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The effect of management strategies on carbon uptake of highway ancillary areas in Northern Germany

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Bachelor thesis, 15 credits, in **Physical Geography and Ecosystem Analysis**

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Abstract

Carbon storage capacity estimations of terrestrial vegetation are necessary to understand the limit of possible carbon emissions. General approximations, of a landscapes carbon pool capacity, can be performed using the InVEST-model. It estimates the carbon pool storage of a landscape, based on land use land cover classes, which this thesis aims to test on the highay-ancillary environment of the A7-motorway in northern Germany. Furthermore, the carbon sink capacity is compared to alternative roadside utilization, like the installation of photovoltaic systems. It is also investigated what degree of pool size change can be expected with different management strategies and intensities. The study includes an InVEST-model-approach based GIS analysis of the current carbon pools of the A7-highways ancillary areas, on which different management and planting strategies are executed. The results and discussion show comparative estimations of the total and mean storage capacities of areas under different management regiemes. The effectiveness is also discussed in comparison with the states mean pool values of shrublands, grasslands and forested areas, to delineate the roadside vegetations storage effectiveness. It is found that roadside vegetation is less produtive then Schleswig-Holsteins other landcovers. Typically roadside areas consist of planted vegetation that leads to the smallest total carbon pool and not of management strategies with high levels of effectiveness. Management intensities impact the carbon storage and gentle maintenance leads to higher total storage, but alternative utilization of the ancillary areas leads to the highest total contribution to reaching the goal of a global warming reduction.

Keywords: InVEST- model, Highway ancillary areas, carbon pool estimations, management factors

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Abbreviations

AG	above-ground
BG	below-ground
ABG	above-ground biomass
BGB	below-fround biomass
C stock	carbon stock
GHG	greenhouse gas
LULC	land use land cover
SH	Schleswig-Holstein (federal state)
SOC	soil organic carbon

Introduction

The Intergovernmental Panel on Climate Change (IPCC) predicts a global temperature rise of 2℃ by 2025 and warns of the dangers to human health, well-being, and life, that global heating can cause (IPCC, 2022). Limiting anthropogenically caused global warming requires net zero CO2 emissions (IPCC, 2022). In 2022 however, emissions from fossil fuel burning reached a record high, even though CO2 emissions must decline by 45% from 2010 to 2030, to hold the temperature rise to 1.5℃ (IPCC, 2022). Modeled pathways that limit global warming to 2℃ or 1.5℃, all involve fast GHG emission reductions (IPCC, 2022) and in order for countries to meet their GHG emission allowances, they must find strategies to reduce their emissions (Weil, 2021). One structure that was introduced is the Carbon Price Equivalent Metric, to internationally compare emissions and to adopt an economy-wide carbon price (Weil, 2021). A standard way of tracking the economies' emissions is to calculate companies' carbon dioxide equivalent emissions (CO2e), based on their direct (Scope 1,2) and indirect (Scope 3) emissions (Downie et al., 2012). These estimations should help organizations to choose appropriate carbon management strategies and follow the emission reduction strategies that were agreed upon on a national level (Downie et al., 2012). Only with precise knowledge in all areas and discussions about what optimal management is, can organizations adapt to different strategies and a GHG emission reduction can be achieved.

Terrestrial vegetation plays an important role in the global carbon cycle, as it sequesters 112-169 PgC every year (Sha et al., 2022). This is the uptake by photosynthesis which is counter-balanced by respiration rates, so that the net uptake from 2007 to 2016 was about 3.6 PgC each year (Keenan et al., 2018). However, vegetation carbon sequestration varies under different land management strategies (Sha et al., 2022). According to the so-called global carbon gap estimation from 2001 to 2018, the world's terrestrial plants can sequester an extra 13.74 PgC each year, if optimal land management practices are determined and applied to individual local environments (Sha et al., 2022). Hence, it is necessary to investigate the carbon flows and balances of terrestrial ecosystems and understand how they are managed and what impact this has on pool sizes, in order to help policy makers to weigh in this factor in finding management strategies.

Germany is aiming to reduce CO_2 emissions by 80% in 2030 (Reker et al., 2022). However, Germanies' federal motorway is highly developed at the same time, with no prescibed tempo limit. It has historically and does currently play an important role in the countries economy (Dupuy et al., 1996). The dense highway system represents one of Europe's largest and most connected networks (Dupuy et al., 1996). In the before mentioned CO_2 reduction plan, photovoltaic (PV) systems play a crucial part in, as they are planned to be constructed alongside traffic infrastructures like railways and roads (Reker et al., 2022).

This recent discussion leads to the question of how highways and their ancillary areas are used in general. Since highways are a prominent feature within the country their adjacent roadside vegetation also takes up a relatively large portion of all the state's total areas. A US study underlines the importance of their highway vegetation and demands research on management techniques and their impact on carbon storage (Ament et al., 2014). The researchers estimate that more woody shrubs and less management would help optimize carbon storage, and critique the current commonly found features of landscape lawns (Ament et al., 2014; Climate M.L.D., 2014). A Scientific American article states that different planting strategies, and a management with less frequent mowing, increased the ancillary area carbon sequestration from 35 to 350 percent (Climate, 2014). Based on this assumption highway authorities of New Mexico were granted a one million dollars endowment to find methods which boost the carbon capture (Climate, 2014). The article even goes so far as to suggest that roadside shrubs and grasses have the potential to reduce carbon pollution and make a significant contribution to combating climate change (Climate, 2014). This study tries to investigate how reasonable these claims are, by investigating the subject in the context of Northern Germany highway ancillary area management and its associated carbon sink capacity.

1.1 Study aim

The aim of this thesis is first to delineate highway ancillary areas for a highway in northern Germany and second, to investigate the current utilization of highway ancillary areas with regard to their carbon sink capacities, by quantifying the vegetation cover of differently planted areas and finding their respective carbon pool sizes. Furthermore, this study attends to address the shortcomings of current management approaches, as well as to demonstrate the effectiveness and degree of impact of adapting to alternative strategies.

1.2 Hypothesis

1. Highway ancillary areas do not contribute to a considerable quantaty of the federal states total carbon stock, and their management causes larger carbon emissions in relation to what is being stored (as for the example of the US highways shown by Ament et al., 2014).
2. Management impacts the effectiveness of highway ancillary areas, in relation to their C stock capacities (Wiesmeier et al., 2019; IPCC. 2006).
3. There are possibilities to increase the current carbon pool storage of the highway ancillary areas.
4. An alternative utilization of the german motorway sideareas will lead to a more impactful contribution to the goal of limiting GHG emissions.

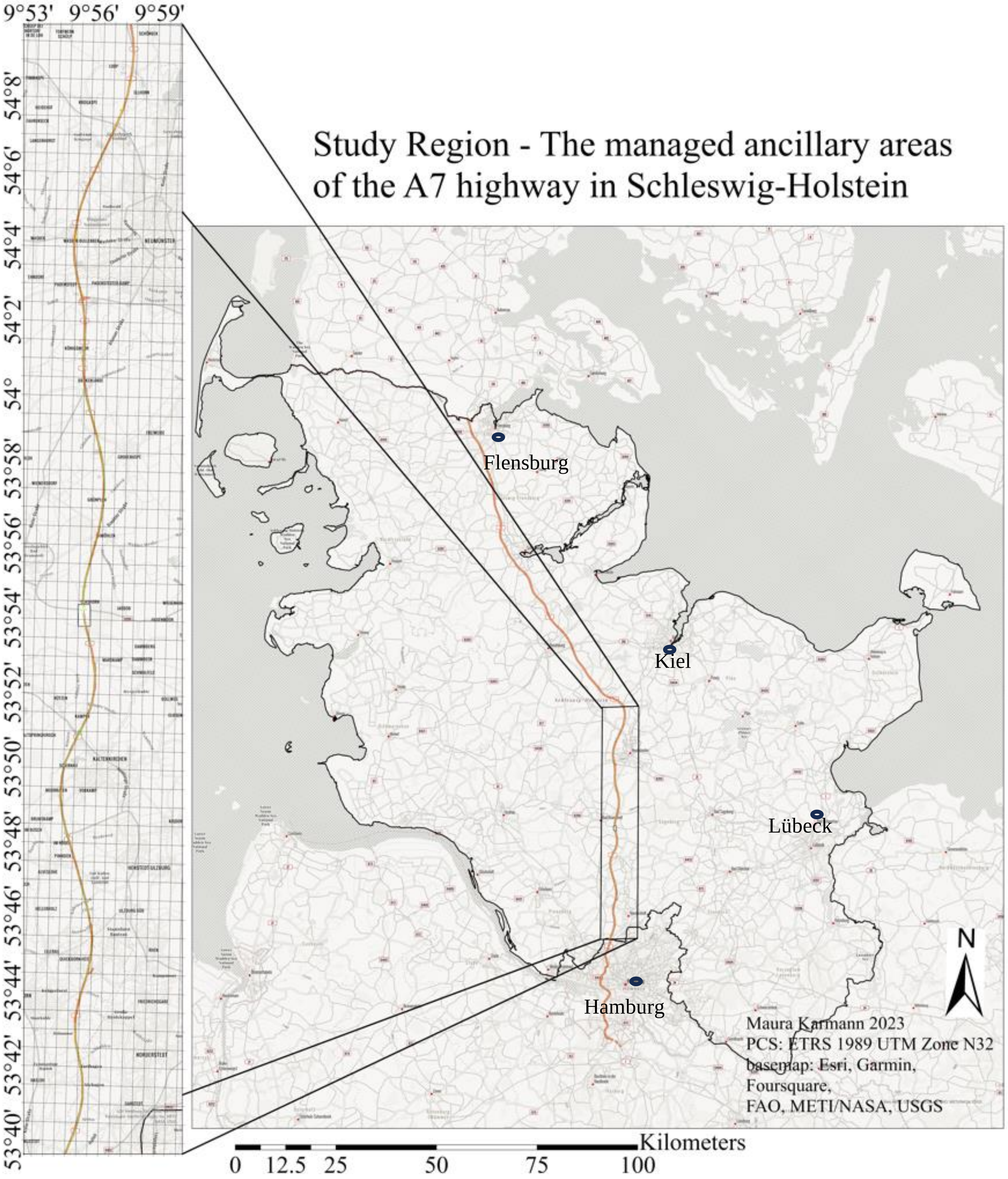
2 Background

2.1 Carbon pool storages – (optimal) carbon storage of different land cover types

Continuous carbon pools are usually geologic formations that capture and store atmospheric CO_2 (Lal, 2008). Terrestrial vegetation plays a significant role in mitigating climate change, as it absorbs about 30% of anthropogenic CO_2 emissions (Vicca, 2018). Different terrestrial ecosystem models help to apply knowledge from measurements of field sampling or remotely sensed data to larger areas, based on ecosystem characteristics, such as soils, weather, species composition or management history (USGCRP, 2018). To estimate, how much carbon is stored within a landscape, it can be useful to look at the carbon pools of the above-ground biomass (AGB), below-ground biomass (BGB), soil organic carbon (SOC), and dead organic matter (InVEST documentation, n.d.). Measuring the carbon stock changes and pools, of vegetation and soils over time helps to analyze the vegetation C stock capacity of different land cover types (Ament et al., 2014). Grasslands, for instance, store about one third of global terrestrial carbon stocks, with a high soil carbon sink (Bai et al., 2022). The SOC pool of grasslands makes up approximately 89% of their total C stock (Eze et al., 2018). This landcover type was used most in this study, as it was assumed that the landscape lawns of ancillary areas are similar to grasslands.

2.2 Highway ancillary areas

Highway ancillary areas are typically managed to provide safety and roadside management typically includes large-scale clearing and mowing to create clear zones (Weiskotten, 2003). Companies also take care of species protection through the installation of fences and other constructions, to guarantee a safer environment. Weiskotten (2003) finds that these areas make up roughly one percent of the New York state's land area, and he demands an advancement in management practices, to promote wildlife and environmental protection. Similar priorities are the foundation for roadside management of the A7-motorway in SH (Figure 1), northern Germany. The managed area is located enclosed to the 65 kilometers of constructed highway between the "Hamburg-north-west" and the "Bordesholm motorway triangle", which generally consists of six lanes (Via Solutions Nord, n.d.).



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PCS: ETRS 1989 UTM Zone N32
basemap: Esri, Garmin, Foursquare,
FAO, METI/NASA, USGS

Figure 1. Study Area - the managed Ancillary areas of the A7 highway in SH, northern Germany

2.3 Previous studies

A study that explored the potential of roadside carbon capture and storage (CSS) in relation to the establishment of “road effect zones” in the US used measurements of net CO_2 exchange from globally distributed eddy covariance towers, grouped the plants into functional vegetations types and then estimated their distribution along the roadsides (Ament et al., 2014).

According to the plant functional type distribution, the study sets up different biomes and calculates their total annual carbon flux (Ament et al., 2014). The study finds that the federal land management agencies, that manage 485,255 kilometers of US roadways (7.5% of US total roads) have the potential to collectively capture and store more than 8 million metric tons of carbon in their roadside vegetation, which is the equivalent of 1.6% of the annual GHG emissions of their transportation sector (Ament et al., 2014). This estimation however does not include constraining factors of roadside areas, such as soil compaction, pollution, and soil-nutrient limitations (Ament et al., 2014).

3 Data and Methodology

3.1 Study site and Maintenance measures

The A7 ancillary areas, which are managed by the “Via Solutions Nord” highway company are situated within a strip between 53°40’ N and 54°10 N at longitude 9°56’E, and they generally experience temperate climatic conditions with high annual rainfall rates (Germany | Facts, Geography, Maps, & History, 2023). They can be split up into 15 main areal types, which all tend to experience high vegetation growth rates due to favorable conditions. These all follow different methods regarding what is planted on them, and how they have to be maintained throughout the year. They are generally combinations of different types of shrubs and grasses that are planted, as well as a few singular trees. The company classifies the 15 measures as hedges and woody plantings, landscape lawns, and temporarily maintained protective areas, that can be seen in Table 1. After digitization, these areas were found to occupy a total area of 2.065km², with measure 8, the herb-rich landscape lawn, being the most commonly used one (Figure A11). Most often this is directly planted as a strip next to the highway and constitutes more than half of the ancillary areas.

Table 1. Main maintenance measures applied in the study area, listed according to the companies classification system.

Measure		Maintenance
	Hedges and woody plantings	
1	Restoration of wooden areas	
2	Single tree planting	
3	Hedge planting	
4	Woody planting with lawns inbetween	Mowing at least once a year
5	Woody plantings	Cutting every 10-15years
6	Median greening (inbetween the tracks, shrubs and grasses)	
7	Greening of the noise barrier	
	Landscape lawns	
8	Herb-rich landscape lawn	Mowing at least once a year
9	Landscape lawn classified as biotope area	
10	Landscape lawn	
11	Lawn (30% flowers 70% weeds)	Mowing 1 to 2 times (autumn)
	Rekultivative/ Protective measures	
12	Recultivation of temporarely occupied areas	After restoration back to arable fields
13	Preservation of woody slopes	
14	Greening bridge	
15	Single tree planting protective zones	

3.1.1 The Georeferencing and Digitization Process for the ancillary areas and respective measures 1-15

To create a polygon layer showing both roadsides of the 65km highway, 67 tiff files, provided by the company, each showing approximately 1km of the highway, with a scale of 1:1000, were used. These plans show the intended construction proposal from 2012 and some adaptations have since been made, which are not regarded in this study. The construction plans were manually georeferenced and the measures (listed in Table 1) were digitized to the Coordinate System ETRS 1989 UTM Zone N32 in ArcGIS Pro. As a reference layer, for the georeferencing of the plans, the digital topographic map (DTK) tiles (Table 2) were used.

3.2 Data Acquisition and processing environment

Further polygon and raster layers were retrieved from the Esri, the GDI-SH, and the NASA EARTHDATA – ORNL DAAC databases (Table 2). All data was transformed to raster datasets for processing and calculation purposes, of the tools that were used, clipped to the state boundary, and projected to the ETRS 1989 UTM Zone N32 Coordinate System. The cell size for detailed calculations was X=0.2m; Y=0.2m, according to the bDOM (image-based digital surface model), which was used for aspect calculations of the ancillary areas. Large-scale calculations were performed with raster layers that have a cell size of X=10m and Y=10m. For further information on the data and its sources, see Table 2.

Table 2: Overview of used data

Variable	**Source**	**Description**
Schleswig Holstein state boundary	Esri Deutschland	shapefile of administrative state boundaries (“Bundesländer 2021 mit Einwohnerzahl”)
LULC Schleswig holstein	Esri	2022 LULC derived from ESA imagery at 10m resolution (Rangeland; Trees; Crops; Built Area (diregarded); flooded vegetation; bare ground; and ninimal areas of clouds and snow and ice
A7		Europe-road.zip shapefile from April 26th 2016; last modified January 13th 2020
Ancillary areas	Via Solutions GmBH	Georeferencing, Digitization and Classification of the entire 65km A7 ancillary areas
bDOM surface model (similar to a DEM)	GDI-SH	Orthophotos of 20cm resolution, multiple GeoTIFFs downloaded each 1km tiles; the image-based digital surface model (bDOM) depicts the surface of the earth including objects on it (such as buildings and vegetation that has a grid width of 20cm); the height accuracy is ± 0.5 m. (GDI-SH, n.d.)
Organic Soil Carbon content (Corg)	GDI-SH	WMS:Boden; The estimates are based on the Corg stocks that result from the product of humus content in mass, the soil; the dry bulk density of the soil and the observation debth (I chose the 30cm debth as data from other articles and management impacts relate to the upper 30cm soil layer); unit: t/ha (equal to MgC/ha); scale 1:250000; data name BÜK250; date of creation: 28.05.2021 (SH-MIS, 2021)

Landcover Schleswig-Holstein	Esri Land Cover	Annual Sentinel-2 10-meter resolution map 2017-2022; based on AI land classification with 6 spectral bands; 9-classes (Esri, n.d.)
Aboveground Biomass (AGB) Carbon Density	NASA EARTHDATA – ORNL DAAC (Distribution Active Archive Center for Biochemical Dynamics)	GeoTIFF (.tif) file in MgC/ha aboveground living biomass carbon stock density combining woody and herbaceous plants of 2010; 300m resolution; Scaling of 0.1 was changed to 1; annual temporal resolution; created by overlaying vegetation specific carbon density maps from sattelite images, allocating estimates for respective gridcells and using ancillary maps of tree cover/ landcover in percent (Spawn et al., 2020)
Aboveground Biomass carbon uncertainty	NASA EARTHDATA – ORNL DAAC	2010 GeoTIFF (.tif) file (Mg C/ha): Uncertainty (the cumulative standard error occuring in harmonization process) of aboveground living biomass carbon density (2010); 300m resolution; Scaling of 0.1 was changed to 1; annual temporal resolution (Spawn et al., 2020)
Belowground Biomass (BGB) Carbon Density	NASA EARTHDATA – ORNL DAAC	2010 GeoTIFF (.tif) file; combined living woody and herbaceous carbon stock (e.g. roots) in MgC/ha; not including soil organic matter or dead/dislocated root tissues; 300m resolution; Scaling of 0.1 was adapted; annual temporal resolution; data generation see AGB Carbon Density description (Spawn et al., 2020)
Belowground Biomass carbon uncertainty	NASA EARTHDATA – ORNL DAAC	2010 GeoTIFF (.tif) file (Mg C/ha): Uncertainty (the cumulative standard error occuring in harmonization process) of belowground living biomass carbon density (2010); 300m resolution; Scaling of 0.1 was changed to 1; annual temporal resolution (Spawn et al., 2020)
ATKIS- digitale topographic maps (DTK)	GDI-SH	ETRS89/UTM- based image tiles 2 times 2km (equal to 40 times 40 cm - scale); GeoTIFFs that show, buildings, infrastructure and traffic attributes and vegetation

3.3 InVEST model description and approach

The InVEST model was developed by the partners of the Natural capital project (Guo et al., 2022). In this study the InVEST-model approach was used to estimate the total carbon pool storage which assumes that the Carbon storage is equal to the sum of all four carbon pools within a land-use land-cover (LULC)-class. Due to a lack of available data, the pool of dead organic matter is usually disregarded in InVEST-estimations and set to zero in this study. The mean storage (Carbon in MgC/ha) and the total error were calculated, as well as the total carbon (Carbon in MgC) that the measures store. The total carbon storage per ancillary area measure is based on the total carbon pool value in MgC/ha (all 3 pools) multiplied by the measures total area in hectares (Figure A11). For the highway-ancillary areas this mean and total storage was calculated using the values that were estimated on average, as well as with the consideration of the influence that the aspect (depending on the slopes orientation to the sun) has on carbon pool sizes. Photosynthesis rates, or the abundance of soil organisms that help sequestration rates are disregarded in this InVEST-model approach and the aggregation of carbon in the different pools is considered uniformly, since mean values are used (InVEST documentation, n.d.), which sets aside the spatial variability of the study site.

3.4 Carbon pool estimation for the state SH

For later comparisons, the total carbon pool of SH was calculated. This was a straight-forward approach, since the LULC-classes were already defined (Figure A8). Water and built-up areas were reclassified to a NODATA value, since only the terrestrial vegetation storage was calculated. Since the NASA EARTHDATA – ORNL DAAC-data is scaled by the factor of 0.1, these layers were multiplied by 0.1, using the 3D Analyst Tool “Times”, to get the values in MgC/ha. Then the AGB and BGB C stock mean values, as well as the mean error from the AGB and BGB uncertainty layers were determined (Table A1; Figure A9), using the respective biomass-carbon or uncertainty raster and the LULC-classes raster. These were put into the “Zonal Statistics as Table” Spatial Analyst Tool, which provides the mean values that the InVEST-model uses to sum up the C stock pools of each LULC-class. The SOC layer is subject to the same approach, but was transformed to a 10m times 10m raster using the “Feature to Raster” tool. It was however scaled correctly and the SOC values at a 30cm debth were in the correct unit. Total C stock (from the 3 pools) was then multiplied with the LULC total area, to estimate storage capacities (Table A1).

3.5 Carbon pool estimations for ancillary area measures 1-15

The InVEST-model approach was also used to find the ancillary areas of C stocks. But because the resolution of the AGB and BGB layers was quite rough, compared to the level of detail, that the digitized ancillary areas bring along, a different approach was used to calculate the mean storages of each of the 15 measures.

3.5.1 Estimations for Single trees and shrubs

To estimate the Carbon storage of the planted trees I used Aguaron and McPherson’s (2012) urban-based Allometric Biomass equation, which was established for urban broadleaf trees in Sacramento, California.

$$Tree\ C\ (kg\ C\ tree^{-1}) = 0.5 * (0.16155 * DBH^{2.310647}) \qquad \text{Eq.1}$$

The input data for the height (H) and Diameter at Breast Height (DBH) are based on a study measuring three tree species, commonly found in the planted areas (Catoni et al., 2015). As the trees were planted in 2012 with an average of 60-100cm starting point and they are not growing in forests and are regularly pruned and replaced by new ones if they die, I expect them to only reach these heights on average (Table 3). Catoni et al. (2015) also measured these trees growing together, which they are in the planted areas and these measurements seem applicable for an age of 10 years, as the annual diameter growth estimations for *Acer campestre* (Weissert et al., 2016) show. Values for Quercus robur (QR), are reassured by DBH-values for young trees on a low floodplain in northern Germany, where the minimum DBH is 5cm and the mean DBH is 14cm (Shupe et al., 2022). The according height of QR trees was on average 11m for young trees (Shupe et al., 2022), the values from Catoni et al. (2015) should not cause an overestimation of the carbon storage for the A7-areas. 21m corresponds to the maximum height of young trees on low floodplains and is used in the study by Catoni et al. (2015), but this describes rather older trees, so the DBH chosen as an input variable relates to smaller, younger trees, as QR also gets regularly pruned (Shupe et al., 2022).

Table 3. Carbon content calculations for planted trees and shrubs. The results include above and belowground biomass and were multiplied by 0.5 to convert biomass to Carbon values.

Species	H(m)	DBH(cm)	Tree C (kgC/tree)	C_above	C_below
Acer campestre (AC)	9	25	137.2	96.5	40.7
Corylus avella (CA)	6	9	12.9	9.1	3.8
Quercus robur (QR)	21	6.7	6.5	4.9	1.9
				mean: 36.8	mean: 15.5
Colutea arborescens; Colutea arborescens; Elaeagnus angustifolia; Ribes alp. “Schmidt”; Tamarix ramosissima	60-100cm	not quite breast height-estimate of shoots at this height: 2cm	Shrubs: 0.4	1.125	0.48

Based on my own calculations for carbon storage in each landclass in Schleswig Holstein (Table A1; Figure A10), the ratio of aboveground carbon storage to belowground carbon storage is 0.297 for forests and trees in this climate. I used this ratio to derive the distribution of above and belowground Carbon storage for the trees that are planted.

3.5.2 Deriviation of other carbon pool values

Compared to forests, grassland C stocks have not yet been investigated much (IPCC, 2006) and in order to find representative C pool mean values for the ancillary areas that include grasses, I investigated the soil types of the ancillary areas, by overlaying the Corg-data with the digitized roadside areas. Since sandy soils seem to be the predominant soil class of the ancillary areas (Figure A12), and as the SOC and the AGB, and BGB (as well as the uncertainty layers) do not have a precise resolution, I assume to minimize the error, by calculating the mean values for these classes. This shows that the mean soil type is sand, and since SOC stocks, in particular, vary with soil types (IPCC, 2006), the mean grassland variable was determined by using the raster calculator with a raster of the SH-LULC, which only included grasslands and with a Corg soil raster, which only shows areas that have a sandy soil at a 30cm depth. From this multiplication, mean values were derived for the grassland SOC values (Figure A6).

Based on the soil class distribution of the ancillary areas, I not only calculated the average SOC storage at a 30 cm debth for grasslands but also for shrubs on sandy soils in the state (Figure A4; Figure A5; Figure A6). To calculate the size of the below-ground biomass carbon pool for grassland the values of the areas of sandy soils within grassland areas were multiplied with the BGB carbon raster layer. The corresponding level of uncertainty was derived by multiplying the grassland areas with sandy soils of the district with the BGB uncertainty layer. From the before-produced layer showing the BGB grassland values the resulting uncertainty layers were respectively added and subtracted. The resulting rasters show the BGB values with the accounted uncertainty estimation.

The mean Below Ground Biomass C stock for grasslands in Schleswig-Holstein that are located on sandy soils is 7.96 Mg/ha (± 4.25) (Table 4; Figure A7). The lower estimated value is therefore 3.71 Mg/ha. This corresponds to the total carbon storage of grasslands in cold temperate and wet climate zones, which is estimated to be 7 Mg/ha (±150%) (IPCC, 2006). And the according ratio of below-ground biomass to aboveground biomass in cold temperate and wet climate zones is 4.0 (IPCC, 2006). The related mean AGB value of the district is therefore 1.99 Mg/ha (± 0.66).

Mean SOC values are based on raster overlays of the forest, grass, shrubs, or grass and shrubs areas that have sandy soils. Their mean Soil Organic Carbon value (in MgC/ha) at a 30cm depth was used and assigned to measures 1-15, depending on which land class medium value best represents the vegetation that was planted within each area (Figure A4; Figure A5; Figure A6).

3.5.3 Measure calculations – estimating the mean carbon pool storages (1-15) by weighing in the amount of shrubs, trees and grasses that are planted

To retain the carbon storage of trees and bushes in MgC/ha from the Biomass to carbon content relations of individual plants, I looked at the number of trees planted, within a certain area, at a certain distance. For Measures 1, 3, and 13, there were 45 shrubs planted in a 4m times 13.5m area (54m²). This results in an average BG carbon stock of 12.916 kgC/m² (or MgC/ha) and an average AG carbon stock of 30.67 kgC/m² (or MgC/ha). Measure 2 assumes single tree planting, so the *Acer Campestre* values were used instead, resulting in an AG carbon storage of 80.42MgC/ha and a BG carbon storage of 33.92 MgC/ha. The same values were used for measure 15. BG carbon values for grasses are based on the estimations for sandy soils of grasslands in Schleswig-Holstein (measures 8 to 12). Measure 14, the greening bridges, were split into a ratio of 1/3 (shrubs and hedges) and 2/3 (grasses), which represents the ratio of planted shrubs to grasses that was carried out, and the values were weighted accordingly. Measure 4 was calculated based on a ratio of 55% shrubs and 45% grasses that were planted. The carbon stocks above and below- ground were weighted respectively. Measure 5 was weighted based on a ratio of 75% hedges and 25% planted grasses. Measure 2 is compiling two measures at once, a line of shrubs in the middle, surrounded by grasses, which makes up for the median area between the highway lanes. The shrubs are planted in a 0.5m wide box. 25 plants are within 12.5m, which leads to a carbon storage of 1.6 kgC/m², and using the same ratio that applies to hedges and shrubs, the above-ground and below-ground carbon distribution can be derived. Around this box are two 1m wide strips of grass. The ratio for measure 6 is therefore ¼ shrubs to ¾ grass. There were no records of climbers and creepers and their specific carbon storage, therefore I applied the same values as in measure 6 for measure 7, since climbers also grow on a slim area and they do not produce a lot of biomass (Othman et al., 2016).

3.5.4. The Aspect factor – a site-specific variable

To get a better site specific view on the SOC content and a more precise view of the soil carbon data for this small scale approach, I considered some additional factors. Soil carbon is a source of large uncertainty and scaling results in uncertain outcomes, as there is a large spatial and temporal heterogeneity and data is usually retrieved from a few point sources (Patton et al., 2019). Therefore, I chose to also regard the aspect factor to weigh the mean Soil Organic carbon content within each area.

Soil organic carbon (SOC) concentration rates inrcrease from South facing slopes to North facing slopes in grasslands (Zhu et al., 2017). A ratio found for grasslands is that North facing slopes have four times the SOC rate of South facing slopes and twice the SOC ratio of west facing slopes within the topsoil layer. General linear model and mixed linear model analyses show that the Aspect has the highest effect an SOC concentrations at hill scales (Zhu et al., 2017). South facing slopes generally experience higher soil temperatures, which leads to more rapid organic mineralization (Zhu et al., 2017). The soil moisture content of north facing slopes is oftentimes higher than that of east facing slopes in the topsoil (30cm), which leads to higher SOC concentrations in the north-facing areas (Lenka et al., 2013). Based on these findings I attributed North facing slopes a factor of 2, South facing slopes a factor of 0.5 and both west and east facing slopes a factor of 1 to calculate the SOC rates for different slope aspects. According to this ratio North-East and North-West facing slopes got the factor 1.5 and South-East and South-West facing slopes were attributed a factor of 0.75.

Catoniet al., 2015 examined the sensitivity to light of the species Q. Robur and C.avella, by measuring the ratio of respiration to photosynthetic rate. Q. Robur was found to be shade intolerant and C. Avella was found to be light tolerant (Catoni et al., 2015). The net photosythetic rate, the leaf respiration rate, and the photosynthetic nitrogen use efficiency were over 100% higher in the sun than in the shade leaves (Catoni et al., 2015). For C. Avella the photosynthetic rate of sun leaves was three times higher than the rate in shade leaves and the respiration was 20% higher. In Q. Robur the net photosynthetic rate in sun leaves was found to be eight times as high as that in shade leaves and respiration rates were about 4.4 times as high (Catoni et al., 2015). Both species are found in the ancillary areas and it is worth to factor in the impact of light availability. The light availability, which determines plant growth can be calculated by considering the aspect toward the sun. South-facing slopes are exposed to more direct sunlight and experience a longer growing season than north-facing slopes. This is because they experience frost and snow for fewer days in the year. I did not find a direct correlation between the specific plants and growth factors depending irridation. However, I wanted to attribute the AGB and plant growth to sunlight angles. I believe the depiction will be more accurate, when accounting for the variation in different growing seasons and the difference in biomass growth. I chose to attribute South-facing slopes a factor of two. North-facing slopes a factor of 0.5, East and Weast- facing slopes a factor of 1. South-West and South-East facing slopes a factor of 1.5 and North-East and North-West facing slopes a factor of 0.75. The flat areas in both cases were not changed and kept the original mean values.

3.5.5. Weighting the mean AG and BG Organic Carbon pools and the SOC pools of measures 1 to 15 with their developed Aspect factor

After reclassifying the aspect raster with these values (see Figure A2 in Annexes, aspect factor for SOC), I used the raster calculator to multiply the aspect value raster (Figure 2a) with the mean SOC raster, which is based on mean values for shrubs, trees, grasses and combinations of them (A4; A5; A6). The multiplication of these two rasters results a raster layer that shows the SOC pool depending on the areas slope-angles toward the sun (Figure 3b). After creating this raster with a weighted-in aspect factor (Figure 3b), I used the tool Zonal Statistics as table, where the zones were the Measures 1 to 15. From this, I derived the mean SOC value (in MgC/ha) of each measure, where the impact of aspect distributions is factored in.

Just like for the SOC the Above-ground and the Below-ground biomass carbon pools (Figure A1 in Annexes) were weighed with the aspect factor. The same factor was used to weigh below- and above-ground carbon pools. The measure 1 to 15 classification raster was respectively reclassified, to show the AGB and BGB mean carbon values. I also used raster layers, where the mean uncertainty was included to multiply with the aspect-factor raster. Figure 2b shows the impact that the Aspect-factor has on the BGB-carbon pool and the impact on the AGB can be seen in Figure 3a. Then again, I used the tool Zonal Statistics as table tool, where the zones were the Measures 1 to 15. I derived the mean AGB and BGB carbon values (in MgC/ha) of each measure, where the impact of aspect distributions is factored in. The corresponding error was calculated based on the difference of the raster multiplications of BGB and AGB layers with aspect, where the uncertainty was factored in, and the raster layers, where just the mean value was used.

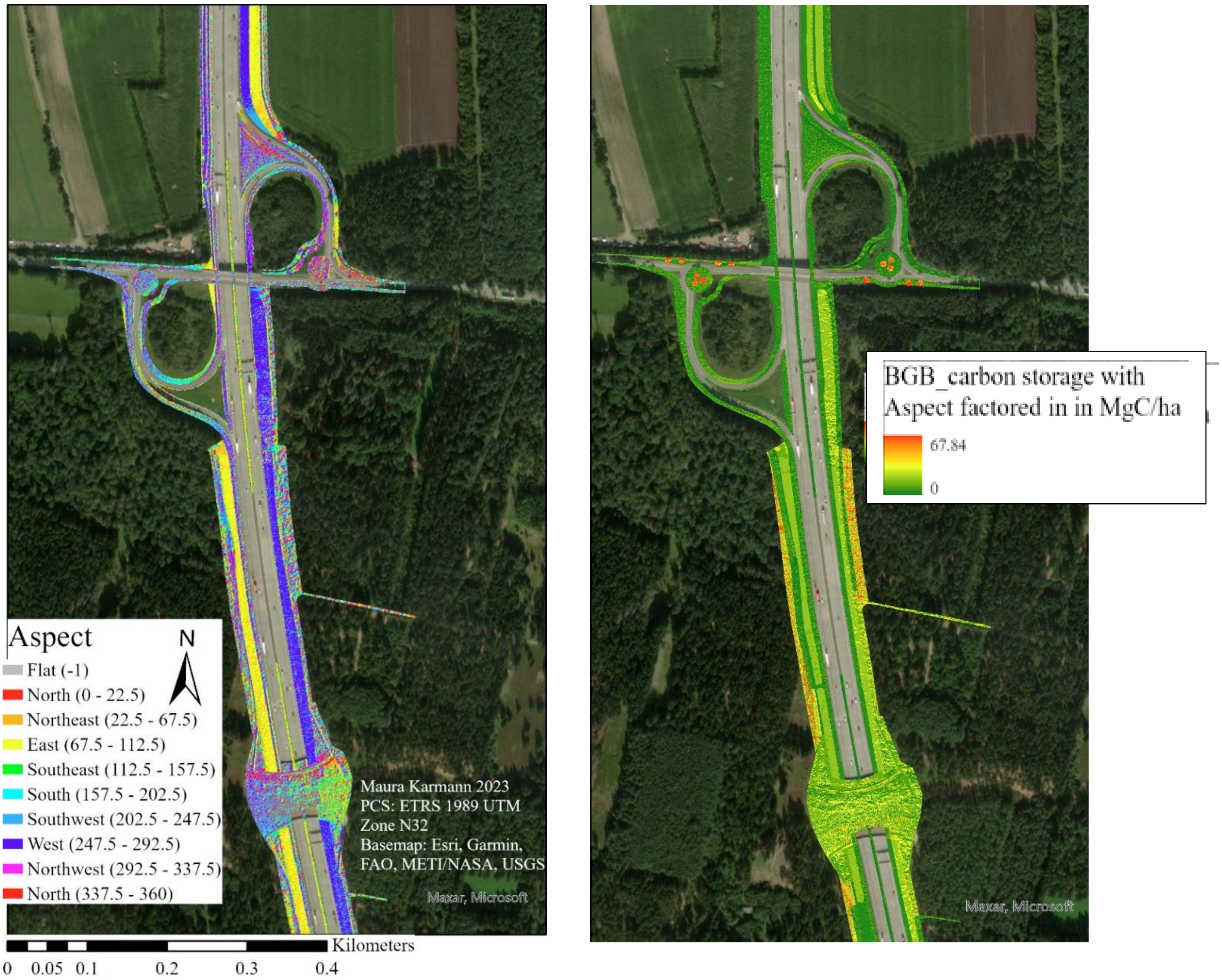


Figure 2a and b. Aspect of Ancillary areas in degrees (3) and the Belowground organic biomass carbon storage weighted by the Carbon Biomass Aspect factor (Figure A1 in Annexes).

Figure 3 a and b. Aboveground carbon storage (a) and Soil Organic Carbon storage (b) weighted by Aspect factors (see Figures A1 and A2 in Annexes).

3.6 Calculating the effect of management intensities in the carbon pool stocks

The impact of land use management in grasslands can be calculated with different precision following the IPCC methodology (IPCC, 2006). The IPCC grassland chapter provides default soil C stock change factors, that are used by the *Tier 1* estimation. This *Tier 1* approach is based on SOC stock changes over a finite period of time that followed a management change, which impacted the soil carbon storage (IPCC, 2006). After the management change, a steady state of the SOC pool can be assumed. They have estimated the emission/ removal factor based on the computation from a global dataset, where studies on degraded, normally managed and improved grasslands were carried out. Improved grassland management consists of a limited input of fertilization (both organic and inorganic fertilizers), sowing legumes or more grass species, and irrigation habits (IPCC, 2006). These grasslands showed high C input rates. The default stock change factor, in mineral soils, was calculated for the top 30 cm soil, and only areas, where a specific management strategy was applied for more than 20 years, were calculated. The default IPCC relative stock change factors for grassland management in temperate regions are 1.0 for nominally managed (non degraded, Error: NA); 0.95 (±13%) for moderately degraded grasslands, 0.7 (±40%) for severely degraded, and 1.14 (±11%) for improved grasslands (IPCC, 2006). These values represent the influence of management to a depth of 30cm and the default SOC stock change in mineral soils after 20 years (IPCC, 2006). This impact factor was multiplied with the original values for the carbon stocks of measures 8 to 12, which served as the reference soil C stock in the Tier 1 approach. The results will therefore show the C stocks after a 20-years time period of each management intensity.

Mentioned factors and the Tier 1 approach were used to calculate the management impact on the ancillary areas, since they lay on mineral soils, for which this management factor has been developed. Therefore, I calculaed the effect that the Management factor has on the SOC Measures 8 to 12 ,and how that would impact the storage of the total carbon pools. The results show the difference in carbon stocks after 20 years and the impact of management factors (IPCC, 2006). The impact factors were multiplied by the soil carbon stocks of the grassland areas to estimate the carbon storage capacity (pool) under different management regimes. This was only estimated for the grassland areas (Landscape lawns, measures 8-12). For this the ABG was substracted from the total C-pool and the remaining soil-pool was multiplied by the respective relative stock change factor. This was done for the carbon stocks that regarded the Aspect factor and the pool calculations which did not. The total errors were also calculated, based on error estimations of the relative stock change factors, whih were mentioned before (IPCC, 2006). After the changed soil stocks were found, the AGB was readded, to show the total pools of the grassland areas, for better comparison with the InVEST-model-approach results.

3.7 The Alternative of photovoltaic

Single PV-panels

To estimate the total area of possible PV-panel installments, the aspect-raster was reclassified to a raster that only included South-east to South-west cells (values of 112.5 to 247.5 degrees) and one that only included South-facing cells (values of 157.5 to 202.5 degrees). These were further filtered six times respectively with the majority-filter tool, set to 4 neighboring cells, in order to receive larger areas with South-facing slopes. Based on Fonseca's (2023) estimations of PV-productivities, it was assumed that the average annual electricity yield was 200 Watt per hour per m², at 100%, which was used for the South-facing slopes and about 95% for SE and SW-facing slopes, which results in 190 Watts per hour per m². This might differ from the exact numbers for the sunshine hours at the A7-area since the average amount of Watts per hour per square meter that the article states, was used (Fonseca, 2023). The peak yield for SH is 1002 kWh/kWp (Fonseca, 2023) and this varies drastically under different weather conditions, which this study did not investigate. Results only show an average estimate. After the majority filter was applied, the rasters were resampled with an output cell size of X=2.44m and Y=1.14m, which is equivalent to the highest standard Solar panel dimension (Lejtman, 2022).

Solar roof

A different approach is to cover the highway with a solar panel roof. The PV panels are estimated to have a capacity of 180 watts per square meter (Power Info Today, 2020). For the 65 kilometers long A7-network part, assuming a width of 40m of the six-lane highway the sum was calculated.

4 Results

4.1 Georeferenced ancillary areas and their attributed measurement strategies

Figure 4 shows a sample area of the digitized 15 landclass-polygon layer (description in Table 1) that was used to calculate all mean and total roadside carbon pools.

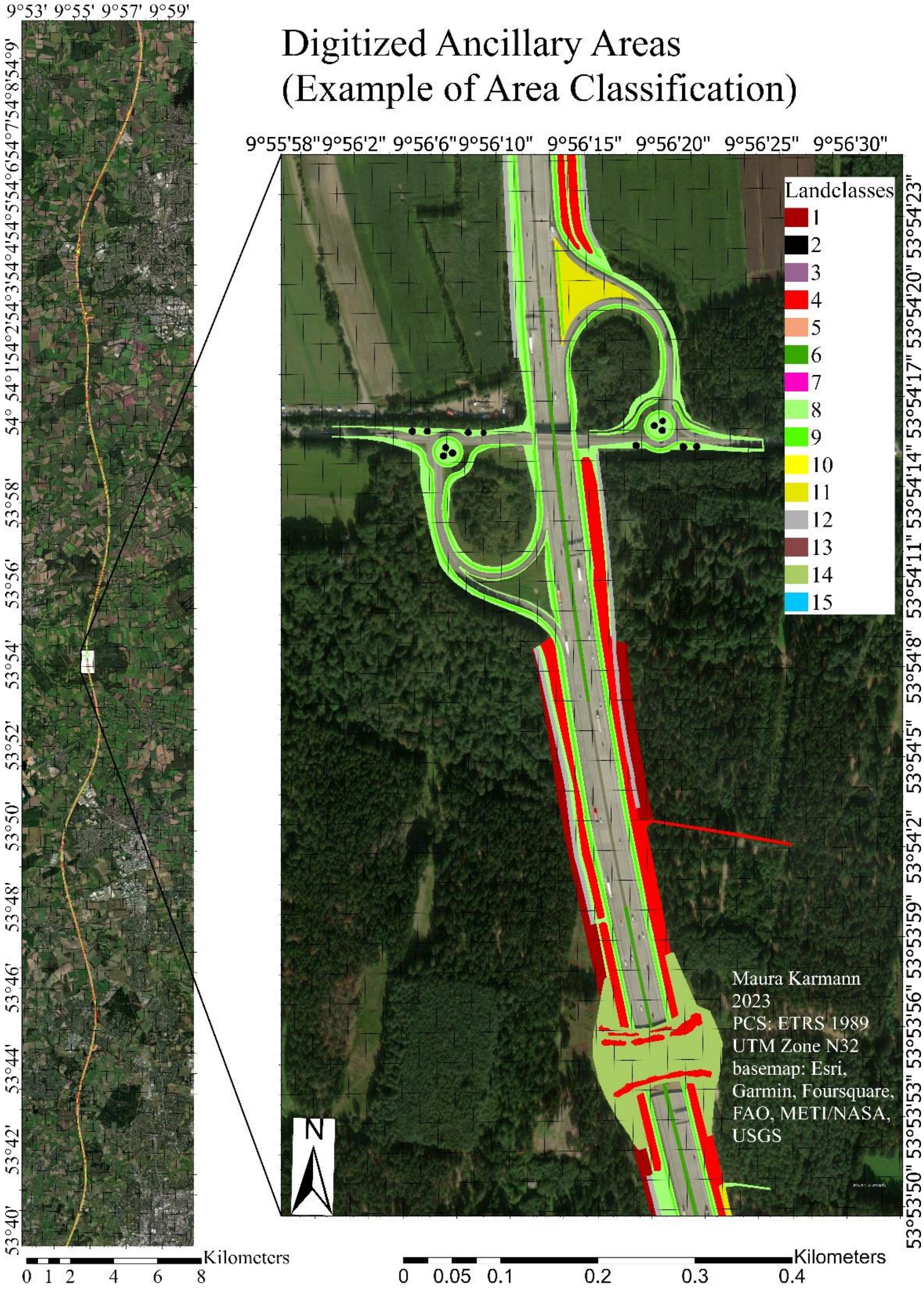


Figure 4. Measures 1 to 15 excerpt of classified ancillary areas (classification in Table 1)

4.2 Carbon pool estimations for different measurement strategies

After calculating the mean C stock values for the AGB, the BGB and the SOC pool, which are also respectively weighted with the corresponding aspect factor (Table 4, also shown are their error estimates), the data can be used as input into the InVEST-model. Table 4 shows that the highest AGB, BGB and SOC carbon stocks are situated in areas, where single trees were planted (Measure 2 and 15) and that the average influence of the Aspect factor is to increase the mean carbon pools.

Table 4. Carbon pools (in MgC/ha) of the current areas (input in the InVEST model). The (±) error is solely based on the grasses error, since the other vegetation (shrubs, trees, hedges, climbers) are estimates and calculated based on my findings of planting strategies and plans. Since these values are not derived with a method that has a clear error calculation, I do not regard their error in further calculations. It is however important to note, that these values might differ and field studies and validation help to give a higher level of accuracy.

Measure	Aboveground Biomass carbon without Aspect factoreed in (MgC/ha)	AGBC with Aspect factored in (mean in MgC/ha)	Belowground Biomass carbon without Aspect factored in (MgC/ha)	BGBC with Aspect factored in (mean in MgC/ha)	Soil Organic Carbon without Aspect factored in (MgC/ha)	SOC with Aspect factored in (MgC/ha)
1	30.67	34.893	12.916	14.699	60.6	68.02
2	80.42	93.687	33.92	39.516	91.1	102.71
3	30.67	33.856	12.916	14.262	11.1	12.56
4	17.76 ± 0.29	18.825 ±0.31	10.69 ±1.92	11.331 ± 2.04	60.6	64
5	23.335 ± 0.17	24.8 ±0.18	11.68 ± 1.06	12.41 ± 1.13	11.1	11.91
6	1.78 ± 0.5	1.961 ±0.55	6.09 ± 3.19	6.71 ± 3.52	60.6	67.46
7	1.78 ± 0.5	1.868 ± 0.53	6.09 ± 3.19	6.391 ± 3.35	60.6	63.67
8	1.99 ± 0.66	2.168 ± 0.72	7.96 ± 4.25	8.6734 ±4.63	69.8	76.16
9	1.99 ± 0.66	2.145 ± 0.71	7.96 ± 4.25	8.579 ±4.58	69.8	75.64
10	1.99 ± 0.66	2.197 ± 0.73	7.96 ± 4.25	8.787 ±4.69	69.8	76.91
11	1.99 ± 0.66	2.279 ± 0.76	7.96 ± 4.25	9.117 ± 4.87	69.8	76.31
12	1.99 ± 0.66	2.247 ±0.75	7.96 ± 4.25	8.986 ±4.8	69.8	78.16
13	30.67	31.659	12.92	13.337	60.6	64.26
14	11.55 ± 0.44	13.265 ± 0.51	9.61 ±2.83	11.037 ± 3.25	60.6	67.71
15	80.42	89.777	33.92	37.867	91.1	10.27

To set the pool results in proportion, Schleswig-Holstein's total land cover is 133320km² without the built-up areas and lakes, which were disregarded since only the terrestrial carbon pools were detected. The managed areas are in total 2.065km² (see Figure A11 in Annexes), which makes them 0.0155% of the state's total area. The relative carbon stored is, however, 0.000062% of the state's total carbon pool. The total carbon stored in the ancillary areas is approximately 16,067 MgC (mean values, aspect disregarded), and approximately 25,923,460,563 MgC are stored in the states C stock pool (Table A1, Annexes).

Figure 5 shows the total carbon storage per ancillary area measures, which correlates with their prominence (Figure A11). The areas with an ancillary area management practice, that is used often (Figure A11), are those that have the highest total carbon storage values (Figure 5). Furthermore Figure 5 shows, that the applied aspect ratio leads to an increase in all the roadside carbon storages.

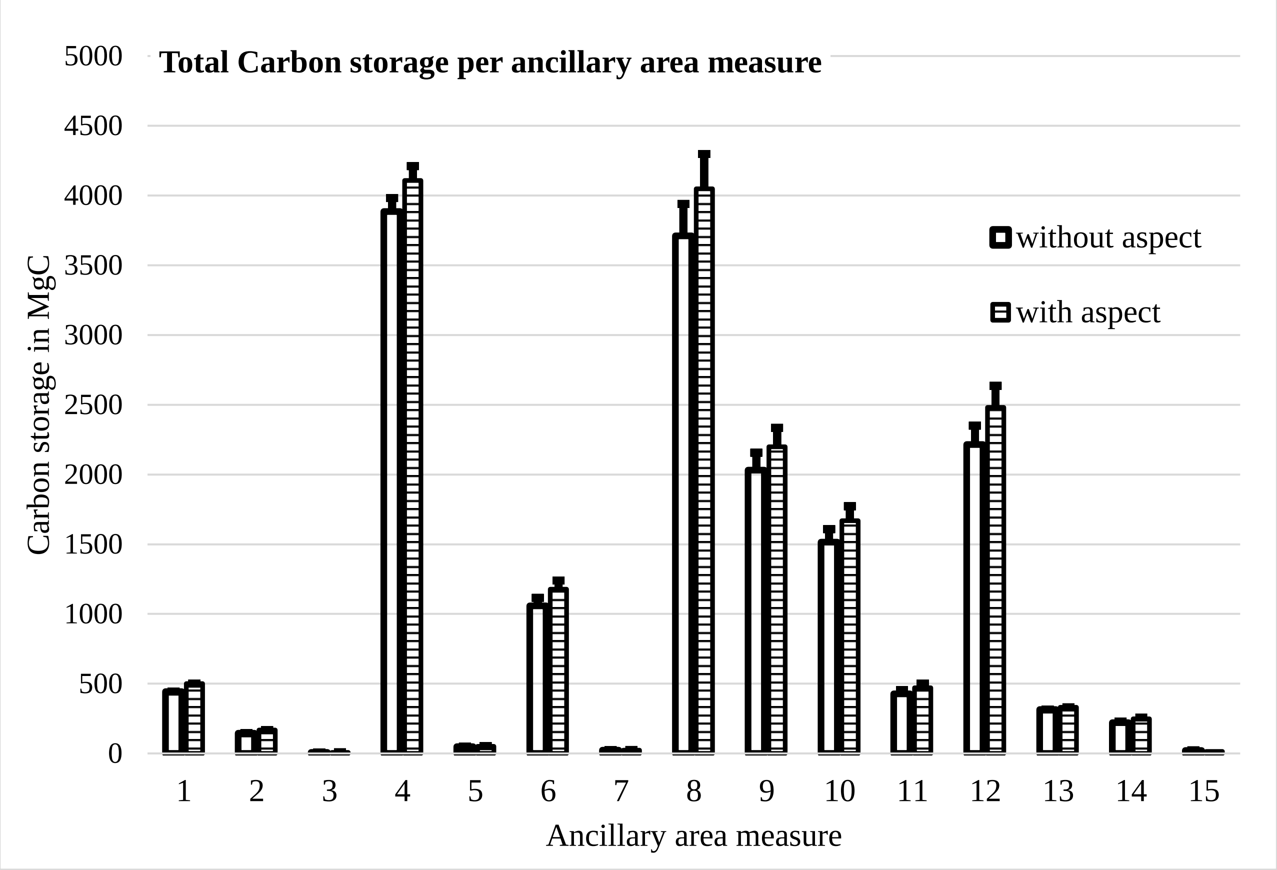


Figure 5. Measures 1 to 15 Total Carbon storage in MgC

Figure 6 shows the efficiency of the different ancillar areas in MgC per area for the the pool size, where the C stock is the sum of AGB carbon, the BGB carbon, and the SOC pools. The storage per hectare is shown disregarding the mean change, due to the aspect’s influence and with regard to the changes that the aspect causes. A smaller mean storage, after the aspect is regarded, shows that the vegetation grows under less favorable conditions, produces less biomass, or has a reduced SOC turnover rate, in this site-specific case.

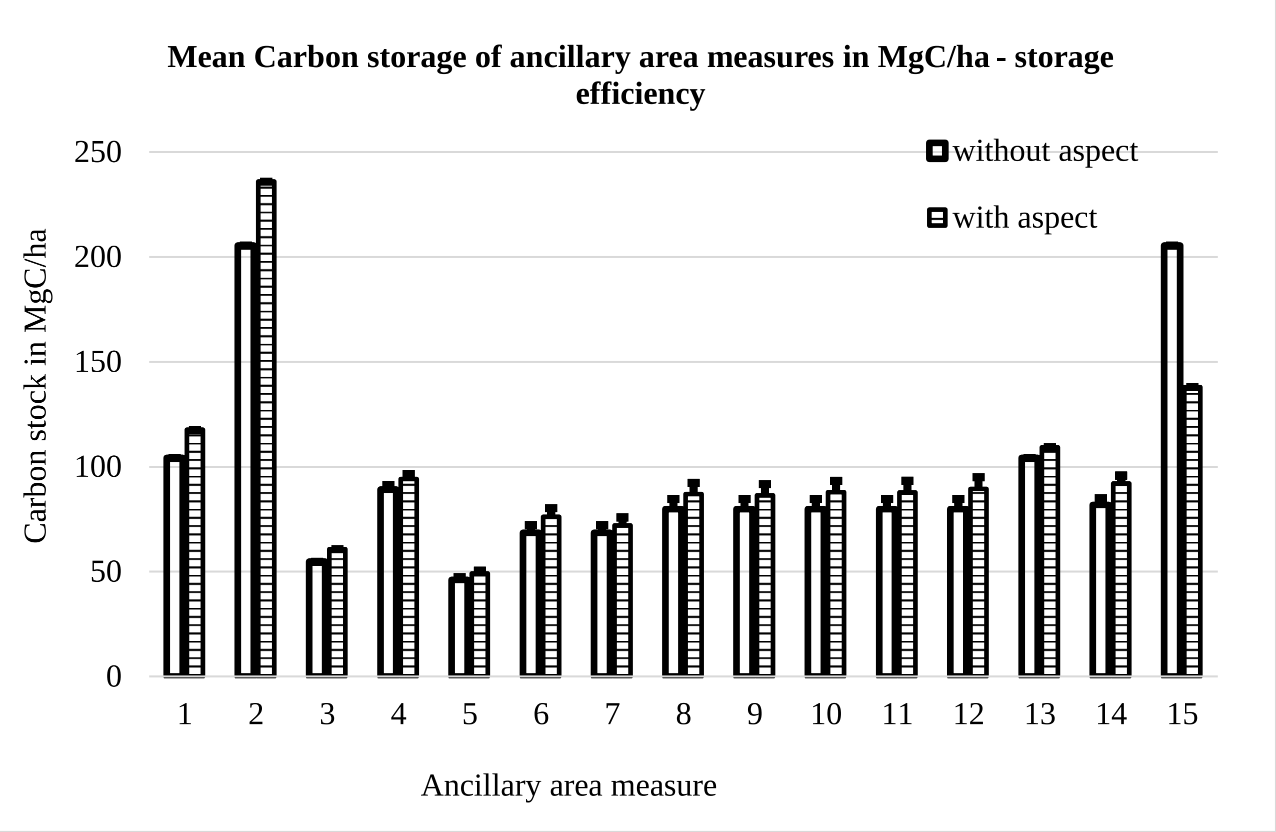
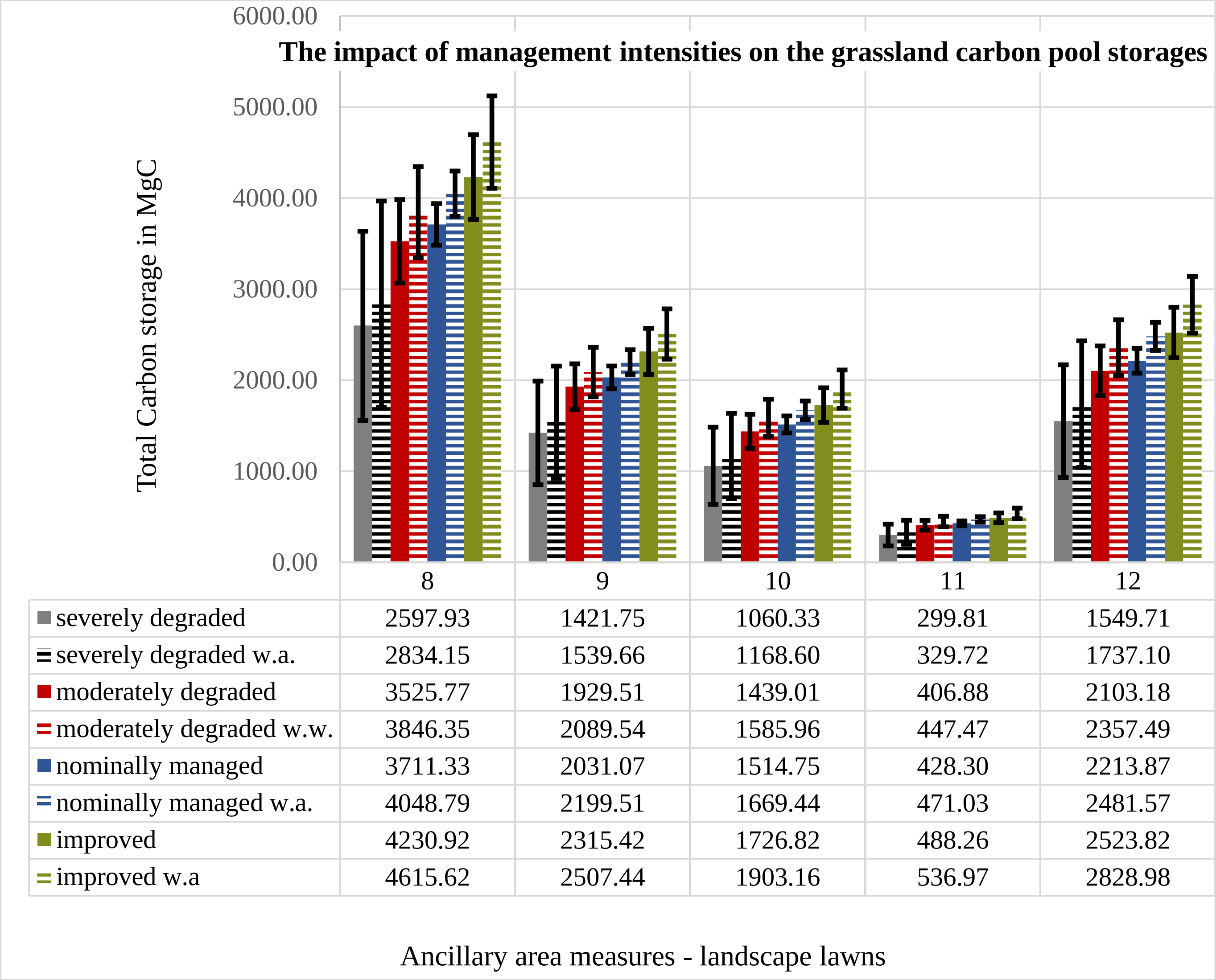


Figure 6. Mean ancillary area Carbon storage of measures 1 -15

This phenomenon can also be compared to the estimates for the state of SH. Forests make up 15% of the area of the state but store 19.5% of the carbon, shrublands are only in 0.3% of the area of SH and store 0.4% of the carbon, croplands make up 81% of the federal state and store 74.4% of the carbon, and grasslands make up for 3.6% of SH and for 5.6% of its total carbon storage (Figure A1). In the ancillary areas, more or less 28% of the total area are shrubs, 71.6% is made up by grasses and only 0.4% consists of tree areas. Shrubs contribute 31%, trees 1%, and grasses 68% to the total C stock.

4.3 The impact of management intensities

Landscape lawns are the most prominent feature in the ancillary areas, as determined before (Figure A11). It is importanat to estimate their limit of C stock holding capacity under different management intensities so that the maximal expected C pool under this landscape-lawn-management style can be determined. Figure 7 shows the impact of different land management factors on the grassland carbon pools. Even though the calculations for the changed C stocks were only performed using the soil carbon pool values, the graph shows the total C stock with the AGB added back to generate the total C stock value, as the InVEST-model approach generates its outputs. The results demonstrate the estimated improvement and degradation, that different management approaches can have. Figure 7 shows that management intensities can cause a difference of 2000 MgC (Ancillary area measure 8), that is stored in the roadside lawn-areas.



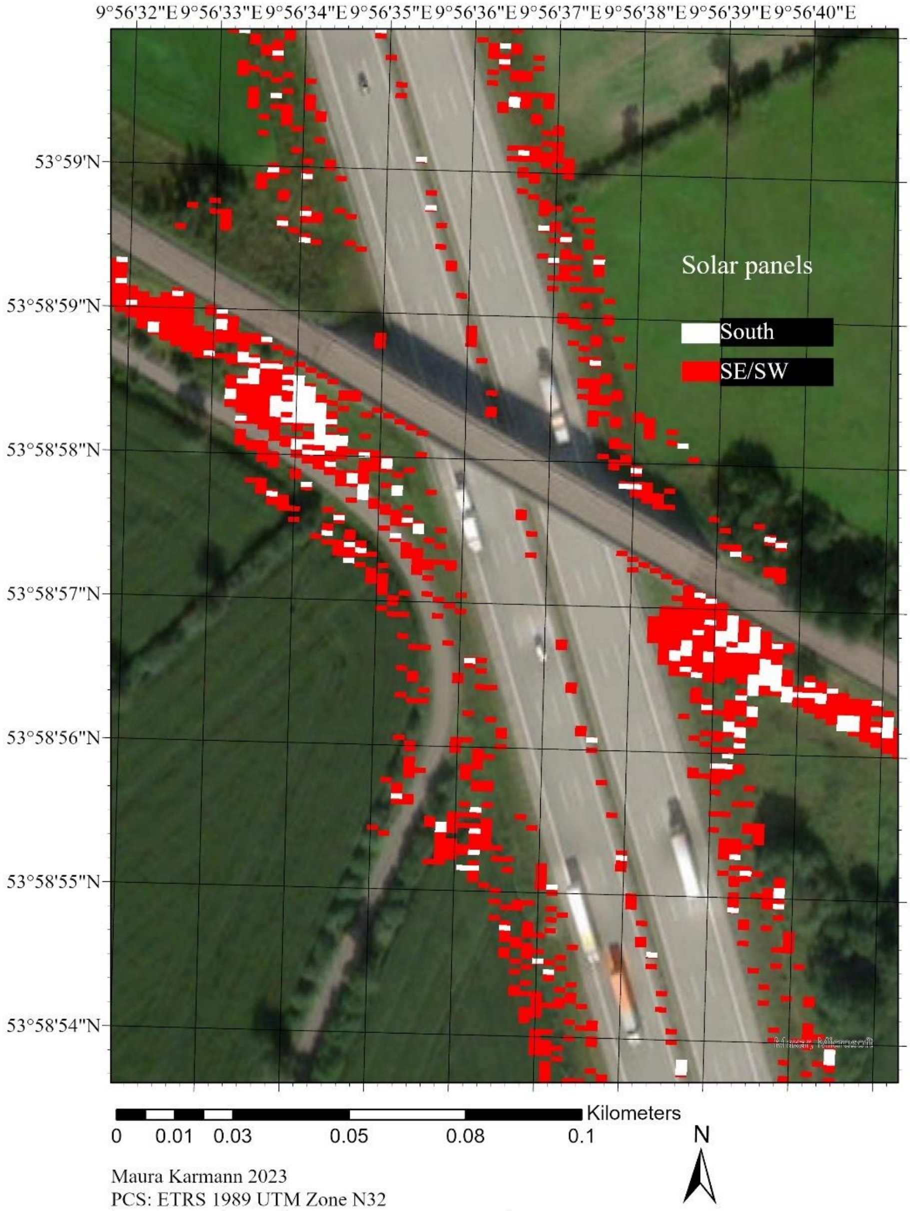
	8	9	10	11	12
■ severely degraded	2597.93	1421.75	1060.33	299.81	1549.71
= severely degraded w.a.	2834.15	1539.66	1168.60	329.72	1737.10
■ moderately degraded	3525.77	1929.51	1439.01	406.88	2103.18
= moderately degraded w.w.	3846.35	2089.54	1585.96	447.47	2357.49
■ nominally managed	3711.33	2031.07	1514.75	428.30	2213.87
= nominally managed w.a.	4048.79	2199.51	1669.44	471.03	2481.57
■ improved	4230.92	2315.42	1726.82	488.26	2523.82
= improved w.a	4615.62	2507.44	1903.16	536.97	2828.98

Figure 7. Different estimations of carbon storage capacities of the grassland areas (landscape-lawns) of the roadside areas. Based on IPCC grassland relative stock change factors for the 30cm topsoil of mineral soils. Differences in storages regarding the aspect (w.a.) are included.

4.4 Solar panel calculations

Single PV-panels

The total coverage of south-facing slopes would result in an area of 47,260.5 m^2 and the panels on SE and SW directed slopes would cover an extra 359,430 m^2. With the expected Watts per hour, this leads to 9 GW/h (79TW/yr) for the South-facing PV panels and 68 GW/h (596TW/yr) for SE and SW-facing slopes. The Greenhouse Gas Equivalency calculator converts this to 61,713,911 tons CO_2 equivalent and 465,588,492 tons CO_2 equivalent (US EPA, 2023). Figure 11 shows an example of the coverage of ancillary areas with PV-panels on areas with South-facing and SW/SE-facing slopes, where the precision of this calculation can be estimated visually.



Maura Karmann 2023
PCS: ETRS 1989 UTM Zone N32
basemap: Esri, Garmin, Foursquare, FAO, METI/NASA, USGS

Figure 11. Map of single PV-placements on south, SE and SW facing slopes.

Solar roof

According to the presented lengths and widths a roof coverage results in a yearly average capacity of 468GW. This is the equivalent of 4 102.5TW a year. According to the Greenhouse Gas Equivalency calculator, this equals 3,204,826,828 tons of CO_2 equivalent (US EPA, 2023).

5 Discussion

5.1 Findings – A Discussion of Results

To put into perspective how effective management is with regard to carbon storage, one must investigate the emissions that come with management. The company that manages the A7 motorway has tracked its yearly emission sources in a Scope 1-3 approach. Scope 1 is calculating the annual direct emissions, which entails the combustion of fuels in mobile and stationary emission sources. Scope 2 is the sum of indirect emissions from the generation of purchased electricity, for example for the operation of motorway facilities. Scope 3 calculates other indirect emissions, this includes for instance purchases of products and services, construction measures, vehicles and equipment, waste, fuel, and energy-related activities. The Scope calculations were introduced to the company in 2020 and serve as a general orientation, since the tool is still being improved. The sum of emissions is foreseen to become more precise, since some parameters will be added or need adjustment. Future emission estimations are likely to increase with time and precision. For the year 2021, emissions of all 3 scopes add up to a total of 1,069.367 tCO2e.

To account for management-related emissions, the fuel combustion from the direct emissions in Scope 1 must be regarded, which make up a total of 230.1 tCO2e, as well as additional fuel-related activities, which result in 55.3 tCO2e, and the purchase of machinery, that was approximately 128.0 tCO2e. The management alone, therefore, results in a total of approximately 413.4 tCO2e in 2021. But with waste products (474.3 tCO2e) and all the other company-related emissions, one must account for an annual sum of 1,069.367 tCO2e.

One MgC is a tonne of carbon and to convert a quantity of carbon to the equivalent quantity of carbon dioxide, one must multiply it by 3.67 (US EPA, 2023). 16,067.23 (± 774.25) MgC are therefore 58,966.73 (± 2787.3) tCO2e, which is the total C stock of the roadside vegetation. According to these estimations, the emissions only make up 1.8% of the C stock. But this does not mean that the management strategies are non-invasive. This study has focussed on the storage capacity in relation to management, but to accurately compare emissions, one must calculate the sequestration rate. The turnover rate is potentially very low and the companies emissions might even exceed the rate of carbon that is yearly sequestered. It must also be mentioned, that the Greenhouse Gas equivalency calculator is based on the American electricity-mix, which the CO2 equivalency is derived from (US EPA, 2023). Based on potential differences to the German power composition, the estimate of avoided carbon dioxide emissions differ from the before presented results since a different national emissions factor applies (US EPA, 2023). A future study with a higher level of precision should convert the before mentioned equivalency values.

The results further show that management intensities can cause a difference of 2000 MgC (Ancillary area measure 8) carbon storage and minimal interventions seem advisable. But generally, in the Northern German environment, the relative carbon storage amount does not appear to be a significant sink, as the Scientific American article suggests (Climate, 2014). However, the option of solar panel installment based on the CO_2 equivalencies, is a strategy that is most suggestable. With the installment of south-facing panels alone, 1 047 times as much CO_2e is obtained, than what is currently stored in the roadside carbon pools. With South, SE, and SW facing panels 8 942 times the CO_2e is generated in a year and the solar roof would lead to a 54 350 times higher CO_2 equivalent. The solar roof and panels on the ancillary areas are not mutually exclusive, and potentially both PV installments can be applied. Just the PV roofs posts would be anchored on the ancillary areas directly near the roadway, where no PV panels could be located, which was not calculated, as all South-facing slopes were included. However, emissions originate from the sourcing of materials, PV construction, and installment, as well as operating the PV systems and their infrastructures, which further investigations should regard and estimate the respective carbon equivalencies.

5.2 Study limitations, possible errors, and a future validation

Overall it should be noted that InVEST-model carbon pool estimations deliver general approximations, but additional input is needed to refine the results that the model produces (Guo et al., 2022). To validate this study, field measurements are needed with for instance eddy covariance measurements, in order to find the amount of carbon that is fixed through the difference of uptake (by the process of vegetation photosynthesis) minus release of carbon (through ecosystem respiration) over a specific period of time (Huiling et al., 2017). This would give insight into the pool storages with higher accuracy and additionally their sequestration rates. Furthermore, a direct pool measurement approach is possible, where the AGB, BGB, and SOC could be measured with sampling techniques. Sampling the SOC can be achieved through newer spectroscopic approaches, or by measuring the soil's oxidation rates (Johns et al., 2015). Similar approaches can be used for the AGB and BGB, such as Terrestrial Laser Scanning, which is recommended for grasslands (Cooper et al., 2017). These approaches would be less time-consuming than direct and destructive measurements (Cooper et al., 2017), but they need more equipment. Sampling can be done representatively as the study site is relatively small. Generally, a validation would enhance this study and rectify the assumptions that were made because of the lack of data on CO_2-flux measurements. Aditionally, the level of uncertainty and respective errors would be minimized, as a site-specific approach with measurements does not rely as much on mean values. With the help of this data, a refined local management impact factor for these grassland-areas can be derived, that is not based on the general Tier 1 approach (IPCC, 2006). Furthermore, site measurements would also be important to test during different times of the year since the sequestration, the vegetation C stock, but also the SOC stock likely vary with seasonal differences. A study at that level of precision could also take into account the fourth carbon pool of dead biomass, which was disregarded. For this, the amount of dead biomass which is taken out or left at the site has to be tracked. Dead biomass when taken out of the area too much, can lead to a depletion of soil carbon, the current state of the carbon cycle and its pools in the areas is unclear. In a more precise future approach this fourth factor should be measured.

The extent of carbon sequestered from particular land uses is oftentimes overestimated, when the aspect factor is disregarded (Lenka et al., 2013). The applied aspect factors based on the study by Zhu (2017) however, increase all mean C stock values. Even though the smallest impact factors from their study were chosen, the change factors might not apply in the northern German climate. To validate these results, measurements of SOC stocks relating to the Aspect are needed. The mean SOC values and pools might therefore be more representable of the SH-local conditions than resulting values from aspect calculations. Nevertheless, the factor was considered to understand what impact this has on the total carbon stocks in the study area, without validation for aspect-related SOC and AGB/BGB stock changes, the error estimation is unclear and is potentially as much as 200%, as this was the maximum change factor chosen. Another uncertainty is the equation used to calculate the tree carbon pools, which was developed for Californian broadleaf trees. This will not lead to a great deviation since the total area of planted trees is minimal, nevertheless, for validation purposes the equation needs to be tested and the tree diameter at breast height measured.

5.3 Highway ancillary areas: a special environment - additional points of discussion and further factors to mention

Vehicular pollution can affect roadside plants in various ways since they are the first target of vehicular emissions (Muthu, 2021). Some plants experience a reduced growth rate and a reduction of leaf numbers, as well as leaf and flower damage from dust (Muthu et al., 2021). Various changes in plant health on morphological, biochemical, and physiological levels arise that may reduce the biomass, carbon stock, and sequestration levels (Rani et al., 2023). This effect is called carbon nanomaterial-based toxicity and it affects highway plants particularly. Roadside vegetation is however seen as a buffer between agricultural plants and the pollution source, but the effectiveness of different vegetation to buffer potential toxic nanomaterial is unclear. In particular, the so-called emission plume damages plants. To avoid highway impacts local research needs to find a minimal distance of the vegetation to these plumes (Muthu et al., 2021). Different air pollutants inhibit photosynthesis, reduce vegetation production and growth and the rate of carbon sequestration (Rani et al., 2023). Therefore, further research on the highway vegetation is needed, to understand their growth patterns, growth and sequestration limitations, as well as their ability to sequester carbon. Hence, the found carbon pool results potentially differ significantly as well. The vegetation in the managed area was chosen based on parameters like salt-resistance, the enhancement of biodiversity, and native species. Future studies can investigate the vegetation’s performance on the air pollution tolerance index (APTI), to assess how well the green belts sink and filter air pollutants (Bhadauria et al., 2022). Bhadauria determined the APTI values of different tree species and found that plants vary in sensitivity/tolerance level to air pollution. To find the optimal vegetation to plant in highway ancillary areas this factor needs to be studied and local types of pollution sources have to be identified. When APTI values of the shrubs and trees are known and tolerant species are planted, the highest possible pollutant filtration and carbon sequestration levels can be reached (Bhadauria et al., 2022).

There was also a correlation found between the proximity of soils to German motorways and the level of pollution that they experience. This contamination negatively affects the soil, groundwater, and surface waters, so the SOC content, pool capacities, and sequestration rates are likely negatively impacted as well (Aljazzar et al., 2016).

For the optimal management strategy not just the carbon storage should be regarded, but also its impact on biodiversity. A study on Australian roadside shrubs in fragmented agricultural landscapes finds that the disturbance factor from roadworks is significantly impacting the shrub structural dynamics and soil composition (Spooner et al., 2014). When choosing a management strategy, the conservation of biodiversity might play a more prominent role, since the sink potential of ancillary areas is overall minimal (Mody et al., 2020). The replacement of roadside shrubs with wildflower meadows is one approach tosupport insect conservation. The meadows do however require regular mowing for their permanent existence, which affects meadow-living animals and leads to higher emissions (Mody et al., 2020). Anthropod taxa generally profit from flower meadows, whereas birds require less biodiverse, exotic woody vegetation (Mody et al., 2020).

In some highway ancillary areas, the factor of erosion control should factor in the most when choosing a management approach. Areas that are prone to erosion are best stabilized with the use of shrubs in boreal Scandinavia since they typically have a greater deep-root system compared with herbaceous plants (Jägerbrand et al., 2014). Considering other factors like root density, root length, and diameters of the studied vegetation, Jägerbrand et al., recommend a mixed approach of planting shrubs and grasses for the most erosion-resistant root stabilization.

Recent studies show that SOC storage is increased with plant diversity (Bai et al., 2022). This is another factor that can be measured and influence the potential carbon storage, as well as the decision of which seed-mixtures are best chosen for landscape-lawn establishment. For the overall estimation of carbon storage, grass areas were all treated the same way, since the same management and seed mixtures are generally used. But the company has provided compensation areas, where *Rhinantus* plants were sown to establish a higher degree of biodiversity (Via Solutions Nord, n.d.). In a validation process, measurements on different grassland areas should be performed, to give an insight into the effect this has on their C stock performance.

6 Conclusion

The applied management strategies are not very efficient in storing carbon. The total carbon storage is highest in the areas where commonly used management strategies are applied, but these do not align with the most productive measures.

Highway ancillary areas do not contribute to much of SHs total carbon stock and on average they likely store less carbon than the average forests, shrublands, and grasslands of the state. However, the management-related emissions compared to the total storage, seem minimal and the assumption that management causes higher rates of emissions than the amount of carbon that is stored in the areas, is false. But this should be evaluated further, based on future Scope-estimations and sequestration calculations.

The total C stock estimations between the 15 measures do differ, where areas with shrubs and trees store more carbon, which should be implemented to achieve higher C stock rates alongside highways. Management intensities also determine the productivity of the most common feature of landscape lawns.

The management intensity reduction and the establishment of more shrub-areas is not the only possibility to increase the current carbon pool storage since the highest level of carbon equivalency can be achieved by constructing a solar roof over the highway. But this would change the total setup of the current project and its features, as more construction would occur.

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8 Appendix

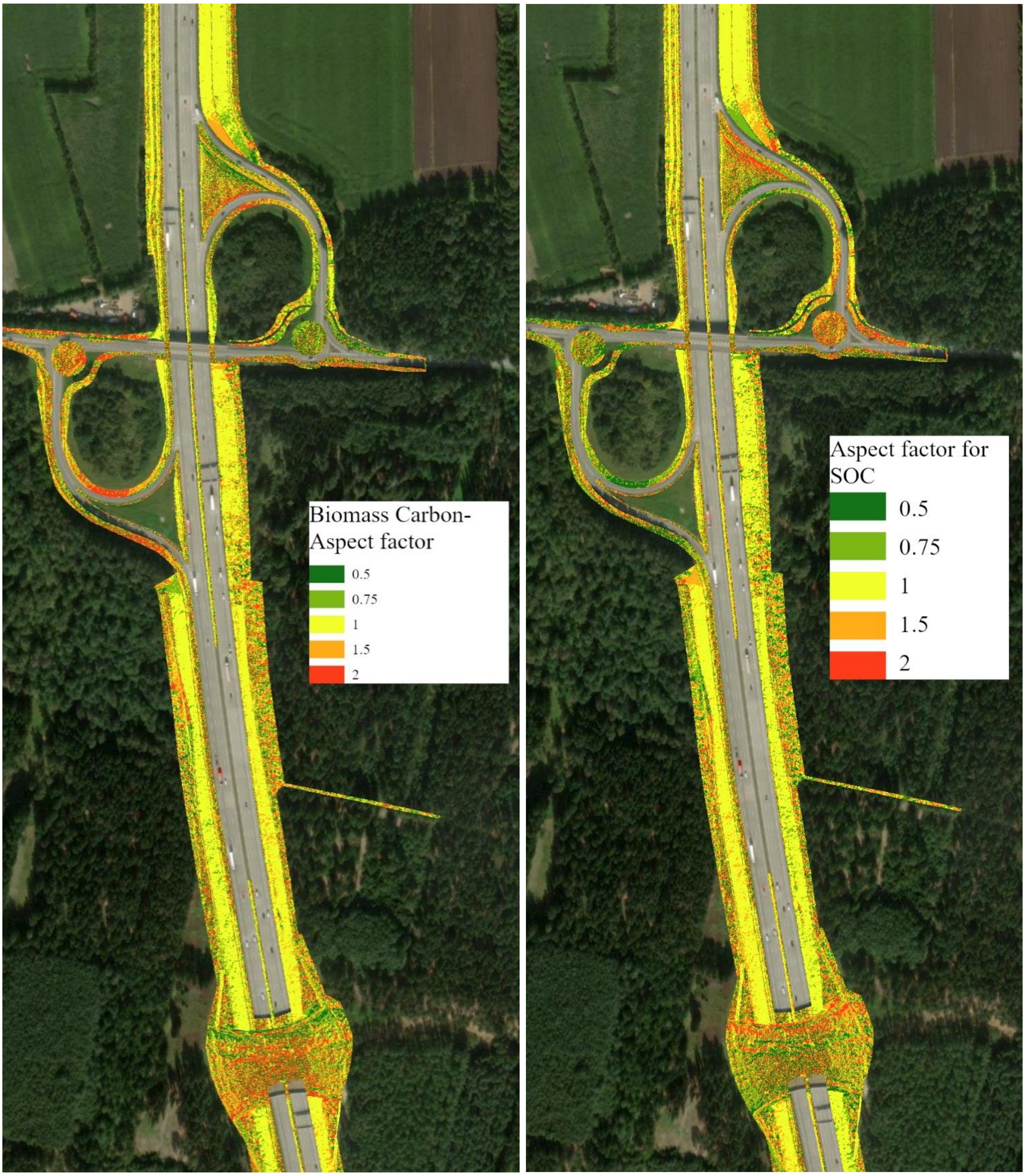
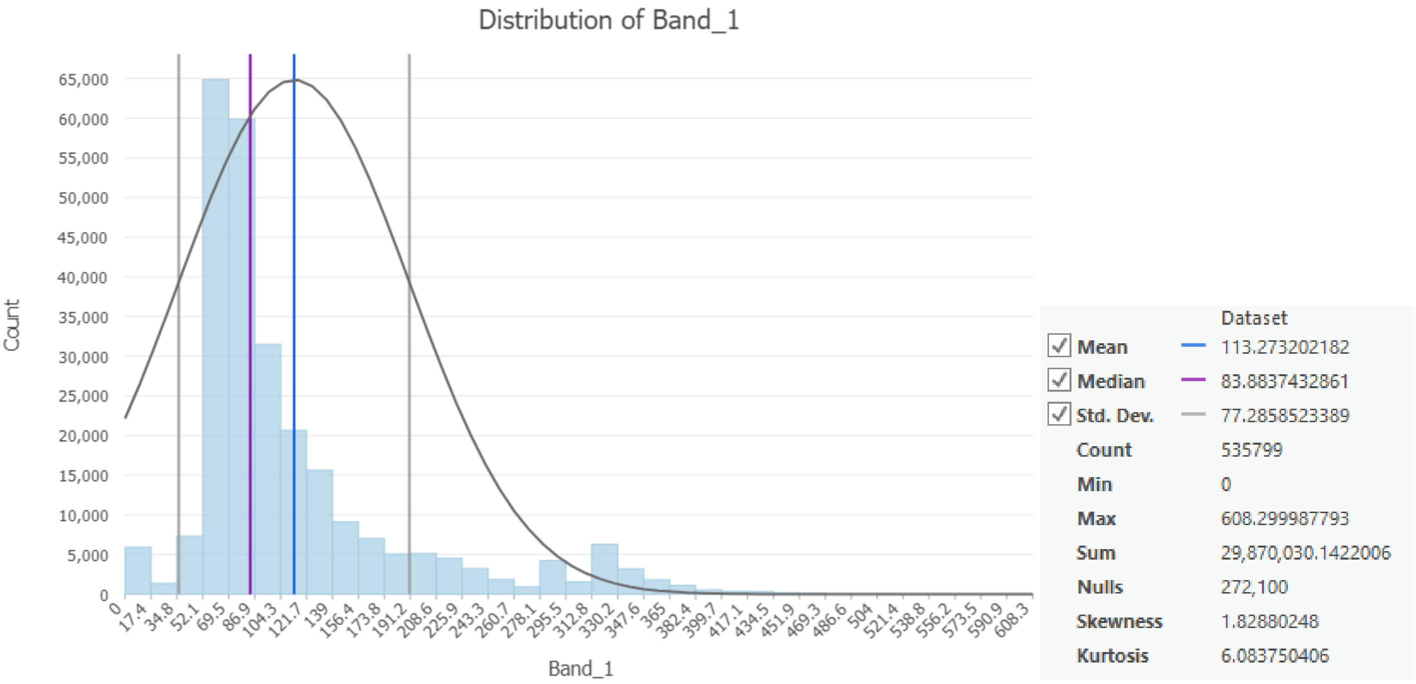


Figure A1 and A2. Aspect factors for ancillary areas in example area – weights for below-ground and above-ground biomass carbon pools (A1) and for Soil Organic Carbon pools (A2).



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☑ Std. Dev.	—	77.2858523389
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Skewness		1.82880248
Kurtosis		6.083750406

Figure A3. Normal distribution of Total Carbon storage in Schleswig-Holstein in MgC/ha

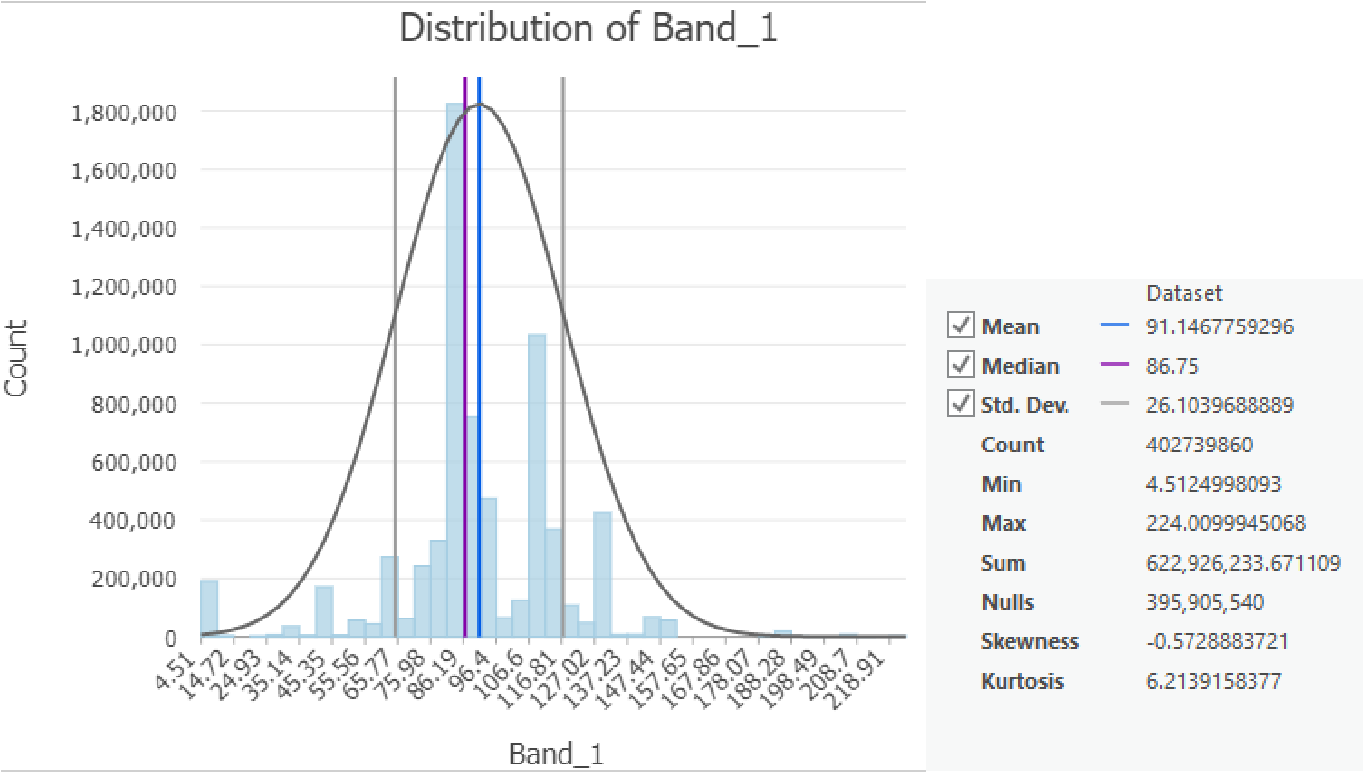

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Figure A4. Normal distribution of Sandy soils SOC storage of forests in Schleswig-Holstein

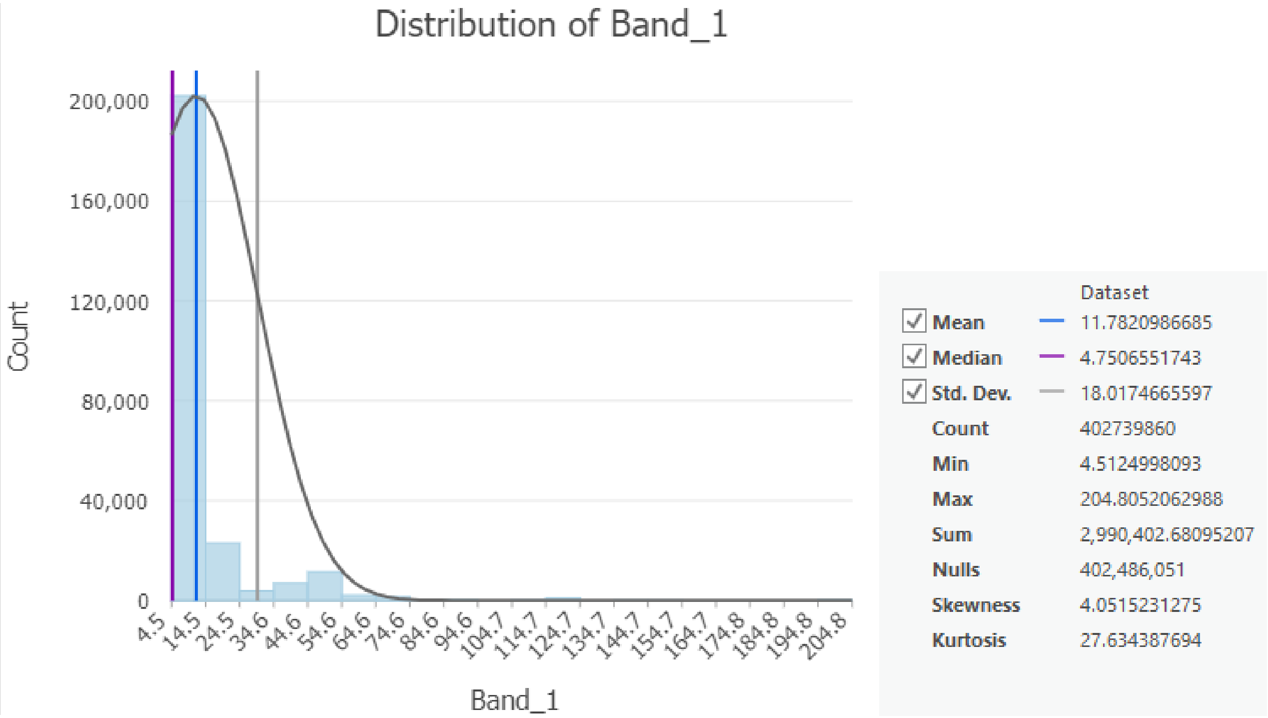

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Figure A5. Shrubs SOC normal distribution on sandy soils in the county Schleswig-Holstein

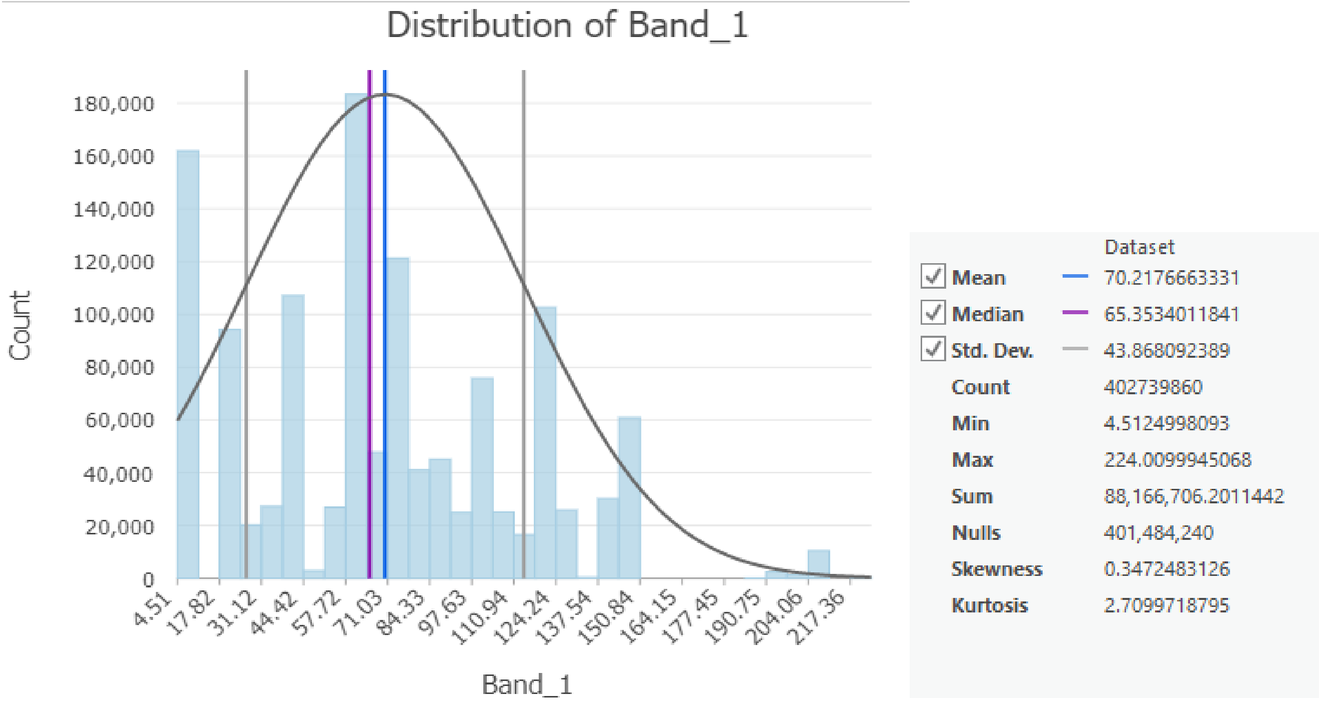

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Figure A6. Grasses SOC storage on sandy soils normal distribution in the county Schleswig Holstein

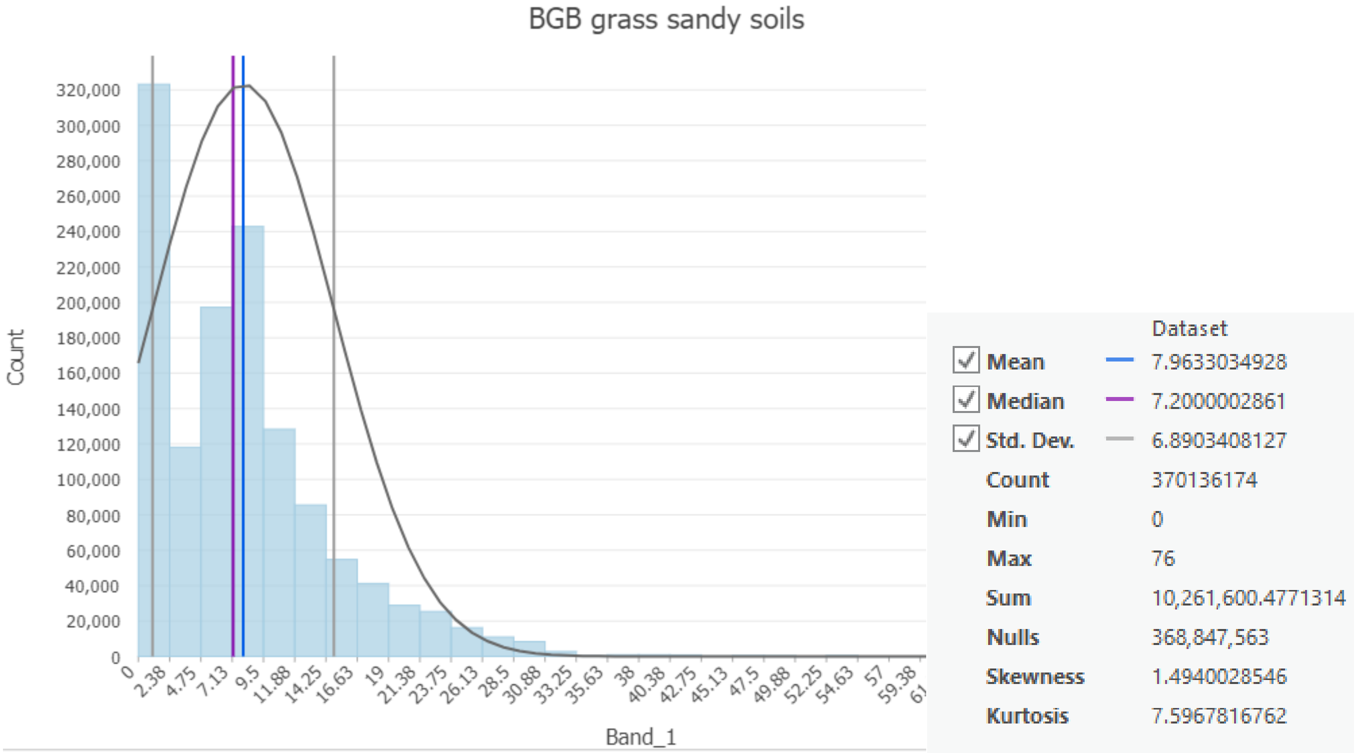

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Figure A7. Normal distribution of Grasses Below Ground Biomass storage of sandy soils in Schleswig-Holstein.

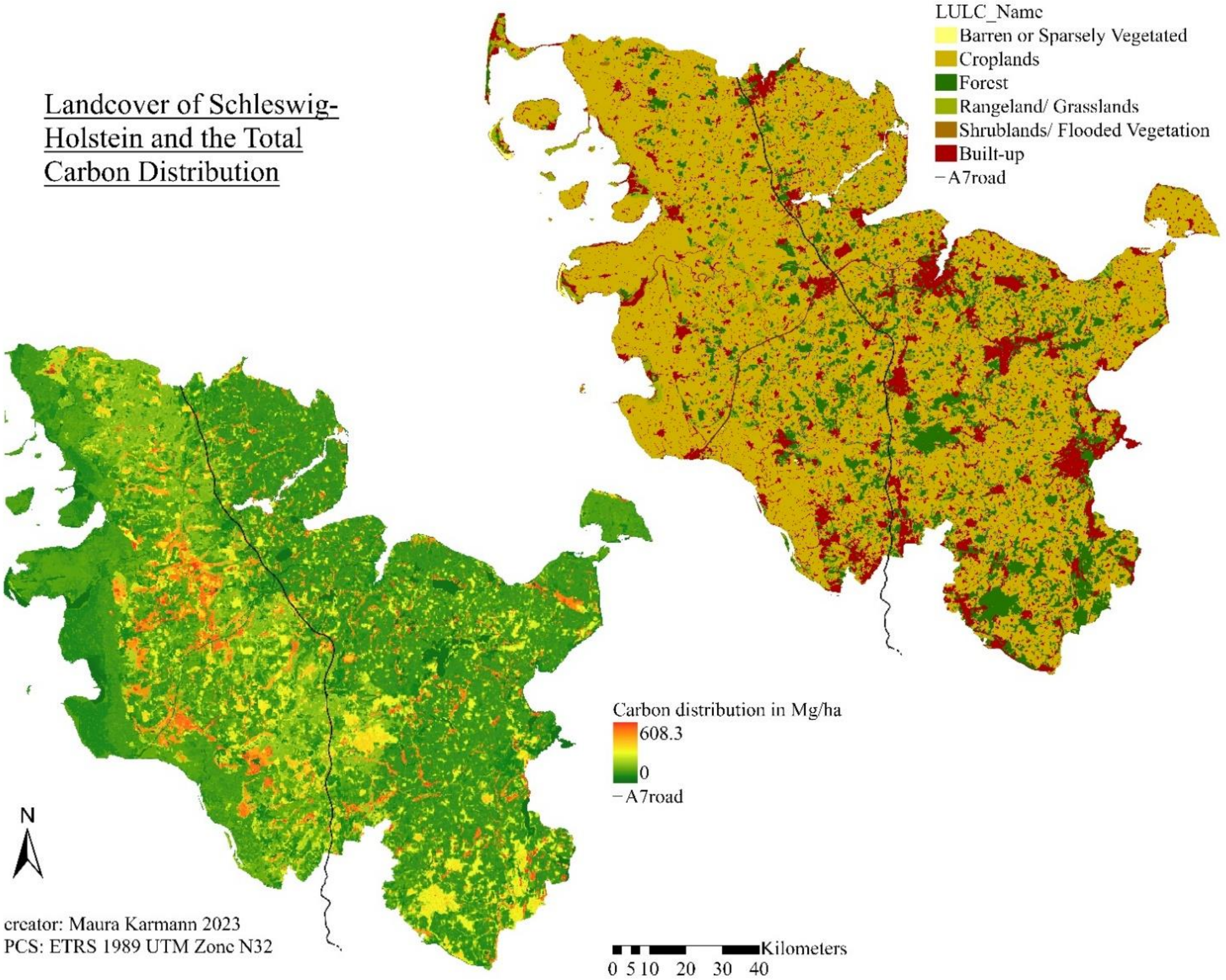

Figure A8. InVEST-model approach of calculating the states total carbon pool, total carbon distribution in MgC/ha (left) and Land use Land cover distribution of the state (Schleswig-Holstein, right).

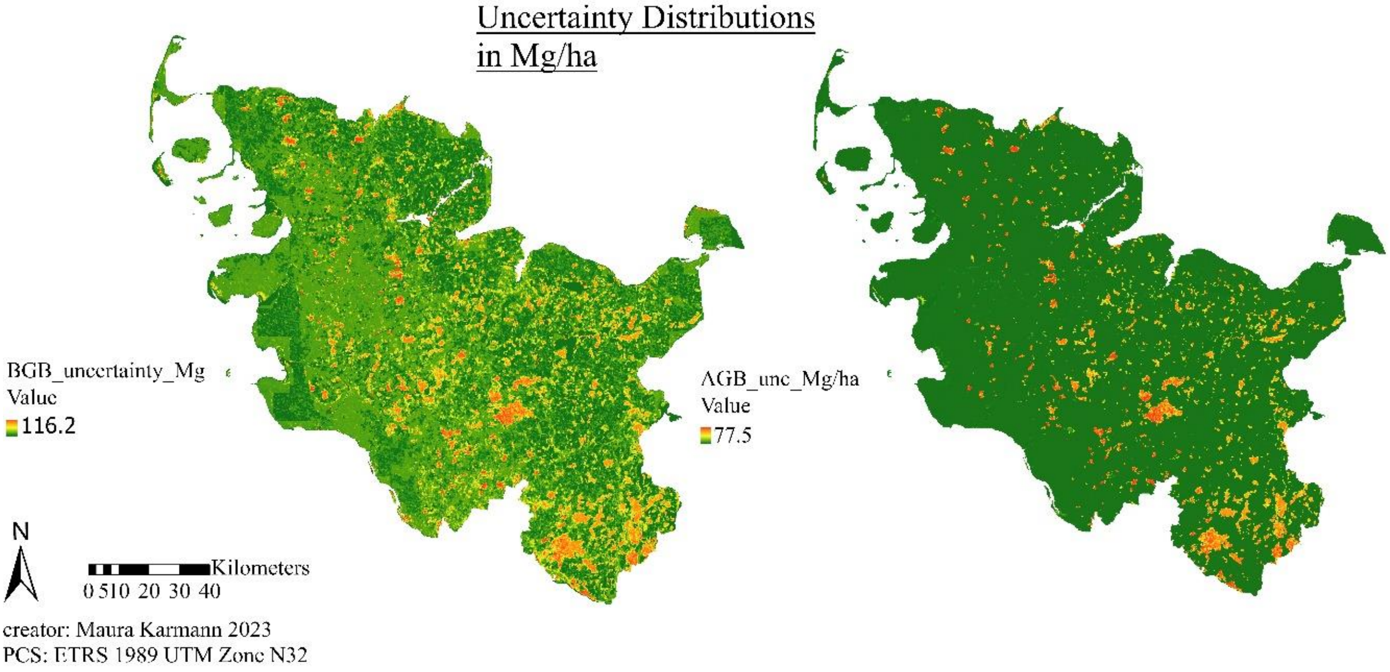

Figure A9. Uncertainty distributions of carbon pool estimation layers (BG organic biomass carbon pool uncertainty layer- left, AGB carbon pool uncertainty layer -right)

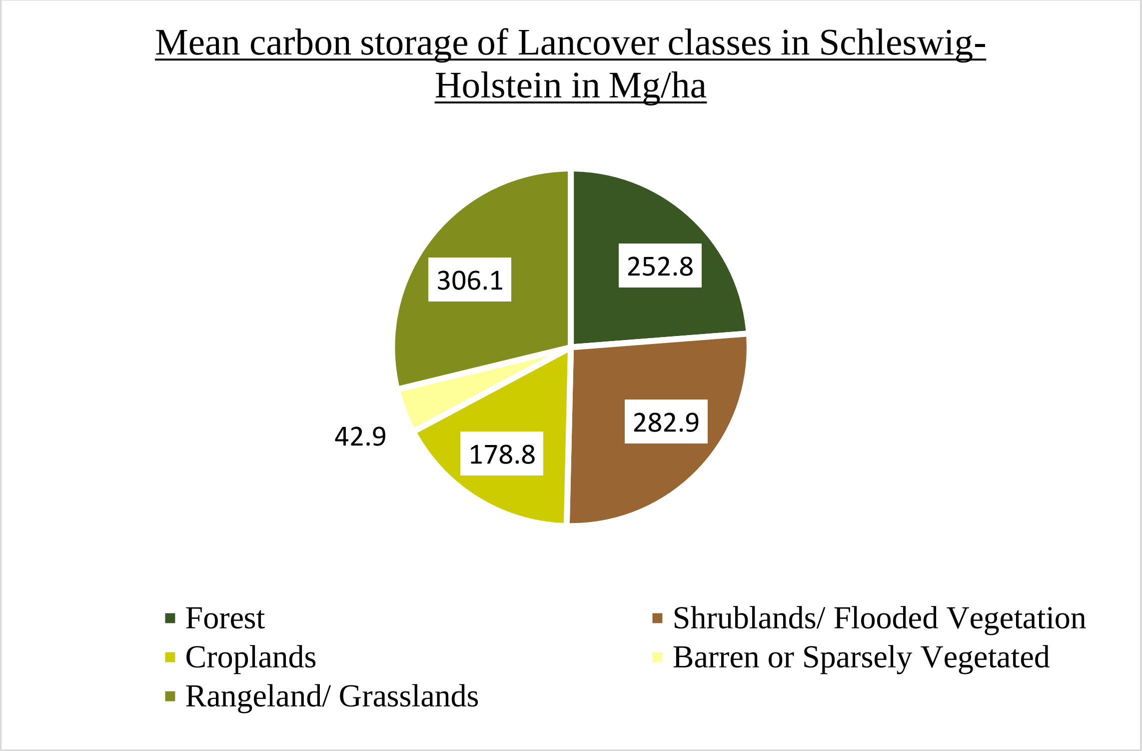

Figure A 10. Total mean carbon storages of LULC-classes SH

Table A1. SH carbon pools

LULC_Name	Area (ha)	C_above	C_below	C_soil(30cm)	C_dead	Sum	C stock in Mg
Forest	200288.6	64	19	103.7	0	186.7	5063676874.5
Shrublands	3703.26	7	9	100.1	0	116.1	109383415.9
Croplands	1079303.5	10	6	91.5	0	107.5	19299234540.5
Sparsely Vegetated	1334.79	4	2	14	0	20	5723462
Grasslands	47372.57	14	9	126	0	149	1450070706.5

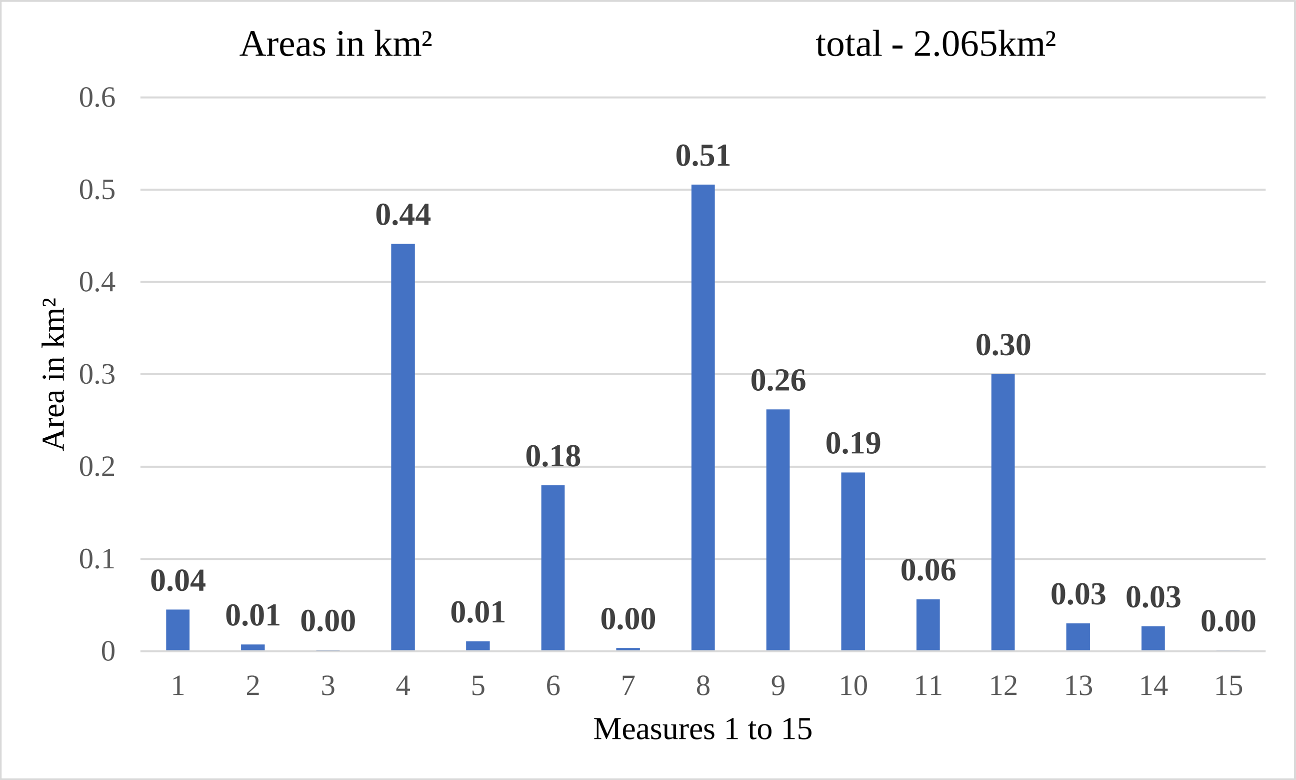

Figure A11. Total areas of measure 1 to 15.

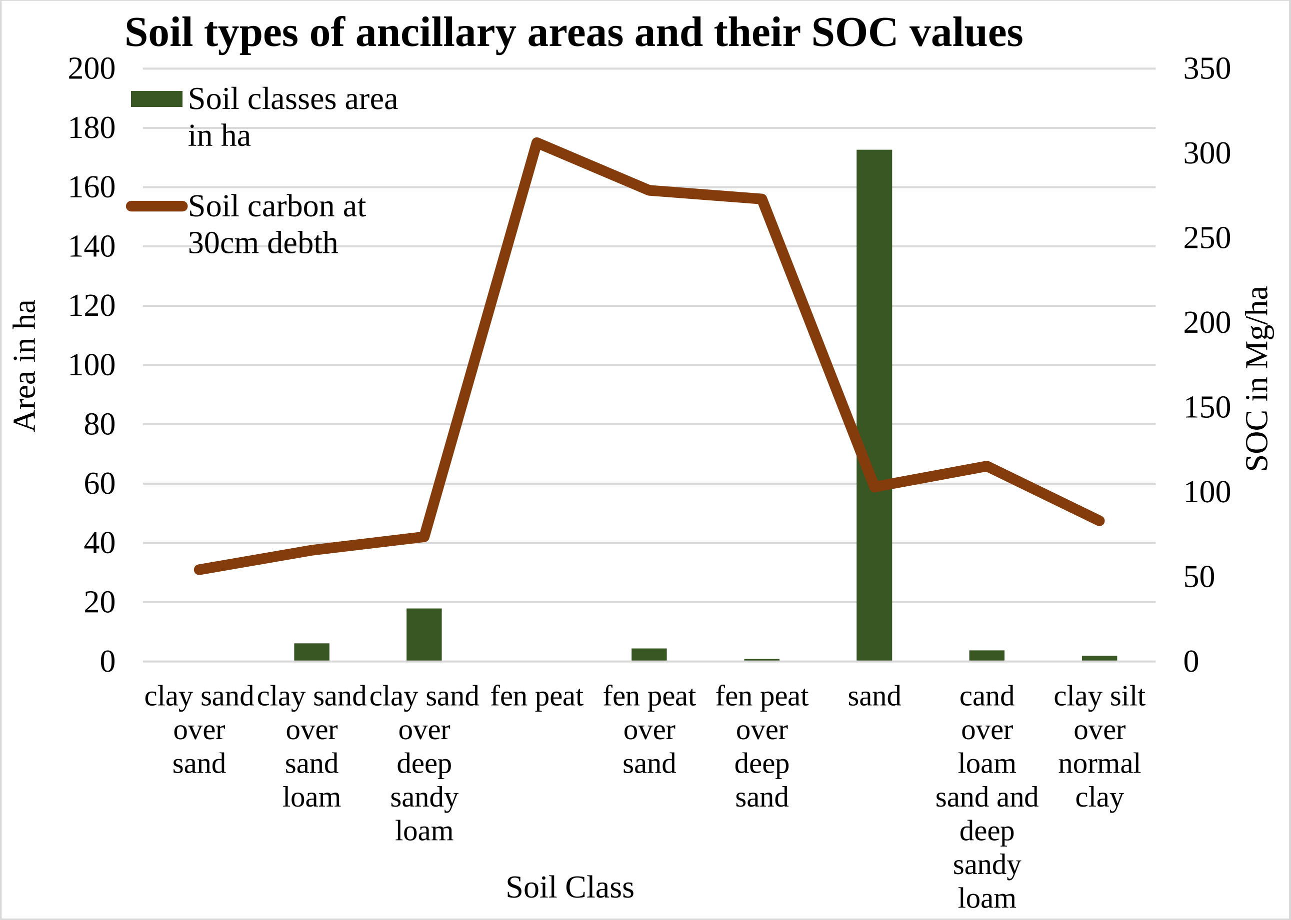

Figure A12. Soil classification of the total A7 highway ancillary areas.