HUNGARIAN UNIVERSITY OF AGRICULTURE AND LIFE SCIENCES

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COMPLEX EVALUATION OF ECOSYSTEM SERVICES IN AGRICULTURAL LANDSCAPES

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1. INTRODUCTION

1.1. Background

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 (IPBES, 2019; MEA, 2005).

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). 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). 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).

Spatial development planning is essential for aligning human needs with ecological health. It aims to guide sustainable changes in land use and cover, 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).

1.2. 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). 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., 2014).

Presently, there are no ES maps and models specifically tailored to the WC agricultural landscapes for landscape-level planning. 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). 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.

1.3. 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.

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. MATERIALS AND METHODS

2.1. 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). 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). 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).

2.2. Description of the study areas

The agricultural landscape study areas were selected based on several criteria; medium-sized regions (± 500-3000 km^2) with mixed land use land cover (two 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.

2.2.1. 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 1. 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).

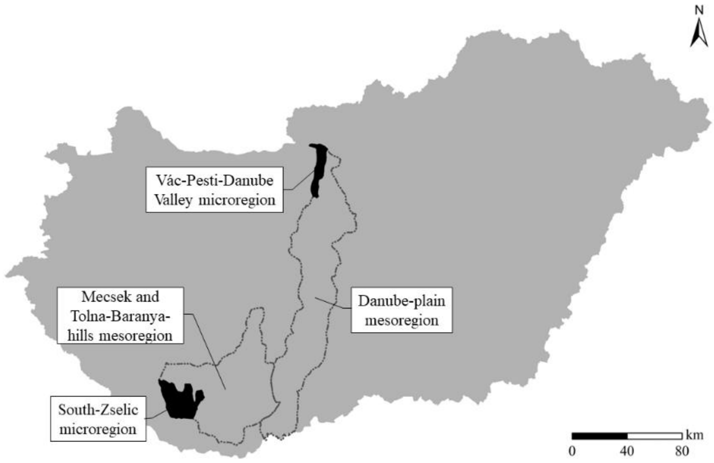


Figure 1. The locations of the pilot study areas in Hungary; north, Vác-Pest-Danube Valley and, south, South-Zselic microregions.

Pilot Study Area 1

The northern study area (73 km^2), the Vác-Pest-Danube Valley microregion (208 km^2) situated within the Dunamenti-plain (Danube) mesoregion, stretches 42 km down the Danube River. It 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). The area is characterized by wooded-steppe vegetation and wetland habitats along the Danube banks, with extensive agricultural areas (TAKI, 2022). 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 (Agrártudományi Kutatóközpont, 1992).

Pilot Study Area 2

The South-Zselic microregion (511 km^2), the southern study site, within the Mecsek and Tolna-Baranya-hills mesoregion, is found in the southern part of the Transdanubian hills (Dél-Dunántúl), see Figure 1. 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. 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). 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. 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).

2.2.2. 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 2.

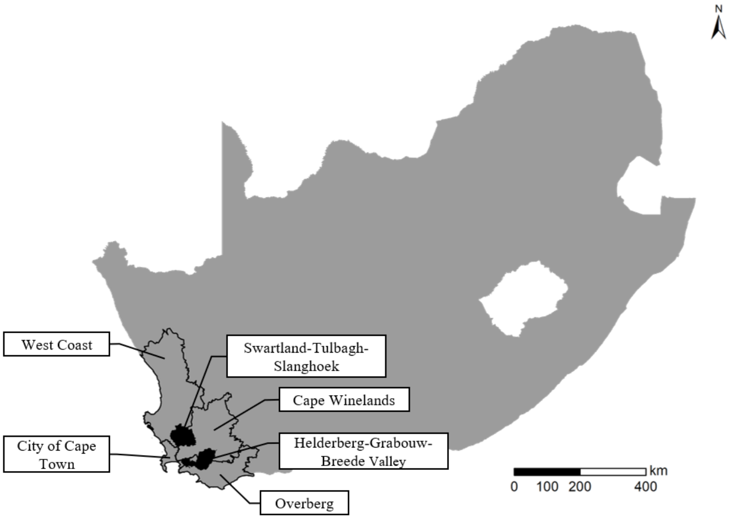


Figure 2. Location of the Swartland-Tulbagh-Slanghoek (study area 1) and Helderberg-Grabouw-Breede Valley (study area 2) agricultural landscape areas in the Western Cape, South Africa. District Municipal boundaries of the West Coast, City of Cape Town, Cape Winelands and Overberg are shown in black outline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

The WC has a dry Mediterranean climate with 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 that occurs across the region. 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 (DWAF, 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 (Partridge et al., 2022). Figure 3 shows the LULC of the study areas (SANBI, 2018). 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 (Linder, 2003).

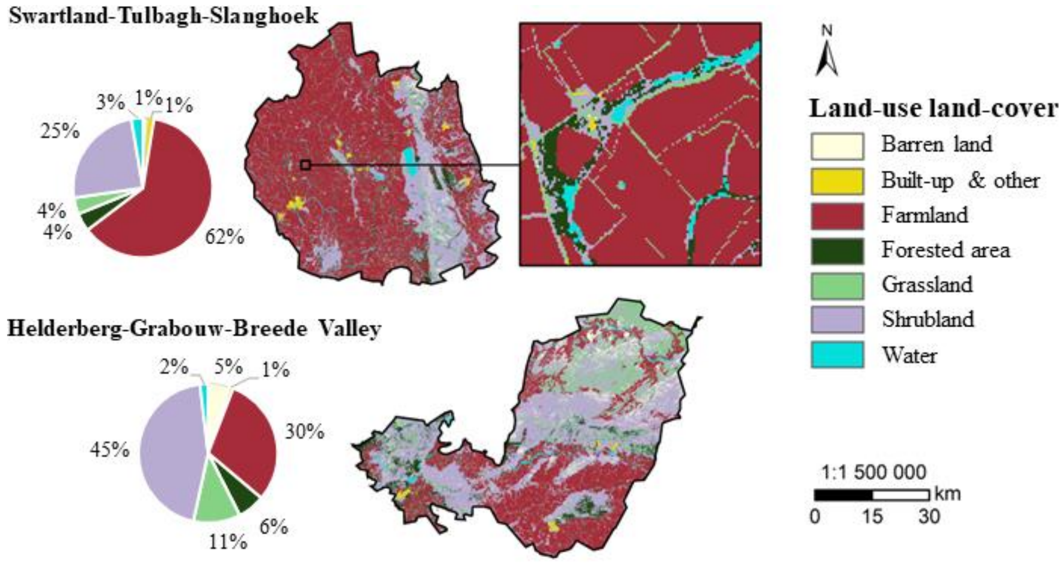


Figure 3. Generalized land use land cover map of the two agricultural study areas showing % coverage of each LULC in both areas, and a close-up of an area that shows LULC variation. LULC types; barren land, built-up and other types, farmland, forested area, grasslands, shrublands, and waterbodies and wetlands (1:1500000) (SANBI (2018), with author's calculations).

Study Area 1: Swartland-Tulbagh-Slanghoek

The Swartland-Tulbagh-Slanghoek study area (3138 km^2) 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). Two major water sources for farming cross the area; the Berg River and the Breede River.

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). 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 (Batjes, 2004). Various soil types are found along the Berg River, from sandy sediments in the lower catchments to distinct clay accumulations in the middle catchment (Clark & Ratcliffe, 2007). These rich clayey soils have attracted agricultural development that has caused extensive transformation of riparian habitat along the Berg River (Kamish, 2008).

Study Area 2: Helderberg-Grabouw-Breede Valley

The Helderberg-Grabouw-Breede Valley study area (total area: 3025 km^2) 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). The Breede River is a major water source for farming (DWAF, 2003). 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). The dominant soils across the area are Lithic Leptosols, Albic Arenosols, Eutric Regosols, and Eutric Leptosols (Batjes, 2004).

2.3. Data collection & analyses

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. Maps were stored, viewed, edited and analysed with ArcGIS (ESRI version 10.4.1).

Field work (soil sampling) and laboratory analysis

Soil samples were collected during the pilot study 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. While Hungary's inventory had samples from 0-30 cm and 30-60 cm depths, the South African inventory was based on 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). In both countries, sampling sites were selected based on purposive sampling, a non-probability sampling method. Locations were selected based on the observed representativeness of a LULC class, environmental conditions, and good spatial coverage (Zhu et al., 2008).

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. 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. 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, 2018).

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.

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. Samples were taken from 0–20 and 20–40 cm depths, following the sampling depth of the 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. Samples were analysed for SOC with the Walkley Black method, measured in the form of C % (FAO, 2018).

Western Cape farmer interviews

Semi-structured interviews were conducted with 30 local commercial farmers, 15 from each study area, to add depth, detail and meaning to the ES assessments (Drury et al., 2011; Newing et al., 2011). 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). Qualitative content analysis was done, where word analyses 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.

2.4. InVEST ecosystem service modelling

Global atmospheric regulation

SCS of the study areas were assessed 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 soil samples. The CLC2018 LULC raster map was used as input and 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). SCS inventories for farmland, forested areas, and grassland LULC classes were created from the 1992 national AGROTOPO SOC stock dataset and soil sampled CS data. 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 minimum, mean, and maximum values of the soil samples. SCS maps and the total aggregated CS were produced and reported.

The soil carbon mapping of the two 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. SCS inventories for shrubland, grassland, farmland, and orchards were developed from national SOC stock datasets, and soil sampled CS data (Batjes, 2004; ISRIC, 2015). SCS maps and the total aggregated CS were produced and reported.

Soil erosion control

Avoided soil erosion and avoided export, as ES indicators, were assessed in the two study areas in the WC. Input data were prepared for the InVEST Sediment Delivery Ratio (SDR) model; Digital Elevation Model, rainfall erosivity (R factor value), soil erodibility (K factor value), P and C coefficients, LULC raster maps, biophysical tables, watersheds map and several calibration parameters (i.e.,), based on 2018 data (Natural Capital Project, 2022). The Revised Universal Soil Loss Equation (RUSLE) is used to estimate the annual amount of soil erosion (Renard et al., 1997). The SDR model enhances the RUSLE by considering additional factors such as hydrological connectivity and sediment delivery to streams (Natural Capital Project, 2022). 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. 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). Results were summarised and reported.

Food production

Crop yield was assessed in the two WC study areas. The model produced a crop yield map for each crop type per study area and production year (2012/2013, 2017/2018). The top five crop types by extent (>10,000 ha planted area) were displayed, including wheat, grapes, canola, apple and barley. Total crop yields (ha) are reported. Total planted area (ha) per study area was summarised to indicate area change between the production years to analyse crop change over four years.

2.5. 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 (DEA, 2019). LULC types were reclassed into 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).

2.6. Developing ecosystem service-supporting recommendations

To refine ES recommendations for the WC 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, their integration into planning processes, and the potential impact on decision-making. The assessment specifically looked for the identification of ES, the methods used for mapping and evaluating them, and the existing approach to understanding land use impacts on ES. Results are reported, offering policy proposals that bolster the frameworks' capacity for supporting ES-centric spatial planning. Priority areas for local landscape-level spatial planning and development were evaluated, based on maps of farms, Critical Biodiversity Areas (CBA) and Ecological Support Areas (ESA), soil carbon and avoided erosion. Maps were assessed to identify priority areas. 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.

3. RESULTS AND DISCUSSION

3.1. 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?

Pilot Study in Hungary
The SCS based on the soil sampling data for both study areas in Hungary is shown in Table 1, with the minimum, mean, and maximum CS (Mg·ha^{-1}), standard deviation, and variance.

Table 1. SCS 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
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

Methodology to develop Carbon Stock Inventories
SCS inventories for farmland, forested areas, and grassland are reported in Figure 4. The Danube plain (north) mesoregion has higher CS 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. 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.

Soil Carbon Stocks in the Western Cape, South Africa
The SCS based on the soil sampling data (at 0–20 and 20–40 cm depth) for both study areas are shown in Figure 6. SCS inventories for shrubland, grassland, farmland, and orchard LULC are reported in Figure 5, developed from the national South African CS data and soil sample CS datasets.
Overall, the soil samples have higher CS for all LULC by about 20 to 30 Mg·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·ha^{-1} for 20 to 40 cm depth compared to national data (Figure 5). Soil samples have higher overall CS for both depths for all LULC. National data and the sample's minimum values were all relatively low (<40 Mg·ha^{-1}) for all LULC.

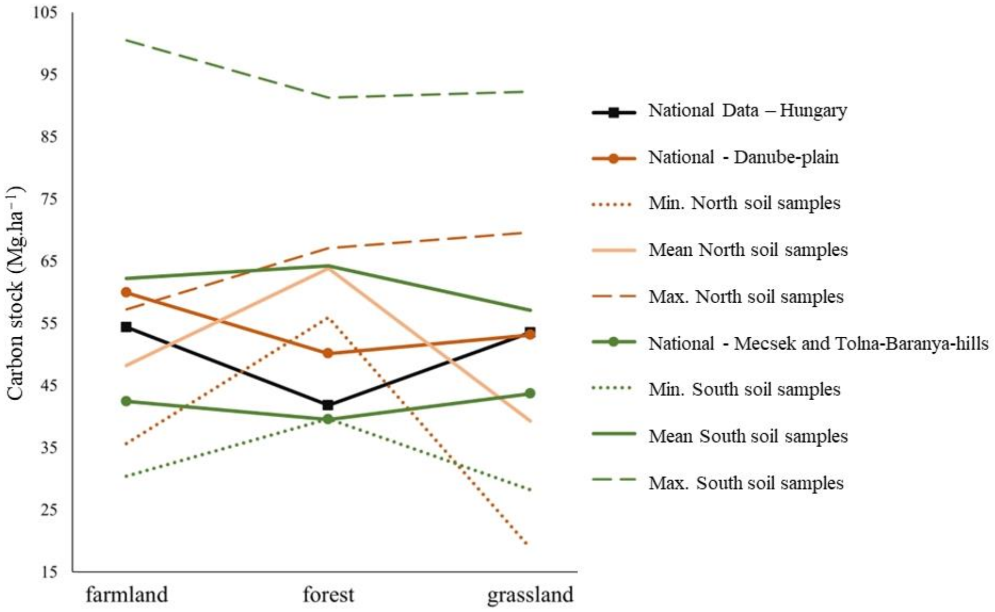


Figure 4. Variation of the carbon stock values for farmland, forested areas (forest), and grassland LULC classes shown for Hungary and the Vác-Pest-Danube Valley (north) and South-Zselic (south) agricultural landscape study areas. Based on separate datasets, the national soil database and soil sample data (TAKI, 2022).

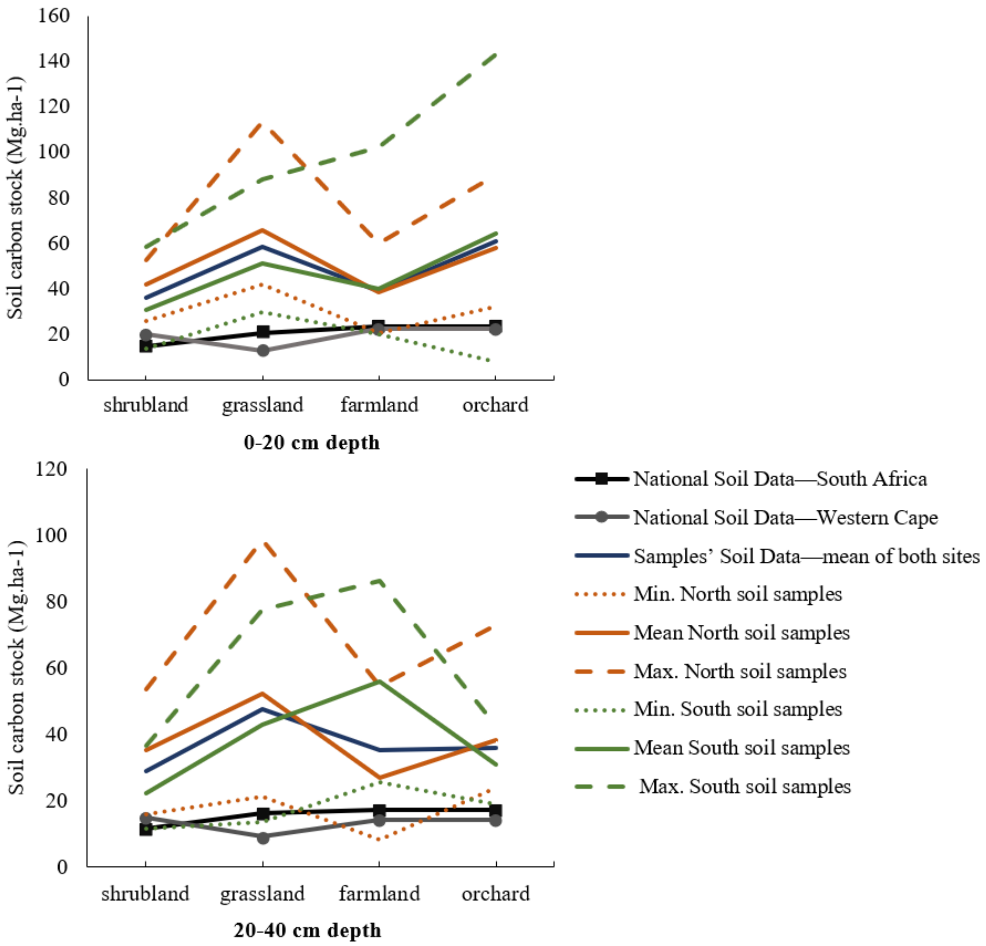


Figure 5. Variation of the carbon stock values for shrubland, grassland, farmland, and orchard LULC classes shown for South Africa (National Soil Data), Western Cape (National Soil Data), study areas combined sampling data, and the Swartland-Tulbagh-Slanghoek (North) and Helderberg-Grabouw-Breede Valley (South) agricultural landscape study areas. Based on separate datasets, the national soil database and soil sample data (ISRIC, 2015).

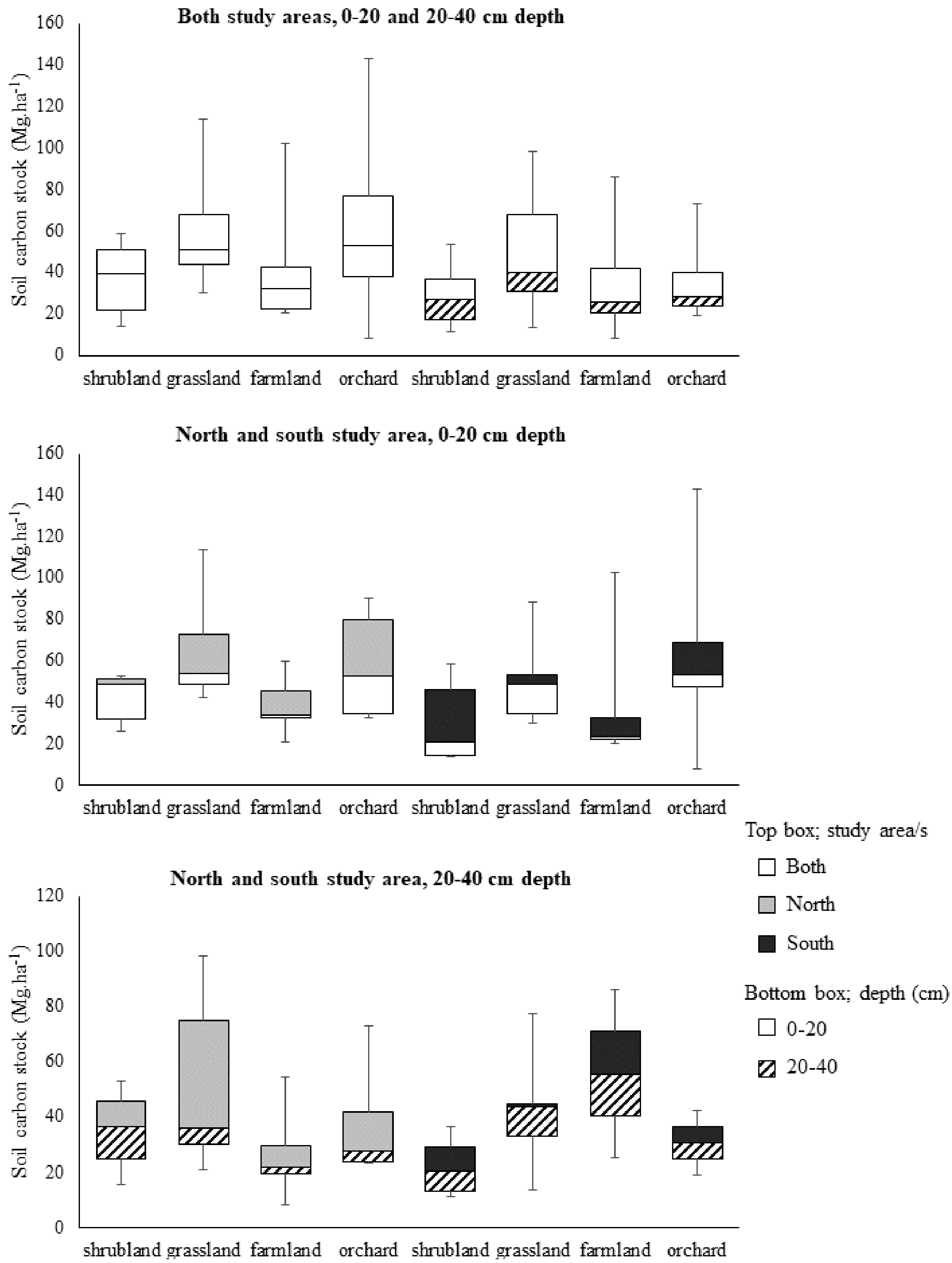


Figure 6. Box plots of soil carbon stock measured from soil samples taken from farmland, forested areas (forest), and grassland LULC in the Swartland-Tulbagh-Slanghoek (North) and Helderberg-Grabouw-Breede Valley (South) agricultural landscape study areas in South Africa, 2021. The upper, middle and lower lines show the third quartile, mean, and first quartile, respectively, where the error bars indicate maximum and minimum.

3.2. 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?

3.2.1. Global atmospheric regulation

3.2.1.1. Pilot study - Hungary

The SCS map results of the InVEST soil carbon models of the two study areas in Hungary are shown in Figure 7, based on the five SCS inventories. 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. 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. Total aggregated SCS (Mg) for 0 to 30 cm depth, i.e., the potential amount of soil carbon stored in each landscape study area, is reported in Figure 8. Figure 8 also shows the mean aggregated CS per hectare for both study areas.

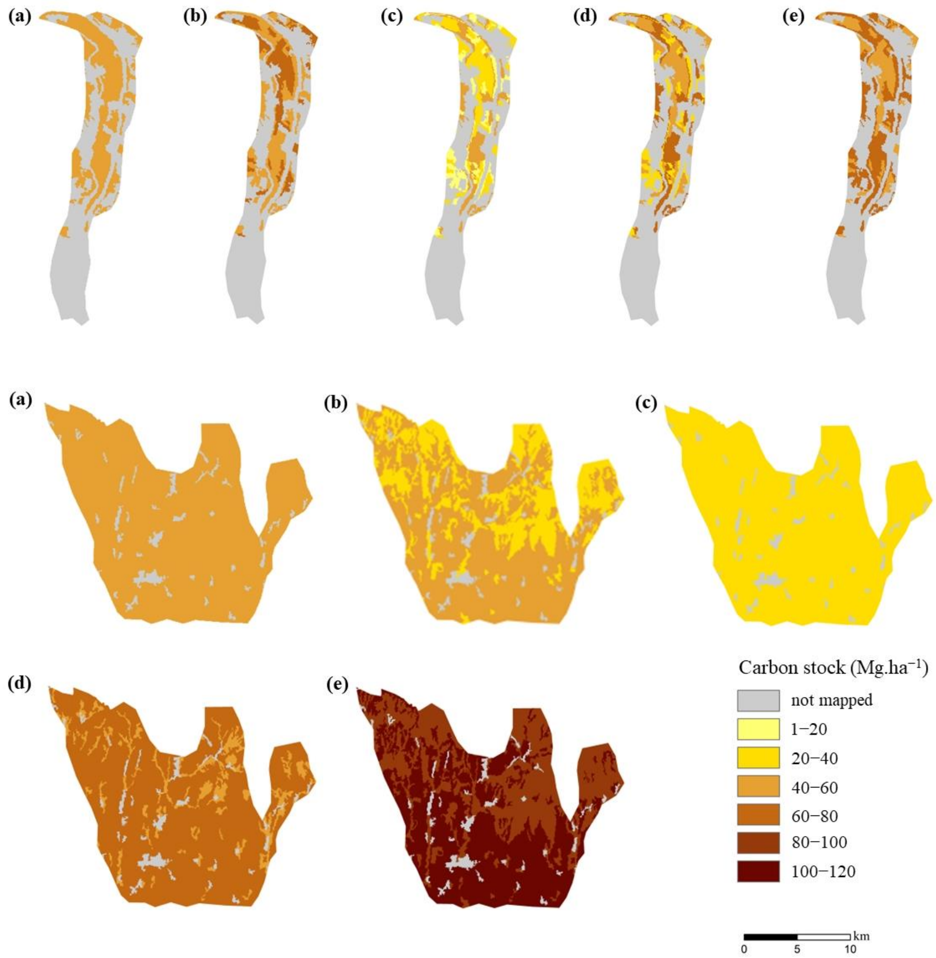


Figure 7. Soil carbon stock (Mg·ha^{-1}) maps of the northern Vác-Pest-Danube Valley (top) and southern South-Zselic (below) study areas in Hungary, based on the soil (0–30 cm) carbon values from the (a) national soil carbon data, (b) mesoregion soil carbon data, and the (c) minimum, (d) mean, and (e) maximum values of the soil samples (1:250 000).

The results of the InVEST SCS spatial models show great variation based on the CS inventory used to develop them, showing how the models are sensitive to data input. Mapping these InVEST SCS models from different datasets established a clearer, more informative, valuation range of topsoil carbon stored in the agricultural landscape study areas, from 0-30 cm depth. Where national CS data is useful to view general spatial trends over large areas (>500 km^2), soil sample-based CS inventories are useful for the medium-large scale (i.e., app. 80 to 500 km^2), as seen for these study areas, to view meaningful soil CS ranges.

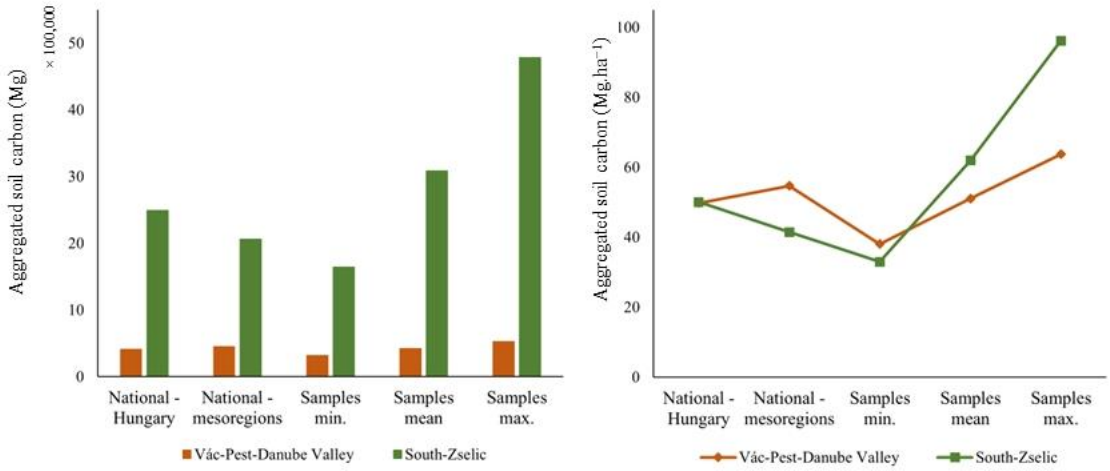


Figure 8. (left) Total potential aggregated soil carbon stock (Mg) stored in 0–30 cm soil depth in the Vác-Pest-Danube Valley and South-Zselic study areas, Hungary, and the (right) mean potential aggregated soil carbon per mapped hectare for both study areas, calculated from each carbon stock inventory dataset, for 0–30 cm depth.

3.2.1.2. Western Cape, South Africa

Study Area 1: Swartland-Tulbagh-Slanghoek
Based on the developed SCS inventories, 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 9. 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.

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, are shown in Figure 10. 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 $Mg{\cdot}ha^{-1}$).

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. 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. 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.

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). 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. 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. The total potential aggregated SCS (Mg) for 0–20 and 20–40 cm depths for both landscape study areas are reported in Figure 11.

Both landscapes, at 0–40 cm depth, present 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.

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 Mg across the landscapes.

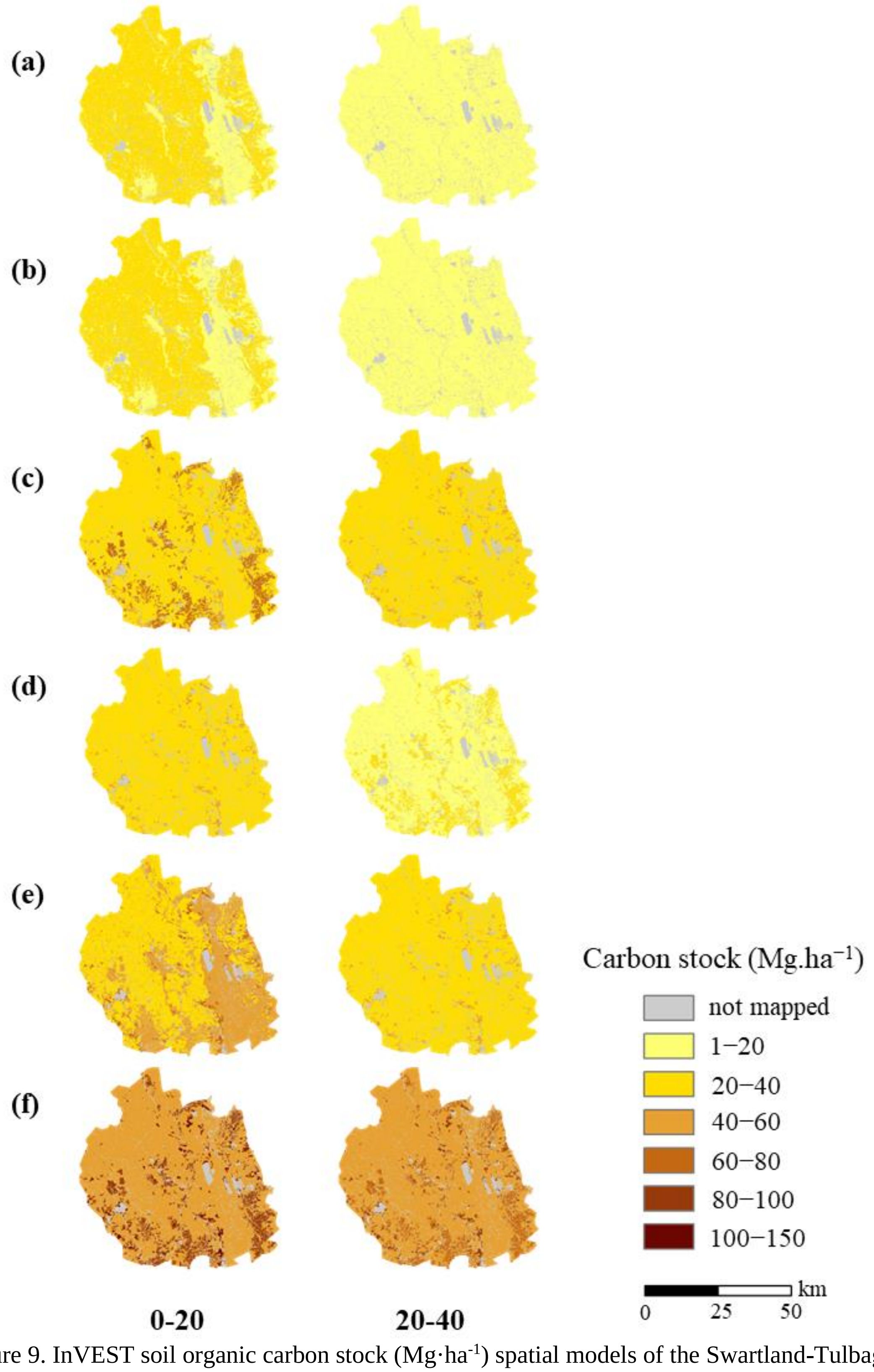


Figure 9. InVEST soil organic carbon stock (Mg·ha^{-1}) spatial models of the Swartland-Tulbagh-Slanghoek (north) study area in the Western Cape, based on the soil (0–20 and 20–40 cm) carbon values from the (a) national soil carbon data of South Africa, (b) Western Cape province-wide national soil data, 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).

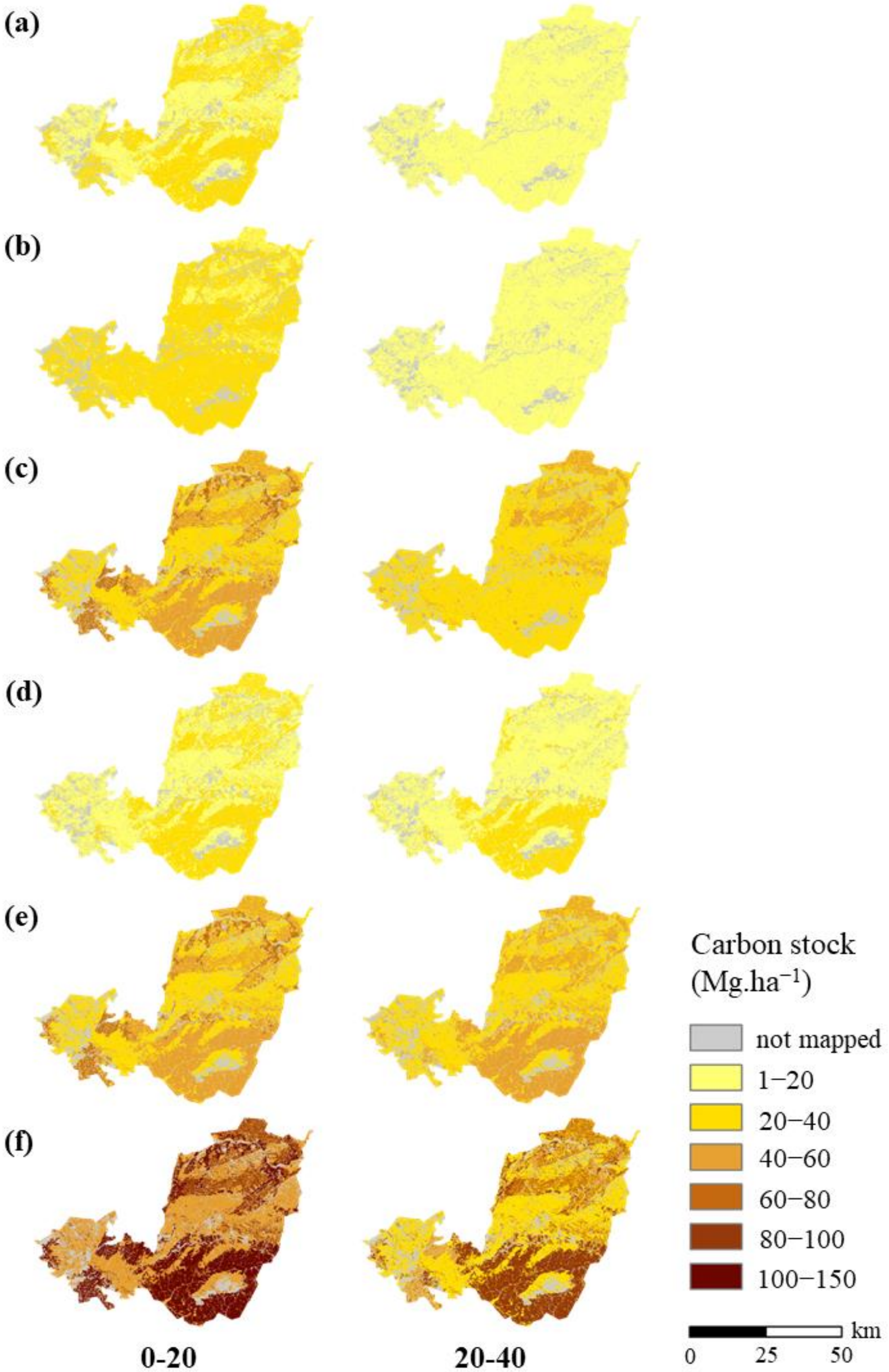
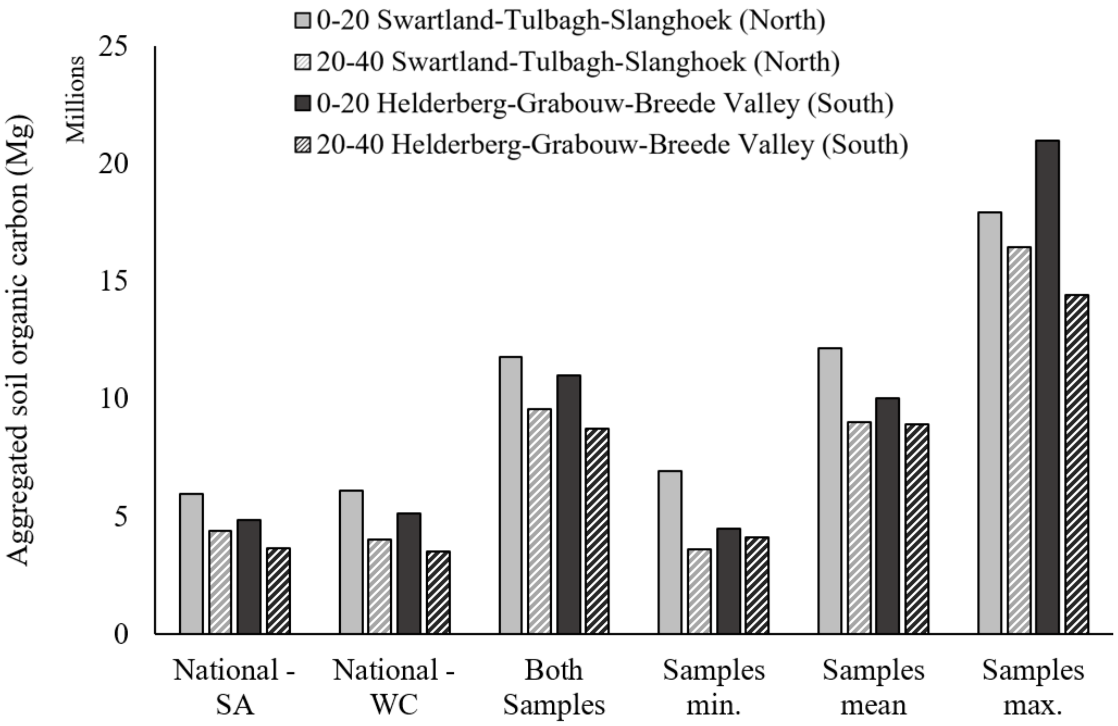


Figure 10. InVEST soil organic carbon stock ($Mg \cdot ha^{-1}$) spatial models of the Helderberg-Grabouw-Breede Valley (south) study area in the Western Cape, based on the soil (0–20 and 20–40 cm) carbon values from the (a) national soil carbon data of South Africa, (b) Western Cape province-wide national 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).



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

Figure 11. (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.

3.2.2. Soil erosion control

Figure 12 shows the sediment retained (avoided erosion by vegetation), an InVEST SDR model output, with and without erosion control measures applied on agricultural LULC. 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. Table 2 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. Agricultural land, such as cropland and orchards, experiences 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). 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.

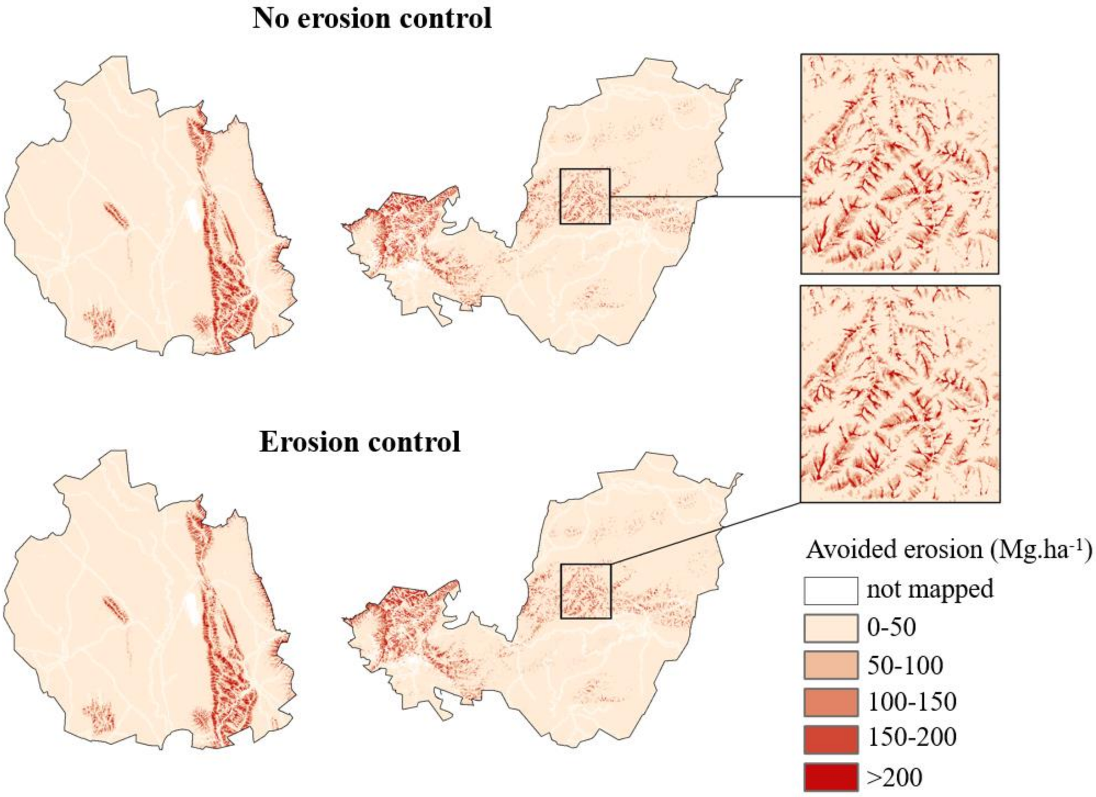


Figure 12. InVEST SDR model output of soil sediment retained annually via avoided erosion by vegetation (Mg·ha^{-1}), under erosion control and none, of the (left) Swartland-Tulbagh-Slanghoek (north) and (right) Helderberg-Grabouw-Breede Valley (south) landscape study areas (1:100,000), with enlarged areas (1:250,000).

Table 2. 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

3.2.3. Crop production

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. 15–24% of cropland is occupied by fruit crops.

Based on the InVEST Crop Production model, the total crop yields of 2012/12 and 2017/18 are reported for both study areas. 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). 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).

The top five crops by extent mapped by the InVEST Crop Production model are shown in Figure 13. 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.

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). 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. 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).

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.

3.3. 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?

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. 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 14 and Figure 15 show the spatial extent of the transition of various LULC classes between 1990 and 2018 of both study areas.

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, where 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).

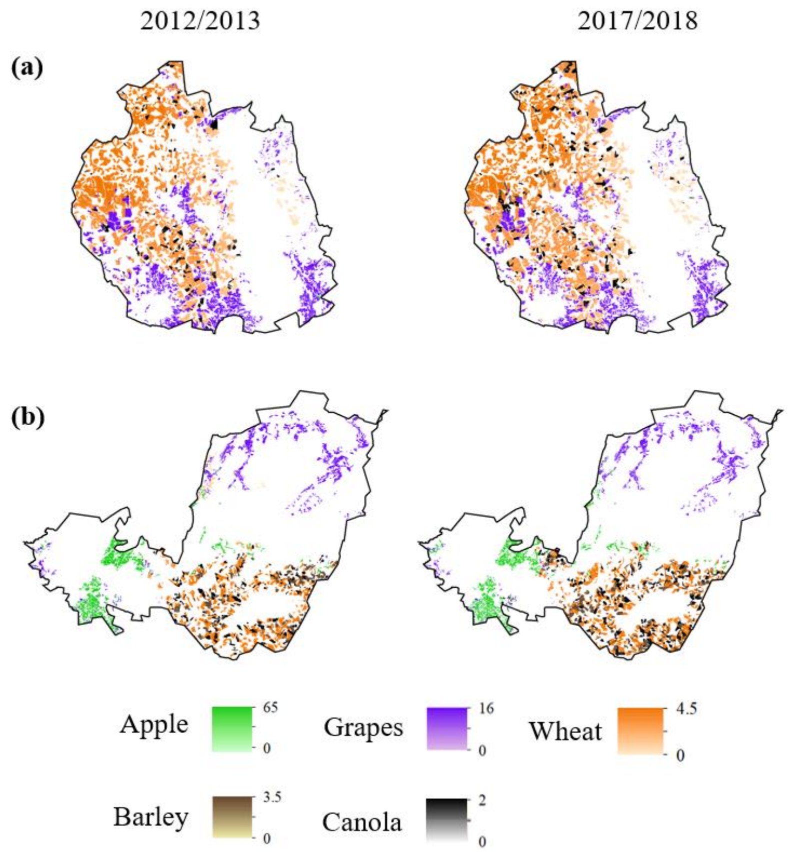


Figure 13. Crop yields (Mg) for the top five crops by extent of the (a) Swartland-Tulbagh-Slanghoek (north) and (b) Helderberg-Grabouw-Breede Valley (south) study areas mapped by the InVEST Crop Production model, based data from the 2012/13 and 2017/18 Crop Censuses.

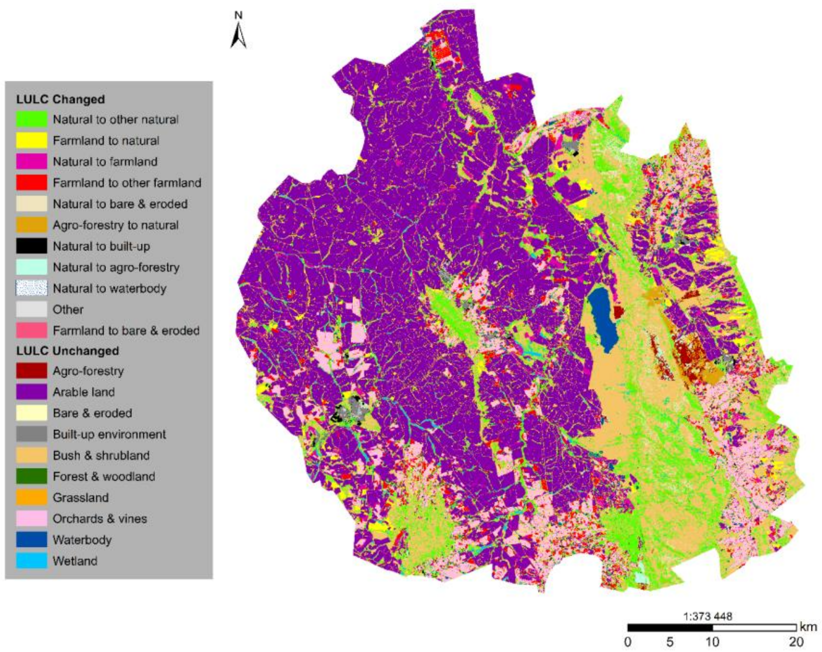


Figure 14. Land use land cover spatial extent change map of the Swartland-Tulbagh-Slanghoek (north) landscape study area between 1990 and 2018, indicating changed and unchanged LULC (DEA, 2019).

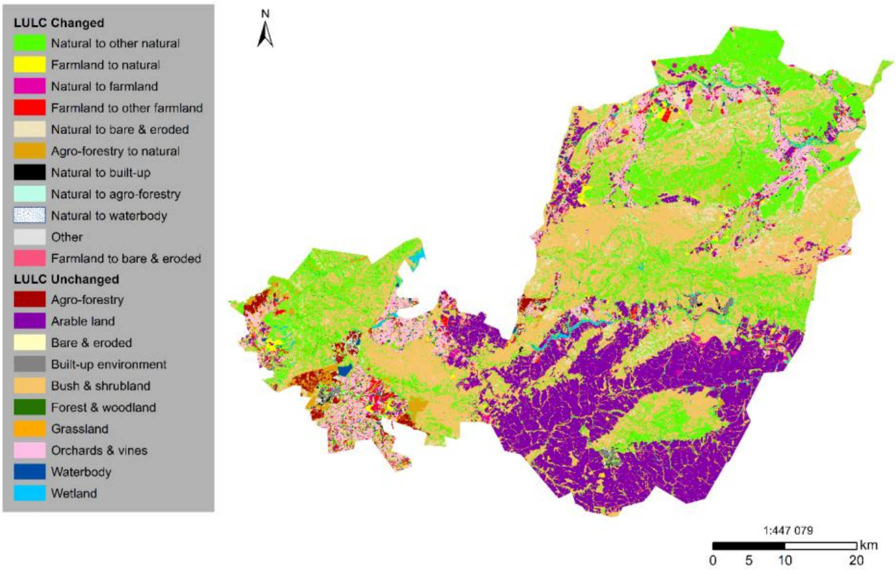


Figure 15. Land use land cover spatial extent change map of the Helderberg-Grabouw-Breede Valley (south) landscape study area between 1990 and 2018, indicating changed and unchanged LULC (DEA, 2019).

3.4. Farmers' impacts on ecosystem services on farmland

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 3. 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.

Table 3. 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 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. • Market price volatility prompts strategies for financial risk management, such as farming intensification and production diversification.

Categories of Drivers	Description
Policy and Regulations	• Agro-tourism and value-added activities are responses to economic and climatic uncertainties. • 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.

Impacts of farmers

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

Table 4 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. 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.

Table 4. 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	Ecosystem service (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	• The 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.

Themes	Farmer Actions and Impacts	Ecosystem service (ES) impacts
Biodiversity	Biodiversity loss	• Erosion and compaction diminish the soil's water retention and filtration capabilities, exacerbating runoff and sedimentation issues. • 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.

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 5 for a summary. However, there are also instances where their actions have unintentionally led to degradation or damage to ES, as shown in Table 4.

Table 5. 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	Implementing efficient water management practices like rainwater harvesting and drip irrigation; 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

Themes	Farmer actions and agricultural practices	Ecosystem service (ES) Impacts
		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.

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.

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

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 (laws and policies) play the most crucial role in farmer decision-making. 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.

3.5. 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 with respect to ES. 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 modelling tool, that could be instrumental in quantifying 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 on protected areas, 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.

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

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 provides a nuanced, evidence-based approach to environmental management, integrating ecological considerations directly into the spatial planning process. 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.
Figure 16 shows the demarcations and spatial distribution of suggested priority areas for consideration for 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 $Mg \cdot ha^{-1}$).
This research identifies three key conservation priority areas. Priority Area 1 comprises smaller, significant regions (north: 57 km^2, south: 143 km^2) known for their soil carbon storage and erosion control, recommending their incorporation into local planning frameworks as active management sites with strict development regulations. Priority Area 2 includes larger areas of medium conservation importance (north: 939 km^2, south: 1200 km^2) and suggests targeted conservation efforts by local and government bodies, with specific guidelines based on local soil and erosion needs. Priority Area 3 involves broader landscape levels, recommending their integration into general conservation programs that incentivize practices supporting ES, guided by insights from farmer interviews.

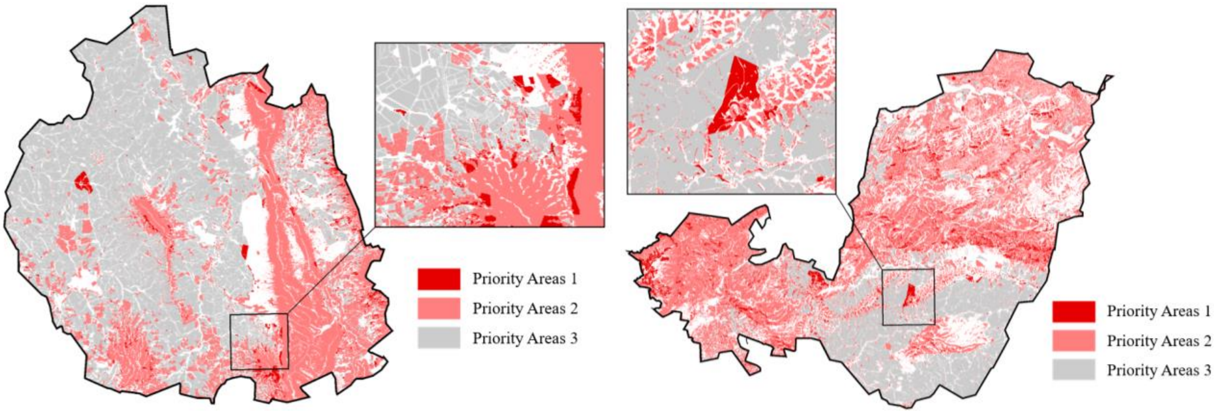


Figure 16. Identified priority areas for spatial planning and development policy considerations for both agricultural landscape study areas (1:100000).

These policy maps offer a tangible representation of how ES like soil carbon, soil erosion control, and crop production can be mapped and thus integrated into local spatial planning policies. This structured approach would facilitate the alignment of planning efforts with ES local conservation goals in the WC (Cowling et al., 2008; von Haaren et al., 2019).

4. CONCLUSIONS AND RECOMMENDATIONS

4.1. Conclusions

SCS, 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.

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 drier the Helderberg-Grabouw-Breede Valley region.

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. A nuanced relationship between agricultural practices and ES impacts was identified. Farmers adopt strategies to enhance beneficial services that support agricultural productivity. Some practices lead to negative consequences, including soil degradation, water mismanagement, pollution, biodiversity reduction, and habitat and ecosystem function loss. To mitigate adverse impacts and promote environmental sustainability, farmers are increasingly implementing ES-supporting practices.

Significant policy misalignments and gaps in existing municipal spatial planning and development frameworks are identified. 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 is showcased, and these findings advocate for an urgent revision of spatial planning frameworks for agricultural landscapes in the WC.

4.2. Recommendations

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.

This study proposes several recommendations to enhance spatial planning in the WC, ensuring a sustainable balance between agricultural productivity and ES conservation. It advocates for the integration of InVEST models into spatial planning frameworks to facilitate the evaluation of land use scenarios, optimizing crop production in alignment with environmental conservation, and thereby bolstering the long-term sustainability and resilience of the agricultural sector. Emphasis should be placed on developing policies that prioritize ecological integrity as much as agricultural yield, fostering a balance between agricultural development and environmental stewardship through sustainable land management practices. Further research is essential to understand the economic and environmental factors influencing farmer decisions, providing the basis for policies that support ES-enhancing practices that align with farm management realities. Expanding the use of tools like InVEST for ES assessments in spatial planning, along with the development of management guidelines and educational programs, will equip stakeholders—farmers, planners, policymakers—with the necessary tools for the sustainable management of ES on farmland. Continued support for research and educational initiatives that deepen the understanding of ES in agricultural landscapes is critical, including investigations into the efficacy of conservation agriculture, the impact of technological innovations on ES, and the integration of ES approaches into South African spatial planning policy. These comprehensive recommendations aim to enhance the scientific basis for decision-making and improve the effectiveness of spatial planning in fostering sustainable agricultural practices and conserving ES.

5. KEY SCIENTIFIC FINDINGS AND IMPORTANT OUTPUT

1. **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. Compared to the baseline practice of using generalised national (country-level) carbon stock (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.
2. **Novel CS datasets produced:** Localised soil CS inventory datasets were developed for the four study areas in Hungary and Western Cape, from which InVEST carbon mapping was done to produce CS maps of the study areas, these were: (a) country-wide CS based on national soil data; (b) (meso)region-specific CS; and the soil sample data was used to map the (c) minimum, (d) mean, and (e) maximum of CS for the study areas.
3. **Novel results reported and ecosystem service (ES) assessment maps produced of agricultural landscapes Western Cape:** InVEST models were used to map and assess three ES indicators—SCS (as a proxy for global atmospheric climate regulation), soil erosion control, and crop production—across two agricultural landscape study areas in the Western Cape, 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.
4. **Novel results reported on the dynamics of farmer decision-making that impacts ES on farms in the Western Cape study areas;** This study is the first one 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. 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.
5. **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 Western Cape, where farmers recognize the critical role of wind in mitigating mold growth on vineyard foliage.
6. **Novel showcasing of the integration of ES assessment in spatial planning:** This study is the first to showcase the integration of InVEST model outputs for CS, soil erosion control and food production into the spatial planning for the Swartland-Tulbagh-Slanghoek and Helderberg-Grabouw-Breede Valley agricultural landscape study areas, Western Cape. The policy proposal maps delineate ES hotspots and recommend incorporation into regional and municipal spatial planning, offering an evidence-based approach to Western Cape municipal spatial planning and development frameworks to include consideration of ES in local government spatial planning for agricultural landscapes.

6. REFERENCES

Abd Elbasit, M. A. M., Knight, J., Liu, G., Abu-Zreig, M. M., & Hasaan, R. (2021). Valuation of Ecosystem Services in South Africa, 2001–2019. *Sustainability*, *13*(20), 11262. doi: 10.3390/su132011262

Agrártudományi Kutatóközpont. (1992). *Hungary Agrotopographical Database* [Spatial Soil Information System]. In *national soil database*. Hungary: Talajtani Intézet. Retrieved from http://enfo.agt.bme.hu/gis/korinfo/; https://dosoremi.hu/en/maps/soil-organic-carbon-stock-1992-0-30-cm/

Batjes, N. (2004). *SOTER-based soil parameter estimates (SOTWIS) for Southern Africa* [Vector data]. In *Report 2004/04*. Online: ISRIC - World Soil Information. Retrieved from https://data.isric.org/geonetwork/srv/eng/catalog.search#/metadata/6eb4dafe-a184-44e3-9ed1-d2f73020725d

Beck, H. E., Zimmermann, N. E., McVicar, T. R., Vergopolan, N., Berg, A., & Wood, E. F. (2018). Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Scientific Data*, *5*(1), 180214. doi: 10.1038/sdata.2018.214

Bennett, E. M., Peterson, G. D., & Gordon, L. J. (2009). Understanding relationships among multiple ecosystem services. *Ecology Letters*, *12*(12), 1394–1404. doi: 10.1111/j.1461-0248.2009.01387.x

Borrelli, P., Robinson, D. A., Fleischer, L. R., Lugato, E., Ballabio, C., Alewell, C., … Panagos, P. (2017). An assessment of the global impact of 21st century land use change on soil erosion. *Nature Communications*, *8*(1), 2013. doi: 10.1038/s41467-017-02142-7

Borsos, B. (2013). The Eco-Village Concept in a Model Experiment in South-West Hungary. *Journal of Settlements and Spatial Planning*, *4*(1), 69–76.

Bourne, A., Holness, S., Holden, P., Scorgie, S., Donatti, C. I., & Midgley, G. (2016). A Socio-Ecological Approach for Identifying and Contextualising Spatial Ecosystem-Based Adaptation Priorities at the Sub-National Level. *PLOS ONE*, *11*(5), e0155235. doi: 10.1371/journal.pone.0155235

Cegielska, K., Noszczyk, T., Kukulska, A., Szylar, M., Hernik, J., Dixon-Gough, R., Jombach, S., Valánszki, I., & Filepné Kovács, K. (2018). Land use and land cover changes in post-socialist countries: Some observations from Hungary and Poland. *Land Use Policy*, *78*, 1–18. doi: 10.1016/j.landusepol.2018.06.017

Choruma, D. J., & Odume, O. N. (2019). Exploring Farmers' Management Practices and Values of Ecosystem Services in an Agroecosystem Context—A Case Study from the Eastern Cape, South Africa. *Sustainability*, *11*(23), 6567. doi: 10.3390/su11236567

Clark, B., & Ratcliffe, G. (2007). *Berg River baseline monitoring programme. Final report volume 5: Synthesis* (No. DWAF Report No. P WMA 19/G10/00/2107; p. 111). Pretoria, South Africa: Department of Water Affairs and Forestry.

Cowling, R. M., Egoh, B., Knight, A. T., O'Farrell, P. J., Reyers, B., Rouget, M., Roux, D. J., Welz, A., & Wilhelm-Rechman, A. (2008). An operational model for mainstreaming ecosystem services for implementation. *Proceedings of the National Academy of Sciences*, *105*(28), 9483–9488. doi: 10.1073/pnas.0706559105

Crossman, N. D., Burkhard, B., Nedkov, S., Willemen, L., Petz, K., Palomo, I., … Maes, J. (2013). A blueprint for mapping and modelling ecosystem services. *Ecosystem Services*, *4*, 4–14. doi: 10.1016/j.ecoser.2013.02.001

CWDM. (2022). *Cape Winelands Spatial Development Framework 2021/2026* (p. 125). Cape Winelands, South Africa: Cape Winelands District Municipality. Retrieved from Cape Winelands District Municipality website: https://www.capewinelands.gov.za/download/cwdm-sdf-2021-2026/?ind=1657101038560&filename=CWDM-SDF-2021-2026.pdf&wpdmdl=13994&refresh=65c3cb1eb50d11707330334

Daily, G. C. (2013). Nature's Services: Societal Dependence on Natural Ecosystems (1997). In Libby Robin, Sverker Sörlin, & Paul Warde (Eds.), *The future of nature: Documents of global change* (pp. 454–464). Connecticut, United States: Yale University Press. doi: 10.12987/9780300188479-039

DEA. (2019). *2018 South African National Land-Cover Change Assessments (Comparison of SANLC 2018 with SANLC's 1990 & 2013/14)* [Raster dataset]. Pretoria, South Africa: Deptartment of Environmental Affairs. Retrieved from https://egis.environment.gov.za/data_egis/data_download/current

Drury, R., Homewood, K., & Randall, S. (2011). Less is more: The potential of qualitative approaches in conservation research. *Animal Conservation*, *14*(1), 18–24. doi: 10.1111/j.1469-1795.2010.00375.x

du Plessis, J., & Schloms, B. (2017). An investigation into the evidence of seasonal rainfall pattern shifts in the Western Cape, South Africa. *Journal of the South African Institution of Civil Engineering*, *59*(4), 47–55. doi: 10.17159/2309-8775/2017/v59n4a5

DWAF. (2003). *Breede River Basin Study* (No. PH 00/00/3102; p. 170). Pretoria, South Africa: Department of Water Affairs and Forestry.

EEA. (2012). *Natura 2000 Network Viewer*. In *Natura 2000 Dataset*. European Environment Agency. Retrieved from https://natura2000.eea.europa.eu

Elmqvist, T., Tuvendal, M., Krishnaswamy, J., & Hylander, K. (2011). *Managing Trade-offs in Ecosystem Services* (p. 17). Division of Environmental Policy Implementation Paper N° 4, United Nations Environment Programme.

FAO. (2018). *Soil organic carbon mapping cookbook* (2nd edition). Rome, Italy: Food and Agriculture Organization of the United Nations.

FAO. (2022). *Global Soil Organic Carbon Sequestration Potential Map – GSOCseq v.1.1: Technical report*. Rome, Italy: FAO. doi: 10.4060/cb9002en

Findlater, K. M., Satterfield, T., Kandlikar, M., & Donner, S. D. (2018). Six languages for a risky climate: How farmers react to weather and climate change. *Climatic Change*, *148*(4), 451–465. doi: 10.1007/s10584-018-2217-z

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., … Snyder, P. K. (2005). Global Consequences of Land Use. *Science*, *309*(5734), 570–574. doi: 10.1126/science.1111772

Garbach, K., Milder, J. C., Montenegro, M., Karp, D. S., & DeClerck, F. A. J. (2014). Biodiversity and Ecosystem Services in Agroecosystems. In N. K. Van Alfen (Ed.), *Encyclopedia of Agriculture and Food Systems* (2nd ed., pp. 21–40). London, U.K.: Academic Press. doi: 10.1016/B978-0-444-52512-3.00013-9

Gergely, A. (2011). Habitat mapping of Natura 2000 sites in Szentendre Island in the Central Region of Hungary – experiences of the remapping. *Problemy Ekologii Krajobrazu*, *30*, 377–380.

Giliomee, J. H. (2006). Conserving and increasing biodiversity in the large-scale, intensive farming systems of the Western Cape, South Africa. *South African Journal of Science*, *102*(9–10), 375–378.

Goodenough, A., & Hart, A. G. (2017). *Applied Ecology: Monitoring, Managing, and Conserving*. London, U.K.: Oxford University Press.

Goodness, J., & Anderson, P. M. L. (2013). Local Assessment of Cape Town: Navigating the Management Complexities of Urbanization, Biodiversity, and Ecosystem Services in the Cape Floristic Region. In T. Elmqvist, M. Fragkias, J. Goodness, B. Güneralp, P. J. Marcotullio, R. I. McDonald, … C. Wilkinson (Eds.), *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities: A Global Assessment* (pp. 461–484). Dordrecht: Springer Netherlands. doi: 10.1007/978-94-007-7088-1_24

GreenCape. (2016). *Agriculture 2016 Market Intelligence Report* (p. 60). Cape Town, South Africa: GreenCape. Retrieved from GreenCape website: https://green-cape.co.za/wp-content/uploads/2022/10/GreenCape-Agriculture-MIR-2016-3.pdf

Grunewald, K., & Bastian, O. (Eds.). (2015). *Ecosystem Services – Concept, Methods and Case Studies*. Berlin, Germany: Springer.

IPBES. (2019). *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* (No. ISBN 978-3-947851-20-1; p. 1144). Bonn, Germany: IPBES secratariat. doi: 10.5281/zenodo.6417333

ISRIC. (2015). *Africa Soil Profiles database: Africa SoilGrids—Soil organic carbon (SOC)* [GTiff data]. Online: ISRIC - World Soil Information. Retrieved from https://data.isric.org/geonetwork/srv/eng/catalog.search#/metadata/9a66a37e-8a4e-463b-b83a-fd49049c323a

Kaleeswari, R. K., Rageswari, R., & Prabhaharan, J. (2013). *Handbook of Soil Fertility*. Lanham: Satish Serial Publishing House.

Kamish, W. (2008). *Hydrosalinity modelling of the Berg River using ACRU Salinity* (Master Thesis). Stellenbosch University, Stellenbosch, South Africa.

KSH. (2019). *Magyarország közigazgatási helynévkönyve, 2019 (Gazetteer of Hungary)* (No. ISSN 1217-2952; p. 234). Budapest, Hungary: Hungarian Central Statistical Office (Központi Statisztikai Hivatal).

Linder, H. P. (2003). The radiation of the Cape flora, southern Africa. *Biological Reviews of the Cambridge Philosophical Society*, *78*(4), 597–638. doi: 10.1017/S1464793103006171

Matson, P. A., Parton, W. J., Power, A. G., & Swift, M. J. (1997). Agricultural Intensification and Ecosystem Properties. *Science*, *277*(5325), 504–509. doi: 10.1126/science.277.5325.504

MEA (Ed.). (2005). *Ecosystems and human well-being: Synthesis* (Millennium Ecosystem Assessment Overall Synthesis Report). Washington, DC, U.S.: Island Press.

Metzger, M. J., Rounsevell, M. D. A., Acosta-Michlik, L., Leemans, R., & Schröter, D. (2006). The vulnerability of ecosystem services to land use change. *Agriculture, Ecosystems & Environment*, *114*(1), 69–85. doi: 10.1016/j.agee.2005.11.025

Municipal Demarcation Board. (2018). *District & Local Municipalities (South Africa)* [Feature Layer]. Online: Municipal Demarcation Board. Retrieved from https://dataportal-mdb-sa.opendata.arcgis.com/

Nasir Ahmad, N. S. B., Mustafa, F. B., Muhammad Yusoff, S. Y., & Didams, G. (2020). A systematic review of soil erosion control practices on the agricultural land in Asia. *International Soil and Water Conservation Research*, *8*(2), 103–115. doi: 10.1016/j.iswcr.2020.04.001

Natural Capital Project. (2022). InVEST 3.13.0.post5+ug.gce76c6e User's Guide [InVEST documentation]. Retrieved 17 April 2023, from InVEST User Guide website: https://storage.googleapis.com/releases.naturalcapitalproject.org/invest-userguide/latest/en/index.html

Newing, H., Eagle, C., Puri, R., & Watson, C. W. (2011). *Conducting Research in Conservation: Social Science Methods and Practice*. London: Routledge. doi: 10.4324/9780203846452

Orosz, G., Ónodi, G., Sipos, B., Molnár, D., & Váradi, I. (2015). Szentendre Eco Island in the Agglomeration of Budapest. *Conference Proceedings*, 183. Rome, Italy: Università di Pisa.

Partridge, A., Morokong, T., & Sibulali, A. (2022). *Western Cape Agricultural Sector Profile: 2020* (p. 65). Elsenburg, South Africa: Western Cape Department of Agriculture.
Pasquini, L., & Cowling, R. M. (2015). Opportunities and challenges for mainstreaming ecosystem-based adaptation in local government: Evidence from the Western Cape, South Africa. *Environment, Development and Sustainability*, *17*(5), 1121–1140. doi: 10.1007/s10668-014-9594-x
Petrokofsky, G., Kanamaru, H., Achard, F., Goetz, S. J., Joosten, H., Holmgren, P., … Wattenbach, M. (2012). Comparison of methods for measuring and assessing carbon stocks and carbon stock changes in terrestrial carbon pools. How do the accuracy and precision of current methods compare? A systematic review protocol. *Environmental Evidence*, *1*(1), 6. doi: 10.1186/2047-2382-1-6
Power, A. G. (2010). Ecosystem services and agriculture: Tradeoffs and synergies. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *365*(1554), 2959–2971. doi: 10.1098/rstb.2010.0143
Renard, K. G., Foster, G., Weesies, G., McCool, D., & Yoder, D. (Eds.). (1997). *Predicting soil erosion by water: A guide to conservation planning with the revised universal soil loss equation (RUSLE)*. Washington, D. C: U.S. Department of Agriculture.
Reyers, B., O'Farrell, P., Cowling, R., Egoh, B., Le Maitre, D., & Vlok, J. (2009). Ecosystem Services, Land-Cover Change, and Stakeholders: Finding a Sustainable Foothold for a Semiarid Biodiversity Hotspot. *Ecology and Society*, *14*(1), 38. doi: 10.5751/ES-02867-140138
Rutherford, M. C., Mucina, L., & Powrie, L. W. (2006). Chapter 3: Biomes and Bioregions of Southern Africa. In L. Mucina & M. C. Rutherford (Eds.), *The vegetation of South Africa, Lesotho and Swaziland (Strelitzia)* (Vol. 19). Pretoria, South Africa: South African National Biodiversity Institute. Retrieved from http://hdl.handle.net/20.500.12143/328
SANBI. (2018). *The Vegetation Map of South Africa, Lesotho and Swaziland, Mucina, L., Rutherford, M.C. and Powrie, L.W. (Editors)* [Feature Layer]. Online: South African National Biodiversity Institute. Retrieved from http://bgis.sanbi.org/Projects/Detail/186
Sándor, S., Pál, A., László, Á., József, G., Ágoston, J., Ferenc, K., … Pécsi, M. (1990). *Magyarország kistájainak katasztere I-II [Cadastre of the small regions of Hungary I-II]* (S. Marosi & S. Somogyi, Eds.). Budapest, Hungary: Geographical Research Institute of the Hungarian Academy of Sciences.
Schulze, R. E. (2009). *South African Atlas of Climatology and Agrohydrology* (2nd ed.). Pretoria, South Africa: Water Research Commission.
Schulze, R. E. (Ed.). (2017). *Agriculture and Climate Change in South Africa: On Vulnerability, Adaptation and Climate Smart Agriculture*. Durban, South Africa: Centre for Water Resources Research.
Sitas, N., Prozesky, H. E., Esler, K. J., & Reyers, B. (2014). Opportunities and challenges for mainstreaming ecosystem services in development planning: Perspectives from a landscape level. *Landscape Ecology*, *29*(8), 1315–1331. doi: 10.1007/s10980-013-9952-3
Smith, H. F., & Sullivan, C. A. (2014). Ecosystem services within agricultural landscapes—Farmers' perceptions. *Ecological Economics*, *98*, 72–80. doi: 10.1016/j.ecolecon.2013.12.008
Stats SA. (2011). Statistics by place; Statistics South Africa. Retrieved 30 September 2022, from Statistics South Africa website: https://www.statssa.gov.za/?page_id=964
Szabó, Z., Prohászka, V., & Sallay, Á. (2021). The Energy System of an Ecovillage: Barriers and Enablers. *Land*, *10*(7), 682. doi: 10.3390/land10070682
TAKI. (2022). *DOSoReMI (Digital , Optimized , General Soil Maps and Spatial Information in Hungary)* [Raster]. Budapest, Hungary: Hungarian Institute of Soil Science. Retrieved from https://dosoremi.hu/
Tyson, P. D., & Preston-Whyte, R. A. (2000). *The weather and climate of southern Africa* (2nd ed.). Cape Town, South Africa: Oxford University Press.
von Haaren, C., Lovett, A. A., & Albert, C. (2019). *Landscape Planning with Ecosystem Services: Theories and Methods for Application in Europe*. Amsterdam, The Netherlands: Springer Netherlands.
WCDM. (2020). *West Coast District Spatial Development Framework* (p. 165). West Coast, South Africa: West Coast District Municipality. Retrieved from West Coast District Municipality website: https://www.weskusdm.gov.za/download/spatial-development-framework-2020/
WCG. (2014). *Western Cape Provincial Spatial Development Framework* (p. 111). Cape Town, South Africa: Western Cape Department of Local Government; Department of Environmental Affairs and Development Planning. Retrieved from Western Cape Department of Local Government; Department of Environmental Affairs and Development Planning website: https://www.westerncape.gov.za/eadp/files/atoms/files/psdf_report.pdf
WCG. (2019). *Western Cape Land Use Planning Guidelines Rural Areas* (p. 93). Cape Town, South Africa: Western Cape Government Department of Environmental Affairs and Development Planning. Retrieved from Western Cape Government Department of Environmental Affairs and Development Planning website: https://www.westerncape.gov.za/eadp/sites/eadp.westerncape.gov.za/files/atoms/files/Rural%20Areas%20Guideline_web_0.pdf
Zhu, A. X., Yang, L., Li, B., Qin, C., English, E., Burt, J. E., & Zhou, C. (2008). Purposive Sampling for Digital Soil Mapping for Areas with Limited Data. In A. E. Hartemink, A. McBratney, & M. de L. Mendonça-Santos (Eds.), *Digital Soil Mapping with Limited Data* (pp. 233–245). Dordrecht: Springer Netherlands. doi: 10.1007/978-1-4020-8592-5_20

7. LIST OF PUBLICATIONS

JOURNAL ARTICLES AND CONFERENCE FULL PAPERS

1. **Nel, L.**, Boeni, A.F., Prohászka, V., Szilágyi, A., Kovács, E., Pásztor, L., Centeri, C. InVEST soil carbon stock modelling as an ecosystem service in agricultural landscapes. Sustainability (2022) 14(9808):1-19. DOI: 10.3390/su14169808. **(Q1, IF: 3.251)**
2. Masoudi, M., Centeri, C., Jakab, G., **Nel, L**., Mojtahedi, M. GIS-Based Multi-Criteria and Multi-Objective Evaluation for Sustainable Land-Use Planning (Case Study: Qaleh Ganj County, Iran) “Landuse Planning Using MCE and Mola”. International Journal of Environmental Research (2021). DOI: 10.1007/s41742-021-00326-0. **(Q2, IF: 1.5)**
3. **Nel, L.** Riparian conservation management needs habitat quality mapping. Columella Journal of Agriculture and Environmental Sciences (2020) 7(2): 15-23. DOI: 10.18380/SZIE.COLUM.2020.7.2.15.
4. **Nel, L.**, Masoudi, M. Potential Carbon Sequestration Across Szentendre Island. Tájökológiai Lapok (2020) 18(2): 165-173. ISSN: 1589-4673 **(Q4)**
5. **Nel, L.**, Teffo, T.R., Mabuyakhulu, M.V., Munnisunker, S., Kruger, P.J., Nzimande, N.P. Sustainable development of South Africa: an in-country perspective. In: Zihaly, G. (Ed.). Sustainability in Transforming Cities. 26th International Sustainable Development Research Society (ISDRS): Proceedings of peer-reviewed contributors. Budapest, Hungary: Faculty of Economic and Social Sciences, Budapest University of Technology and Economics (2020) pp. 906-918.
6. **Nel, L.** Landscape Metrics of Szentendre Island, Hungary (1998-1999). In: Celkova, A. (ed) 26th International Poster Day: Transport of Water, Chemicals and Energy in the Soil-Plant-Atmosphere System: Proceedings of peer-reviewed contributors. Pozsony, Slovakia: Slovak Academy of Sciences, Institute of Hydrology, (2019) pp. 140–151.
7. **Nel, L.**, Szilágyi, A. Selection Of Indicators For Assessment Of Soil-Related Agricultural Ecosystem Services And Sustainable Management. In: Anežka, Čelková (eds.) 25th International Poster Day and Institute of Hydrology Open day: Transport of Water, Chemicals and Energy in the Soil-Plant-Atmosphere System: Proceedings of peer-reviewed contributors. Pozsony, Slovakia: Institute of Hydrology SAS, (2018) pp. 103-118.

CONFERENCE ABSTRACTS

1. **Nel, L.**, Szilágyi, A. Using ecosystem service maps to improve environmental management. In: 29th Session of the Permanent European Conference for the study of the Rural Landscape: Living together in European Rural Landscape Abstract Book, Department of Anthropology, Geography and History, Universidad de Jaén (2021) pp. 82. Online Session 29-30 September 2021 [https://eventos.ujaen.es/file_manager/getFile/94660.html]
2. Szilágyi, A., Jakab, G., Fodor, H., Kun, R., **Nel, L.**, Centeri, Cs. Total organic carbon content and quality of soils from different farming systems. In: 29th Session of the Permanent European Conference for the study of the Rural Landscape: Living together in European Rural Landscape Abstract Book, Department of Anthropology, Geography and History, Universidad de Jaén (2021) pp. 80-81. Online Session 29-30 September 2021 [https://eventos.ujaen.es/file_manager/getFile/94660.html]
3. **Nel, L.**, Centeri, C., Kovács, E., Vona, V., Vona, M. A talaj szervesszén-tartalmának vizsgálata laboratóriumban és talajszkennerrel az InVest modell ökoszisztéma elemzésének pontosításához. Talajtani Vándorgyűlést, „Alkalmazkodó mező- és erdőgazdálkodás”, Sárváron, 2020. szeptember 25-én. http://talaj.hu/
4. **Nel, L.**, Simba, L.D., Centeri, C., Kovacs, E. Natural Vegetation Change across the Western Cape Province, 1990-2018. In: 2020 Fynbos Forum Booklet with Abstracts, Department of Conservation Ecology and Entomology, Stellenbosch University, South Africa (2020). [https://fynbosforum2020.co.za/wp-content/uploads/2020/09/FYNBOS-FORUM-2020_Abstracts_Final_ALL.pdf]
5. **Nel, L.**, Teffo, T.R., Mabuyakhulu, M.V., Munnisunker, S., Kruger, P.J., Nzimande, N.P. Sustainable development of South Africa: an in-country perspective. In: Zihaly, G. (Ed.). Sustainability in Transforming Cities. 26th International Sustainable Development Research Society (ISDRS): Proceedings of peer-reviewed contributors. Budapest, Hungary: Faculty of Economic and Social Sciences, Budapest University of Technology and Economics (2020) pp. 191.
6. **Nel, L.** Landscape Metrics of Szentendre Island, Hungary (1998-1999). In: Celkova, A. (ed) 26th International Poster Day: Transport of Water, Chemicals and Energy in the Soil-Plant-Atmosphere System: Proceedings of peer-reviewed contributors. Pozsony, Slovakia: Slovak Academy of Sciences, Institute of Hydrology, (2019) pp. 282–283.
7. **Nel, L.**, Centeri, Cs., Kovács, E. Mapping Carbon Storage on Szentendre Island, Hungary. In Zdruli, P; Sallaku, F; Costantini, E; Dazzi, C (eds.) Soil's contribution to people: from food to life supporting services. 9th ESSC International Congress, book of abstracts and field excursion. Napoli, Italy: Le Penseur, (2019) p. 95.
8. **Nel, L.** Mapping River Conservation Priority Areas along the Berg River, South Africa. In: Jakab, Gusztáv; Csengeri, Erzsébet (eds.) XXI. Century Water Management at The Intersection of Science: II International Conference on Water Science. Szarvas, Hungary: Szent István University, (2019) p. 293.
9. **Nel, L.**, Szilágyi, A. Selection of Indicators for Assessment of Soil-Related Agricultural Ecosystem Services and Sustainable Management. In: Čelková, A. (ed.) 25th International Poster Day and Institute of Hydrology Open day: Transport of Water, Chemicals and Energy in the Soil-Plant-Atmosphere System: Proceedings of peer-reviewed contributors. Pozsony, Slovakia: Institute of Hydrology SAS, (2018) p. 251.