From Field Surveys to Climate Mitigation Support: Scaling Regional Hedgerow Carbon Estimates via Multi-Resolution Remote Sensing

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1 ABSTRACT

Hedgerows provide a variety of essential ecosystem services, acting as a major tool for carbon sequestration to counteract the impacts of climate change. However, determining the amount of carbon stored in hedgerows at a regional level has been challenging. Field surveys can be precise but are time-consuming and labor-intensive, primarily deriving biomass from stem measurements under the canopy. Whereas remote sensing technologies can cover large geographic scales, they often lack the ability to estimate the detailed sub-canopy structure of linear woody features at the local scale. To bridge this gap and calibrate remote sensing models using local field data, a method was developed in this study to estimate hedgerow carbon storage by integrating field survey data with canopy height model (CHM) volume estimation for the Salzlandkreis region in central Germany.

Field sampling was conducted across three study sites, where diameter at breast height (DBH) and height were measured for 4,382 woody plants (diameter > 3.5 cm). Based on this data, forestry form-factor equations were used to calculate individual tree volumes, and above-ground biomass was subsequently estimated based on species-specific wood density. To generalize these localized measurements to the regional scale, volume-to-biomass ratios (VBR) were established. These VBR values were derived from correlations between field-measured biomass and volumes obtained from multi-resolution remote sensing datasets.

By multiplying the converted woody biomass by the canopy volume, the regional estimates of hedgerow above-ground carbon storage ranged from 96,538 to 104,341 Mg C (354,294 –382,931 Mg CO_2e). This corresponds to carbon densities ranging from 57 to 70 Mg C ha^{-1} when normalized to the total hedgerow area in Salzlandkreis.

This research demonstrates that moderate-resolution state datasets, when properly calibrated and validated against field measurements and high-resolution UAV data, can produce regional-scale carbon estimates, which would be impossible through field-only approaches. This study provides a framework for integrating remote sensing data with varying spatial resolutions and field validations, supporting evidence-based regional carbon estimation.

Keywords: Hedgerow carbon storage, Multi-resolution remote sensing, Volume to biomass ratio, Field-remote sensing integration, Regional carbon estimation

2 INTRODUCTION

Hedgerows serve many important functions in terms of providing ecosystem services. These services include carbon sequestration, provision of habitat for biodiversity, protection against soil erosion, regulation of water flow, and natural pest management (Heath et al., 2017; Montgomery et al., 2020). Specifically, their role in carbon sequestration is especially relevant as this is considered an essential tool to mitigate the local and global effects of climate change (Drexler et al., 2021).

Biffi et al. (2023) estimated that 3- to 6-year-old hedgerow stands contained approximately 8.34 Mg C ha^{-1}(megagrams of carbon per hectare), whereas mature stands (>39 years old) contained approximately 40.42 Mg C ha^{-1}. Additionally, studies conducted in Germany indicate much higher totals, with an average biomass carbon stock of approximately 105 ± 11 Mg C ha^{-1}, of which approximately 40% was stored in the root system (Drexler et al., 2023). Drexler et al. (2021) reported that the average amount of aboveground biomass present in hedgerows is about 47 ± 29 Mg C ha^{-1}.

In order to accurately determine the carbon sequestration potential of hedgerows across all regions, in terms of both location and extent, species composition and health condition, extensive assessments over broad areas will need to be conducted (Staley et al., 2023). Traditional on-the-ground survey methods, however, are labor-intensive, expensive and often impractical or unable to be applied at large scales such as a regional or national level. Given these constraints, there is currently increasing interest in using remotely-sensed data from technologies such as unmanned aerial vehicles (UAVs) equipped with high-resolution cameras (Broughton et al., 2025).

UAV-based photogrammetry can generate centimeter-scale digital surface models (DSMs), Orthomosaics and point-cloud based 3-D models of individual hedgerows enabling precise measurements of their structural properties including height, width and volume. On the other hand, state aerial imagery data generally offers lower spatial resolutions, typically ranging between 20 cm and 1 m per pixel (ground sampling distance), when compared to the near range capabilities of UAVs; however, it enables the creation of large-scale topographic information through digital terrain models (DTMs) and DSMs which can be used to create canopy height models (CHMs) for biomass estimations (Bazzo et al., 2023). By integrating fieldwork data (ground truth data) and high-resolution UAV data for calibration and medium-resolution state datasets for regional coverage, a scalable framework for hedgerow carbon storage estimation becomes achievable.

This study has two objectives: 1) to provide a remote sensing methodology to extend those estimates to larger areas by using canopy height model (CHM), and 2) to provide an estimation of the carbon stored in hedgerows across Salzlandkreis, Saxony-Anhalt, Germany. Through this approach, this study demonstrates the potential of combining high accuracy field sampling with broad area remote sensing analyses, which could provide the policy relevant information concerning the ecosystem services carbon storage estimation provided by hedgerows, supporting data-driven climate action and landscape planning.

3 MATERIALS AND METHODS

The multi-stage methods applied in this study comprised two distinct components: field surveys using multi-resolution remote sensing and biomass estimation; and remote sensing data acquisition and processing.

(1) Field Surveys and Biomass Calculation: In order to determine hedgerow characteristics (type of tree, diameter, height, and width) field surveys were conducted at three sample sites in Salzlandkreis. These characteristics were then used to determine carbon storage.

(2) Remote Sensing Data for Volume Calculation: Multi-resolution Remote Sensing data were collected, including digital surface model data obtained from a drone system (6 cm / pixel resolution), high resolution aerial data that are part of the iDSM (image-based DSM; 20cm / pixel resolution), and medium resolution aerial data that are part of the DSM (1 m / pixel resolution). From the DSMs the volumes of hedgerows were calculated.

(3) Correlation Coefficient: In this step, a correlation coefficient was calculated to quantify the relationship between the field-determined biomass (Step 1) and the Remote Sensing-determined hedgerow volumes (Step 2).

(4) Regional Scale Quantification : A CHM was created from the DSM and iDSM data to calculate the volume of all hedgerows in Salzlandkreis. The total carbon storage for the entire region was then calculated by multiplying the total volume of hedgerows by the correlation coefficient established in Step 3.

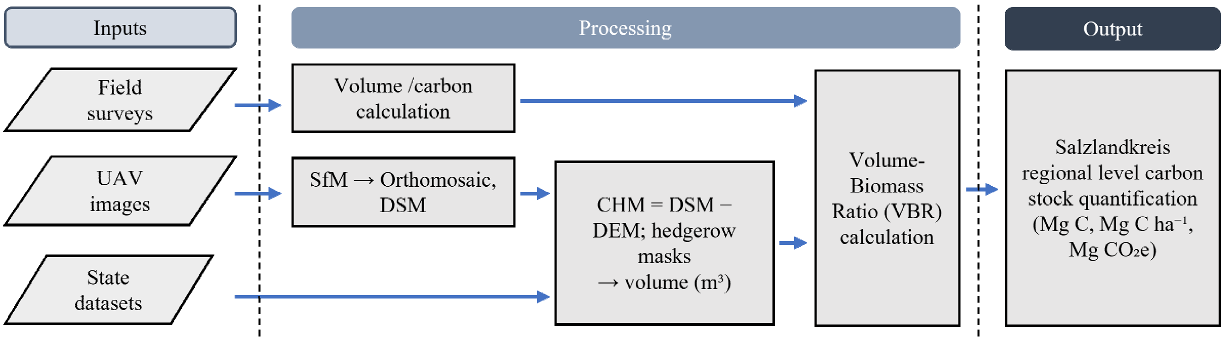

Fig. 1: Research workflow.

3.1 Study Area

The Salzlandkreis (Salzland district; total area: 1,427 km²) is located in central Saxony-Anhalt, Germany, and is characterized by an agricultural landscape typical of the North German Lowlands, representing intensive agricultural landscapes in this region. In this study, researchers initially identified six locations with a high density of hedgerows within the Salzlandkreis through the application of ArcGIS Pro's Density analysis tools. Subsequently, through site visits, researchers ultimately selected three sample research area (1.5km x 1.5km/each) from those six candidate study sites (see figure 2 and 3).

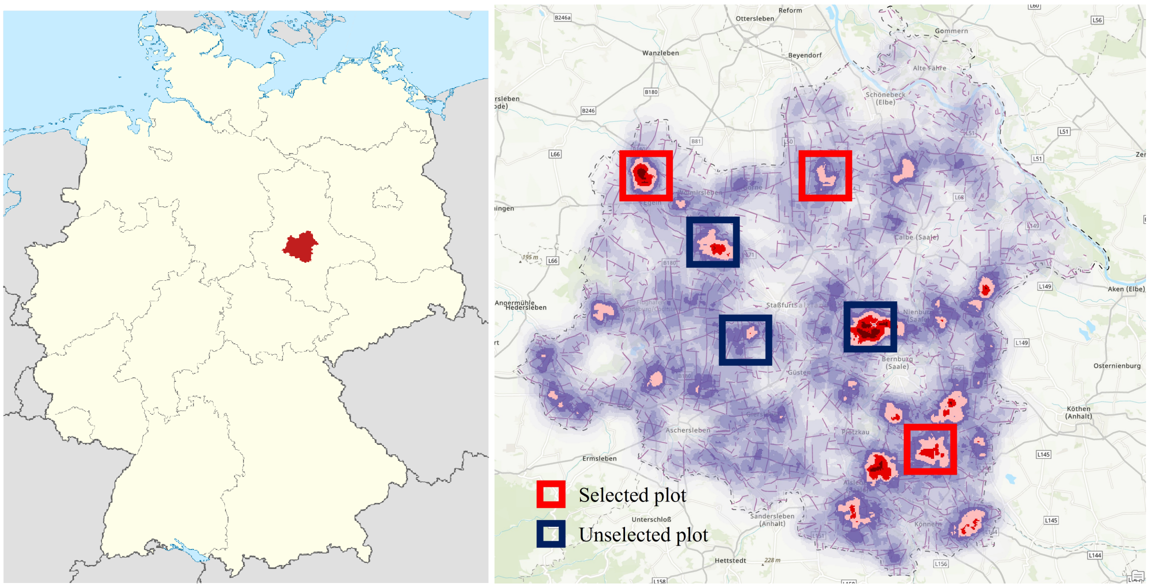

Fig. 2: Location of Salzlandkreis in Germany (left) and three selected research plots (red) in Salzlandkreis (right).

Fig. 3: The three selected research plots (located in Westeregeln, Unseburg, and Peissen from the top to bottom).

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3.2 Methods

3.2.1 Field Survey and Biomass Measurement

At three research sites, tree-species-specific values for the calculation of CO_2 potential and standing biomass were recorded for 4,382 woody plants. For this, all woody plants (diameter > 3.5 cm) were measured using Nikon Forestry Pro rangefinder which is a tree height measuring device ranging of 7.5 to 1600 m and a diameter tape measure. Relevant parameters such as tree species, tree height (h), diameter at breast height (DBH), and nature conservation-relevant characteristics were recorded in a mapping sheet. The calculations of the comparison values for carbon storage and gross carbon were carried out with the software I-Tree Eco (USDA forest service software suite), taking into account the characteristics measured in the field for each woody plant. The calculation of the tree volume was carried out using a form-factor-based volume estimation formula as applied in forest inventory. Only the stem volume without branches and roots is considered here (see Figure 4). The form factor (f) describes the deviation of the stem shape of a tree from a perfect cylinder. Depending on location and tree species, the form factor lies between 0.45–0.52. For the calculations, this was uniformly set to 0.5. The individual tree volume was calculated as follows:

$$V\left[m^3\right] = \left(\frac{DBH\,[cm]}{200}\right)^2 \cdot \pi \cdot h\,[m] \cdot f$$

where:

V = individual tree volume without branches and roots

DBH = diameter at breast height (1.3 m above ground)

h = tree height

f = form factor (species-dependent correction value)

For the calculation of biomass B [kg], the individual tree volume V [m^3] is multiplied by the species-specific basic density WD [kg/m^3] for each tree species (see Table 1), according to the following formula:

$$B\,[kg] = V\left[m^3\right] \cdot WD\left[kg/m^3\right]$$

where:

B = biomass

V = individual tree volume

WD = wood density

Species	Wood Density (kg/m³) at 12-15% Moisture Content
Populus x canadensis	410
Fraxinus excelsior	650
Tilia platyphyllos	490
Acer platanoides	590

Table 1: Examples of average raw densities of selected wood species (Source: Grabner, 2017; Steuer, 1985; Kollmann, 1982).

3.2.2 Remote Sensing Data Acquisition and Processing

High-resolution aerial imagery was acquired at three research sites using a DJI Mavic 3 Enterprise RTK (Real Time Kinematic) drone with a 20M pixels RGB sensor. Flights were conducted at 50 m above ground level (AGL) from multiple viewing angles with 75% forward and 75% side overlap to support 3D reconstruction. Structure-from-Motion (SfM) photogrammetry was applied to generate a 6 cm/pixel resolution digital surface model (DSM) and a 3 cm/pixel resolution orthomosaic. These products enabled precise measurement of hedgerow structural attributes. Official state aerial datasets were used: DSM1 (1 m resolution) and iDSM20 (0.2 m resolution), provided by the State Office for Surveying and Geoinformation of Saxony-Anhalt (Landesamt für Vermessung und Geoinformation Sachsen-Anhalt, LVermGeo). The DSM1 was provided as GeoTIFF to be used directly and the iDSM20 was provided as compressed point clouds (LAZ). Those were converted to LAS format. They were then rasterized to GeoTIFF for analysis.

These multi-resolution datasets (DSM1, iDSM) were jointly used to derive hedgerow volumes at scale, with UAV dataset calibrating and validating volume–biomass relationships for regional application.

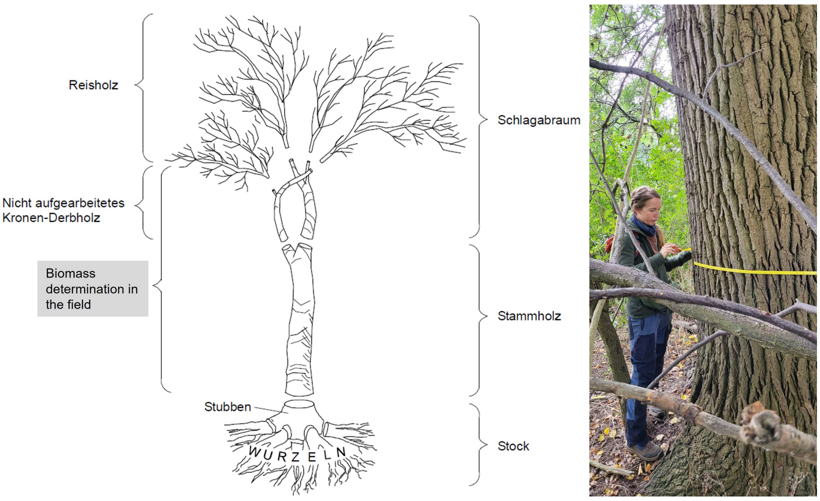

Fig. 4: Field survey and biomass measurement (the figure on the left source: Englert, H et al., 2009).

3.2.3 Calculation of Volume-Biomass Ratio (VBR)

The use of line features provided by the State and manually added in the creation of hedgerow mapping areas that were extended with 20 m radius buffer in order to identify the analysis zones. The canopy height model (CHM) was made through the CHM = DSM – DTM equation (see Fig. 5). The threshold was increased from 1.2 meters to 2.2 meters because of adjacent tall crop fields (such as sunflower fields) that are unrelated to hedgerow vegetation. Hedgerow volumes were obtained by calculating the canopy height over pixels multiplied by pixel area, using zonal statistics in ArcGIS Pro Raster Calculator according to:

$$V_i = \sum_{j=1}^{n}(h_{ij} \times A_{\text{pixel}})$$

where:

V_i = total canopy volume of hedgerow i in Salzlandkreis (m³)

n = total number of pixels within the buffer zone where CHM ≥ 2.2 m

j=1 = no sub-divisions (the object consists of one element)

h_{ij} = canopy height at pixel (i, j) above 2.2 m threshold (m)

A_{pixel} = pixel area (1 m² for DSM1; 0.04 m² for iDSM20)

Biomass was calculated by multiplying the volume of each zone by the Volume-Biomass Ratios that derived from the three-test site analysis for each data.

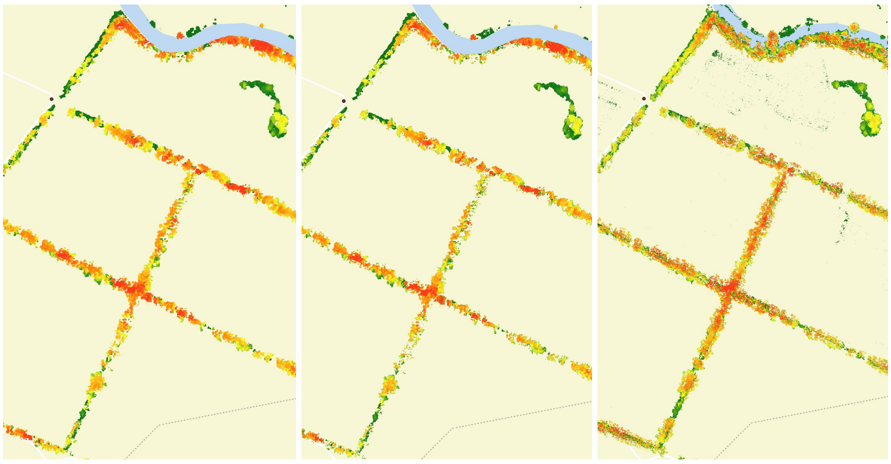

Fig. 5: Canopy height model (CHM) at Westregeln study area using DSM1, iDSM20 and UAV data sets (from left). DSM1, DSM20, DTM source: State Office for Surveying and Geoinformation of Saxony-Anhalt (LVermGeo).

4 RESULTS

Using the methods discussed previously, conversion factors for converting remote sensing volume to biomass at a number of resolutions were developed. The conversion factors are summarized in Table 2 as both the volume-biomass ratio (VBR), and as biomass density (kg m^{-3}). Results indicated that the high-resolution UAV data set had the lowest Volume Biomass Ratio (0.6) and correspondingly the highest biomass density (1.66 kg m^{-3}).

	DSM1	iDSM20	UAV
Volume-Biomasse Ratio (VBR)	0.97	0.78	0.60
Woody Biomass (kg/m³) in Field Vegetation	1.03 kg m^{-3}	1.29 kg m^{-3}	1.66 kg m^{-3}

Table 2: Average values of the volume-biomass ratio (VBR) for DSM1 (1 m spatial resolution), iDSM20 (0.2 m spatial resolution), and UAV (0.06 m spatial resolution), and mean value, woody biomass in kg per 1 m³ of field vegetation.

Table 3 presents total aboveground hedgerow carbon stock estimates for the 1,427 km² Salzlandkreis area using both DSM1 (1m spatial resolution) and iDSM20 (0.2 m spatial resolution). Aboveground total carbon stock ranges were 96,538 – 104,341 Mg C (equivalent to 354,294 – 382,931 Mg CO_2e).

Category	DSM1 (1 m)	iDSM20 (0.2 m)	Unit
Salzlandkreis Area	1,427 km² = 142,700 ha		–
Hedgerow Area	1,690	1,484	ha
Total Hedgerow Volume (≥ 2.2 m)	187,452,364	161,768,729	m³
Total Hedgerow Biomass	193,076	208,682	Mg dry weight
Total Hedgerow Carbon Storage	96,538	104,341	Mg C
Total Carbon Sequestration Potential	354,294	382,931	Mg CO_2e
Carbon Density	57	70	Mg C ha^{-1}
Total Carbon Sequestration Density	210	258	Mg CO_2e ha^{-1}

Table 3: Total Salzlandkreis aboveground hedgerow carbon stock estimates.

On this basis, the carbon storage capacity (and corresponding CO_2 equivalents) of specific hedgerow structures can be determined and evaluated at specific areas. Beyond carbon, integrating these results with other ecosystem service metrics enables a holistic evaluation of individual structure for planning purposes. The derived volumetric estimates also provide a baseline for exploring hedgerow biomass as a potential resource; however, determining sustainable extraction levels would require additional research on growth rates, species composition, and ecosystem service impacts. Consequently, these carbon assessments would provide a foundation for enhancing nature conservation planning. In combination with agroforestry systems, sustainable regional utilization concepts for biomass can be developed and implemented.

5 CONCLUSION AND OUTLOOK

This research demonstrated a feasible and applicable approach for estimating hedgerow carbon content in the Salzlandkreis region using DSM with resolutions of 1 m and iDSM 20 cm, in combination with empirical biomass-volume relationships for calibrating biomass estimates from aerial data including UAV high resolution data.

Utilizing this process, estimated regional above ground carbon stock density for mapped hedgerows were found to be in the range of 96,538 – 104,341 Mg C (equivalent to 354,294 –382,931 Mg CO_2e). This corresponds to carbon densities of 57 to 70 Mg C ha^{-1} when normalized to the total hedgerow area in Salzlandkreis, representing a difference of approximately 23% deviation between the two difference types of data: iDSM20 and DSM1.

There are several limitations to the findings of the current study. For example, the estimates represent only the above-ground woody biomass of the hedgerows; therefore, the below-ground biomass and soil organic carbon (substantial components of mature central European hedgerows) have not been accounted for in the estimates. Additionally, the CHM threshold may need to be site-specifically calibrated based on other land types and regions. Furthermore, the age and management of the hedgerows, which would both affect biomass and carbon stock estimates were not considered as part of the estimation using the remote sensing method. Finally, this study reveals how data resolution affects results: low-resolution data may smooth canopy features, which can lead to vegetation volume underestimation. Conversely, fine-scale data, including UAV data, can capture temporal seasonal changes, which would affect the regional aggregation of estimates.

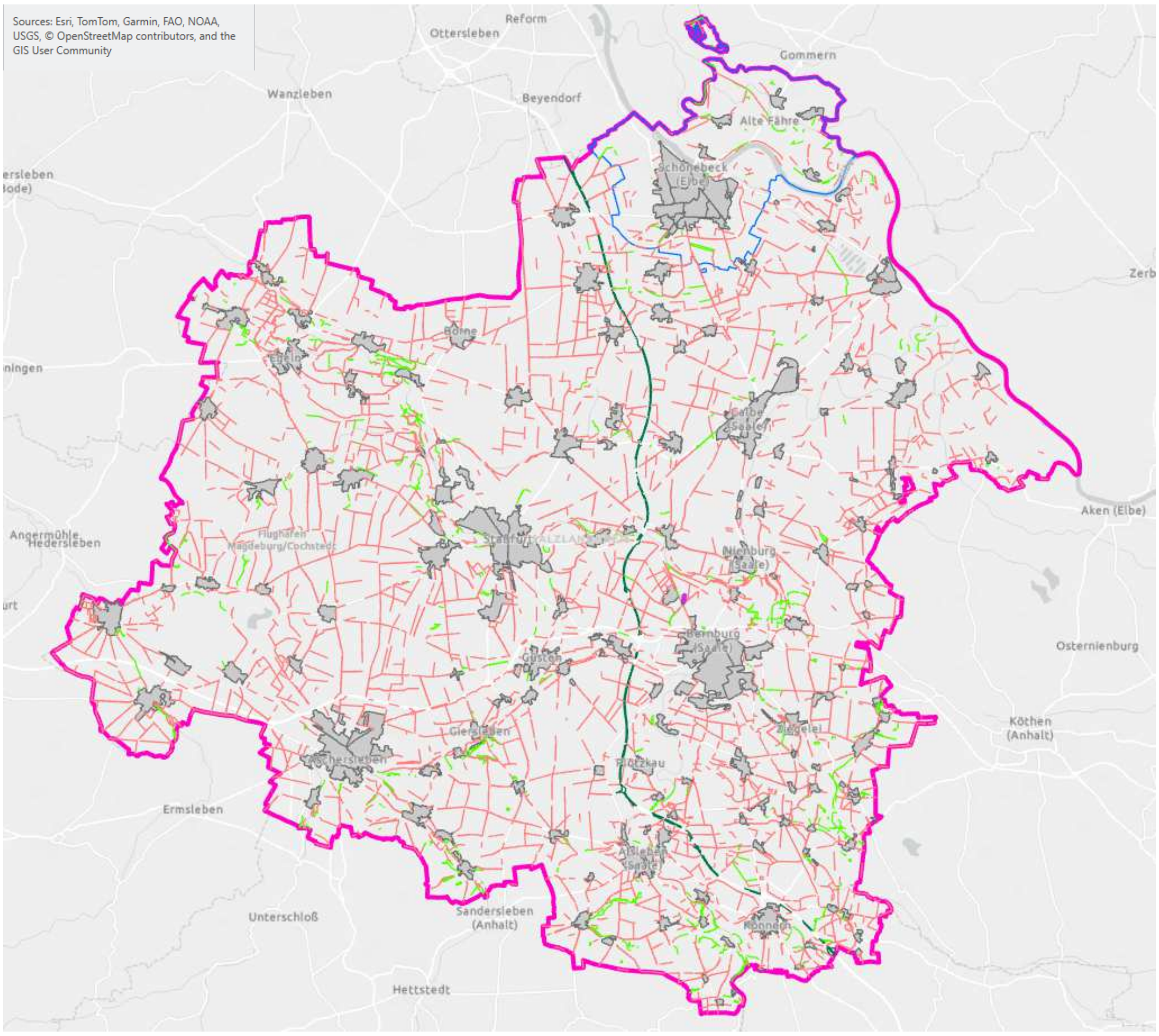

Fig. 6: Hedgerows in Salzlandkreis, Map base: ESRI. Data sources: basic-DLM, manual digitizing and administrative boundaries.

Future research should expand upon the current study by incorporating additional carbon pools (such as below-ground biomass and soils) into the framework to estimate the total carbon content of the hedgerows. The results of this study could also have a substantial impact on the spatial management of resources by providing high-resolution, decision-based information for identifying valuable regions for conservation purposes, allocating optimal use of land for agricultural and urban development, and creating hedgerow-based networks to assist with climate adaptation in rural areas. Additionally, future studies should focus on analyzing the temporal changes of these carbon stocks over time and comparing data across different vegetation zones and countries to establish standardized global baselines.

The spatial data generated in this study provide a foundation for evaluating a wide range of ecosystem services at the regional level, such as: hedgerow health mapping; assessing agroforestry potential; quantifying sustainable harvestable biomass; and creating multi-year carbon balances. Co-development of management and utilization concepts with agricultural and municipal stakeholders will facilitate the conversion of the hedgerow carbon stock estimates into practical mitigation strategies and regional bio-economy opportunities.

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