land use decisions. • Financial obligations, such as loan repayments, influence practices and the ability to invest in conservation. • Market demands and consumer preferences guide the cultivation of specific crops, like grape varieties. • Export opportunities and cost management of production inputs (like pesticides) are significant economic considerations. • Financial viability can lead to intensification for profit maximisation, selling farmland, impacting landscape management and ecosystem services.
Risk and Uncertainty	• Climate variability, including droughts and unpredictable rainfall, affects water availability and crop viability. • Farmers adapt to environmental risks by selecting drought-resistant crops, improving irrigation, and soil conservation. • Wildfires and their effects on farmland necessitate emergency preparedness and impact infrastructure maintenance. • Market price volatility prompts strategies for financial risk management, such as farming intensification and production diversification. • Agro-tourism and value-added activities are responses to economic and climatic uncertainties.
Policy and Regulations	• Lack of government financial support for sustainability and conservation shapes decision-making. • Local government initiatives against invasive plant species offer support through labour and seedlings for replanting. • Environmental regulations on water use, quality, and land use require compliance to avoid legal and financial liabilities. • Third-party certifications enforce environmental standards and influence market access. • Personal values and a commitment to sustainability drive compliance beyond formal regulations.

Economic factors hold substantial sway over farmers' decision-making processes in the WC. Given the diverse agricultural landscape, most farmers explained that they prioritize profitability above all other considerations. This comes into consideration when selecting the commodities (crops/livestock) they produce, managing natural resources like soil and water, and land conversion through agricultural expansion. Many farmers speak of the financial pressures of repaying loans on their farmland or agri-business. A farmer explained, *"We are not in the financial position to let our fields go fallow for a year. Everything has to be put to work."* (farmer_12, study area 1) When speaking about nature conservation vs. degrative agricultural practices another farmer shared, *"It's a tough one because we owe the bank a ton of money. And we have to make money every year. The previous 3 years, the drought was horrific. Our yields were maybe a fifth of what they should have been… that has a knock-on effect and you can't do the projects you want to do. You have to go back to the bank and get yourself further in debt. One bad year can actually put you back 3 years in terms of what you want to do."* (farmer_28, study area 2)

Farmers said that they carefully consider market demand and prices, aiming to maximize financial returns. With the province being known for its wine production, farmers said they often weigh the economic viability of cultivating different grape varieties (cultivars), taking into account market trends and consumer preferences. Additionally, agricultural enterprises in the region are highly influenced by food export opportunities, further emphasizing the significance of economic factors in decision-making. This is evident in the explanations of how farmers have changed the crops or livestock that they farm for greater financial gain, either because of new market opportunities or that it decreases management or input costs. One farmer explained, *"Many of the decisions are driven by the current economy, choices of pesticides used has moved away from harder broad spectrum to a softer precision spray due to the high cost of broad-spectrum sprays. Managing your cost of production is a big economic driver on the choices made on the farm."* (farmer_13, study area 1) Another farmer shared, *"…Water is becoming a challenge… to manage our soil sustainably, if we farm how we had farmed from 1980 up to 2005, there would be 40 years left for agriculture, then the soil is gone, it would be nothing anymore… From the late 1970s since then it was the chemicals boom in agriculture, so they went in with hard chemicals which was great at the time but then the biological systems started deteriorating, and the more it broke down the more fertiliser was used to get the same results. Now we know that if you are not going to address your biological system and take care of it then the chemical corrections won't mean anything."* (farmer_22, study area 2)

In some areas, some farmers sold their farmland as they are not profitable, which had an unintended impact on the environment, *"Recently in the past 30 years, family farms that have been here for 100 years have been bought out due to economic factors, sold to larger businesses and enterprises. And these guys only come in for one reason, to make money. And all of them, because they have other issues outside this place, they will extract and use up the resources and just move on."* (farmer_26, study area 2)

Risk and uncertainty pose significant challenges for farmers in the WC. Climate and natural resources' variability, including prolonged droughts and unpredictable rainfall patterns, is a prevailing concern among all farmers as it directly impacts water availability and growing conditions. Farmers explained that they try to make informed choices to mitigate the impacts of climate risks and adapt to changing conditions. This has involved selecting drought-tolerant crop varieties, implementing efficient irrigation systems (changing from overhead spraying to drip irrigation, and irrigating at night for lower evapotranspiration), and adopting conservation practices (less topsoil tilling, planting cover crops and mulching) that enhance water availability and management. Water availability is a crucial factor that shapes decision-making, particularly in relation to irrigation practices, crop selection, and water management strategies. Furthermore, natural wildfire occurrence threatens farmland properties and mandates the need for fire breaks and community cooperation during an emergency. One farmer explained an unexpected impact due to fires, *"Negative impacts of being so close to nature is the risk of wildfires. After wildfires in the mountains the amount of silt coming off the mountains during rains and blocking our irrigation piping is very costly, it clogs everything."* (farmer_21, study area 2) Another farmer that lives next to a nature reserve said*, "In the climate we are in and with the [wild]fires] we are experiencing lately, we have to try and manage the beauty, nature and fire here."* (farmer_4, study area 1)

The unpredictability of market prices also contributes to the overall risk landscape. Farmers said that they are cautious of price fluctuations and employ strategies to manage financial risks, such as diversifying their production and value offering, expanding production or exploring alternative markets. This may also contribute to the degree in which farmers engage with outsiders on conservation initiatives. One farmer shared, "*I think the nature is important, but I must balance the financial component with the nature one."* (farmer_14, study area 1) Another farmer said, *"Farms have gotten bigger, with farmers buying up smaller farms in the past 30 years. It gets more difficult with time to stay financially viable. As a farmer, you have to expand to make it."* (farmer_3, study area 1) This would explain the increased focus on agro-tourism in many agricultural landscapes, particularly those that present taste offerings of their products. A farmer explains, *"Maybe in the last 10 years, things have changed dramatically in the wine scene… We had wonderful cultivars, we had wonderful winemakers and it brought with it a lot of tourism. People want to come and see… And there's a lot of accommodation, Bed and Breakfasts, little eatery places, stuff that are starting to pop up."* (farmer_10, study area 1)

Policy and regulations play a pivotal role in shaping farmers' decision-making processes in the WC. Farmers explained that they don't generally receive governmental financial support and subsidies to promote environmental sustainability, biodiversity conservation, and land stewardship. Though, local government initiatives aim to decrease invasive alien plant infestations on farmland, and often provide labour, when available, and indigenous plant seedlings for farmers to replant. Compliance with environmental regulations, such as those related to water use and quality or land use, is also a significant consideration for farmers. They acknowledge the importance of adhering to these policies and regulations as they face legal and financial liability if found non-compliant.

Furthermore, many farmers pointed out that much of their environmental compliance (in sustainable resource use, environmental safety, and sometimes environmental conservation) is mandated by third-party certification bodies, such as the international-level Global Good Agricultural Practices (GlobalGAP) and national-level Integrated Production of Wine (IPW, for wine producers). They prioritize adopting sustainable farming practices and ensuring the conservation of natural resources to meet the stringent standards set by these certification bodies, which is checked yearly through in-person audits of farms. Compliance with environmental regulations and guidelines is mandatory to gain access to lucrative markets and maintain long-term relationships with international buyers. However, not all farmers mentioned direct involvement with third-party certification bodies. Some farmers emphasized that their environmental compliance is driven more by personal values and the desire to protect the ecosystem. They expressed a genuine commitment to sustainable farming practices and conserving the environment.

Additionally, several other drivers were discerned through the interviews, which were indirectly mentioned, namely, quantity and quality of available land, access to credit, resources, technological advancements (such as precision farming), peer networks and community interactions, level of education and training in agriculture, cultural traditions and heritage, social norms and family dynamics. The availability of land significantly influences farmers' decision-making, determining the scope and nature of agricultural activities they can engage in. The quantity and quality of land directly impact the choices made by farmers and the scale at which they operate. One farmer said that he couldn't implement soil conservation methods, *"We have very rocky soil, but the typical minimum till equipment didn't work so well here."* (farmer_20, study area 2)

Overall, the economic factors, risk and uncertainty, and policy and regulations identified by farmers underscore the intricate web of drivers and pressures on their decision-making. Balancing economic viability and managing risks associated with economic and environmental variability are critical factors that shape agricultural practices in these study landscapes. Along with the other confounding influences mentioned that shape farmer decision-making. Understanding how these drivers shape farmers' choices, both singularly and interactively, is crucial for addressing challenges and promoting ES-supporting actions on commercial farms in the WC.

4.4.2. Impacts of farmers

Research Question (v): What specific impacts do farmers have on ES on their farms?

Table 22 summarises the impacts farmers have on ES provisioning and functioning on their farms that were directly or indirectly mentioned during farmer interviews. It is important to note that the impacts' intensity varies depending on factors such as geographical location, farming practices, and the surrounding ecological context.

Table 22. Summary of themes, farmer actions and impacts, and potential degrading or damaging impacts on ecosystem services (ES) on farms, based on the Western Cape farmer interview responses.

Themes	Farmer Actions and Impacts	Potential degradations and damaging ES impacts
Land Use Changes	Land conversion, denaturalisation and cultivation	• Conversion of natural areas to farmland decreases biodiversity, disrupts habitats, and alters ecosystem's ability to provide ES like soil erosion control, pollination and natural pest control. • Agricultural expansion impacts soil health, reducing its capacity for water filtration and nutrient cycling.
Water Management	Water management practices; Water pollution and mismanagement	• Efficient irrigation practices, while conserving water, can alter the hydrological cycle, potentially affecting groundwater recharge and surface water flows. • Practices leading to chemical runoff and sediment discharge impact water quality, ecosystem health and reduces availability of clean water.
Farm Expansion	Farm and infrastructure expansion	• Infrastructure development on farms leads to habitat fragmentation, which can disrupt wildlife corridors and decrease the overall resilience of ecosystems. • Expanding farm areas often involves altering land cover, which can reduce the potential for soil carbon storage and sequestration.
Cultural Impacts	Loss of cultural sustainability and social cohesion	• Shifts towards larger, commercial farming structures can weaken community ties and reduce the collective engagement in environmental stewardship and community-based ecosystem management.
Pollution	Pollution; Chemical use	• Use of chemicals and wastewater discharge leads to pollution affecting water quality, nutrient cycles, and aquatic health. • Pollution undermines the capacity of ecosystems to provide clean water and contributes to the degradation of ecosystem resilience.
Soil Health	Soil degradation	• Soil degradation from overuse and poor management practices reduces soil fertility and structure, compromising agricultural productivity and the soil's ability to store carbon and support biodiversity. • Erosion and compaction diminish the soil's water retention and filtration capabilities, exacerbating runoff and sedimentation issues.

Themes	Farmer Actions and Impacts	Potential degradations and damaging ES impacts
Biodiversity	Biodiversity loss	• Loss of natural habitat diminishes local flora and fauna, impacting ecosystem resilience and the provision of services like pollination and natural pest control. • Disrupting natural habitats can lead to a decline in species that contribute to ecosystem functioning and productivity and an increase in invasive alien species.
Climate Change	Greenhouse gas emissions	• Agricultural practices, particularly those reliant on fossil fuels and intensive livestock production, contribute significantly to greenhouse gas emissions, affecting global climate regulation services. • Altering land use patterns without considering carbon sequestration can reduce the ecosystem's ability to contribute to mitigating climate change.
Waste Management	Waste mismanagement	• Inadequate waste management on farms can lead to the accumulation of pollutants, impacting soil health and water quality, and affecting the broader ecosystem's ability to provide ES.
Agricultural Practices	Lack of sustainable practices; Intensive farming	• Disregarding sustainable techniques and best practices for short-term gains undermines long-term environmental sustainability. • Intensive farming practices often compromise the ecosystem’s ability to provide services, such as soil formation and nutrient cycling.
Wildlife Interactions	Impact on wildlife	• Fencing and other protective measures can reduce biodiversity and affect services related to wildlife conservation, seed dispersal and pest control.

Farmers acknowledged an expansion of agricultural land encroaching upon natural areas. The conversion of natural land into farmland was seen as a notable change in both landscapes. Some farmers expressed their concern regarding the transformation of environmentally-sensitive natural areas into cultivated farmland. They emphasized the importance of conserving the remaining pockets of sensitive vegetation, recognizing their ecological significance and the need for their protection. Some farmers are actively engaged in conservation efforts to safeguard these remaining natural areas. A farmer shared, *"If you look around this area, the natural strandvelde have all been cultivated, little natural areas of this sensitive vegetation type are left... Myself and the farmers around me conserve these pockets because we know that they are special and should be protected."* (farmer_27, study area 2) Another farmer said, *"Things that have changed over the years is that the farms are utilizing more of their open land. All the bare ground that there was, has now been cultivated and planted.”* (farmer_5, study area 1)

Farmers have witnessed the expansion of farms and the consolidation of agricultural lands through the acquisition of neighbouring properties. They expressed mixed sentiments regarding this. One farmer said, *"More farming expansion. And the other thing is buying out neighbours and the farms getting bigger... Denuding the platteland of the farmers. Which is quite an important sustainability issue. Like a cultural sustainability, an emotional thing, where you have a sustainable town and* *people working together, and now when farms get bigger and bigger you get more of a commercial input like in the cities."* (farmer_25, study area 2)

The expansion of farms and associated infrastructure development has had multifaceted impacts on ES provisioning and functioning. While larger farms and improved infrastructure may enhance agricultural productivity, they often come at the expense of natural areas and ecological connectivity. The encroachment of farming activities and the construction of roads and buildings fragment habitats, limit species movement, and disrupt ecosystem processes (Elmqvist et al., 2011; Power, 2010). Additionally, the shift towards larger commercial entities and the subsequent decline in social cohesion within farming communities pose challenges for maintaining cultural sustainability and community-based management approaches. These results underscore the importance of adopting landscape-scale planning and management strategies that consider ecological connectivity, protect natural areas, and promote social and cultural values.

The increase in agricultural land is seen by farmers as a reflection of changing farming practices and the need to adapt to economic pressures. There is also a growing awareness of the importance of conserving and protecting the remaining natural pockets. The conversion of natural areas into farmland raises concerns about the potential loss of ecological diversity and the alteration of ecosystem functioning. The conversion of open land into cultivated fields has led to increased agricultural productivity but has resulted in the loss of natural areas and reduced biodiversity. This land use change has significantly altered the habitat availability and composition, potentially disrupting key ecological processes and functions. The findings highlight the trade-off between agricultural expansion and the conservation of natural areas as a prominent factor for supporting ES in these agricultural landscapes.

Farmers acknowledge certain practices that unintentionally degrade or damage ES. Habitat degradation and fragmentation emerge as a concern, with instances of wetland and riparian zone encroachment and inadequate land use planning reported. Farmers highlight the need for improved land use practices and the preservation of critical habitats to mitigate these impacts.

Pollution and waste mismanagement are identified as factors negatively affecting ES. Inadequate waste management practices and pollution of land and water bodies can lead to the degradation of water quality, soil health, and overall ecosystem functioning. Farmers recognize the importance of responsible waste disposal and pollution prevention measures. A farm manager from a very large commercial farm said, *"We are using fertilizer on a large scale to keep up with production and [produce] quality fruits. [The farm] is also trying to connect with sustainability on the farm. The farm is constantly managing pollution and has its own inhouse department of biodiversity, so in that way it tries to address issues like pollution. The farm is working with two consultants. They* *are helping me to identify and ascertain where we are not adhering to the law, and any damage we are inflicting on the ecosystems on the farm."* (farmer_17, study area 2) Another farmer shared, *"I have to use a sand filter to filter water from the river as it is downstream from [a town] and the wastewater works. Sometimes the water from the river is too polluted to use. I only extract what is needed from the boreholes so that it doesn't run dry when I can't use river water.*" (farmer_11, study area 1)

Furthermore, intensive farming practices are identified as potential drivers of ES decline. Excessive water extraction, overuse of synthetic fertilizers, and the adoption of intensive monoculture practices are mentioned as practices that can have negative consequences.

The farmers' responses shed light on their observations and concerns regarding water issues and their potential impacts on water-related ES. Water management practices have undergone significant transformations in both landscape study areas, with farmers transitioning from flood irrigation to overhead irrigation, to more water-efficient methods such as drip irrigation. This shift has been driven by water scarcity concerns and the need to optimize agricultural water use in the WC. However, the increased demand for water resources, coupled with potential water pollution issues highlighted during interviews, raises concerns about the sustainability of water-related ES. One farmer shared his thoughts, *"Water is scarcer, the use of water and water management has become important as there is less water than usual... Everyone went over to [drip irrigation], this was a big trend in the valley."* (farmer_2, study area 1) The farmers' statements indicate that they recognize the importance of water and its management in maintaining ES. Water scarcity and pollution are acknowledged as significant challenges that can impact water-related ES. The adoption of more efficient irrigation methods demonstrates their response to water scarcity, while their collective efforts (or lack thereof) to address water pollution highlight their growing focus on safeguarding water quality and its associated ES. Their responses suggest that although farmers have adapted their irrigation practices to cope with limited water availability, careful attention must be given to balancing agricultural water needs with the preservation of aquatic ecosystems and water quality.

Overall, the results highlight the complex interactions between farming practices and ES on farms. It is evident that farmers play a significant role in shaping the ecological landscape through land use changes, water management decisions, and farm expansion. Challenges remain, including habitat degradation, pollution, and intensive farming practices, which degrade and damage the provisioning and functioning of various ES important for agriculture.

4.4.3. Ecosystem service supporting actions and agricultural practices

Research Question (vi): What environmentally sustainable practices do farmers implement on their farms that support ES provisioning and functioning?

Farmers recognize the importance of ecosystem functioning on their farms, and throughout the interviews directly or indirectly referred to various 'provisioning' and 'regulating and maintenance' ES. Many farmers are striving to implement practices that support and enhance these services, see Table 23 for a summary. However, there are also instances where their actions have unintentionally led to degradation or damage to ES, shown in Table 22.

In terms of actions that support ES, several consistent themes emerge from the farmers' perspectives. Soil health and conservation practices were frequently mentioned, including the adoption of conservation tillage techniques, the use of organic matter and compost, and the implementation of erosion prevention measures. These actions contribute to improved soil fertility, reduced erosion, and enhanced water infiltration, thereby supporting vital ecosystem functions. One farmer said, *"The farm is not organic, but we are working on a minimum to no till on the cereal field. Recently we are looking at farming more environmentally friendly. At this stage we are using precision farming, we do complete soil analysis every 2 years to minimize the chemical inputs and we make use of probes to manage irrigation. In the past we used to apply chemicals broadly on the fields, but with the information from soil tests, we can now be more specific on soil corrections."* (farmer_22, study area 2) Another shared his practices, *"[I am] managing soil health, was spraying around 5 times a year. The symbiotic relationship continues with the weeds, where I leave the one-year-old annual weeds to feed the microbes that in turn feed the protea [flowers]. This saves on fertilizer, saves on chemicals, and support the soil structure to absorb rainfall better that minimizes the problem with erosion. This method takes time and can only be done by building the soil health and cannot be done overnight. It takes several years to succeed but this is a cheaper way of farming that saves on water and production costs."* (farmer_4, study area 1)

Biodiversity conservation is another prominent theme among the farmers. Many emphasized the preservation of natural habitats within their farms, of which most have full or semi-pristine natural areas of shrubland, grassland, wetlands or riparian zones. Planting indigenous vegetation is a common strategy employed by farmers to enhance biodiversity and provide habitat for beneficial organisms, predominantly pushed by local government initiatives such as LandCare. By nurturing diverse ecosystems, farmers acknowledge the provision of pollination, pest control, and nutrient cycling services. A result to highlight would be that many farmers spoke on their concern of the natural environment, so much so that they have declared allocated sites as nature preserves or conservation areas within which their farming practices are limited to curb environmental impacts. Previously only a few studies have pointed to this cultural identity within farming communities. Active biodiversity and ES conservation has been happening on WC farms for the past few decades (Giliomee, 2006). This is an important consideration in any conservation initiative, and one that WWF-SA has fostered in their sustainable food systems initiatives, such as the Conservation Champion programme (WWF-SA, 2014).

Water management and conservation practices also feature prominently. Farmers emphasize the use of rainwater harvesting techniques, drip irrigation methods, and sustainable water utilization, brought about by drought conditions in 2017/2018. These approaches not only enhance water availability for crops but also reduce water stress on ecosystems, maintaining stream flows and supporting aquatic biodiversity. A farmer said, *"We have been looking at water saving techniques for a long time and implemented night irrigation 15 years ago, probably about 90% of our irrigation was done at night to limit evapotranspiration for a while."* (farmer_14, study area 1) In sharing water, another farmer said, "*We are managing our water as sustainably as possible as we are the first farm that takes water from the river that flows from the mountain, we are conscious about the water we use and take just enough so that those [farmers] downstream also get enough."* (farmer_21, study area 2)

Pest and disease management is a recurring topic, with farmers embracing integrated pest management (IPM) strategies. This involves utilizing natural predators and biological controls while minimizing pesticide use. Crop rotation and diversification are additional practices adopted to manage pest and disease pressures sustainably. A farmer said, *"We spray less herbicides and pesticides which decreases input costs. We have found that the healthier our [orchard] trees are, with natural resistance, we have less insect pest occurrence, it has something to do with the pH of their stomachs and not wanting to eat the leaves. If we get diseases or pests, we have to spray specifically for it. I don't know that in commercial agriculture that we would never have pests. But we have significantly decreased spraying. And now there are a lot more variety of insecticide products that we can choose from, some are more environmentally friendly."* (farmer_8, study area 1) Several farmers noted the valuable function of strong winds blowing through vineyards and orchards in reducing disease pressure, a common natural benefit experienced by farmers in the WC, and yet, it is not currently recognised as an ES within the CICES framework.

One farmer shared his observations on the recent rise of precision farming technology and associated practices in the area, *"There's so much more technology which has come on the market on how to improve your farming. So, we really make use of a lot of precision farming technology. Probes in the soil, we actually use drones to produce more accurate imagery of our orchards.*

When we are spreading fertiliser or something, we measure more accurately with a computer. It has arrived on the farms pretty quickly these past 3 years." (farmer_13, study area 1)

Table 23. Actions and agricultural practices by Western Cape commercial farmers that support and enhance ecosystem service (ES) provisioning and functioning on farms, based on the farmer interview responses.

Themes	**Farmer actions and agricultural practices**	**Ecosystem service (ES) Impacts**
Soil Health and Conservation	Utilizing organic fertilization and proper irrigation cycles; use of compost to enhance soil organisms; implementing carbon storage through cover crops and mulching and minimal tillage; regular soil analyses to track soil health; employing erosion prevention measures, such as no-till and contour planting.	Enhanced soil fertility and structure, increased water retention, and improved soil biodiversity, contributing to carbon storage and sequestration.
Biodiversity Conservation	Removing invasive alien plants; creating microclimates on farms; protecting natural vegetation and replanting; incorporating livestock grazing in rotational systems.	Maintain and enhance habitat diversity, supporting a variety of species and promoting ecological balance. Biodiversity conservation aids in pollination, pest control, and maintains genetic diversity.
Water Management	Efficient water management practices, like drip irrigation and rainwater harvesting; using own dams and reservoirs; erosion prevention measures.	Improved water efficiency reduces stress on local water resources, ensuring sustainable water availability for agriculture and surrounding ecosystems. Erosion control measures help maintain soil structure and water quality by preventing sediment runoff.
Livestock Management	Managing grazing pressure, implementing rotational grazing, and utilizing strategic salt and mineral licks.	Prevents overgrazing, protects soil cover, and supports biodiversity, contributing to the maintenance of ecosystem functions and services.
Chemical Reduction and Organic Practices	Transitioning to integrated pest management and organic inputs; incorporating livestock into pest control; adopting organic and biodynamic practices.	Reduces chemical runoff and pollution, enhancing water and soil quality. Promotes beneficial insects and soil organisms, contributing to natural pest control (increased yields) and nutrient cycling.
Renewable Energy and Carbon Emissions	Transitioning to biodiesel and managing total carbon emissions; using solar power.	Reduces greenhouse gas emissions and the farm's carbon footprint, enabling self-management and awareness for sustainability.

Waste Management	Implementing composting practices and utilizing organic waste.	Converts waste into resources, enhancing soil health and reducing landfill and chemical fertilizer use, contributing to nutrient cycling, soil health and waste regulation services.
Fire Management	Implementing fire breaks and using controlled burns.	Reduces risk of uncontrolled wildfires, protecting ecosystems while maintaining the role of fire in regeneration.

Farmers express the need for a balanced approach that considers the ecological implications of their practices. Precision agricultural practices are being adopted to address this. A farmer shared, *“Every time we replant or plant an orchard, we do a very detailed soil sampling survey, to identify [soil] corrections. Irrigation is developed based on this data and we check whether drainage is needed and how it needs to be inserted. And with that the soil map is used to make fertilizer requirements more accurate. So, if we have different types of soil in a block, then we want to be able to set our fertilizer spreader to adjust the amount for a specific area, so that you don’t need to spread too much fertilizer.”* (farmer_18, study area 2) Another farmer had similar sentiments, *“Our fertiliser programmes are adjusted according to soil sample analyses, it is important to adapt the precision of the fertilization so that you spread it efficiently and not all over the place where it is not necessary. We aren’t really using nitrogen fertilizers anymore and make use of microbial fertigation in our irrigation systems.”* (farmer_8, study area 1)

In conclusion, the perspectives shared by farmers highlight their awareness of the impact of agricultural practices on the natural environment, and by extension on ES. There is a general commitment to implementing practices that support and enhance these services, such as promoting soil health, conserving biodiversity, and practicing sustainable water and pest management. As one farmer shared, "*We need to farm with nature, not against it. And it makes me excited for the benefits that we will get in this generation and also there will be benefits for the next generation also.*" (farmer_11, study area 1)

4.4.4. Impacts of influencers

Research Question (vii): What impacts do influencers have on farmer decision-making that affect ES?

It is evident that farmers’ decision-making on farms is influenced by a variety of factors. Among these, three key influencers emerged as particularly significant in shaping their choices and actions. These influencers include neighbouring farmers, farmer associations and organizations, and consultants and experts.

Neighbouring farmers were consistently mentioned as influential in farmers' decision-making processes. They describe these close relationships and regular interactions with neighbouring farmers as creating opportunities for knowledge exchange, sharing experiences, and learning about local practices and challenges. Their interactions provide valuable insights into practical aspects of farming, with most farmers explaining that they predominantly discuss pest control strategies, weather conditions, and crop management techniques. Some farmers mentioned that they sometimes discuss sustainable practices for resource conservation. The information and advice obtained from neighbouring farmers contribute to informed decision-making on the farm that can impact ES provisioning and functioning. As one farmer shared, *"…My neighbouring farmers, we will meet each other while out working and of course we will have discussions about how it's going and what is and isn't working… We know each other very well. From month-to-month we discuss pest infestations, crop and weather information, frost and those things."* (farmer_1, study area 1)

Farmer associations and organizations were also identified as key influencers. Farmers explained that being members of these associations provides them with access to a network of peers and experts, facilitating knowledge sharing and collaboration. Study groups, research initiatives, and events like farmer days are organized by these associations which offer platforms for discussion and learning. Farmers said that they benefit from the expertise of specialists and fellow farmers, enabling them to make more informed decisions about various aspects of farming. One farmer said, *"Much of the support that we as farmers receive is from regional [and provincial] agricultural associations… They mostly provide information and help with [legal compliance]."* (farmer_6, study area 1) Another shared his experience, *"There is the [local] farmers association with 100 or so farmers that form part of it all from around this area. Sometimes when we have our monthly farmer meetings, we will have some people come as speakers and address our farming challenges or issues or give us information about some practise on the farm that is more environmentally friendly."* (farmer_11, study area 1)

The involvement of consultants and experts, as service providers, emerged as another influential factor in farmers' decision-making processes. Agronomists, soil scientists, horticulturalists, and other experts play a crucial role in providing specialized knowledge and advice to farmers. Farmers explained that, by collaborating with these professionals, it allows them to optimize their farming practices, address specific challenges, and make informed decisions regarding crop selection, soil management, irrigation techniques, and sustainability practices. One farm manager that worked for a large farming company explained their situation, *"I think the most important guys right now are our consultants, such as for pruning practices and techniques, showing us how best to prune our trees for the right balance of sunlight, leaf density, fertile flower heads, and tree health so that* *we're getting a consistently good crop yield year after year. And then we also use a crop protection consultant. Who helps us to protect the harvest, but not against all costs. They look at the specific practices and techniques that are the best way and using the best practises to counter disease and pests. So, we really depend on the protection consultant. And then we have an irrigation consultant that helps us to irrigate effectively and efficiently so that we can optimally manage our water and irrigation, to save water where we can and save on electricity, electric costs by decreasing pumping. These 3 consultants really support us by bringing the best practises to the table."* (farmer_17, study area 2)

Although most farmers would engage experts collectively, *"My neighbours, also farms, they also share information with us about yield and crop protection. We all use the same consultants. We have specialists like soil scientists and horticulturalists to develop the right management practices for us and monitor implementation, and a technical adviser for crop protection. They consult with each other as well."* (farmer_18, study area 2) And other farmers use facilitated knowledge exchange events to gain specialised knowledge, *"…We depend heavily on [the local fruit industry organisation], they have a yearly symposium to listen to experts speak about relevant and interesting topics, with local and international speakers, to exchange information. And then the university we contact frequently, we have a good relationship. Students and professors come speak to us or we approach them."* (farmer_25, study area 2)

Table 24 summarises and details all influencers mentioned in farmer interview responses, including government, conservation and environmental organisations, salespeople and service providers, community and cooperatives, online resources, bank managers, personal networks, farm staff, and other information sharing groups.

Table 24. A summary of the influencers (stakeholders, with details of the information channels), which influence WC farmers' decision-making on farming practices that impact ES on farms, based on the farmer interviews.

Influencers (scale)	**Information Channels**
Government and Policies (national, provincial, regional, municipal)	• Government websites and portals • Government agencies and departments • Publications and reports • Agriculture extension officers
Farmer Associations and Organizations (provincial, regional, local)	• Newsletters and bulletins • Meetings, workshops and conferences • Online platforms and forums

Influencers (scale)	Information Channels
Conservation and Environmental Organisations (regional, local)	• Websites and online resources • Collaboration meetings and workshops • Publications and research papers
Consultants and Experts (regional, local)	• Consultation sessions • Training programs and workshops • Reports and assessments
Neighbouring Farmers (local landscape)	• Farm visits and informal gatherings • Phone calls and messaging • Local community meetings
Salespeople and Service Providers (regional, local community)	• Sales visits and demonstrations • Catalogues and brochures • Trade shows and exhibitions
Community and Cooperative (local community)	• Cooperative meetings • Community events • Cooperative newsletters and communication channels
Online Resources and International Farming Websites (international, national, regional)	• Websites and online platforms • Online forums and social media groups • Webinars and online training programs
Bank Managers and Financial Considerations (national)	• Personal meetings • Phone calls and emails • Banking platforms and portals
Personal Networks (local community)	• Paternal family sources • Personal meetings and farm visits • Phone calls and messaging • Informal gatherings and events
Farm Staff (local community)	• Staff
Information sharing events, i.e., study groups, research initiatives, farmer days (regional, local community)	• Workshops and training sessions • Presentations and panel discussions • Networking and informal interactions

While neighbouring farmers, farmer associations, and consultants were highlighted as the most common influencers, it is important to acknowledge that loan institutions (banks) and government (law and policies) play the most crucial role in farmer decision-making, as outlined in section 4.4.1 on drivers of decision-making.

Overall, these findings suggest that farmers are influenced by a range of actors and factors when it comes to decision-making processes and the provision of ES on farms. By considering these diverse influences, farmers can make well-informed decisions that incorporate scientific knowledge, local expertise, and practical experience, ultimately contributing to sustainable and effective agricultural practices.

4.5. Improving ecosystem services support in agricultural landscapes

Research Question (viii): How are ES integrated into spatial planning processes, and what gaps exist?

The review of the Western Cape Provincial Spatial Development Framework (2014), Cape Winelands District Spatial Development Framework 2021/2026 (2022), West Coast District Spatial Development Framework (2020), and Western Cape Land Use Planning Guidelines for Rural Areas (2019) frameworks reveals a significant misalignment of policies with respect to ES. Table 25 details the review of the integration of ES into the spatial planning frameworks, identifying crucial gaps.

Despite recognizing the importance of certain services like water purification and habitat provision, there is a noticeable absence of detailed methodologies for comprehensive assessment and integration of ES. This oversight extends to a lack of explicit policies or regulations that mandate the incorporation of ES in land use planning decisions and development approvals. The frameworks do not refer to specific tools or models, such as the InVEST mapping tool, that could be instrumental in assessing and visualizing ES, suggesting a systemic unpreparedness in safeguarding the multifaceted spectrum of ES within spatial planning.

Moreover, the spatial planning frameworks exhibit a narrow focus, primarily focussing on areas designated as protected areas, i.e., CBA and ESA, which leads to the exclusion of broader landscapes that are equally crucial for the maintenance of ES. This approach results in the conservation and management of ES being restricted to these limited zones, neglecting agricultural landscapes that also play a pivotal role in providing vital ES. The frameworks analysed do not adequately account for the constraints and vulnerabilities of ecosystem features in agricultural landscapes, indicating a gap that could potentially undermine the effectiveness of ES conservation efforts in these regions.

The outcomes of this research resonate with the observations made by Sitas et al. (2014b), who explored how ES were factored into development planning within South Africa's Eden District Municipality. They identified several hurdles, including the misalignment of policies, but also pinpointed significant prospects for enhancing the planning framework. Notably, they highlighted the potential for incorporating ES into disaster-risk mitigation and the broader spatial planning process, suggesting that a more cohesive approach to development could be facilitated by integrating ES into planning strategies (Sitas et al., 2014b).

Table 25. Review of the integration of ecosystem services (ES) into selected Western Cape spatial planning frameworks, with gaps identified.

	Are ecosystem services (ES) recognised and integrated into spatial planning processes?	**What gaps exist in terms of ecosystem services support in spatial planning?**
Western Cape Provincial Spatial Development Framework (WCG, 2014)	ES are recognized, with only specific mentions of water purification, habitat provisioning, and crop pollination. Water, soil and biodiversity are mentioned as key natural resources to conserve. However, few considerations are given to ES integration, except where it refers to delineating urban growth limits, identified as an important step to protecting critical ecological areas, with special mention of using environmental mapping as a supporting tool. Additionally, Policy R1 commits to protecting ES through the use of Critical Biodiversity Areas (CBA) mapping to inform land use decisions. It advises using the latest CBA mapping to delineate Spatial Planning Categories that reflect appropriate land use activities, integrating ES considerations.	• Explicit Integration of ES: While the value of ES is acknowledged, no descriptions are given to identifying and categorising ES. • Comprehensive ES Mapping and Assessment: Though the CBA mapping is mentioned, these maps do not identify individual ES, and only map specific high-value ecological areas based on unexplained parameters. • Policy and Regulation for ES: While policies for protecting biodiversity and ES are vaguely mentioned, there is little to no indication on how they are to be implemented and under what circumstances, essentially leaving it up to individual spatial panners to decide per development.
Western Cape Land Use Planning Guidelines for Rural Areas (WCG, 2019)	ES are acknowledged indirectly through the emphasis on conservation and biodiversity management within the context of land use planning. The guidelines encourage the management of biodiversity on existing smallholdings within CBA and Ecological Support Areas (ESA), suggesting measures to minimize impacts on biodiversity. Methodologies for integrating ES into spatial planning processes are not detailed, nor does it provide a direct acknowledgment of ecosystem functions within the planning documents. A focus is placed on preserving biodiversity and ecological infrastructure.	• ES are primarily discussed in the context of ESA, with a focus on supporting the functioning of Protected Areas or CBA, indicating a narrow scope of ES consideration. • Where conservation mechanisms are mentioned, it is limited to protected areas, established natural areas through title deeds, and conservation zones which essentially excludes all farmland from consideration of preservation of ES.
Cape Winelands District Spatial Development Framework 2021/2026 (CWDM, 2022)	ES are recognized and integration into spatial planning is advocated. The protection and restoration of CBA and ESA are proposed to maintain ES and protect biodiversity. An outline of how to incorporate ES into urban management is included, mentioning ES prioritisation and ES assessment.	• Conservation and management of ES are limited to only the CBA and ESA which have limited spatial distributions across agricultural landscapes. • Lacks details on methodologies for ES mapping, assessment, and integration into planning processes. • Lacks information on the monitoring and evaluation of ES.
West Coast District Spatial Development Framework (WCDM, 2020)	ES are recognized but integration is not specifically mentioned, except indirectly when referring to environmental management of protected areas, CBA and ESA.	• Conservation and management of ES are limited to only the CBA and ESA which have limited spatial distributions across agricultural landscapes. • Lacks details on methodologies for ES mapping, assessment, and integration into planning processes. • Lacks information on the monitoring and evaluation of ES.

Research Question (ix): How can InVEST ES models be used to improve the current spatial planning and development of agricultural landscapes of the WC?

The InVEST ES models serve as a useful tool for advancing spatial planning and development in the agricultural landscapes of the WC. The application of InVEST models provide a nuanced, evidence-based approach to environmental management, integrating ecological considerations directly into the spatial planning process. This research advocates for the establishment of comprehensive guidelines that delineate how ES assessments can be integrated within various stages of spatial planning and decision-making. By utilizing the InVEST models' outputs in this study, the potential for evidence-based amendments to spatial planning policies is demonstrated, emphasizing support for soil carbon storage, crop production, and soil erosion control.

A policy focal point for agricultural landscapes is the strategic delineation of areas characterized by high levels of ES provisioning (or proxy indicators) of soil carbon storage, crop production, and soil erosion control. Evaluation of the study areas' farms, CBA and ESA sites, soil carbon and avoided erosion maps has produced Figure 33 and Figure 34, which show the spatial distribution of suggested priority areas for consideration of its integration into spatial planning and development frameworks for these landscape study areas. These priority areas show various levels of valuable ES provisioning, such as regions with significant topsoil carbon storage (>50 $Mg \cdot ha^{-1}$) and areas where soil erosion is considerably mitigated (>30 $Mg \cdot ha^{-1}$).

Three priority areas have been discerned through this analysis:

- Priority Areas 1: These are smaller, highly focused regions of high conservation significance due to their substantial soil carbon storage and erosion control benefits (total size: north 57 km^2, south: 143 km^2). Local spatial planning frameworks should incorporate these areas as active management sites for land managers and conservation officers. Development policies must adopt stringent regulations to prevent land use changes that could degrade the ES provided by these high-value sites.
- Priority Areas 2: Encompassing larger extents of medium conservation significance (total size: north 939 km^2, south: 1200 km^2), these areas should be targets for directed conservation efforts by local municipalities and governmental partners. Here, spatial planners should apply nuanced guidelines, tailored to either soil carbon or erosion functions based on local needs, with strict rules on permissible land management practices to support and enhance ES.
- Priority Areas 3: At the landscape level (total size: north 1887 km^2, south: 889 km^2), these areas call for integration into general conservation programs that incentivize ES-supporting

actions and management strategies identified through this study, including insights gained from farmer interviews (see Table 24).

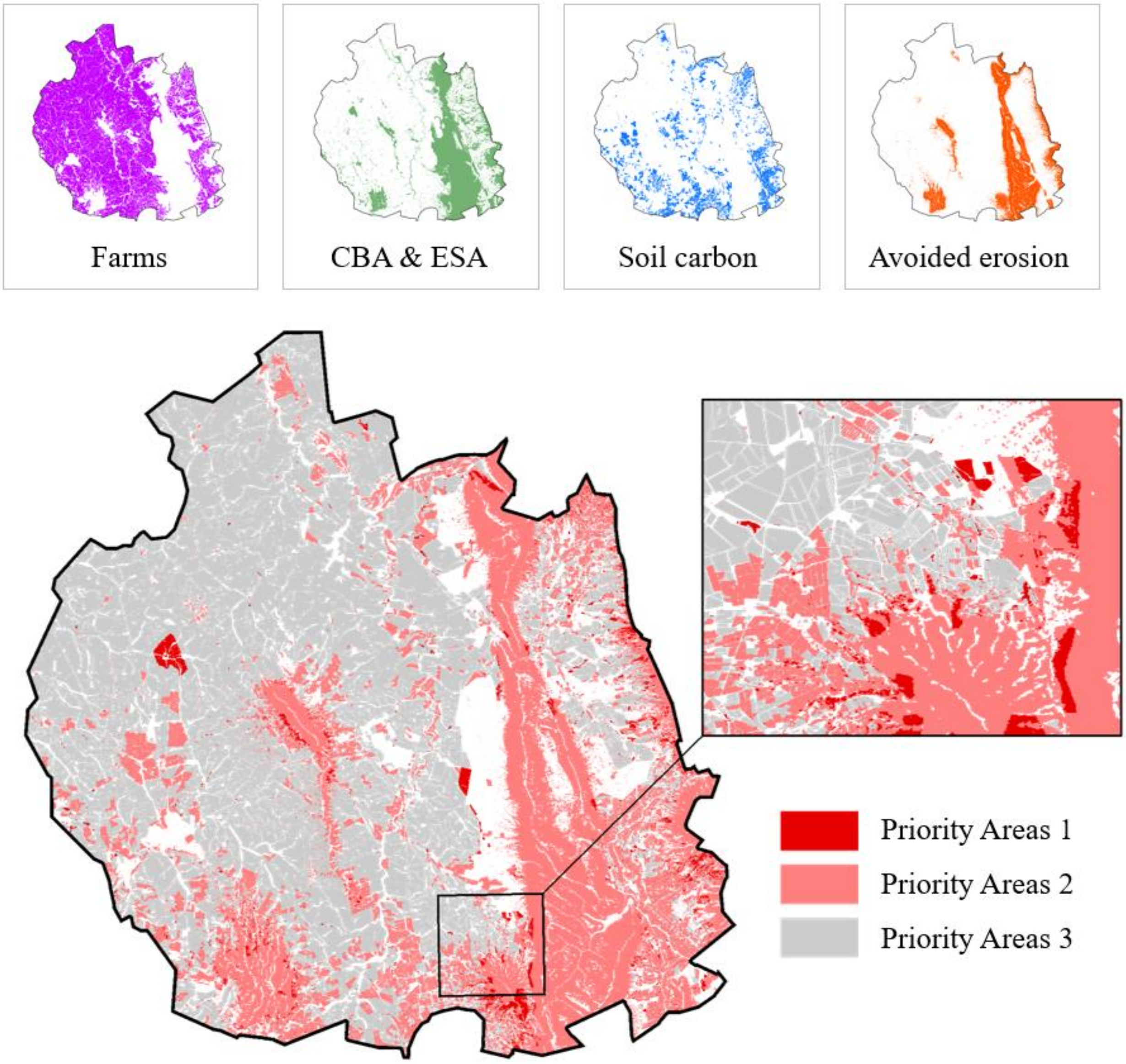


Figure 33. Identified priority areas for spatial planning and development policy considerations in the Swartland-Tulbagh-Slanghoek (north) agricultural landscape study area (1:100,000), based on farms, CBA and ESA sites, soil carbon and avoided erosion maps.

These policy maps offer a tangible representation of how ES like soil carbon, soil erosion control, and crop production can be mapped, assessed, and thus integrated into local spatial planning policies. The InVEST models provide a robust framework for assessing, planning, and monitoring landscapes by integrating social, biophysical, and economic valuation assessments. As outlined by Cowling et al. (2008), strategic objectives and instruments for implementation should be clearly identified within planning frameworks. This structured approach would facilitate the alignment of planning efforts with local ES conservation goals in the WC (Cowling et al., 2008; von Haaren et al., 2019).

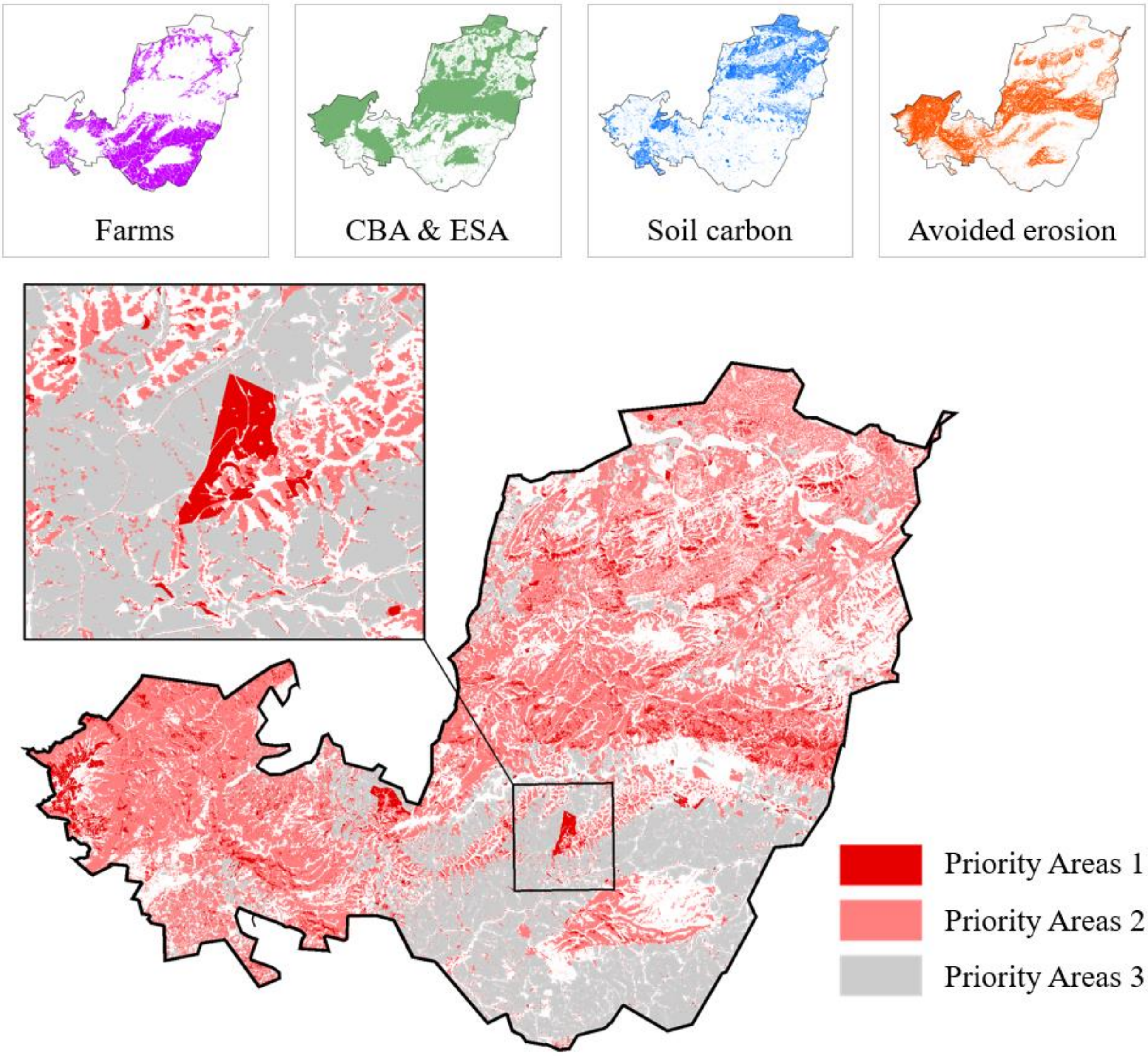


Figure 34. Identified priority areas for spatial planning and development policy considerations in the Helderberg-Grabouw-Breede Valley (south) agricultural landscape study area (1:100,000), based on farms, CBA and ESA sites, InVEST output soil carbon and InVEST output avoided erosion maps.

Integrating ES modelling into municipal spatial planning is critical, as it not only maps the biophysical attributes and distributions of ES but also clarifies their flow towards beneficiaries across different temporal and spatial scales (Kremen, 2005; Longato et al., 2021). Such modelling is key to evaluating how spatial development and changes in land use affect these services across landscapes and time (Egoh et al., 2008; Zulian et al., 2018). Through a strategic approach in spatial planning, municipalities have the opportunity to foster land use practices that not only preserve but also enrich ES, thereby advancing both environmental sustainability and the well-being of the community (Tscharntke et al., 2005; von Haaren et al., 2019). This involves incorporating a deep understanding of the driving factors behind land use changes and their effects into the fabric of planning frameworks, ensuring that development initiatives align with the principles of ES conservation (Lescourret et al., 2015). Moreover, the adoption of regulatory measures aimed at addressing these drivers—such as implementing zoning regulations to curb the overuse of natural resources, offering incentives for adopting sustainable agricultural methods, and imposing limitations on land use alterations detrimental to ES—is essential for maintaining the balance between development and ecological preservation (Petersen et al., 2013; Sitas et al., 2014a, 2014b).

A review study by Longato et al. (2021) revealed that municipalities in various countries, including Finland, Belize, the Bahamas, Australia, Latvia, and Germany, have practiced incorporating ES into their spatial planning. The various applications produced a range of tools to bolster ES-support within landscapes: maps for ES planning, scenario maps forecasting ES supply, and matrices to evaluate ES values and trade-offs. Additionally, they engaged in scenario development and collaborated with communities for conservation efforts, aiming to pinpoint critical areas for protection and to guide sustainable land use management (Longato et al., 2021).

There is still a substantial need for WC municipal planning frameworks to more comprehensively integrate ES. By adopting such integrative tools and approaches—such as the InVEST modelling tool—district municipalities can enhance their land use strategies, ensuring that ES are conserved and optimized in their spatial development plans (Sitas et al., 2014b).

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

This study focussed on the complex evaluation of three ES—global atmospheric climate regulation, soil erosion control, and crop production—within two WC agricultural landscapes, using the InVEST modelling tool. Soil carbon stock, as a proxy for global atmospheric climate regulation, was assessed, revealing that the Swartland-Tulbagh-Slanghoek and Helderberg-Grabouw-Breede Valley agricultural study areas are significant carbon sinks, highlighting their role in regional climate change mitigation efforts. The findings demonstrate that local SCS inventories, which displayed higher values than national datasets, underscore the necessity for integrating localized data to refine CS models to improve their accuracy. In terms of soil erosion control, modelling showed that the spatial distribution of vegetation and application of various mitigation strategies can significantly reduce topsoil erosion in the study areas. The assessment of crop production highlighted the crucial role of agriculture in regional food security as WC grain and fruit farmers achieve high levels of food productivity in these agricultural landscapes. Despite the total cultivated area remaining relatively stable from 2012 to 2018, there are significant regional variations in crop yield between study areas due to crop types and environmental factors. These results demonstrate the use of the InVEST tool in mapping and modeling ES in agricultural landscapes, offering a valuable resource for spatial planners. It shows great potential in integrating evidence-based environmental insights into practical applications, which not only deepens our understanding of these ES but also illustrates how their assessment can contribute to the development of agricultural landscapes that are resilient and multifunctional.

Analysing the recent spatial development trends in LULC within the agricultural landscape study areas provided insights into how land use dynamics are influencing the provisioning of ES. The study highlights significant LULC changes, with notable shifts observed over a 28-year period. In the Swartland-Tulbagh-Slanghoek study area, approximately 28% of the LULC underwent changes, characterized by an expansion of farmland and forested areas, coupled with a reduction in shrubland and grassland. Conversely, the Helderberg-Grabouw-Breede Valley study area experienced a more pronounced transformation, with about 38% of LULC changing, marked by an increase in grassland, bare and eroded land, forested areas, and farmland, while shrubland and wetlands declined. A prominent trend identified in both study areas is the increase in farmland at the expense of natural vegetation, signalling a significant land conversion trend towards agricultural use. The rise in bare and eroded lands raises concerns about potential soil erosion or the impacts of the drought conditions in the drier Helderberg-Grabouw-Breede Valley region.

Such LULC trends are vital as they can substantially affect the provisioning and regulation of ES, impacting the overall functionality of these landscapes.

Examining the influence of farmers on ES within the agricultural landscapes of the WC, based on farmer interviews, this study investigated drivers of decision-making, farmers impacts on ES and influencers. Results reveal the complex interplay between economic, environmental, and regulatory elements that shape the stewardship of farmland and the provisioning of ES. Farmers are found to operate within a framework where economic incentives and market demands significantly affect their choices regarding crop and livestock production, resource management, and land cover transformation for agricultural expansion. These decisions are profoundly impacted by the variability of climate and natural resources, with the unpredictability of weather patterns and resource availability posing significant challenges to agricultural productivity and sustainability in the WC. A nuanced relationship between agricultural practices and ES impacts was identified. Farmers adopt strategies to enhance beneficial services that support agricultural productivity, such as optimizing soil health and water use. Some practices lead to negative consequences, including soil degradation, water mismanagement, pollution, biodiversity reduction, and habitat and ecosystem function loss. The transition from natural landscapes to farmlands is a notable trend, illustrating the significant role farmers play in landscape transformation, which has broad implications for ES provisioning. To mitigate adverse impacts and promote environmental sustainability, farmers are increasingly implementing ES supporting practices. These include sophisticated soil and water management practices, strategic livestock management, reduced chemical usage, and conservation initiatives that aim to preserve biodiversity. Significant knowledge exchange and information dissemination takes place through networks comprising neighboring farmers, agricultural associations, consultants, and research institutions. Results highlight the need for spatial planning frameworks that align with farmers' production realities.

This study also reviewed the current integration of ES into municipal spatial planning and development frameworks in the study areas in the WC, aiming to develop evidence-based policy recommendations that incorporate considerations of ES and socio-ecological land management. Significant policy misalignments and gaps in existing frameworks were identified, particularly in the methodological clarity and explicit policy directives needed for the effective incorporation of ES into localised land use planning and development approvals. There is a need for a broader focus on ES support, extending beyond protected areas, to include agricultural landscapes. These landscapes are identified as essential zones for supporting ES, which are crucial for sustainable food production, economic growth, and ecological resilience. Integration of InVEST model outputs into policy proposals was showcased, and these findings advocate for an urgent revision of spatial planning frameworks for agricultural landscapes in the WC.

In conclusion, this comprehensive evaluation underscores the interdependence of ES, agricultural practices, and spatial planning in shaping the future of the WC's agricultural landscapes. This study contributes significantly to the understanding of ES management in agricultural landscapes in the WC, offering actionable insights for local policymakers, land managers, and the farming community.

5.2. Recommendations

The conclusions drawn from this study provide valuable insights for policymakers, land managers, and farmers in the WC. Based on the study's findings, recommendations are made to help foster multifunctional agricultural landscapes in the WC that not only conserve biodiversity and enhance ES but also ensure sustainable and equitable livelihoods for stakeholders involved in the agricultural sector.

This study emphasizes the importance of acknowledging local variability in CS assessments and adapting soil management strategies to the WC's unique environmental conditions. Utilizing tools like the InVEST modelling suite can facilitate the integration of ES assessments into spatial planning, enhancing the decision-making process to ensure that agricultural landscapes remain productive and ecologically balanced. A core aspect of these recommendations is the integration of ES into spatial planning. Through the adoption of InVEST models, spatial planners in the WC can be equipped with a robust framework for balancing the needs of food production with ES conservation. This approach will ensure the long-term sustainability and resilience of the region's agricultural sector. Moreover, optimizing crop production through informed land use planning, based on the evaluation of various land use scenarios, can lead to a more sustainable alignment between agricultural practices and environmental conservation. The incorporation of localized soil data is highlighted as a crucial factor in refining CS models, which underscores the role of land managers and farmers in climate change mitigation efforts. Encouraging local municipalities to incentivize such practices can amplify their impact.

Results emphasize the necessity of sustainable land management approaches that do not merely focus on agricultural yield but also prioritize ecological integrity. This dual focus is crucial for developing policies that foster a balance between agricultural development and environmental stewardship. By adopting such an integrated approach, policymakers and land managers can contribute to a regional provincial framework that values the interdependencies between agriculture and the ecosystem, promoting practices that are sustainable, resilient, and beneficial for both human and environmental well-being.

Sustainable farming approaches that integrate ecological principles, conserve natural areas, promote biodiversity, and foster social cohesion are crucial for maintaining the long-term resilience and sustainability of both agricultural systems and the surrounding ecosystems. Further research, education, and policy support to enable farmers to adopt more sustainable practices and mitigate unintended consequences on ES is crucial. Understanding how the identified drivers shape farmers' choices, both singularly and interactively, is important to address challenges and promoting ES-supporting actions on commercial farms in the WC. This approach necessitates a comprehensive understanding of farmer decision-making processes, which are influenced by a spectrum of factors from economic considerations to environmental constraints. Acknowledging these drivers is essential for the formulation of policies that resonate with the realities of farm management, promoting practices that enhance ES provisioning. Better understanding the interests and needs of influencers on farmers, and sources of information, can support the development of evidence-based spatial management guidelines for agricultural landscapes in South Africa to enhance ES functioning. In addition, the importance of knowledge transfer and capacity building is emphasized, particularly through the use of models and tools such as InVEST, to facilitate the integration of ES assessments into spatial planning processes. This is complemented by the advocacy for decentralized and collaborative planning policies that empower local actors to partake in landscape changes, promoting bottom-up, actor-led development processes that are multifunctional and consider the diverse needs and values of stakeholders (Cowling et al., 2008; Reyers et al., 2009).

To ensure sustainable food production, the WC must focus more on future-oriented spatial planning that prioritises ES-support, and that minimizes land use conflicts and considers the perspectives of various stakeholders affected by planned management measures (Reyers et al., 2009; Sitas et al., 2014b). Understanding these viewpoints is essential for effective landscape management and the promotion of sustainable agricultural landscape management (Reed, 2008).

The study's insights into these discrepancies highlight an urgent need for spatial planning frameworks to evolve, accommodating a more nuanced understanding of ES within agricultural landscapes. This need underscores the potential of tools like the InVEST models to bridge these gaps, offering a robust framework for planning and monitoring that can significantly enhance landscape level decision-making.

The implementation of InVEST would enable the mapping and assessment of important ES, as results from this study show, thus reinforcing the scientific foundation for landscape level spatial planning. This mapping can be instrumental in enhancing the existing sector plans, particularly by aiding in the delineation of CBA and ESA, and identifying overlaps with ES hotspots. Moreover, spatial planning would be greatly improved with explicit guidelines on integrating ES assessments into all stages of the decision-making processes.

Finally, the study underscores the significance of supporting ongoing research and education initiatives that further deepen the understanding of ES and their integral role in agricultural landscapes. This involves the development of evidence-based management guidelines and educational programs aimed at equipping farmers, planners, and policymakers with the needed knowledge and tools for the sustainable management of ES on farmland. Areas of investigation include the efficacy of conservation agriculture on ES, the impact of technological innovations on ES provisioning, and the integration of the ES approach into South African spatial planning policy.

The findings emphasize the necessity for adaptive strategies that address the challenges posed by climate change, water scarcity, and evolving land use patterns. By fostering sustainable agricultural practices, this research advocates for the creation of multifunctional landscapes that support both agricultural productivity and ecosystem health, ensuring resilience against environmental uncertainties.

6. KEY SCIENTIFIC FINDINGS AND IMPORTANT OUTPUT

- **Methodological improvement in localised soil carbon assessment:** This study presents a refined methodology that integrates localized soil sampling to improve the accuracy of assessment and quantification of soil carbon stocks (SCS) across agricultural landscapes, using the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) modelling tool. This study, conducted in the Swartland-Tulbagh-Slanghoek (3138 km^2) and Helderberg-Grabouw-Breede Valley (3025 km^2) study areas of the Western Cape (WC), South Africa, marks a substantial improvement over prior assessments that relied on more generalised CS databases. This improvement lies in the use of localized data samples, which results in a more accurate representation of CS spatial distribution, which is tailored specifically to regional planning and resource management needs.
    - Compared to the baseline practice of using generalised national (country-level) CS values, the use of local soil samples to determine CS is an improvement in methodology. This novel methodology for integrating soil samples into CS assessments represents a methodological advancement, allowing for more precise and context-specific planning that recognizes the heterogeneity of soil carbon across agricultural landscapes.
    - For the Hungarian pilot study in the Vác-Pest-Danube Valley (208 km^2) and South-Zselic (511 km^2) microregions, 75 soil samples were collected from farmland, forests and grasslands and used to determine localised CS. In the WC, the methodology was replicated with 40 samples collected from shrubland, grasslands, commercial farmland, and commercial orchards across the two extensive study areas, which were incorporated into the CS datasets for soil carbon mapping. These samples were collected personally, ensuring reliability and authenticity of data.
    - **Novel CS datasets produced:** Localised soil CS inventory datasets were developed for the four study areas in Hungary (Table 9) and WC (Table 11 and Table 12), from which InVEST carbon mapping was done to output CS maps of the study areas, these were: (a) country-wide CS based on national soil data; (b) region-specific CS, in which the study areas are situated, based on that specific regions' data in the national soil dataset; and then the soil sample data was used to map the (c) minimum, (d) mean, and (e) maximum of CS for study areas (see Figure 20, Figure 22 and Figure 23).
- **Novel results reported and ecosystem service (ES) assessment maps produced of agricultural landscapes in Hungary and WC:** InVEST models were used to map and assess three ES' indicators—SCS (as proxy for global atmospheric climate regulation), soil erosion

control, and crop production—across two agricultural landscape study areas in the WC, South Africa (with a pilot study in Hungary only mapping SCS). These spatially explicit ES map outputs serve as valuable tools for spatial planners and landscape managers, as they can facilitate the development of targeted policies and informed strategies that support ES conservation in these agricultural landscapes.

- For the Vác-Pest-Danube Valley pilot study area, Hungary, the total aggregated CS was estimated between 313,700 Mg and 525,273 Mg (with a mean of 424,204 Mg) for 0-30 cm soil depth. For the South-Zselic pilot study area, Hungary, the total aggregated CS was estimated between 1,639,510 Mg and 4,783,027 Mg (with a mean of 2,811,051 Mg) for 0-30 cm soil depth (see Figure 21). For the Swartland-Tulbagh-Slanghoek study area, WC, the total aggregated CS was estimated between 5,945,196 Mg and 17,915,485 Mg (with a mean of 12,160,932 Mg) for 0–20 cm soil depth, and total CS estimated between 4,013,536 Mg and 16,437,342 Mg (with a mean of 8,992,836 Mg) for 20–40 cm soil depth. For the Helderberg-Grabouw-Breede Valley study area, WC, the total aggregated CS estimated between 4,493,291 Mg and 20,982,875 Mg (with a mean of 10,040,137 Mg) for 0–20 cm soil depth, and total CS estimated between 3,527,115 Mg and 14,403,730 Mg (with a mean of 8,992,860 Mg) for 20–40 cm soil depth (see Figure 24).
- With soil erosion control methods applied, it is estimated that 18% more topsoil erosion is avoided across the Swartland-Tulbagh-Slanghoek study area annually, and 9% more erosion avoided in the Helderberg-Grabouw-Breede Valley study area (Table 15). Sediment trapping and retention by vegetation, planting methods (contours) and practices (cover crops and minimum tilling) provide erosion control by decreasing between 22 to 38% soil loss annually in the WC study areas (Table 14).
- Of the 34 crops assessed for food production in both the Swartland-Tulbagh-Slanghoek and Helderberg-Grabouw-Breede Valley study areas in the WC, the most extensively planted crops are wheat, grapes, canola (rapeseed), barley and apples.
    - The crop types with the highest yields for 2017/18 in the Swartland-Tulbagh-Slanghoek study area were grapes, wheat, pears, peaches/nectarines and plums, with a total of 866,736 Mg of all crops produced (-2.93% difference from 2012/13).
    - The crop types with the highest yields for 2017/18 in the Helderberg-Grabouw-Breede Valley study area were apples, grapes, pears, and wheat, with a total of

872,730 Mg of all crops produced in 2017/18 (+1.03% difference from 2012/13).

- Revealing significant land use land cover change trends, approximately 28% of the Swartland-Tulbagh-Slanghoek area and 38% of the Helderberg-Grabouw-Breede Valley area underwent land cover changes over 28 years, indicating shifts towards increased farmland and, in the south, a rise in bare and eroded lands due to factors like soil erosion and drought conditions.
- **Novel results reported on the dynamics of farmer decision-making that impacts ES on farms in the WC study areas;** This study is the first to identify the specific factors that influence farmer decision-making that impacts ES on farms in the Swartland-Tulbagh-Slanghoek and Helderberg-Grabouw-Breede Valley study areas. Interviews were conducted with 30 commercial farmers, 15 located in each study area. This primary research provides a critical understanding of the economic, environmental, and social factors that drive actions and practices that damage and support ES on farms in the WC.
    - Several novel insights emerged from the interviews, such as the primary drivers of agricultural decision-making being economic considerations, the management of risk and uncertainty, and the influence of policy and regulations (Table 21). Farmers significantly impact ES on farmland, which includes—but is not limited to—soil and water management, pollution, biodiversity loss, land cover transformation, and the deterioration of habitat and ecosystem functioning (Table 22). Farmers recognise the need for improved land use practices and the preservation of critical habitats. A range of environmentally sustainable practices adopted by farmers to mitigate their impact on ES are also identified; effective soil and water management, livestock management, reduced chemical use and less physically degrading impacts on soil, waste and wildfire management (Table 23). In terms of the influences on farmer decision-making, neighbouring farmers, farmer associations, and agricultural consultants were identified as playing the most influential roles (Table 24).
    - This study has pinpointed a novel potential threat to environmental conservation in these agricultural landscape study areas: the expansion and consolidation of farmlands by large commercial entities primarily driven by profit maximization.
    - **A new category of ES for consideration within the Common International Classification of Ecosystem Services (CICES) is proposed**: Interviews identified the benefits of the disease pressure reduction service provided by strong winds for farmers, which has an economic benefit. This ES is particularly pertinent for viticulture in the

WC, where farmers recognize the critical role of wind in mitigating mould growth on vineyard foliage.

- **Novel showcasing of the integration of ES assessment in WC spatial planning:** This study is the first to showcase the integration of InVEST model outputs for carbon stock and soil erosion control into the spatial planning for the Swartland-Tulbagh-Slanghoek and Helderberg-Grabouw-Breede Valley agricultural landscape study areas, WC. The policy proposal maps delineate ES hotspots and recommend incorporation into regional and municipal spatial planning, offering an evidence-based approach to WC municipal spatial planning and development frameworks to include consideration of ES and socio-ecological land management in local government spatial planning for agricultural landscapes.

7. SUMMARY

The conservation of ecosystem services (ES) is crucial for human well-being, particularly in agricultural areas where specific services are optimized for financial benefit, at the expense of others. The absence of localized information on key ES in most high-economic production landscapes with intense land use poses a risk of irreparable environmental degradation. A study was done on the complex evaluation of ES in two agricultural landscapes in the Western Cape province of South Africa. The research aimed to improve the accuracy and applicability of assessments of key ES (global atmospheric climate regulation, soil erosion control, and crop production) in agricultural landscapes, analyse the impact of spatial development trends on ES provisioning, identify and evaluate the drivers of farmer decision-making that affect ES provisioning, and develop evidence-based recommendations for integrating ES considerations into municipal spatial planning frameworks.

This study used a mixed-methods approach by combining biophysical and social data, including soil sampling, remote sensing data, Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) modelling, and farmer interviews, to evaluate ES in the Swartland-Tulbagh-Slanghoek and Helderberg-Grabouw-Breede Valley agricultural landscape study areas in the Western Cape. InVEST models were used to map three ES indicators in the study areas: soil carbon stock (SCS), soil erosion, and crop yield. SCS mapping used a methodology developed during a pilot study in Hungary that integrated soil samples into CS inventories for more accurate ES mapping, developing carbon stock inventories for farmland, grassland, orchards and shrubland. Using remote sensing data and GIS tools, land use land cover changes between 1990–2018 were analysed to determine trends that impact the provisioning of ES. Regional spatial planning frameworks in the Western Cape were reviewed to identify gaps in supporting ES, and recommendations were developed for improving ES support in agricultural landscapes by integrating InVEST models, based on the results of this study.

ES assessments indicated variability in SCS based on land use and data source, with localized soil samples enhancing model accuracy, resulting in SCS maps for the study areas. Soil erosion assessments identified high-risk areas requiring management intervention, while crop production models provided insights into crop yield variation and spatial distribution. Observed land use land cover trends over 28 years included increased farmland and reduced natural vegetation, alongside the transformation of natural cover and increased bare, eroded areas, underscoring the potential impacts of land use changes on ES provisioning and functioning in agricultural landscapes.

The social research part, based on interviews with farmers, highlighted the complexity of decision-making in agricultural practices, influenced by a range of factors including economic conditions,

policy and regulations, environmental challenges, and personal values. Farmers' activities were found to have significant, diverse impacts on ES, encompassing land management, water use, and conservation efforts, which can both enhance and degrade environmental quality. Practices adopted by farmers, ranging from irrigation and soil conservation to crop management and the use of agrochemicals, reflect a balance between productivity and sustainability. Moreover, farmer decision-making processes are shaped by a variety of information sources, underscoring the role of community networks, professional advice, and institutional support in guiding sustainable agricultural practices. Policy proposals were made on the integration of InVEST model outputs for carbon stock, soil erosion control and food production into local spatial planning.

This research introduces a novel methodology for integrating soil samples into landscape-scale assessments of soil carbon storage, enhancing the precision of carbon stock evaluation. By mapping and assessing these ES, this research provides spatial planners with valuable tools for policy formulation aimed at spatial planning optimization that supports ES. Insights into farmers' decision-making processes revealed key factors influencing ES provisioning in agricultural landscapes, offering a foundation for refining regional planning frameworks to align with local socio-ecological dynamics. The study advocates for the integration of InVEST models into landscape planning in the Western Cape, suggesting these advancements could significantly improve agricultural development strategies and municipal natural resource management. This research contributes to the scientific knowledge and policy development on ecosystem-based management and sustainable agriculture in agricultural landscapes in the Western Cape. This study aimed to contribute to the resilience, productivity, and sustainability of the Western Cape's agricultural landscapes, ensuring their continued provision of vital ES while supporting the region's socio-economic well-being.

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9. APPENDICES

9.1. Appendix 1

Context of research

In this study, the value of nature is considered based on how it benefits humans (instrumental value), and that conservation and natural resource management are guided by a perspective that prioritizes human interests and well-being (enlightened anthropocentric and environmental ethics viewpoint based on traditional western ethical perspectives) (IPBES, 2022). This approach sees nature and it's services as a resource to be used and managed sustainably for human benefit, while also acknowledging the importance of protecting the environment for future generations (Arias-Arévalo et al., 2017; Fellows, 2019). Although, it is clear that current global environmental damage and degradation is inherently caused by culturally linked socio-economic aspects that intensify non-renewable resource use and the unsustainable use of the environment (IPBES, 2019).

Additional information on InVEST models

InVEST Carbon Storage and Sequestration model

InVEST Carbon Model can aggregate carbon stored amounts from above- and below-ground biomass, soil organic matter, and dead organic matter. Each of these aspects can also be mapped independently. This model requires a LULC raster GIS file of a delineated study area, where each cell has a LULC attribute class, e.g., farmland or grassland. As well as a MS Excel comma-separated values (CSV) file that matches each LULC class with carbon pool data, with values extracted from a CS inventory of that region. CS inventories are commonly developed from open-access public online databases (Natural Capital Project, 2022). The model attributes and calculates CS of each LULC classed cell in the raster map, by which it estimates the soil carbon amount according to the CSV CS look-up table. The model produces a SCS GIS raster file of the study area for each modelling iteration, where SCS is displayed in C Mg/ha. It also produces a text result reporting on the model run and summarizing the model's total aggregate CS value (Mg of C) (Natural Capital Project, 2022). SCS maps can be produced in the form of a time series to show spatially explicit changes and calculate carbon sequestration over time (Nelson et al., 2009). A limitation of this model is the oversimplification of the carbon cycle and assumptions pertaining to a linear change in carbon sequestration (Natural Capital Project, 2022).

InVEST Sediment Retention Model

The InVEST Sediment Retention Model requires raster maps of the Digital Elevation Model, rainfall erosivity, soil erodibility, and LULC as input. With information on watersheds and a CSV file with biophysical data on each LULC class. The Model computes a connectivity and conductivity index between cells to determine flow direction and rate, based on parameters such as RUSLE factors (Benavidez et al., 2018; Natural Capital Project, 2022). Then the annual soil loss per raster cell and the sediment delivery ratio is calculated using the RUSLE for which parameter values must be included (Benavidez et al., 2018). Results provide information on avoided erosion and avoided export. Avoided erosion describes the contribution of vegetation to sediment trapping and soil structure. Avoided export describes trapping of sediment from upslope by soil cover. Raster maps are produced of the total amounts of potential soil loss, sediment exported, and sediment deposited (Natural Capital Project, 2022).

InVEST Crop Production Percentile Model

The InVEST Crop Production Percentile Model estimates the yield of 175 different crops based on spatially explicit crop census data, sub-national FAO yield data and nutritional information. Results are reported in tons/ha and percentile yields for a specific crop's climate zone. These percentiles are set at 25, 50, 75 and 95, to explore a range of production intensification levels (Natural Capital Project, 2022). Similar to the Carbon Model, the InVEST Crop Production Model requires a LULC raster map. Except this map must contain an individual LULC class for every crop type and other LULC can be disregarded. A CSV LULC lookup table must be added that describes the crop type, so that it may be matched to the raster data and climatic data. This Model has a built-in directory for crop yield within specific global climate bins, as produced by (Mueller et al., 2012). The Model outputs a crop production raster map for each crop type modelled, results table and an aggregate results report. These report approximations of the observed crop yield outputs within the study areas (Natural Capital Project, 2022).

Additional information on Materials & Methods

Table 26. Bulk density (BD) references from AfSIS (ISRIC, 2015)

SA country level	**BD g/cm3 mean (from subset data) based on AfSIS BD for SA**
0–20	
Farmland	1.388085672
Grassland	1.385512987
Shrubland	1.368550839
20–40	
Farmland	1.411291
Grassland	1.406418071
Shrubland	1.386578245

WC province level	BD g/cm3 mean (from subset weighted data) based on AfSIS BD for WC-SA
0–20	
Farmland	1.288772817
Grassland	1.355114386
Shrubland	1.321537779
20–40	
Farmland	1.311600822
Grassland	1.369438142
shrubland	1.336310316

Table 27. Western Cape Farmer Interview Questions used in this study.

Themes	Questions
Personal Background	▪ What is your name and age? ▪ Farm name and size ▪ Can you tell me about your farming experience and training? ▪ What is your position/title on the farm? ▪ How long have you been farming in this area/landscape? ▪ How would you describe your farm business?
Farm Information	▪ Can you tell me about the farm business you manage? (crops, irrigation, area, comm./organic, etc.) ▪ What do you farm? ▪ Why and how did you decide to farm these crops/livestock? ▪ What environmental benefits/issues do you experience on your farm? (ecosystem services, dis-services) ▪ Do you implement any restoration/rehabilitation actions? and why? ▪ Do you have any natural veld/vegetation on your farm? Is it important to you and why?
Sustainability	▪ Is sustainability important to you for your farm? ▪ What does sustainability mean to you for your farm? ▪ How do you achieve sustainability on your farm? (interventions, using precision farming) ▪ Landscape Actors & Information ▪ Can you tell me about your neighbours? (what do they do) ▪ Do you know one another, share information, help each other out? (shared trust and dependency) ▪ Do you discuss sustainability issues, challenges, ideas? ▪ How would you describe the changes of your landscape in the past few years? (land use changes, threats, spatial development) ▪ What would you like to see change on your landscape? why?
Role-players	▪ What organisational bodies/groups exist that bring together people from your landscape? (farmer groups, fire protection, conservation) ▪ Who are the most important role-players on this landscape to you and your farm?

9.2. Appendix 2

Additional information on study results and outputs

Table 28 compares the differences in the calculated total potential aggregated SCS (Mg) for both landscape study areas between the different CS inventories. The greatest difference in total stored carbon is generally seen between the national (SA or WC) CS and maximum soil samples CS in both landscapes.

Table 28. The differences in the individually calculated total potential aggregated topsoil organic carbon stock (Mg), 0–20 and 20–40 cm, for the Swartland-Tulbagh-Slanghoek (North) and Helderberg-Grabouw-Breede Valley (South) study area landscapes, Western Cape, based on the six carbon-stock inventories. Greatest differences indicated in **bold**.

	National—WC	**Both Samples**	**Samples Min.**	**Samples Mean**	**Samples Max.**
0–20 cm depth					
		Swartland-Tulbagh-Slanghoek (North)			
National—SA	-169 394	-5 848 178	-984 700	-6 215 736	-11 970 289
National—WC	-	-5 678 784	-815 306	-6 046 342	-11 800 895
Both Samples	-	-	4 863 478	-367 558	-6 122 111
Samples min.	-	-	-	-5 231 036	-10 985 589
Samples mean	-	-	-	-	-5 754 553
		Helderberg-Grabouw-Breede Valley (South)			
National—SA	-277 088	-6 140 305	347 231	-5 199 615	-16 142 353
National—WC	-	-5 863 217	624 319	-4 922 527	-15 865 264
Both Samples	-	-	6 487 536	940 690	-10 002 048
Samples min.	-	-	-	-5 546 846	-16 489 584
Samples mean	-	-	-	-	-10 942 737
20–40 cm depth					
		Swartland-Tulbagh-Slanghoek (North)			
National—SA	360 495	-5 215 941	777 860	-4 618 804	-12 063 310
National—WC	-	-5 576 436	417 365	-4 979 299	-12 423 805
Both Samples	-	-	5 993 801	597 136	-6 847 369
Samples min.	-	-	-	-5 396 665	-12 841 170
Samples mean	-	-	-	-	-7 444 506
		Helderberg-Grabouw-Breede Valley (South)			
National—SA	118 137	-5 074 485	-480 773	-5 277 607	-10 758 478
National—WC	-	-5 192 622	-598 910	-5 395 745	-10 876 615
Both Samples	-	-	4 593 712	-203 122	-5 683 993
Samples min.	-	-	-	-4 796 835	-10 277 705
Samples mean	-	-	-	-	-5 480 870

Table 29. Total crop yield (Mg) in 2012/2013 of the 34 crops mapped with the InVEST Crop Production Model in both study areas, with minimum, mean, maximum, standard deviation and

variance of total yield per field production unit, based on the 2012/13 Crop Census (WC DoA, 2014, 2018).

Crops	Yield (Mg)					
	Total	**min.**	**mean**	**max.**	**st. dev.**	**var.**
2012/2013	1 756 256					
Swartland-Tulbagh-Slanghoek (north)	*892 510*					
Apple	5 882	20	100	365	67	4 438
Apricot	1 593	4	47	344	56	3 141
Barley	1 106	55	123	281	74	5 499
Blueberries	849	3	17	52	9	80
Cabbage	130	130	130	130	0	0
Canola (Rapeseed)	10 506	1	39	182	34	1 160
Carrots	2 172	40	128	335	84	6 977
Citrus	15 943	0	61	731	76	5 725
Figs	529	7	17	43	10	102
Garlic	231	24	46	67	15	236
Grapes	389 982	0	49	839	55	3 000
Lemons	2 456	1	56	555	89	7 877
Lupines (Pea)	4 978	0	18	87	15	237
Maize	164	9	23	62	17	288
Nuts	11	11	11	11	0	0
Oats	17	5	8	11	3	8
Olives	5 905	1	17	162	21	437
Onions	1 380	11	99	341	75	5 654
Oranges	7 130	7	84	252	53	2 806
Peach/Nectarine	65 539	3	72	672	52	2 738
Pear	67 616	1	70	651	50	2 460
Plum	44 326	2	55	508	44	1 899
Potatoes	526	229	263	296	34	1 125
Pumpkin	2 108	5	36	84	19	352
Tomatoes	80	80	80	80	0	0
Triticale	100	100	100	100	0	0
Wheat	261 252	1	89	664	77	5 919
Helderberg-Grabouw-Breede Valley (south)	*863 747*					
Apple	485 978	2	128	1 520	106	11 287
Apricot	5 202	2	46	144	28	786
Barley	22 051	1	61	253	47	2 256
Blueberries	340	3	15	28	7	51
Cabbage	1 578	8	38	274	41	1 681
Canola (Rapeseed)	10 869	1	43	213	34	1 181
Citrus	3 197	18	97	284	67	4 530
Figs	10	5	5	5	0	0
Grapes	150 906	1	39	358	30	902
Lemons	254	22	51	69	17	276
Lupines (Pea)	1 959	1	22	114	18	341
Nuts	7	1	2	4	2	2
Olives	2 098	1	14	125	14	189
Onions	1 122	15	160	774	252	63 521
Oranges	758	50	108	287	79	6 270
Peach/Nectarine	17 471	13	98	491	66	4 323
Pear	72 894	2	69	596	59	3 467
Plum	18 202	6	60	353	49	2 422
Potatoes	46	46	46	46	0	0
Pumpkin	558	10	25	67	18	336

Crops	Yield (Mg) Total	min.	mean	max.	st. dev.	var.
Tomatoes	203	203	203	203	0	0
Wheat	68 042	1	87	603	71	5 061

Table 30. Total crop yield (Mg) in 2017/2018 of the 34 crops mapped with the InVEST Crop Production Model in both study areas, with minimum, mean, maximum, standard deviation and variance of total yield per field production unit, based on the 2017/18 Crop Census (WC DoA, 2014, 2018).

Crops	Yield (Mg) Total	min.	mean	max.	st. dev.	var.
2017/2018	1 739 467					
Swartland-Tulbagh-Slanghoek (north)	*866 736*					
Almonds	134	1	4	16	3	8
Apple	4 653	8	89	339	68	4 566
Apricot	718	6	36	78	19	379
Barley	2 522	4	79	307	68	4 603
Blueberries	820	2	13	25	5	27
Cabbage	337	15	42	224	69	4 727
Canola (Rapeseed)	18 318	0	37	237	34	1 182
Citrus	28 594	1	52	437	56	3 179
Figs	232	2	9	20	5	21
Garlic	270	13	30	59	13	178
Grapes	324 325	0	42	802	49	2 438
Lemons	5 763	1	59	621	94	8 900
Lupines (Pea)	282	0	13	45	12	149
Mango	3	3	3	3	0	0
Nuts	24	1	6	10	3	11
Olives	5 011	0	12	149	17	300
Onions	1 044	23	65	158	44	1 953
Oranges	12 981	5	72	498	81	6 542
Peach/Nectarine	47 854	1	62	298	41	1 660
Pear	63 976	1	62	413	44	1 916
Plum	41 197	2	49	409	43	1 854
Pumpkin	2 355	4	34	285	39	1 487
Sweet potatoes	160	13	40	77	24	600
Tea	1 308	2	48	262	56	3 083
Tomatoes	176	48	88	128	40	1 578
Triticale	338	28	85	149	44	1 897
Wheat	303 342	0	84	667	79	6 277
Helderberg-Grabouw-Breede Valley (south)	*872 730*					
Almonds	1	1	1	1	0	0
Apple	492 028	1	119	1 113	99	9 775
Apricot	5 547	3	43	149	27	735
Barley	29 182	1	66	419	58	3 370
Blueberries	456	1	8	23	5	29
Cabbage	1 228	10	38	154	38	1 425
Canola (Rapeseed)	14 687	0	34	210	31	952
Carrots	32	32	32	32	0	0
Citrus	8 135	9	87	703	88	7 717
Figs	11	5	6	6	1	1
Grapes	133 754	1	38	290	28	795

Crops	Yield (Mg) Total	min.	mean	max.	st. dev.	var.
Lemons	2 254	4	50	250	44	1 940
Lupines (Pea)	813	0	17	85	16	248
Nuts	12	6	6	6	0	0
Olives	1 920	0	11	114	14	200
Onions	278	4	21	49	17	274
Oranges	2 098	1	84	271	67	4 523
Peach/Nectarine	22 066	5	87	378	64	4 077
Pear	77 326	1	61	733	57	3 271
Plum	9 229	3	50	271	48	2 315
Potatoes	141	55	71	86	15	240
Pumpkin	89	33	45	57	12	140
Sweet potatoes	33	33	33	33	0	0
Tomatoes	530	129	177	272	67	4 508
Triticale	127	127	127	127	0	0
Walnuts	9	9	9	9	0	0
Wheat	70 745	1	75	686	73	5 298

Table 31. Total planted area (ha) of crops in the Swartland-Tulbagh-Slanghoek (north) and Helderberg-Grabouw-Breede Valley (south) study areas, mapped by the InVEST Crop Production Model, in 2012/2013 and 2017/2018, indicating overall total crop area (ha) change (for both study areas) between years.

	2012/2013			2017/2018			
	North	**South**	**Both**	**North**	**South**	**Both**	**Change**
Total area (ha)	*102 361*	*50 129*	*152 490*	*108 288*	*52 800*	*161 089*	*8 599*
Almonds	0	0	0	89	1	89	89
Apple	90	7 477	7 567	72	7 570	7 641	74
Apricot	80	260	340	36	277	313	-27
Barley	316	6 300	6 616	721	8 338	9 058	2 442
Blueberries	94	38	132	91	51	142	10
Cabbage	8	102	111	22	80	102	-9
Canola (Rapeseed)	5 333	5 517	10 850	9 298	7 455	16 754	5 904
Carrots	59	0	59	0	1	1	-58
Citrus	380	76	456	681	194	874	419
Figs	76	1	77	33	2	35	-42
Garlic	19	0	19	22	0	22	3
Grapes	24 374	9 432	33 805	20 270	8 360	28 630	-5 176
Lemons	100	10	111	235	92	327	217
Lupines (Pea)	4 786	1 883	6 670	271	782	1 053	-5 616
Maize	30	0	30	0	0	0	-30
Mango	0	0	0	0	0	0	0
Nuts	6	3	9	12	6	18	9
Oats	7	0	7	0	0	0	-7
Olives	984	350	1 334	835	320	1 155	-179
Onions	53	43	96	40	11	51	-45
Oranges	159	17	176	289	47	336	160
Peach/Nectarine	1 638	437	2 075	1 196	552	1 748	-327
Pear	1 690	1 822	3 513	1 599	1 933	3 533	20

	2012/2013			2017/2018			
	North	South	Both	North	South	Both	Change
Plum	1 304	535	1 839	1 212	271	1 483	-356
Potatoes	14	1	15	0	4	4	-12
Pumpkin	124	33	157	139	5	144	-13
Sweet potatoes	0	0	0	9	2	11	11
Tea	0	0	0	664	0	664	664
Tomatoes	1	3	4	2	7	10	6
Triticale	20	0	20	68	25	93	73
Walnuts	0	0	0	0	2	2	2
Wheat	60 615	15 787	76 402	70 381	16 414	86 795	10 393

Total farms and fields change, for both study areas, in 2012/13 and 2017/18, and the change in average field size over the four years are reported in Table 32. In the north study area, the number of farms for wheat increased from 490 in 2012/13 to 592 in 2017/18, fields for wheat increased from 2923 to 3623 total farms. The number of farms for grapes decreased from 765 to 742, fields for grapes decreased from 7979 in 2012/13 to 7689 in 2017/18. The number of farms for canola increased from 99 to 157, fields for canola increased from 270 to 494. The number of farms for barley increased from 4 in 2012/13 to 13 in 2017/18, fields for barley increased from 9 to 32. The number of farms for apples increased from 16 in 2012/13 to 17 in 2017/18, fields for apples decreased from 59 to 52. A slight trend of an increased uptake of olives across 50 farms can be seen, with a decreased in peaches and plums.

In the south study area, the number of farms for wheat increased from 214 in 2012/13 to 218 in 2017/18, fields for wheat increased from 783 to 943. The number of farms for grapes decreased from 382 in 2012/13 to 356 in 2017/18, fields for grapes decreased from 3885 to 3480. The number of farms for canola increased from 108 to 137, fields for canola increased from 252 to 437. The number of farms for barley increased from 100 in 2012/13 to 145 in 2017/18, fields for barley increased from 360 to 443. The number of farms for apples increased from 307 to 320, fields for apples increased from 3792 to 4122. A slight trend of an increased uptake of pears, apples, olives, citrus and lemons across farms can be seen, with a decreased in vegetables.

In the north study area, the mean field size for wheat decreased from 20.74 hectares in 2012/13 to 19.43 ha in 2017/18 and decreased from 20.16 ha in 2012/13 to 17.41 ha in 2017/18 in the south. The mean field size for grapes decreased from 3.05 ha in 2012/13 to 2.64 hectares in 2017/18 in the north, and decreased from 2.43 hectares in 2012/13 to 2.40 hectares in 2017/18 in the south. Generally, the field unit sizes decreased slightly for canola, barley and apples, except where barley increased from 17.45 hectares in 2012/13 to 18.82 hectares in 2017/18 in the south study area.

Table 32. Total planting extent (ha), and amount of farms and field units where crops were grown for both study areas, in 2012/13 and 2017/18, and the change in average field size (ha), based on 2012/13 and 2017/18 Crop Censuses (WC DoA, 2014, 2018).

	2012/2013				2017/18				
	Total area (ha)	**Farms**	**Fields**	**Mean field size (ha)**	**Total area (ha)**	**Farms**	**Fields**	**Mean field size (ha)**	**Change**
Both	152 490.21	2 233	26 273		161 088.75	2 348	27 856		
Swartland-Tulbagh-Slanghoek (north)									
Almonds	0.00	0	0	0.00	88.50	9	34	2.60	2.60
Apple	90.49	16	59	1.53	71.59	17	52	1.38	-0.16
Apricot	79.64	16	34	2.34	35.89	9	20	1.79	-0.55
Barley	316.14	4	9	35.13	720.55	13	32	22.52	-12.61
Blueberries	94.33	2	51	1.85	91.13	8	64	1.42	-0.43
Cabbage	8.44	1	1	8.44	21.86	2	8	2.73	-5.71
Canola/Rapeseed	5 332.94	99	270	19.75	9 298.37	157	494	18.82	-0.93
Carrots	58.70	5	17	3.45	0.00	0	0	0.00	-3.45
Citrus/Naartjies	379.59	29	260	1.46	680.81	42	546	1.25	-0.21
Figs	75.59	8	31	2.44	33.13	11	25	1.33	-1.11
Garlic	19.25	1	5	3.85	22.47	1	9	2.50	-1.35
Grapes/Table/Wine	24 373.86	765	7 979	3.05	20 270.29	742	7 689	2.64	-0.42
Lemons	100.23	13	44	2.28	235.24	34	98	2.40	0.12
Lupines/Pea	4 786.21	143	279	17.15	271.47	15	21	12.93	-4.23
Mango	0.00	0	0	0.00	0.36	1	1	0.36	0.36
Maize	30.40	3	7	4.34	0.00	0	0	0.00	-4.34
Nuts	5.69	1	1	5.69	12.25	1	4	3.06	-2.63
Oats	6.61	1	2	3.30	0.00	0	0	0.00	-3.30
Olives	984.25	117	349	2.82	835.17	168	429	1.95	-0.87
Onions	53.07	9	14	3.79	40.15	7	16	2.51	-1.28
Oranges	158.69	17	85	1.87	288.91	28	181	1.60	-0.27
Peach/Nectarine	1 638.48	161	911	1.80	196.35	147	777	1.54	-0.26
Pear	1 690.39	136	962	1.76	599.41	138	1 025	1.56	-0.20
Plum	1 303.71	125	805	1.62	211.69	126	842	1.44	-0.18
Potatoes	14.13	1	2	7.06	0.00	0	0	0.00	-7.06
Pumpkin/butternut	123.99	13	59	2.10	138.53	19	69	2.01	-0.09
Sweet potatoes	0.00	0	0	0.00	9.40	2	4	2.35	2.35
Tea	0.00	0	0	0.00	663.79	7	27	24.58	24.58
Tomatoes	1.13	1	1	1.13	2.49	2	2	1.24	0.11
Triticale	19.96	1	1	19.96	67.63	2	4	16.91	-3.06
Wheat	60 615.22	490	2 923	20.74	70 380.96	592	3 623	19.43	-1.31
Helderberg-Grabouw-Breede Valley (south)									
Almonds	0.00	0	0	0.00	0.51	1	1	0.51	0.51

	2012/2013				2017/18				
	Total area (ha)	**Farms**	**Fields**	**Mean field size (ha)**	**Total area (ha)**	**Farms**	**Fields**	**Mean field size (ha)**	**Change**
Apple	7 476.58	307	3 792	1.97	569.67	320	4 122	1.84	-0.14
Apricot	260.11	49	114	2.28	277.33	51	128	2.17	-0.12
Barley	6 300.27	100	361	17.45	8 337.81	145	443	18.82	1.37
Blueberries	37.81	2	22	1.72	50.62	8	56	0.90	-0.81
Cabbage	102.48	17	42	2.44	79.72	12	32	2.49	0.05
Canola/Rapeseed	5 517.22	108	252	21.89	455.37	137	437	17.06	-4.83
Carrots	0.00	0	0	0.00	0.86	1	1	0.86	0.86
Citrus/Naartjies	76.11	10	33	2.31	193.69	23	94	2.06	-0.25
Figs	1.41	1	2	0.71	1.58	1	2	0.79	0.08
Grapes/Table/Wine	9 431.64	382	3 885	2.43	359.66	356	3 480	2.40	-0.03
Lemons	10.38	3	5	2.08	92.02	19	45	2.04	-0.03
Lupines/Pea	1 883.46	52	88	21.40	781.98	25	47	16.64	-4.77
Nuts	3.35	3	3	1.12	5.81	2	2	2.90	1.79
Olives	349.70	47	153	2.29	319.99	57	172	1.86	-0.43
Onions	43.17	6	7	6.17	10.69	2	13	0.82	-5.34
Oranges	16.87	4	7	2.41	46.68	11	25	1.87	-0.54
Peach/Nectarine	436.78	73	178	2.45	551.65	80	254	2.17	-0.28
Pear	1 822.35	188	1 059	1.72	933.16	212	1 270	1.52	-0.20
Plum	535.36	42	302	1.77	271.43	41	183	1.48	-0.29
Potatoes	1.24	1	1	1.24	3.79	2	2	1.90	0.66
Pumpkin/butternut	32.83	6	22	1.49	5.26	2	2	2.63	1.14
Sweet potatoes	0.00	0	0	0.00	1.92	1	1	1.92	1.92
Tomatoes	2.87	1	1	2.87	7.49	2	3	2.50	-0.38
Triticale	0.00	0	0	0.00	25.45	1	1	25.45	25.45
Walnuts	0.00	0	0	0.00	2.17	1	1	2.17	2.17
Wheat	15 787.10	214	783	20.16	414.07	218	943	17.41	-2.76

Table 33. A summary of the influencers (stakeholders, with details of the information channels used and scale, which influence farmers' decision-making on farming practices that impact ES on farms, based on the farmer interviews.

Influencers (scale)	**Information Channels**	**Response Descriptions**
Government and Policies (national, provincial, regional, municipal)	• Government websites and portals: Official government websites provide information on policies, regulations, and updates related to farming and ecological systems. • Government agencies and departments: Farmers can directly access information through agricultural departments or agencies responsible for implementing policies.	• Government influence is acknowledged, with some farmers desiring more government control in managing areas and reducing risks. • State influence is seen in areas such as forestry management, fire protection, licensing, and legal compliance.

Influencers (scale)	Information Channels	Response Descriptions
	• Publications and reports: Government publications, reports, and guidelines are available both online and in physical form, providing detailed information on policies and practices. • Agriculture extension officers: On-site consultations and farm visits, facilitating collaborative initiatives, organizing workshops and field days to promote awareness and share information.	
Farmer Associations and Organizations (provincial, regional, local)	• Newsletters and bulletins: Associations and organizations often send out newsletters and bulletins to their members, sharing relevant information, updates, and best practices. • Meetings, workshops and conferences: Associations organize meetings, workshops, conferences, and seminars where members gather to exchange knowledge, discuss challenges, and learn from experts. • Online platforms and forums: Many associations maintain online platforms and forums where members can interact, ask questions, and share information.	• Farmers associations play a significant role in providing support, information sharing, and networking opportunities. • Fire and security associations were mentioned by all farmers as key role players. • Local, regional and provincial agricultural associations and specific industry organizations were mentioned as influencers, such as AgriWC, Vinpro and Hortgro.
Conservation and Environmental Organisations (regional, local)	• Websites and online resources: provide information on their initiatives, projects, and resources related to ecological systems on farms. • Collaboration meetings and workshops: Organizations collaborate with farmers through meetings, workshops, and training sessions to share information on conservation practices and their benefits. • Publications and research papers: Conservation organizations publish research papers, reports, and articles on sustainable farming practices and their impact on ecological systems.	• Collaboration with conservation organizations like the WWF-SA, CapeNature, and the Nature Conservancy. • Partnerships with these organizations aim to achieve sustainable production, conserve biodiversity, protect natural areas, and address land fragmentation.
Consultants and Experts (regional, local)	• Consultation sessions: Consultants and experts meet with farmers on-site to provide personalized advice, recommendations, and guidance. • Training programs and workshops: Consultants and experts conduct training programs and workshops to share knowledge on specific topics and practices. • Reports and assessments: After conducting assessments or studies, consultants provide farmers with reports containing valuable information and recommendations.	• Farmers work with consultants and experts in various fields, including soil scientists, horticulturalists, and crop protection specialists. • These professionals provide advice on sustainable practices, soil fertility, pest control, and ecological management.
Neighbouring Farmers (local landscape)	• Farm visits and informal gatherings: Neighbouring farmers frequently visit each other's farms to observe practices, exchange information, and discuss challenges. • Phone calls and messaging: Farmers communicate directly through phone calls, text messages, or messaging apps to share information about pest outbreaks, weather conditions, or other relevant topics. • Local community meetings: Community meetings or gatherings provide opportunities for neighbouring farmers to discuss farming-related matters and share information.	• Neighbours and fellow farmers play a significant role in influencing ES on farms. • They share information, discuss farming practices, and exchange knowledge about pest infestations, crop management, and weather conditions.
Salespeople and Service Providers (regional, local community)	• Sales visits and demonstrations: Salespeople and service providers visit farms to demonstrate their products, discuss their benefits, and provide information on usage.	• Salespeople for feed, chemicals, and equipment provide specific information about products and industry trends.

Influencers (scale)	Information Channels	Response Descriptions
	• Catalogues and brochures: Salespeople often provide catalogues, brochures, and product information sheets containing details about their offerings. • Trade shows and exhibitions: Salespeople participate in trade shows and exhibitions where farmers can interact with them, ask questions, and gather information about products and services.	• Farmers rely on these salespeople for advice and guidance on using agricultural inputs effectively.
Community and Cooperative (local community)	• Cooperative meetings: Cooperatives organize regular meetings where farmers discuss farming practices, share information, and collectively make decisions. • Community events: Community events, such as fairs or festivals, provide opportunities for farmers to gather and exchange information on farming practices. • Cooperative newsletters and communication channels: Cooperatives maintain newsletters, email lists, or other communication channels to share updates, important information, and best practices among members.	• The local community and cooperative are mentioned as influential entities supporting farmers. • The community shows interest and actively collaborates with farmers in sustainable agriculture initiatives.
Online Resources and International Farming Websites (international, national, regional)	• Websites and online platforms: Farmers access information through websites dedicated to farming, agriculture, and ecological systems. These websites provide articles, blogs, videos, and forums for knowledge sharing. • Online forums and social media groups: Farmers engage in online forums and social media groups where they can ask questions, share experiences, and learn from others in the farming community. • Webinars and online training programs: Online resources offer webinars and training programs on various farming topics, allowing farmers to acquire knowledge remotely.	• Farmers utilize the internet to access farming websites, especially from the UK, USA, and Australia. • Online resources provide valuable information on farming practices, market trends, and innovations.
Bank Managers and Financial Considerations (national)	• Personal meetings: Farmers have face-to-face meetings with bank managers to discuss financial considerations and seek advice on loans, investments, or financial management. • Phone calls and emails: Farmers communicate with bank managers through phone calls or emails to inquire about financial matters or seek guidance. • Banking platforms and portals: Online banking platforms provide access to information, statements, and resources related to financial considerations for farming.	• Bank managers are mentioned as influencers, particularly in terms of financial decisions and considerations for farming practices.
Personal Networks (local community)	• Paternal family sources: Farmers often refer to their father's methods of farming as a reference for their own practices. • Personal meetings and farm visits: Farmers meet with family members, friends, or acquaintances involved in farming to share information, experiences, and knowledge. • Phone calls and messaging: Personal networks communicate through phone calls, text messages, or messaging apps to discuss farming practices, seek advice, or exchange information. • Informal gatherings and events: Social gatherings or events provide opportunities for farmers to interact and share information within their personal networks.	• Family members, spouses, and fellow farmers encountered during studies are important influencers. • Personal networks contribute to farmers' knowledge, perception of conservation, and farming practices.
Farm Staff (local community)	• Staff: some farms employ different types of managers, i.e., farm, vineyard or cellar managers, and	• Different ideas, knowledge and expertise contribute to a wider knowledge-base which contributes

Influencers (scale)	Information Channels	Response Descriptions
	foremen's that contribute their knowledge and expertise to decision-making on a farm.	to using various agricultural practices, and technologies.
Information sharing events, i.e., study groups, research initiatives, farmer days (regional, local community)	• Workshops and training sessions: Study groups, research initiatives, and farmer days often include workshops and training sessions where participants share information, discuss findings, and learn from each other. • Presentations and panel discussions: Experts and participants present their research findings, experiences, and insights through presentations and panel discussions. • Networking and informal interactions: These events create opportunities for farmers to network, have informal discussions, and exchange information with other participants.	• Farmers participate in study groups and research initiatives on specific topics, such as grain, sheep, apple orchards, or soil fertility. • These groups provide a platform for knowledge sharing, discussing new practices, and staying updated with research. • Farmer days, organized agriculture events, and tours of farms create opportunities for farmers to meet, share information, and learn from each other.