A Dissertation on topic

GEOSPATIAL TECHNOLOGIES FOR MONITORING CARBON SEQUESTRATION AND ASSESSING NATURE BASED SOLUTION FOR CLIMATE CHANGE MITIGATION

Submitted by

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GEOSPATIAL TECHNOLOGIES FOR MONITORING CARBON SEQUESTRATION AND ASSESSING NATURE-BASED SOLUTION FOR CLIMATE CHANGE MITIGATION

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DECLARATION OF ORIGINALITY

I declare that the work described in this document is my own and not from someone else. All the assistance I have received from other people is duly acknowledged, and all the sources (published or not published) are referenced.

I also declare that I have used Large Language Models (LLMs) i.e., ChatGPT and DeepSeek for tasks like assisting in writing for correction and in literature review, while ensuring the originality, accuracy, and integrity of my research.

This work has not been previously evaluated or submitted anywhere.

Münster, 20 February 2025

Muhammad Qasim

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ABSTRACT

Industrial cities like Duisburg, Germany, face significant challenges in mitigating carbon emissions due to high industrial activity which exacerbate climate change, urban heat island effects, and air pollution. This research addresses the urgent need for localized, scalable solution by exploring the potential of urban afforestation as a nature-based strategy to enhance carbon storage greatest environmental and social benefits. 19.41 km² was classified as high-priority zones which can be a baseline to start implementation of NBS. High-priority areas are concentrated in industrial and densely populated regions, where greening interventions would provide co-benefits such as reduced heat stress, improved air quality, and enhanced flood resilience. The study highlights the importance of integrating nature-based solution into urban and enhance urban resilience. Using a geospatial technologies and process-based model, the study employs the InVEST Carbon Storage and Sequestration Model to quantify carbon storage potential and geospatial analyses to identifies suitable areas for afforestation through exclusion criterion (i.e., excluding landcover classes that are not suitable for afforestation). InVEST model incorporated landcover data and four carbom pools values i.e., Above Ground Biomass (AGB), Below Ground Biomass (BGB), Dead Carbon (C_Dead), Soil Organic Carbon (C_Soil). The results reveal that 44.23 km² (19% of Duisburg's land area) is suitable for afforestation. Implementing afforestation in these areas could increase carbon storage by 120%, offsetting 22% (current carbon offsets are 9%) of city's annual emissions (i.e., 24 million tons). Key indicators such as urban heat island effects, flood risk, air quality, population density, and accessibility to green spaces were integrated to prioritize areas where afforestation would yield the planning and recommends prioritizing high-impact zones for greening, adopting a phased implementation approach. This research aligns with key Sustainable Development Goals, including Good Health (SDG 3), Industry, Innovation and Infrastructure (SDG 9), Climate Action (SDG 13), and Sustainable Cities and Communities (SDG 11) contributing to global efforts to combat climate change, promote urban sustainability, restore ecosystems, and improve public health. This study offers actionable insights for policymakers and urban planners to enhance climate resilience in highly industrialized cities.

Sustainable Development Goals (SGDs):

3 GOOD HEALTH AND WELL-BEING
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
11 SUSTAINABLE CITIES AND COMMUNITIES
13 CLIMATE ACTION

KEYWORDS

Carbon Sequestration

InVEST

Nature Based Solution

Climate Mitigation

Afforestation

GIS

RS

ACRONYMS

AI - Artificial Intelligence

ASC - ASCII (a file format)

CASA - Carnegie-Ames-Stanford Approach

CENTURY - A soil carbon dynamics model

CH_4 - Methane

CO_2 - Carbon Dioxide

CS - Carbon Storage

CSV - Comma-Separated Values

DWD - Deutscher Wetterdienst (German Weather Service)

EPSG - European Petroleum Survey Group (coordinate system)

EPSG:25832 - Coordinate Reference System (ETRS89 / UTM Zone 32N)

EEA - European Environment Agency

GHG - Greenhouse Gas

GIS - Geographic Information Systems

ha - Hectare

IPCC - Intergovernmental Panel on Climate Change

IPCC-TFI - Intergovernmental Panel on Climate Change Task Force on National Greenhouse Gas Inventories

LLMs - Large Language Models

LULCC - Land-Use and Land-Cover Changes

Mg - Megagram (metric ton)

$Mg\ C\ ha^{-1}$ - Megagrams of Carbon per Hectare

m - Meter

MCA – Multi-Criteria Analysis

MOD - Moderate (air quality categorization)

MODIS - Moderate Resolution Imaging Spectroradiometer

NASA - National Aeronautics and Space Administration

NO_2 - Nitrogen Dioxide

NO_x - Nitrogen Oxides

O3 - Ozone

OSM - OpenStreetMap

PM10 - Particulate Matter 10 micrometers or smaller

PM2.5 - Particulate Matter 2.5 micrometers or smaller

RF - Random Forest

RF-Markov - Random Forest-Markov (model)

RS - Remote Sensing

SDG - Sustainable Development Goal

SO_2 - Sulfur Dioxide

UHI - Urban Heat Island

UN - United Nations

UTM - Universal Transverse Mercator

VOCs - Volatile Organic Compounds

NRW - North Rhine-Westphalia

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CHAPTER 1
INTRODUCTION

1 Introduction

1.1 Background

The rapid increase of greenhouse gas (GHG) emissions, mainly due to industrial activities, has highlighted the urgent need for global climate change mitigation strategies. Industrialization, while paramount for economic development, has significantly intensified the release of carbon dioxide (CO_2) and other GHGs into the atmosphere, worsening global warming and disrupting the planet's climate systems [1]. Industrial hubs, characterized by heavy manufacturing and energy-intensive operations, are among the largest contributors to these emissions.

Human activities, particularly the combustion of fossil fuels for energy and industrial processes, are the major cause of climate change. These activities release substantial quantities of GHGs, including CO_2, methane (CH_4), and nitrous oxide (N_2O), which trap heat in the atmosphere and contribute to the greenhouse effect [2]. Since the Industrial Revolution, atmospheric CO_2 concentrations have surged by over 40%, leading to profound disruptions in global climate patterns [3]. These disruptions extend beyond rising temperatures to include melting glaciers, rising sea levels, altered precipitation patterns, and an increased frequency of natural disasters. Despite growing awareness, human-induced emissions continue to accelerate due to rapid industrialization, urbanization, and deforestation [4].

Industrial activities, as one of the largest sources of carbon emissions, consume vast amounts of energy and contribute excessively to GHG emissions. For example, Duisburg, a major industrial hub in Germany and home to the country's largest steel production facilities, accounts for approximately 3.5% of the nation's total CO_2 emissions [5]. The city's steel production, chemical manufacturing, energy generation, and transportation networks collectively emit over 20 million tons of carbon annually. These activities not only elevate atmospheric CO_2 levels but also degrade local ecosystems, compromise air quality, and pose significant public health risks [6]. Addressing these challenges demands a combination of technological innovation, sustainable land-use planning, and environmental conservation efforts.

The escalating impacts of climate change, ranging from rising global temperatures and extreme weather events to biodiversity loss, demand innovative and sustainable solutions to mitigate these effects [7]. Carbon sequestration, the process of capturing and storing atmospheric carbon, has emerged as an essential strategy in this regard. This study provides a comprehensive analysis of the relationship between industrial activities and climate change, emphasizing the role of nature-based solutions (NBS) in enhancing carbon sequestration and adopting climate resilience. Nature-based solutions (NBS) offer a sustainable and long-term approach to climate change mitigation by utilizing natural processes to enhance carbon storage and improve ecosystem resilience [8]. These solutions include afforestation, reforestation, wetland restoration, and the conservation of existing ecosystems [9]. NBS provide multiple co-benefits, such as increasing carbon offset potential, supporting biodiversity, and enhancing ecosystem services [8]. In urban and industrial settings, NBS can play a transformative role by integrating green infrastructures such as urban forests, green roofs, and restored wetlands into the landscape [9]. For a heavily industrialized city like Duisburg, implementing NBS could offset industrial emissions to a greater extent and contribute to long-term climate resilience.

Moreover, NBS are cost-effective and sustainable, making them an increasingly popular strategy for carbon mitigation globally [10]. This research emphasizes the strategic integration of NBS into urban planning and climate policies to achieve significant progress toward carbon neutrality.

1.2 Problem Statement

Industrial regions with high manufacturing activity face significant challenges in mitigating carbon emissions due to limited green spaces, competing land-use priorities, and policy constraints. Duisburg, one of Germany's most industrialized cities, contributes substantially to national CO_2 emissions. While industrial activity drives economic growth, it also exacerbates environmental pressures, necessitating innovative and scalable carbon reduction strategies. Nature-based solutions (NBS), such as urban afforestation and the restoration of degraded lands, offer promising mitigation potential.

However, their implementation in industrial urban areas is restricted by several factors. First, identifying the most suitable carbon storage (CS) models for industrialized regions is important for precisely assessing sequestration potential, yet existing models may have limitations when applied to complex urban-industrial contexts. Second, a comprehensive knowledge of Duisburg's total carbon emissions and current carbon storage capacity is essential to determine the scale of intervention needed. Third, land scarcity and challenging urban development priorities make it difficult to identify suitable areas for afforestation, further complicating large-scale implementation. Finally, the effectiveness of afforestation in offsetting industrial carbon emissions remains uncertain.

Addressing these challenges requires an integrated approach that combines carbon storage modeling, estimation of carbon emissions from available reports, and afforestation suitability mapping. This research aims to provide data-driven insights into how industrial cities like Duisburg can enhance sustainability and resilience while reducing carbon emissions.

1.3 Research Motivation

This study holds significant importance for both scientific study and practical application, particularly in the context of mitigating the environmental impacts of industrial emissions. As industrial activities continue to increase global carbon dioxide levels, the necessity to develop effective mitigation strategies has never been greater. Failure to address these emissions not only worsens global warming but also leads to severe socio-economic and ecological consequences, such as increased frequency of extreme weather events, loss of biodiversity, and threats to public health and infrastructure. From a practical perspective, understanding how urban environments can be optimized for carbon storage provides a detailed pathway for increasing carbon storage potential to offset emissions in densely industrialized areas. Enhancing restoration potential through nature-based solutions, such as urban reforestation or the rehabilitation of degraded landscapes, offers dual benefits: sequestering carbon effectively while improving urban resilience and ecological balance. Scientifically, this research contributes to applying modern geospatial methodologies for assessing carbon sequestration potential in urban-industrial contexts, providing insights into scalable and adaptable climate solutions. By addressing this pressing need, the study bridges a gap in both academic understanding and actionable policy frameworks for climate mitigation.

1.4 Research Gap

Despite the growing interest in nature-based solutions (NBS) for climate mitigation, there is a lack of localized research on their effectiveness in heavily industrialized urban areas. Cities like Duisburg, with high carbon emissions from industrial activities, present unique challenges for implementing NBS, particularly urban afforestation. Existing studies often focus on less industrialized regions, leaving a gap in understanding how much of Duisburg's emissions can realistically be offset through afforestation within the constraints of land availability, pollution levels, and urban planning priorities.

Furthermore, there is no-to-limited research on how afforestation efforts in such regions could be advantageously planned to maximize co-benefits, such as flood mitigation, air quality improvement and public health benefits. Addressing these gaps is crucial for developing targeted, data-driven approaches that integrate afforestation into urban climate policies while enhancing overall environmental and social resilience in industrial cities.

1.5 Research Questions

This study answers the following research questions:

1. Which carbon storage (CS) model is most suitable for evaluating emissions in heavily industrialized regions like Duisburg, based on literature?
2. How much carbon emissions do Duisburg produce, and what is its current carbon storage capacity?
3. Where are the high-potential areas for afforestation in Duisburg?
4. Can afforestation in Duisburg effectively counterbalance industrial carbon emissions?

1.6 Research Objectives

This study aims to provide actionable insights into the role of urban afforestation in mitigating industrial carbon emissions within an urban-industrialized context like Duisburg. The first objective focuses on quantifying carbon storage potential by utilizing a suitable carbon storage model, to assess the sequestration capacity of afforestation efforts in the city. The second objective aims to identify high-potential areas for afforestation by analyzing greening need indicators, including climate change mitigation factors (e.g., flood risk, urban heat island effect), environmental factors (e.g., air quality, proximity to industrial emitters), and social well-being indicators (e.g., population density, accessibility to green spaces). Finally, the study evaluates the effectiveness of afforestation for carbon sequestration, determining its potential contribution to offsetting Duisburg's industrial emissions. By aligning scientific analysis with practical urban planning considerations, this research aims to develop research-driven strategies for integrating afforestation into urban climate policies.

1.7 Thesis Structure

This thesis is organized into six chapters, providing a logical and organized structure that guides readers through the research process, findings, and implications.

- Chapter 1: Introduction introduces the study by providing background information on the relationship between industrial activities and climate change. It defines the problem, highlights the research gap, outlines the study's motivation, and states the research questions and objectives.
- Chapter 2: Literature Review explores relevant scientific studies on nature-based solutions (NBS), carbon sequestration, and geospatial technologies. It examines existing research gaps and establishes the theoretical foundation for this study.
- Chapter 3: Methodology describes the research framework, data collection, and analytical methods used in the study. It details the geospatial tools and models employed to quantify carbon storage and identify high-potential restoration areas in Duisburg.
- Chapter 4: Results present the findings of the study, including estimates of carbon storage potential, identified afforestation areas, and an evaluation of NBS effectiveness in offsetting emissions.
- Chapter 5: Discussion interprets the results in the context of the research questions and compares them with existing literature. It discusses the practical implications of the findings, challenges faced, and the broader significance of NBS for urban climate mitigation.
- Chapter 6: Conclusion summarizes the key findings, provides policy recommendations, and highlights areas for future research.

This structure ensures clear progression from problem identification to actionable conclusions, making the thesis accessible to both academic and professional audiences.

CHAPTER 2
LITERATURE REVIEW

2 Literature Review

2.1 Climate Change and NBS

Climate change is predominantly exacerbated by anthropogenic activities which cause serious challenges to global ecosystems and their carbon storage capabilities. The Intergovernmental Panel on Climate Change (IPCC) highlights how greenhouse gases (GHGs) are exacerbating climate change, and how we need solid mitigation strategies [1]. Recent advancements in climate science have highlighted innovative approaches to carbon mapping and the economic valuation of carbon sequestration. For example, machine learning and spatial-temporal models are increasingly used to assess land-use changes and their impacts on carbon stocks which provide valuable insights for sustainable land management [11], [12].

Urban greening initiatives, such as those implemented in Nador City, Morocco [13], demonstrate the potential of strategic land-use planning to enhance carbon storage. By integrating Geographic Information Systems (GIS) with the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model, researchers have shown that urban greening can significantly boost carbon sequestration while delivering ecological and economic co-benefits [13]. Similarly, studies in megacities like Shenzhen emphasize the importance of remote sensing (RS) technologies in monitoring urban green spaces and their carbon storage capabilities. These insights highlight the need for accurate estimation models to inform urban planning and climate mitigation strategies [14]. These highlights the importance of interdisciplinary approaches that combine ecological, technological, and economic perspectives to address climate change effectively and enhance carbon sequestration efforts.

Nature-Based Solutions (NBS) have emerged as a foundation of climate mitigation strategies, particularly in urban and industrial contexts. NBS utilize natural processes, such as carbon sequestration, evapotranspiration, and soil stabilization, through urban vegetation, green roofs, green facades, and afforestation to enhance urban livability and address climate challenges. The building sector alone contributes nearly 40% of global CO_2 emissions, highlighting the urgent need for sustainable solutions [15]. NBS not only reduce municipal CO_2 emissions but also provide co-benefits such as improved air quality, enhanced biodiversity, and increased urban resilience [6].

For example, a study in the industrial zone of Bragança, Portugal, used microclimatic modeling to show that planting trees to industrial areas could double pollutant removal rates and significantly enhance CO_2 absorption [16]. This highlights the importance of integrating green infrastructure into urban planning to achieve long-term climate benefits. Furthermore, comparative studies on industrial sites have highlighted tree species such as *Moringa oleifera* and *Syzygium cumini* have exceptional carbon sequestration potential which make them particularly suitable for industrial areas [17]. These literature insights highlight the crucial role of vegetation in reducing air pollution and enhancing environmental quality. As a fundamental component of climate strategies, nature-based solutions (NBS) offer scalable and sustainable approaches to lower carbon emissions in urban and industrial areas, contributing to long-term carbon neutrality.

2.3 Geospatial Technologies in NBS

Geospatial technologies such as GIS and RS play an important role in assessing and implementing NBS for carbon sequestration. These technologies facilitate the mapping of current land cover, monitoring environmental changes, and identifying suitable areas for afforestation. Remote sensing is widely used for land-use classification, detecting vegetation health, and estimating biomass, while GIS enables spatial analysis for decision-making [18]. Additionally, process-based models, such as InVEST and CASA, assist in quantifying carbon sequestration potential, and machine learning or multi-criteria analysis techniques are increasingly applied to assess afforestation suitability based on multiple environmental and socio-economic factors [19], [20], [21].

Recent studies highlight the effectiveness of geospatial tools in different contexts. For instance, [22] employed Landsat 8 imagery and GIS to assess the impact of land recovery on carbon sequestration in post-mining areas, demonstrating a notable increase in storage capacity over time. Similarly, [23] used remote sensing and spatial analysis to identify high-potential afforestation zones in Rajasthan, India, and estimate species-specific carbon sequestration rates. Moreover, [24] tracked land-use and land-cover changes over two decades in Khyber Pakhtunkhwa, Pakistan, showing their impact on carbon storage dynamics. These studies explain the essential role of geospatial technologies in mapping, modeling, and optimizing nature-based carbon mitigation strategies.

2.4 Carbon Sequestration Dynamics

Understanding carbon sequestration dynamics in soil and biomass is crucial for developing effective climate mitigation strategies. Land-use and land-cover changes (LULCC) significantly influence carbon storage capacities, and geospatial technologies, particularly RS and land-use-based models, play a key role in estimating sequestration potential. RS data, such as Landsat and MODIS imagery, are frequently used to assess vegetation cover, detect biomass changes, and model carbon fluxes [25]. Process-based models like InVEST and CASA integrate RS-derived land-use classifications with ecosystem parameters to estimate carbon sequestration [26]. Additionally, land-use dependent models help quantify sequestration potential by analyzing how different land categories such as forests, urban green spaces, and agricultural land contribute to carbon storage [27].

Recent studies highlight the effectiveness of these approaches. For instance, [28], [29] demonstrated that reclamation efforts in coal mining areas enhanced carbon sequestration by applying remote sensing and GIS to track reforestation progress and estimate carbon storage gains. Similarly, [30] assessed the impact of Pakistan’s Billion Tree Tsunami initiative using RS-derived forest cover data, revealing a 63% increase in forest area and a 9% rise in carbon storage. In China’s karst regions, [31] employed ecosystem models and satellite data to evaluate ecological restoration efforts, finding substantial improvements in net primary productivity and ecosystem services. Additionally, [32] used land-use simulations to compare urban development and woodland conservation scenarios in the Three Gorges Reservoir Area, demonstrating the stabilizing effect of forest conservation on carbon storage. [33] further highlighted the role of spatiotemporal dynamics in forest carbon sequestration, emphasizing how natural and anthropogenic factors interact over time.

These studies underscore the importance of integrating remote sensing and land-use models to improve carbon sequestration estimates. Understanding how these methods work is essential for applying tools like InVEST to urban-industrial settings, allowing for more accurate assessments of afforestation potential and carbon offset strategies.

2.5 Urban Carbon Offset Strategies

Urban green spaces such as parks, forests, and rooftop gardens are central carbon sinks which provide significant carbon sequestration benefits. Researchers are increasingly focusing on urban green space management as a strategy for achieving carbon neutrality. Optimizing vegetation types and maintaining healthy ecosystems are fundamental approaches to maximizing carbon uptake.

Urban afforestation has significant potential for reducing carbon emissions. In Rajasthan, India, researchers identified 40% of the state as suitable for afforestation, with carbon sequestration rates ranging from 2 to 8 tons per hectare annually [23]. Effective species selection is essential for maximizing sequestration, with fast-growing species like Neem providing short-term benefits, while slower-growing trees enhance long-term carbon storage. In Morocco, studies showed that integrating urban vegetation with green roofs and restored forests significantly increased carbon storage, demonstrating a scalable approach for other cities [13].

2.6 Methods to Assess Afforestation Potential

Recent advancements in assessing afforestation potential emphasize the integration of geospatial technologies, predictive modeling, and participatory approaches to enhance site selection for urban greening. Geospatial tools are increasingly used to map land cover, monitor vegetation health, and model future scenarios under different climate and policy conditions. For instance, in the Three Gorges Reservoir Area, combining the RF-Markov model with InVEST enabled precise carbon storage assessments, demonstrating the effectiveness of conservation-oriented strategies [32].

Another emerging approach is the co-creation of urban greening projects through stakeholder engagement. A study conducted in Amsterdam by [34] illustrates the effectiveness of participatory GIS in integrating spatial analysis with stakeholder-driven decision-making. By incorporating local stakeholder input into spatial modeling, the study identified priority areas for urban greening while ensuring alignment with policy objectives. Stakeholders collaboratively established suitability criteria translated these into different indicator types (e.g., environmental, social, and climate-related), and validated the results through site visits and expert evaluations [34].

This participatory approach not only improved the accuracy of suitability assessments but also fostered transparency, local ownership, and practical implementation of greening strategies. Applying a similar methodology in this study ensures that afforestation prioritization aligns with ecological objectives and community needs, enhancing both the effectiveness and public acceptance of urban greening initiatives.

2.6 Carbon Sequestration Models

Selecting an appropriate carbon storage model is fundamental for accurately assessing sequestration potential, particularly in urban-industrial environments where land-use complexity and high emissions require adapted approaches. Various models, including process-based models (e.g., CASA and CENTURY), empirical models (e.g., IPCC stock-change approach), and integrated spatial models (e.g., InVEST and Urban Biogeochemical Models), have been applied in different contexts.

Process-based models, such as CASA and CENTURY, simulate carbon fluxes based on physiological and ecological parameters. CASA has been widely used in large-scale ecosystem assessments but is less effective in fragmented urban landscapes due to its reliance on coarse-resolution climate and land-cover data [20]. CENTURY, primarily designed for soil carbon dynamics, is useful for evaluating long-term sequestration potential in forest and agricultural landscapes but lacks spatial specificity when applied to urban-industrial areas [35]. Empirical models, such as the IPCC stock-change approach, provide generalized carbon storage estimates based on biomass inventory data but do not account for spatial heterogeneity, making them less effective for urban assessments [36].

Integrated spatial models, such as InVEST, have gained prominence in urban-industrial settings due to their ability to incorporate high-resolution geospatial data and model future land-use scenarios. A comparative study in Shenzhen, China, found that InVEST provided more precise and actionable insights than CASA in estimating urban green space carbon storage, particularly in areas experiencing rapid urbanization [20]. Similarly, InVEST has been successfully used in industrialized cities, such as São Paulo, Brazil, to assess the impact of afforestation on urban carbon balance [12], [37]. Furthermore, a study in the Guangdong-Hong Kong-Macao Greater Bay Area employed InVEST to assess carbon sequestration potential under different urban expansion scenarios, highlighting its suitability for cities with high population density and limited green space [38].

These studies emphasize that while multiple carbon storage models exist, their applicability varies depending on the urban-industrial context. Given its ability to integrate spatial data, simulate land-use changes, and quantify ecosystem services, InVEST emerges as one of the most suitable tools for assessing carbon sequestration in cities like Duisburg, where industrial emissions and land-use constraints necessitate a detailed and flexible modeling approach.

CHAPTER 3
METHODOLOGY

3 Methodology

3.1 Study Area

Duisburg as shown in figure 1, located in western Germany, serves as a major industrial hub, primarily known for its steel production and manufacturing industries. The city is situated at the confluence of the Rhine and Ruhr rivers, making it a critical center for industrial transport and trade. Duisburg experiences a temperate oceanic climate, characterized by moderate rainfall and relatively mild temperatures, which influence vegetation cover and carbon sequestration potential. These climatic conditions, coupled with extensive industrial infrastructure, present a complex interplay between urban development, industrial activity, and environmental restoration.

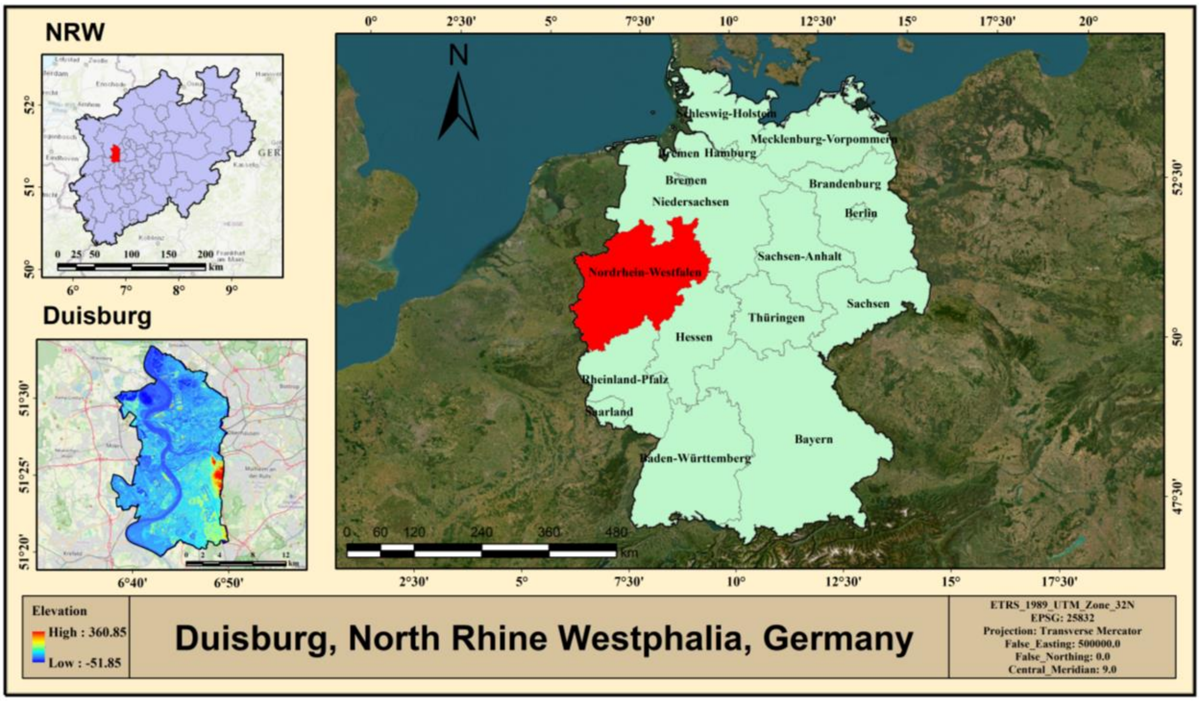


Figure 1 Study Area Location Map

3.1.1 Geographic and Climatic Overview

Duisburg's industrial expansion has been significantly shaped by its strategic location along major waterways, facilitating economic growth but also leading to environmental concerns such as urban heat islands (UHI) and air pollution. The temperate climate supports a variety of vegetation, but much of the natural landscape has been replaced by industrial complexes and urban infrastructure. This transformation influences the need for implementing nature-based solutions (NBS), such as afforestation, to mitigate carbon emissions and enhance environmental resilience.

Urbanization has further led to a decline in green spaces, exacerbating the intensity of UHIs. Higher surface temperatures are observed in industrial and densely built-up areas, contributing to increased energy consumption and thermal discomfort. Simultaneously, Duisburg's extensive river systems make certain areas prone to flooding, particularly during extreme weather events. This combination of industrialization, urban expansion, and climatic vulnerabilities positions Duisburg as an ideal case study for evaluating the effectiveness of afforestation in mitigating environmental stressors.

3.1.2 Industrial and Land Use Characteristics

Land use in Duisburg is predominantly industrial, with large areas dedicated to steel plants, manufacturing facilities, and logistics hubs. These activities have altered the natural landscape, reducing available space for ecological restoration. Urban planning efforts must navigate these constraints while addressing the environmental impacts of industrial emissions. Identifying underutilized or degraded lands for potential afforestation is crucial for enhancing the city's carbon sequestration capacity. The dense urbanization and industrial land use highlights the need for innovative greening strategies that balance economic growth with environmental sustainability.

Duisburg's land cover is characterized by built-up areas, industrial zones, and transportation networks, with green spaces confined to specific parks and riverbanks. The lack of green corridors between these areas limits ecosystem connectivity, reducing the ability of natural vegetation to act as a buffer against pollution. Additionally, emissions from steel production and logistics-related activities contribute to deteriorating air quality. The challenge lies in identifying suitable sites for afforestation without compromising industrial functionality, emphasizing the importance of a strategic, data-driven approach in this study.

3.2 Methodological Framework

3.2.1 Overview

This study employs a geospatial and modeling-based approach to evaluate carbon sequestration potential and identify suitable areas for afforestation in Duisburg. The methodology is structured around two primary objectives: quantifying existing carbon storage capacity using the InVEST model and identifying suitable afforestation sites through a multi-criteria analysis (MCA) framework as shown in figure 2. The integration of multiple spatial datasets, carbon modeling tools, and socio-environmental indicators ensures a scientifically robust and actionable urban greening strategy. The methodological framework consists of three key stages: data preprocessing, carbon storage assessment, and afforestation suitability and prioritization.

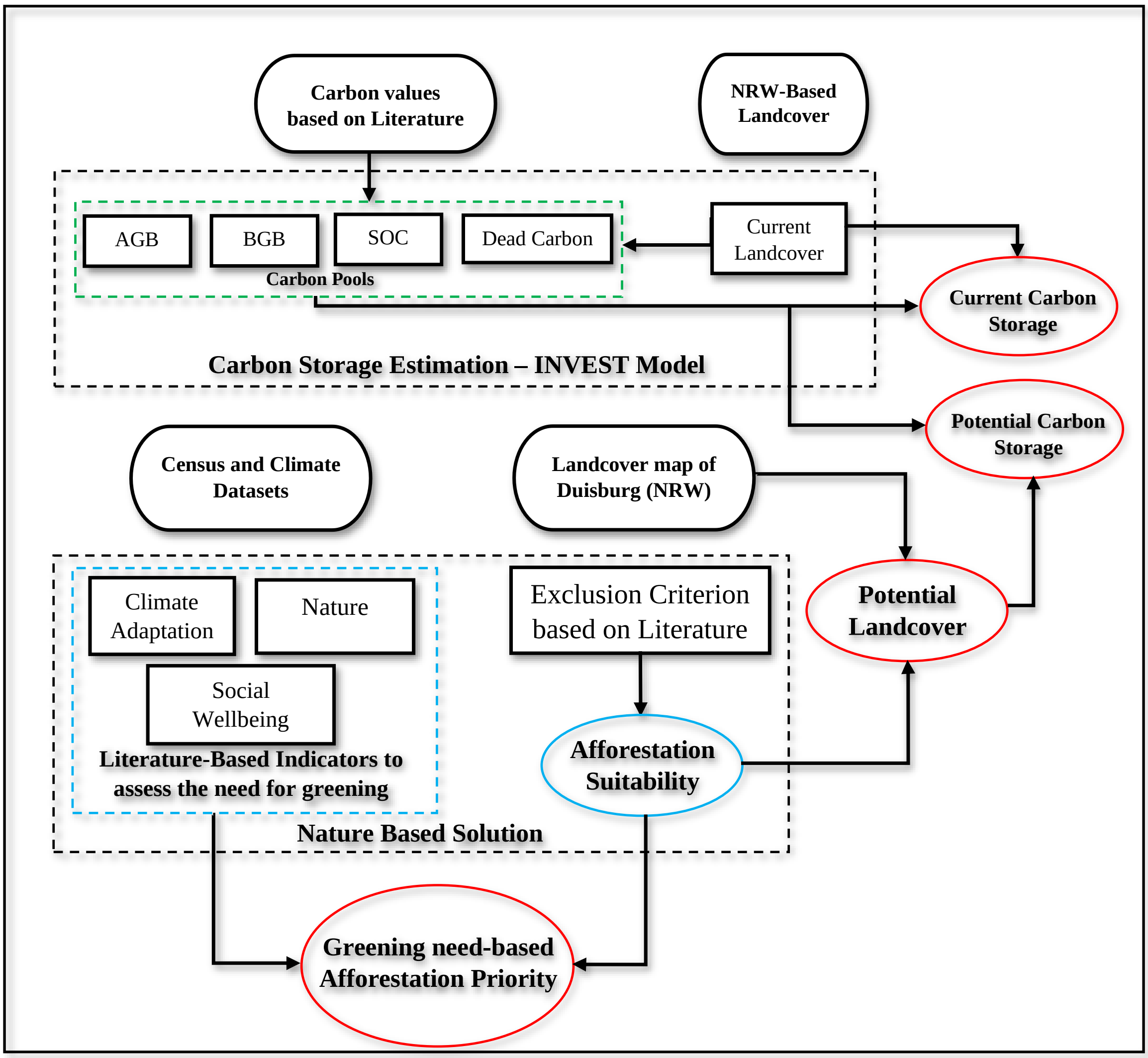


Figure 2 Flowchart of methodology to estimate carbon sequestration potential and assess NBS

The data preprocessing stage involves translating, cleaning, and preparing land cover datasets for analysis. This step ensures that all geospatial data is aligned with the study objectives and formatted correctly for integration into modeling workflows. The carbon storage assessment phase utilizes the InVEST Carbon Storage and Sequestration Model to estimate existing carbon stock across different land cover types. The final stage, afforestation suitability and prioritization, involves the identification of areas suitable for afforestation based on exclusion criteria and the ranking of potential sites according to key environmental and socio-economic indicators.

Each stage in the methodological process follows a structured workflow to ensure consistency and accuracy. The process begins with data acquisition from governmental and scientific sources, followed by rigorous data processing steps such as projection standardization, rasterization, and validation. These refined datasets are then used in the InVEST modeling phase to generate spatial estimates of carbon storage, forming the baseline for further analysis. Finally, the afforestation suitability assessment applies exclusion and prioritization criteria to determine the most viable locations for urban greening interventions. This structured, sequential approach allows for a high degree of replicability and ensures that the findings are scientifically robust.

3.2.2 Selection of Carbon Storage Model

This study selects the InVEST model for carbon storage assessment based on a comprehensive literature review of various carbon sequestration models. The selection process considered the review of effectiveness of different models in urban-industrial contexts, prioritizing those that integrate geospatial data, model land-use dynamics, and providing ecosystem service valuations. While process-based models like CASA and CENTURY offer valuable insights, they lack the spatial resolution needed for fragmented urban areas. Empirical models, such as the IPCC stock-change approach, provide broad estimates but do not account for spatial heterogeneity. In contrast, InVEST has been successfully applied in industrialized and highly urbanized regions, demonstrating its ability to model carbon sequestration in constrained landscapes. Given Duisburg’s complex land-use patterns and high industrial emissions, InVEST offers the most suitable framework for assessing afforestation potential and estimating carbon sequestration capacity. This model will be used to assess the carbon storage potential to offset industrial carbon emissions in Duisburg.

3.2.3 Data Collection

The following table 1 describes the dataset which are used to accomplish the research questions

Table 1: Description of used datasets in this research

Dataset	Source	Format
Temperature	DWD[1]	ASC
Population	WorldPop [39]	raster
Industrial Activity	EEA [40]	CSV & PDF Report
Green Spaces	OSM [41]	Shapefile
Air Quality Parameters	UBA[2]	CSV
Flood Risk	NRW [42]	Shapefile
Landcover Data	NRW [43]	Shapefile

[1] Source: Deutscher Wetterdienst,

[2] Source: Umwelt Bundesamt (https://www.umweltbundesamt.de/daten/luft/luftdaten/luftqualitaet/)

3.3 Data Preprocessing

The preprocessing stage ensures the accuracy and usability of spatial datasets before model implementation. Land cover data for Duisburg was obtained from the North Rhine-Westphalia (NRW) government database, originally provided as a polygon shapefile. The dataset included various land use classes categorized in German, which required manual translation into English to align with international geospatial conventions and modeling software. Official glossaries were cross-referenced to ensure precise translations, such as converting “Nadelbäume” to Coniferous Trees and “Fließgewässer” to Inland Water – Flowing.

Once translated, the dataset was clipped to Duisburg’s administrative boundary using QGIS and ArcGIS, ensuring that computational resources were focused exclusively on the study area. The clipped data was then converted from polygon to raster format with a 10-meter spatial resolution, aligning with the requirements of the InVEST Carbon Storage Model and ensuring uniform spatial resolution across datasets. During this process, erroneous geometries and misclassified land cover types were corrected to prevent computational errors. Invalid geometries, duplicate features, and missing attribute values were systematically removed or interpolated to enhance data integrity. The final step involved coordinate system standardization, with all datasets being reprojected to the EPSG:25832 coordinate system (ETRS89 / UTM Zone 32N), which ensures compatibility with national geospatial standards and high spatial accuracy.

3.4 Carbon Storage Assessment Using the InVEST Model

The InVEST Carbon Storage and Sequestration Model was employed to quantify the carbon storage potential of Duisburg's land cover types. This model is widely recognized in ecosystem service research due to its ability to estimate carbon sequestration across multiple land cover classes. By simulating spatial patterns of carbon storage, the model provides insights into the distribution of existing carbon stocks and the potential for carbon sequestration under different land management scenarios. The InVEST model considers four primary carbon pools: above-ground biomass, below-ground biomass, soil organic carbon, and dead organic matter, making it particularly effective for analyzing land cover-based carbon storage dynamics.

3.4.1 Assignment of Carbon Pool Values

The first step in implementing the InVEST model involved assigning carbon stock values to each land cover class based on existing literature as described in table 2. Since carbon sequestration varies significantly across vegetation types and land cover, the assignment of these values was informed by a comprehensive review of empirical studies from temperate ecosystems similar to Duisburg. Forested areas, particularly deciduous and coniferous tree covers, were assigned the highest carbon values due to their extensive above-ground and below-ground biomass. These values reflect the significant role of trees in carbon sequestration, as they store large amounts of atmospheric CO_2 within their woody structures and root systems.

Table 2: Carbon pool values with respect to landcover classes

Landcover class	C_Above	C_Below	C_Soil	C_Dead	Source
Inland Water - Flowing	0	0	0	0	[19]
Inland Water - Standing	0	0	0	0	[19]
Above-ground Construction	0	0	0	0	[19]
Deciduous Trees	180	120	120	55	[44]
Coniferous Trees	300	200	135	85	[19]
Bushes and Shrubs	7	7	22	2	[19]
Woodlands	275	30	95	10	[44]
Herbaceous Vegetation - Cereals, Perennial Plants, Ferns	2	1	10	0	[45]
Herbaceous Vegetation - Grass	300	200	135	85	[19]
Loose Material	1	1	10	0	[44]
Underground Construction	0	0	0	0	[19]

In contrast, grasslands and shrublands were assigned to lower carbon values due to their comparatively lower biomass. While these ecosystems contribute to carbon storage, their sequestration potential is lower than that of tree-dominated landscapes. Herbaceous vegetation, agricultural lands, and urban green spaces were classified with moderate carbon values, given their limited long-term sequestration capacity. Urban infrastructure, including built-up areas and water bodies, was assigned to a carbon value of zero, as these surfaces do not contribute to carbon storage. These classifications ensured that the model accurately reflected regional land cover dynamics while maintaining compatibility with international carbon accounting frameworks.

3.4.2 Data Preparation and Integration into InVEST

Once the carbon stock values were determined, they were integrated into the InVEST model alongside a preprocessed land cover dataset for Duisburg. The land cover dataset, previously converted from polygon to raster format with a 10-meter spatial resolution, was aligned to ensure consistency with the model's input requirements. This process involved resampling datasets to match the target resolution and standardizing projection systems to EPSG:25832 (ETRS89 / UTM Zone 32N). Ensuring spatial uniformity was crucial for minimizing potential errors in the carbon storage calculations.

To improve the accuracy of the model, additional topographic and soil datasets were incorporated to account for variations in carbon sequestration potential due to elevation, soil type, and land use history. Since soil organic carbon represents a significant proportion of total terrestrial carbon stocks, integrating soil carbon datasets from existing studies enhanced the reliability of the model outputs. By refining these data layers, the model could provide a more comprehensive assessment of spatially explicit carbon storage patterns across Duisburg.

3.4.3 Model Execution and Processing

Once the input datasets were preprocessed and formatted, the InVEST Carbon Storage and Sequestration model was executed to estimate carbon storage across different land cover types in Duisburg. The model operates by assigning carbon stock values to various land-use categories and calculating total carbon storage at a pixel level. This enables a high-resolution analysis of spatial variations in carbon sequestration and allows for the identification of carbon-rich zones as well as areas with limited sequestration potential. The InVEST Carbon Storage and Sequestration model estimates carbon stocks by considering four primary carbon pools: aboveground biomass, belowground biomass, soil organic carbon, and dead organic matter. Each land cover type in the study area is assigned carbon stock values for these pools. The total carbon storage at each pixel is calculated using the following equation:

$$C_{total} = C_{above} + C_{below} + C_{soil} + C_{dead} \qquad (1)$$

where:

C_{above} represents carbon stored in living vegetation, such as trees, shrubs, and grass.

C_{below} accounts for root biomass and is typically estimated as a proportion of aboveground biomass.

C_{soil} refers to the carbon content in the soil, which varies depending on land cover type and soil characteristics.

C_{dead} includes decomposing organic material like fallen branches, leaf litter, and deadwood.
This conceptual framework ensures that the model provides a comprehensive estimation of carbon stocks across different land-use types, allowing for a spatially explicit representation of carbon storage in the study area. To execute the model, two key input datasets were prepared. The primary dataset is the land cover map, which categorizes the study area into different land-use classes. Another crucial input is the carbon stock table, which provides estimated carbon storage values (in megagrams of carbon per hectare) for each land cover type. These values were obtained from published literature and InVEST User's Guide [19] to ensure accuracy and relevance to the study area.

The model execution involves overlaying the land cover map with the carbon stock table, assigning corresponding carbon values to each pixel. The total carbon storage is then computed for each land cover type by summing the four carbon pools. This process is performed in a spatially precise manner, ensuring that the model captures variations in carbon storage across different locations within Duisburg.

3.5 Afforestation Suitability Analysis

The second major component of the methodology focused on identifying areas suitable for afforestation within Duisburg. Given the highly urbanized nature of the city and its industrial legacy, selecting appropriate locations for afforestation required a systematic approach to filter out unsuitable areas while prioritizing regions with the highest potential for carbon sequestration and environmental benefits. This analysis involved both exclusion criteria and prioritization criteria to refine the selection of potential sites, ensuring that afforestation efforts align with both ecological feasibility and urban development constraints.

3.5.1 Exclusion Criteria for Afforestation Suitability

The first step in determining suitable areas for afforestation was applying exclusion criteria to remove areas that are physically or functionally unsuitable for tree planting. Several land cover types were considered inappropriate for afforestation due to their impermeable surfaces, existing land use priorities, or environmental constraints.

Built-Up Areas (Above Ground and Underground Construction): Duisburg has extensive built-up and industrialized zones, including steel production plants, logistics hubs, and residential districts. These areas, classified as above ground and underground construction, were excluded from the afforestation analysis as they consist of impervious surfaces incapable of supporting vegetation growth. Roads, buildings, and paved spaces offer no soil substrate for tree planting, making them unsuitable for afforestation efforts. While green roofs and vertical greening solutions may enhance carbon sequestration in these areas, they were outside the scope of this study.

Inland Water Bodies (Flowing and Standing): Water bodies such as the Rhine River, tributary channels, and artificial reservoirs were also excluded from consideration. While wetland ecosystems play a role in carbon storage through organic sedimentation, they do not support afforestation initiatives. Trees require stable soil conditions to thrive, whereas fluctuating water levels and submerged soils in riparian zones limit long-term tree growth. Nevertheless, floodplain areas adjacent to these water bodies were considered for potential afforestation, particularly where tree planting could help stabilize banks and reduce surface runoff.

Agricultural Lands (Herbaceous Vegetation – Cereals, Perennial Plants, Ferns): Agricultural land use remains an important component of Duisburg's peri-urban landscape, providing food production and economic benefits. Fields classified under herbaceous vegetation – cereals, perennial plants, and ferns were removed from afforestation consideration to avoid conflicts with food security and local agricultural policies. Policy guidelines emphasize the protection of agricultural productivity in heavily industrialized regions, particularly in areas where farmland provides ecosystem services such as soil stabilization and biodiversity conservation.

3.5.2 Identification of Suitable Land Cover Classes for Afforestation

Following the exclusion of unsuitable land cover types, the next step was to identify areas that could feasibly support tree planting efforts. The land cover classes deemed suitable for afforestation were selected based on their ecological potential to sustain vegetation, capacity for carbon sequestration, and potential for environmental enhancement. Three primary land cover classes were identified as suitable:

1. Woodlands: Existing woodland areas, though already partially vegetated, were included in afforestation suitability analysis due to the potential for tree density enhancement and ecosystem restoration. Many of Duisburg's fragmented green spaces consist of sparsely wooded patches, degraded forests, or isolated tree clusters, which could be strengthened through reforestation efforts. Expanding and densifying these areas can improve biodiversity, increase carbon sequestration, and create continuous green corridors across the city.

2. Bushes and Shrubs: Areas dominated by bushes and shrubs were considered viable for afforestation as they represent transition zones that can be converted into mature forests. Shrublands often exist in areas of land abandonment or degraded landscapes where natural succession processes are underway. These zones provide an opportunity for active afforestation interventions, accelerating the transformation of low-biomass shrublands into dense, high-sequestration forests.

3. Herbaceous Vegetation (Grasslands and Open Green Spaces): Grass-dominated areas, including recreational fields, parks, and peri-urban grasslands, were deemed suitable for afforestation as they offer open land with minimal physical barriers to tree planting. These spaces present a significant opportunity to introduce mixed-species plantations, particularly in locations where trees can enhance microclimate regulation, urban cooling, and soil stabilization. While some of these spaces serve recreational purposes, strategic afforestation in selected zones can contribute to long-term carbon storage without compromising public use.

3.5.3 Prioritization Criteria

The prioritization of afforestation sites was based on a multi-criteria analysis (MCA) framework that incorporated environmental, climatic, and social indicators. These indicators were selected based on their relevance to urban resilience and their ability to address specific challenges in Duisburg. The MCA framework allowed for a systematic evaluation of potential afforestation sites, ensuring that the selected areas would maximize both ecological and social benefits. Each indicator was mapped as a separate layer in GIS software, normalized to a common scale of 1 (Very Low Priority) to 5 (Very High Priority), and weighted based on its relative importance, as determined by a review of literature on urban greening priorities [46]. Below, each indicator is discussed in detail, highlighting its significance, data sources, and methodological approach.

3.5.3.1 Urban Heat Island (UHI) Effect

The urban heat island (UHI) effect occurs when urban areas experience significantly higher temperatures than their rural surroundings due to human activities and the dominance of impervious surfaces. In Duisburg, a heavily industrialized city, the UHI effect intensifies heat stress, particularly during the peak summer months of June, July, and August, leading to increased energy consumption for cooling. Afforestation in areas with high UHI intensity can help mitigate these impacts by providing shade, lowering surface temperatures, and enhancing evaporative cooling through transpiration.

To map the UHI effect, temperature data was obtained from the NRW Open Data platform. This dataset, recorded hourly throughout 2024, was filtered to focus on the hottest months of June, July, and August when heat stress is more as compared to other months. The data was processed using GIS software to generate a spatially explicit map of surface temperatures across Duisburg. The highest temperature zones, primarily industrial areas and densely built-up neighborhoods were identified as priority locations for afforestation. The temperature values were normalized on a scale of 1 to 5, with higher values representing greater UHI intensity and thus higher afforestation priority.

Targeting UHI-affected areas for afforestation aligns with global climate adaptation strategies aimed at enhancing urban resilience. Research indicates that urban forests can lower ambient temperatures by up to 5°C, significantly improving thermal comfort and reducing reliance on air conditioning [47]. By prioritizing high-UHI zones, this study seeks to maximize the cooling benefits of afforestation, mitigating heat stress and enhancing the overall livability of Duisburg’s urban environment.

3.5.3.2 Flood Risk

Flood risk is a serious concern in Duisburg, given its location at the confluence of the Rhine and Ruhr rivers. Urbanization and industrial activities have altered natural drainage patterns, increasing the likelihood of surface runoff and flooding during heavy rainfall events. Afforestation in flood-prone areas can mitigate these risks by enhancing water infiltration, reducing surface runoff, and stabilizing soil through root systems.

For this study, flood risk data was directly obtained from the North Rhine-Westphalia (NRW) government, which provided pre-processed flood risk maps for three scenarios: 100-year flood, 1000-year flood, and >1000-year flood. These maps were based on hydrological modeling and historical flood data, ensuring high accuracy and reliability. The flood risk data was categorized into three priority levels, with areas at risk of 100-year floods assigned the highest priority, followed by 1000-year and >1000-year flood risks. This prioritization reflects the greater urgency of addressing more frequent and immediate flood threats.

The flood risk data was integrated into the GIS environment and normalized to a scale of 1 to 5, with higher values indicating higher flood risk and, consequently, higher priority for afforestation. For example, low-lying areas near riverbanks and industrial zones with poor drainage infrastructure were identified as high-priority sites. By targeting flood-prone areas, this study aims to enhance Duisburg’s resilience to climate change while providing additional ecosystem services, such as carbon sequestration and biodiversity conservation.

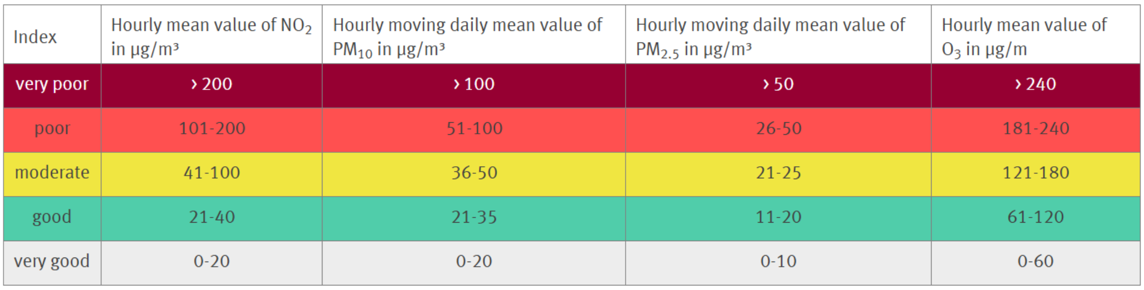
The integration of flood risk into the prioritization framework reflects the growing recognition of nature-based solutions as a cost-effective and sustainable approach to flood mitigation. Research has demonstrated that urban forests and green infrastructure can reduce peak flood volumes by up to 20%, significantly lowering the economic and social impacts of flooding [6], [23], [48], [49]. By utilizing pre-processed flood risk data from NRW, this study ensures that the prioritization of afforestation sites is both scientifically strong and aligned with regional flood management strategies.

3.5.3.3 Air Quality

Air quality is another concern in Duisburg, given its status as a major industrial hub. Industrial activities, transportation networks, and energy production contribute to high levels of particulate matter (PM2.5 and PM10) and other pollutants which cause significant risks to public health. Afforestation in areas with poor air quality can mitigate these impacts by acting as natural filters, capturing pollutants and improving ambient air quality.

To map air quality in Duisburg, data on key pollutants i.e., NO2, PM10, PM2.5, and O3 were collected hourly from eight monitoring stations across the city from NRW geoportal. Using GIS software, the data for each pollutant was interpolated separately to create a comprehensive, spatially explicit map of air quality. This approach considered the classification standards set by the German Environmental Agency, which divides air quality into five categories ranging from 'very good' to 'very poor,' as demonstrated in the accompanying figure 3.

Table 3: Categorization of the air quality parameters (Source: umwelt bundesamt)



Index	Hourly mean value of NO_2 in $\mu g/m^3$	Hourly moving daily mean value of PM_{10} in $\mu g/m^3$	Hourly moving daily mean value of $PM_{2.5}$ in $\mu g/m^3$	Hourly mean value of O_3 in $\mu g/m$
very poor	› 200	› 100	› 50	› 240
poor	101-200	51-100	26-50	181-240
moderate	41-100	36-50	21-25	121-180
good	21-40	21-35	11-20	61-120
very good	0-20	0-20	0-10	0-60

Each air quality parameter was mapped individually, and then the results were combined to assign an overall air quality score to different areas. This score was normalized on a scale of 1 to 5, where 1 indicates 'very good' quality and 5 denotes 'very poor' quality. Areas recording higher values, indicating poorer air quality such as industrial zones and major transportation corridors were identified as priority zones for afforestation.

The prioritization of these areas for greening interventions reflects an acknowledgment of urban forests as a cost-effective, sustainable solution to mitigate air pollution. Research, including a recent study by [16], [50], has shown that urban trees can remove a large amount of particulate matter from the air, substantially improving public health outcomes. By focusing on areas with the poorest air quality, this study aims to maximize the air-purifying benefits of afforestation, thereby enhancing the well-being of Duisburg’s residents and supporting broader climate mitigation efforts.

3.5.3.4 Distance from Industrial Emitters

Proximity to industrial emitters is an important factor in determining the environmental and health impacts of air pollution. Industrial facilities, such as steel plants and chemical manufacturing units, are major sources of pollutants, including sulfur dioxide (SO_2), nitrogen oxides (NO_x), and volatile organic compounds (VOCs). Afforestation near industrial emitters can act as a natural buffer and carbon sinks, reducing the dispersion of pollutants and improving local air quality.

To map proximity to industrial emitters, data on the locations of major industrial facilities was obtained from the Duisburg City Council and the NRW government. A Euclidean distance analysis was conducted in GIS software to identify areas near and far from these facilities. Areas closest to industrial emitters were assigned higher priority for afforestation, as vegetation in these locations can significantly reduce pollutant concentrations and provide localized health benefits. The proximity data was normalized to a scale of 1 to 5, with higher values indicating closer proximity to industrial emitters and, consequently, higher priority for afforestation.

The prioritization of areas near industrial emitters reflects the growing recognition of urban forests as a necessary component of sustainable industrial development. Research has demonstrated that green buffers around industrial zones can reduce pollutant concentrations significantly and improving air quality and reducing health risks for nearby residents [51], [52]. By targeting areas close to industrial emitters, this study intends to improve the environmental performance of Duisburg’s industrial sector while providing additional ecosystem services, such as carbon sequestration and biodiversity conservation.

3.5.3.5 Population Density

Population density is a key social indicator in the prioritization framework, reflecting the need to maximize the social benefits of afforestation. Highly populated areas are prioritized to ensure that the greatest number of residents can benefit from improved air quality, reduced heat stress, and enhanced recreational opportunities.

To map population density, data from WorldPop was used to create a spatially explicit map of population distribution, in the form of people per pixel, across Duisburg. Areas with the highest population density were identified as priority zones for afforestation. For example, densely populated residential neighborhoods and areas with limited existing green spaces were selected for potential greening interventions. The population density data was normalized to a scale of 1 to 5, with higher values indicating greater population density and, consequently, higher priority for afforestation.

The integration of population density into the prioritization context reflects the growing recognition of urban forests as a key factor of sustainable urban development. Research has shown that access to green spaces can significantly improve mental health, reduce stress, and enhance social cohesion [8], [46], [49], [50]. By targeting densely populated areas, this study ensures that the benefits of afforestation are equitably distributed, addressing social inequalities and enhancing the quality of life for Duisburg’s residents.

3.5.3.6 Accessibility to Green Spaces

Accessibility to green spaces is another significant social indicator in prioritizing areas with greening need to reflect the need to address inequalities in urban greening. Areas with limited existing green spaces are prioritized to ensure that all residents have access to the ecological, social, and health benefits of urban forests.

To map accessibility to green spaces, data on the distribution of existing parks, forests, and other green spaces was obtained from the OSM. This dataset was used for the creation of a spatially distributed map demonstrating green space accessibility across Duisburg, utilizing the Euclidean distance tool within a GIS environment. Areas with the lowest accessibility to green spaces were identified as priority zones for afforestation. For example, neighborhoods with limited parks or recreational areas were selected for potential greening interventions. The accessibility data was normalized to a scale of 1 to 5, with higher values indicating lower accessibility and, consequently, higher priority for afforestation.

The prioritization of accessibility to green spaces explains the growing acknowledgement of urban forests as a dynamic element of unbiased urban development. Studies have shown that access to green spaces can significantly improve mental health, reduce stress, and enhance social cohesion [34], [46], [50], [52]. By targeting areas with limited green spaces, this study will make sure that the benefits of afforestation are fairly distributed, addressing social inequalities and enhancing the quality of life for Duisburg’s livelihood.

3.5.3.7 Overlay Analysis

The overlay analysis was employed to produce normalized indicators into a comprehensive "need for greening" map. Initially, individual maps for each indicator type were created by combining their respective indicators. For example, the climate change mitigation (CCM) indicator layer was generated by overlaying Urban Heat Island (UHI) effects and flood risks (FR), assigning equal weights to each to reflect their combined importance.

$$CCM\ Layer\ =\ 50 * UHI_{reclass} +\ 50 * FR\ _{reclass} \qquad (2)$$

Similarly, social well-being (SWB) indicators like population density (PopDensity) and accessibility to green spaces (D2GS) were overlaid to form the social well-being indicator layer.

$$SWB\ Layer\ = 50 * PopDensity_{reclass} +\ 50 * D2GS_{reclass} \qquad (3)$$

Furthermore, air quality (AQ) measures and proximity to industrial emitters (P2IE) were combined to produce nature (N) indicator layer.

$$Nature\ Layer\ =\ 50 * AQ_{reclass} +\ 50 * P2IE_{reclass} \qquad (4)$$

Subsequently, these three distinct indicator layers were reclassified on a scale of 1 to 5.

$$GNB\ Priority\ =\ 33 * CCM_{reclass} +\ 33 * N_{reclass} +\ 34 * SWB_{reclass} \qquad (5)$$

Using equal weights, these layers were then merged using GIS software to create a composite map that identified areas where afforestation would yield the most substantial environmental and social benefits. This final map offered a clear visual representation of priority zones for afforestation, thus facilitating informed decision-making and policy development. Specifically, regions exhibiting high UHI effects, significant flood risk, and poor air quality yet demonstrating suitability for tree growth were given as top priorities for afforestation. This methodological approach provided a scientifically strong and socially equitable framework for urban greening, effectively balancing ecological potential with human necessities.

CHAPTER 4
RESULTS

4 Results

4.1 Landcover Map of Duisburg 2023

The landcover classification map provides a systematic delineation of terrestrial and anthropogenic features within the area of interest, offering very useful insights for ecological assessments, carbon dynamics, and sustainable land-use planning. The landcover map of Duisburg is quite diverse with prominent classes including Underground Construction (25%) across the whole study area which is indicative of extensive subsurface infrastructure, and Deciduous Trees (19%) which is a key contributor to carbon sequestration and ecosystem stability. Meanwhile, other classes such as Herbaceous Vegetation (Grass: 14%; Cereals/Perennials: 11%) and Above-ground Construction (11%) reflect the coexistence of green spaces and urbanized zones, while Flowing Inland Water (5%) and Bushes/Shrubs (5%) enhance landscape heterogeneity. Figure 3 represents the landcover map of Duisburg 2023.

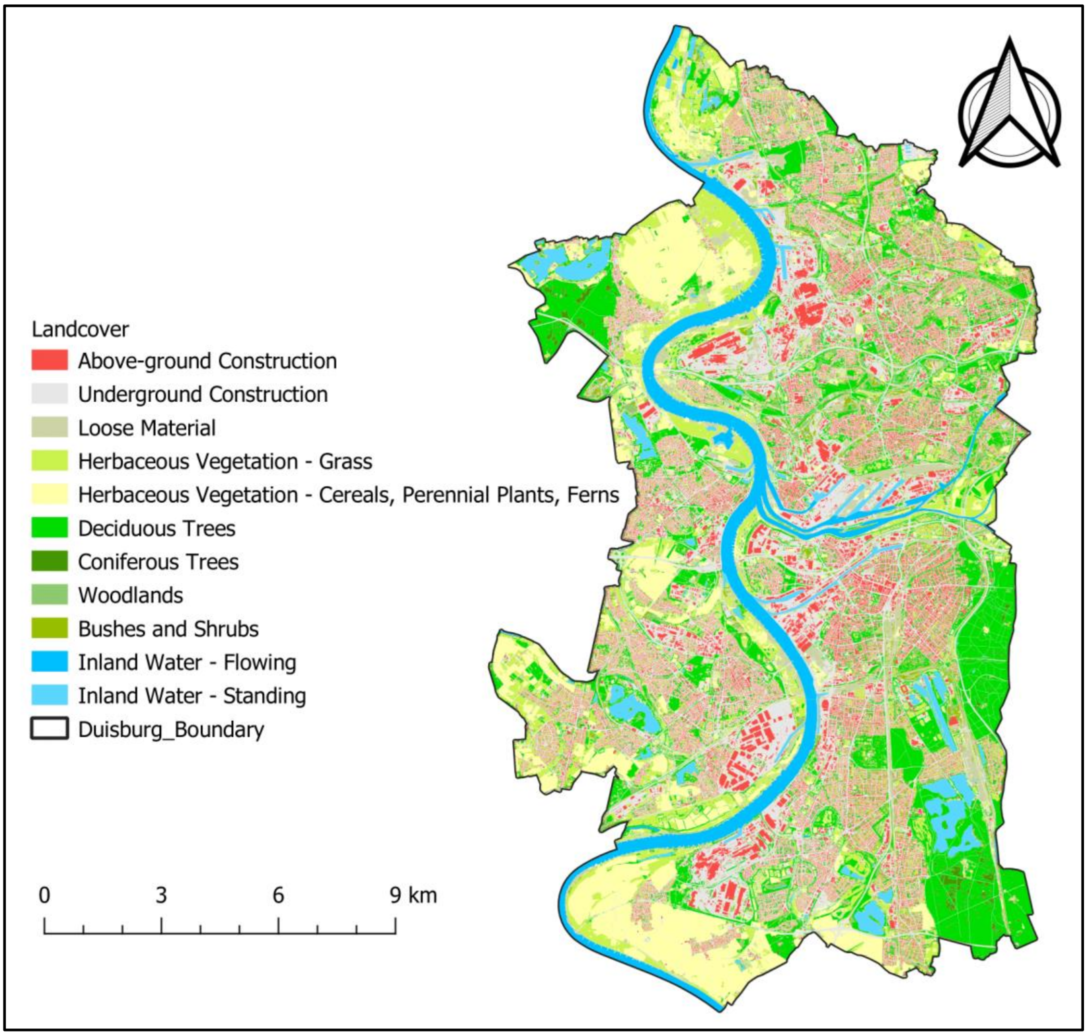


Figure 3: Landcover map of the Duisburg 2023

Spatially, vegetation classes such as Deciduous/Coniferous Trees and Woodlands (1%) are clustered in northern and northeastern regions, forming ecological corridors that support biodiversity and microclimate regulation. Hydrological features, including Standing Inland Water (3%), are concentrated in western and southern areas, sustaining aquatic ecosystems and hydrological balance. Conversely, anthropogenic structures dominate central and southeastern sectors, marked by Underground/Above-ground Construction and Loose Material (5%), signaling urban-industrial activity and land modification.

The Duisburg administrative boundary helps to understand these patterns, enabling targeted strategies for afforestation, conservation, and nature-based urban resilience. Prioritizing areas with high anthropogenic impact and low vegetation cover could increase carbon sequestration potential while still supporting city development. This spatial analysis underscores the importance of including environmental protection in land-use planning to ensure long-term environmental sustainability.

4.2 Current Carbon Storage Capacity

The spatial distribution of current carbon storage in Duisburg, modeled using the InVEST Carbon Storage and Sequestration framework (2023 landcover data), showed in figure 4. Total carbon storage across the study area amounts to 2.52 million metric tons of carbon, equivalent to approximately 9% of annual Duisburg's carbon emissions (24.5 million Mg CO_2-equivalent), highlighting the limited but important aspect of terrestrial ecosystems in offsetting anthropogenic emissions.

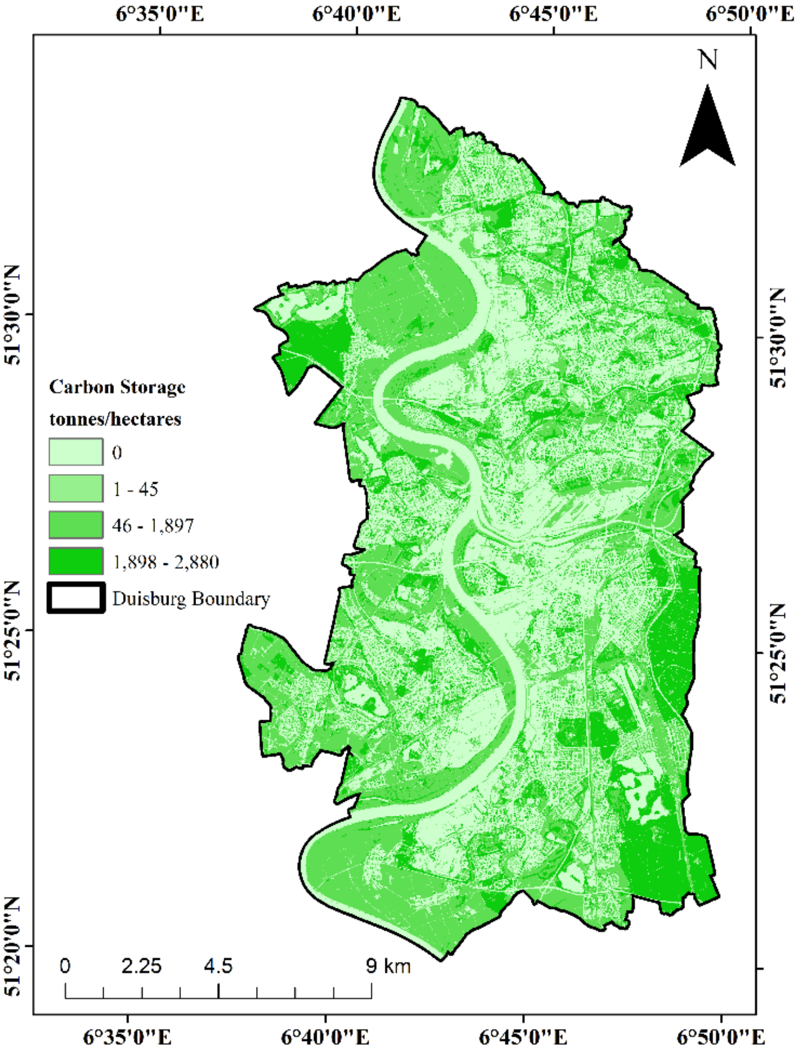


Figure 4: Current Carbon Storage map calculated using INVEST model

The northern and northeastern regions exhibit the highest carbon densities (1,898–2,880 Mg C ha^{-1}), driven by extensive coniferous and deciduous forests. Coniferous stands, with 300 Mg C ha^{-1} in aboveground biomass and 200 Mg C ha^{-1} in root systems, dominate these zones, complemented by substantial soil organic carbon (135 Mg C ha^{-1}) and accumulated woody debris (85 Mg C ha^{-1}). Adjacent deciduous forests contribute slightly lower aboveground stocks (180 Mg C ha^{-1}) but maintain comparable soil carbon retention (120 Mg C ha^{-1}), collectively forming the region's primary carbon sinks. Smaller woodland patches spread across the study area, though less dense, further enhance carbon storage through moderate aboveground biomass (275 Mg C ha^{-1}).

Moderate carbon storage (46–1,897 Mg C ha^{-1}) characterize transitional landscapes in the western and southern peripheries, including grasslands and herbaceous vegetation. Grass-dominated areas retain limited aboveground biomass (6 Mg C ha^{-1}) but sustain modest soil carbon pools (20 Mg C ha^{-1}), while agricultural zones and loose material sites show negligible biomass and marginal soil retention (10 Mg C ha^{-1}). The Rhine River corridor and other water bodies, classified as inland water, contribute no measurable carbon due to the absence of biomass and organic soil layers.

The lowest carbon densities (<45 Mg C ha^{-1}) concentrate in central and southeastern Duisburg, due to high-density urban and industrial landcovers. Above ground and underground construction zones, including impervious surfaces, buildings, and transport infrastructure store no carbon across all pools, as vegetation loss and soil sealing prevent biomass accumulation and organic matter retention. Industrial sites and quarries, dominated by compacted substrates or bare materials, similarly lack sequestration capacity, rendering these areas functional carbon deserts.

This spatial asymmetry highlights the inconsistent role of forests, which occupy 23% of the study area but account for 89% of total carbon stocks. In contrast, urbanized zones covering 35% of the region contribute less than 1% to stored carbon, reflecting the severe limitations of built environments in supporting biosequestration. The findings emphasize the necessity of conserving northern forested corridors and integrating green infrastructure into urban planning to address the severe imbalance between emissions and terrestrial carbon retention.

4.3. Restoration Potential

The analysis of afforestation suitability across Duisburg's 232.83 km² area identified 44.23 km² (19% of the total land area) as suitable for tree-planting initiatives following the application of exclusion criteria (Figure 5). These suitable zones are spatially concentrated in discontinuous clusters across the northern and western sectors of the city. These regions align with existing vegetated landcover classes such as woodlands, shrublands, and grasslands that exhibit favorable conditions for forest expansion, including permeable soils, minimal anthropogenic disturbance, and compatibility with ecological restoration goals.

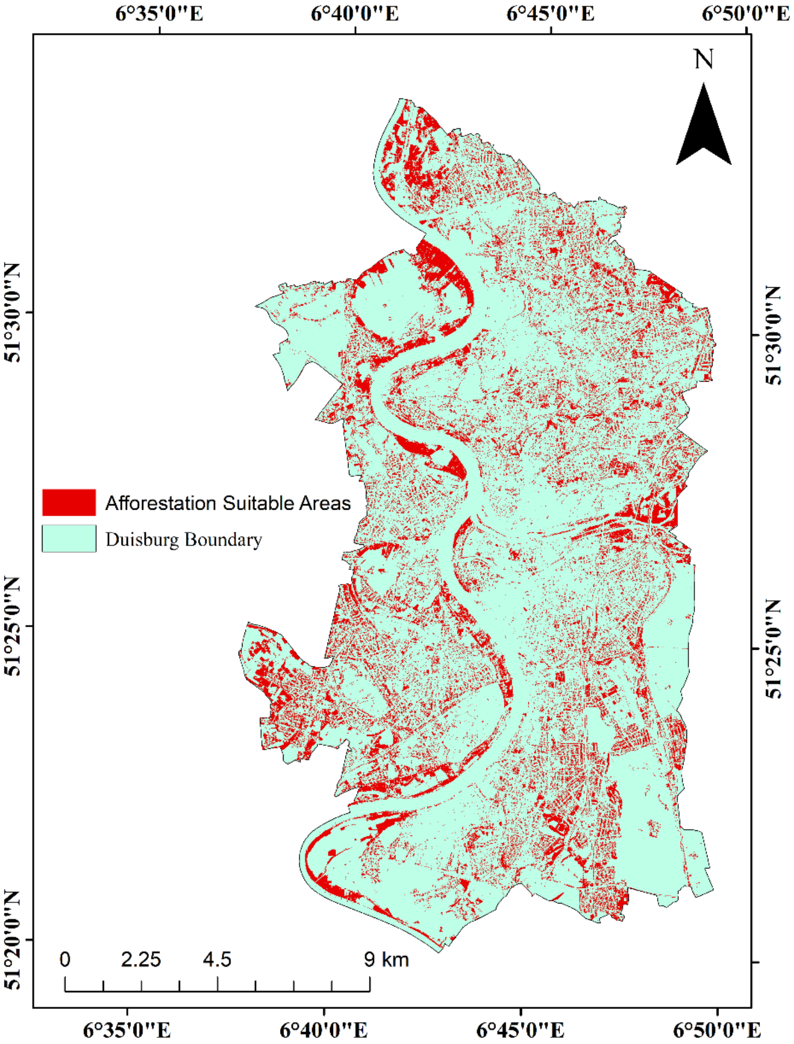


Figure 5: Suitable areas for afforestation based on exclusion criterion

Exclusion criteria eliminated 81% of the study area from consideration, prioritizing the removal of landcover types of incompatible with afforestation. 35% of the study area consists of the urban and industrial zones which were excluded due to impervious surfaces such as buildings, roads, and underground infrastructure, which blocks root establishment and soil organic carbon accumulation. Agricultural lands, covering 28% of the region and classified as herbaceous vegetation for cereals or perennial crops, were omitted to adhere to policy mandates protecting food security in industrialized regions. Water bodies, including the Rhine River and smaller reservoirs, were excluded (5% of the area) as non-terrestrial environments unsuitable for tree growth.

The remaining suitable areas are predominantly located in transitional peri-urban zones where there is less land-use competition. The northern sector hosts the largest contiguous patches of viable land, adjacent to existing woodlands and shrublands, offering strategic opportunities to expand carbon sinks through targeted reforestation. These areas benefit from proximity to established forest ecosystems, which may facilitate natural regeneration and biodiversity connectivity. In contrast, the western areas have smaller, scattered patches of grasslands and shrubs, mixed with buildings and infrastructure. These areas could be useful for creating green corridors to connect urban green spaces. However, since these patches are not continuous, large-scale tree planting may be difficult without proper land-use planning.

A critical finding lies in the stark contrast between Duisburg’s heavily urbanized core and its vegetated peripheries. The northern clusters, in particular, could serve as priority zones for carbon sequestration projects, given their alignment with existing high-carbon forests identified in prior analyses. Conversely, the scarcity of suitable land in the urbanized southeast underscores the need for innovative greening strategies, such as rooftop gardens or street tree programs, to compensate for terrestrial limitations.

These results highlight a pressing trade-off between industrial development and ecological resilience in Duisburg. Protecting and expanding the identified suitable areas particularly in the north could mitigate regional carbon deficits while balancing urban growth. Future planning should integrate these spatially explicit insights to optimize afforestation outcomes within the city’s constrained landscape.

4.4 Carbon Storage Potential After Afforestation Suitability

The Carbon Storage After Suitability map represents the updated carbon sequestration capacity of Duisburg, incorporating afforestation-suitable land areas under the assumption that they will be converted into mixed forest. This assessment, conducted using the InVEST Carbon Storage and Sequestration Model, estimates the potential increase in carbon offset if all identified afforestation-suitable areas were reforested. The results indicate a significant improvement in carbon sequestration capacity compared to the initial assessment based on existing landcover classes shown in figure 6(a).

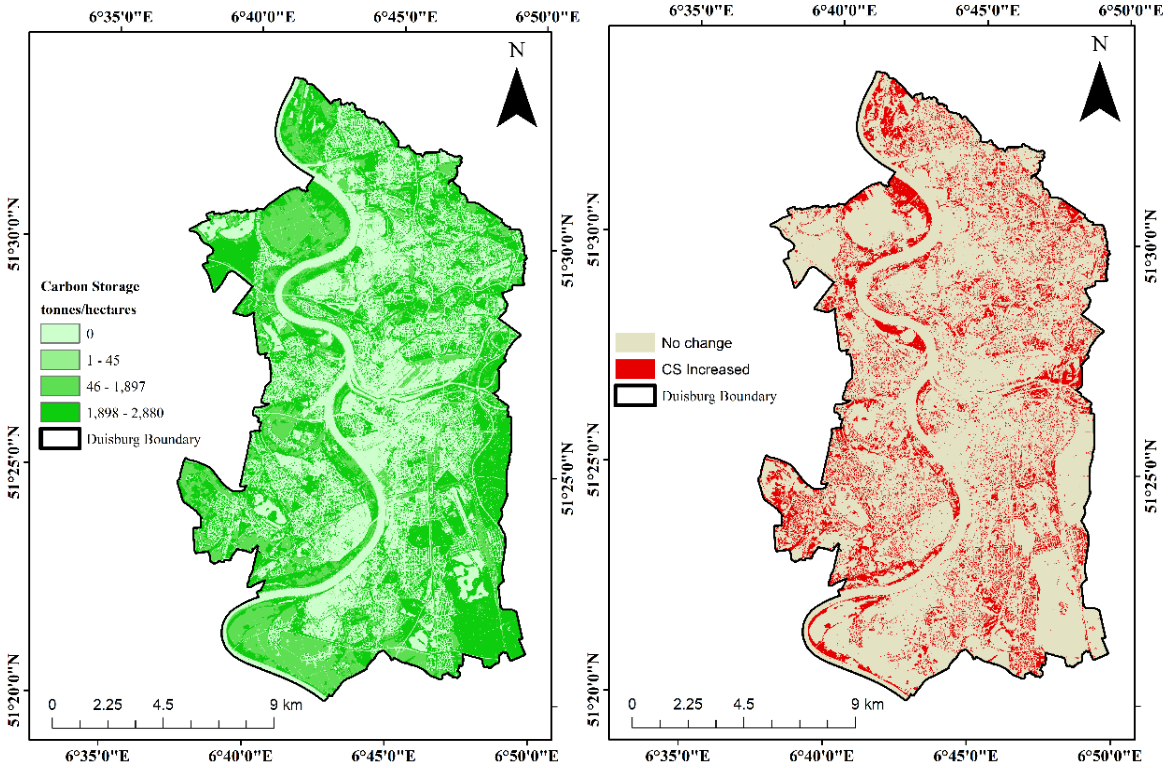


Figure 6: (a) Potential Carbon Storage Map calculated using INVEST model based on Afforestation-Suitability Land Cover (b) Difference between current and potential carbon storage maps

The initial carbon storage of the region was 2.52 million tons, based on the 2023 landcover classification. With the inclusion of newly identified afforestation-suitable areas as mixed forest, the total potential carbon storage increases to 5.56 million tons. This represents a 120% increase in sequestration capacity, highlighting the substantial role afforestation could play in offsetting carbon emissions. However, despite this increase, the total storage potential still falls short of Duisburg's annual carbon emissions of 24.5 million tons, reinforcing the need for additional climate mitigation strategies.

The spatial distribution of increased carbon storage potential follows patterns consistent with afforestation suitability as shown in figure 6(b). The most notable improvements occur in peri-urban and sparsely vegetated areas, where tree planting can substantially enhance carbon sequestration. The northern and western forested regions remain primary carbon sinks, with newly afforested areas expanding their sequestration capacity. Riparian zones along the Rhine River and adjacent floodplains also show improved storage potential, reinforcing their ecological role in carbon sequestration while providing additional flood resilience. Conversely, densely built urban and industrial areas in central and southeastern Duisburg remain largely unchanged, as these regions lack sufficient land availability for afforestation interventions.

While these results quantify the theoretical maximum increase in carbon storage, they do not yet account for land-use constraints, environmental trade-offs, or socio-economic feasibility. Given that afforestation implementation is constrained by factors such as air quality improvement, flood risk mitigation, and urban heat reduction, an essential question remains: which areas should be prioritized to maximize both carbon sequestration and broader environmental benefits?

4.5 Need for Greening

4.5.1 Greening Prioritization Results

The multi-criteria analysis for afforestation prioritization in Duisburg is performed by integrating environmental, climatic, and social indicators to identify spatially explicit greening needs. Below are the results structured by indicator type, emphasizing spatial patterns, driving factors, and synergies between objectives.

4.5.2 Climate Mitigation Indicator

Areas prioritized under this indicator reflect regions most vulnerable to urban heat island (UHI) effects and flood risks. The highest priorities ("High" to "Very High") were assigned to the southern and central urban cores, where impervious surfaces and limited vegetation exacerbate summer heat stress, as evidenced by high surface temperatures during June to August. These zones align with densely built neighborhoods and industrial zones, where afforestation could mitigate thermal discomfort through shade and evapotranspiration. Concurrently, flood-prone areas along the Rhine River's western banks and smaller tributaries were prioritized, focusing on 100-year floodplains. Vegetation in these riparian zones is expected to enhance water infiltration and reduce surface runoff, addressing dual risks of flooding and erosion. Notably, overlapping UHI and flood risk hotspots in southeastern industrial suburbs emerged as critical targets for adaptive greening as shown in figure 7.

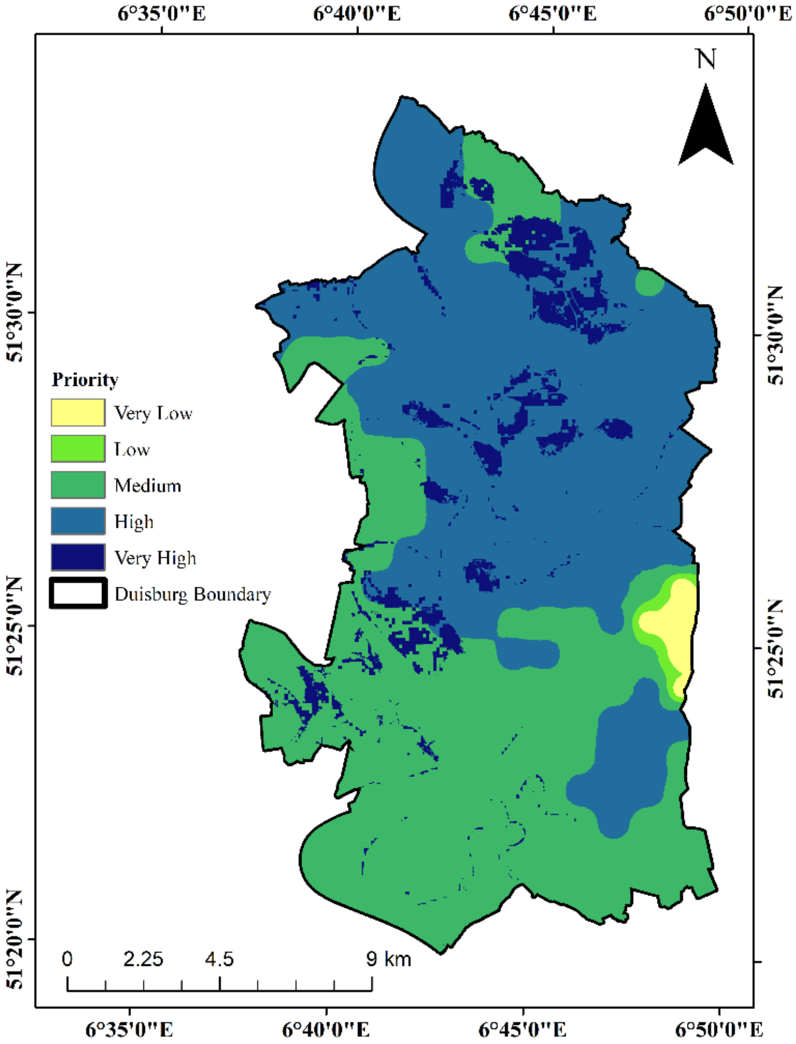


Figure 7: Climate Mitigation Indicator for greening need

4.5.3 Nature Indicator

Prioritization for climate mitigation centered on improving air quality and proximity to industrial emissions. The southeastern industrial corridor, characterized by steel production facilities and logistics hubs, received “Very High” priority due to elevated winter concentrations of NO_2, $PM_{2.5}$, and PM_{10} (December–February 2024). These pollutants peak in colder months due to temperature inversions and increased fossil fuel combustion. Afforestation here could act as a biofilter, intercepting particulate matter and absorbing gaseous pollutants. In contrast, northern forested regions and low-density suburbs scored “Low” priority, reflecting cleaner air profiles as shown in figure 8. The equal weighting of industrial proximity and air quality data highlighted the Rhine-Harbor area as a strategic location for mitigating industrial emissions through targeted tree planting.

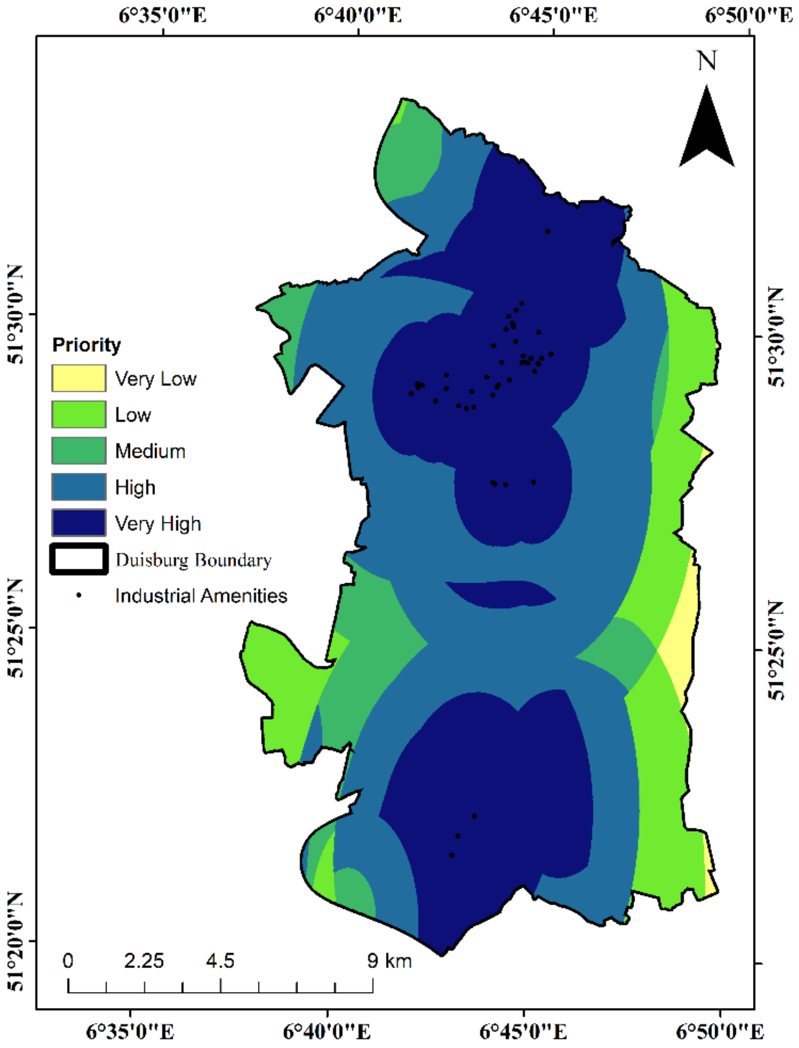


Figure 8: Nature Indicator for greening need

4.5.4 Social Well-Being Indicator

Social prioritization emphasized equitable access to green spaces and addressed high population density. The central and southern residential districts, including densely populated neighborhoods such as Rheinhausen and Hochfeld, were assigned “Very High” priority due to limited existing greenery and high demand for recreational infrastructure shown in figure 9. These areas suffer from green space deficits, exacerbating socio-economic disparities in health and leisure opportunities. Conversely, northern suburbs with established parks and woodlands ranked “Low,” as existing green infrastructure already meets community needs. A secondary focus was placed on areas farther than 500 meters from existing parks, particularly in the southeastern urban periphery, where afforestation could bridge accessibility gaps and encourage social consistency.

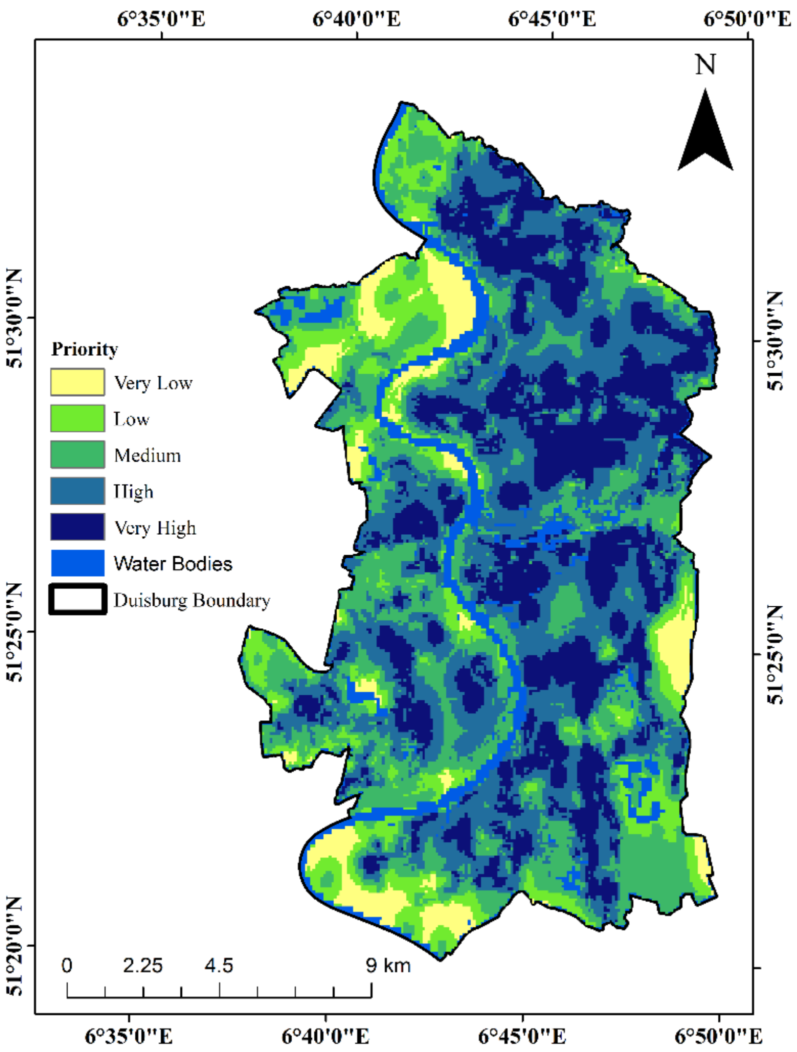


Figure 9: Social well-being indicator greening need

4.5.5 Composite Greening Priorities

The combination of all indicators revealed distinct spatial patterns and trade-offs (figure 10). The southern and central urban core emerged as a high-priority nexus, combining acute social needs (population density, green space deficits) with environmental stressors (UHI, air pollution). These areas demand adaptive strategies, such as heat-tolerant tree species and compact green pockets, to overcome space constraints. The Rhine River industrial corridor represents a critical overlap of climate mitigation and adaptation priorities, where afforestation could simultaneously buffer emissions, reduce flood risks, and provide green buffers for nearby communities. In contrast, northern floodplains and existing woodlands, while ecologically valuable, ranked lower in social urgency, underscoring the challenge of balancing conservation with urban equity.

4.5.6 Need for Greening Priority Analysis

The Need for Greening Priority map delineates spatially explicit afforestation priorities across Duisburg, derived from a multi-criteria decision analysis integrating climate adaptation, mitigation, and social well-being indicators. This synthesis categorizes zones into high-priority (red) and non-priority (green) classes, revealing pronounced spatial disparities driven by landcover heterogeneity, anthropogenic pressures, and socio-ecological vulnerabilities represented in figure 10.

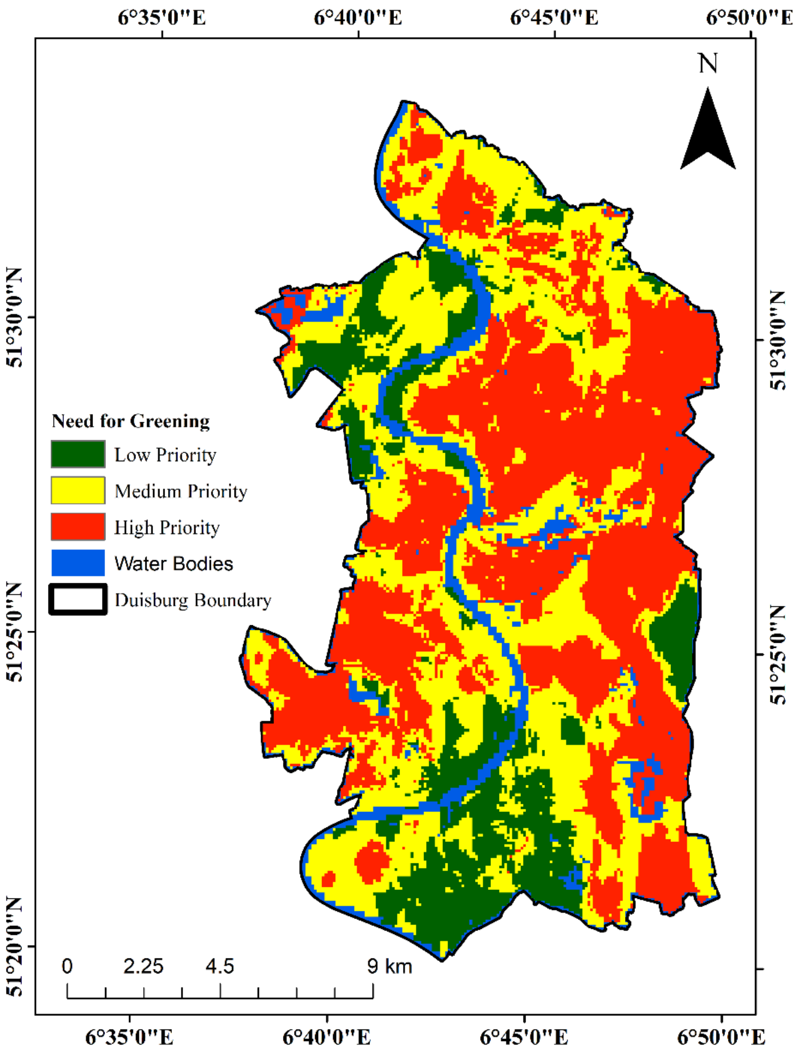


Figure 10: Greening priority map based on greening need indicators

High-priority areas cluster predominantly in central and southern Duisburg, coinciding with intensively urbanized and industrial landscapes. These regions are characterized by impervious surfaces, minimal vegetation cover, and elevated urban heat island (UHI) intensities, as evidenced by peak summer surface temperatures (June–August 2024). The southeastern industrial corridor, a hub for steel production and logistics, exhibits critically high concentrations of NO_2, $PM_{2.5}$, and PM_{10} during winter thermal inversions (December–February 2024), necessitating strategic greening to mitigate airborne pollutants. Adjacent residential districts, including Rheinhausen and Hochfeld, are further prioritized due to dense populations and deficits in green space accessibility (<500 m from existing parks), exacerbating socio-environmental inequities.

Western riparian zones along the Rhine River floodplain also rank as high-priority, reflecting vulnerability to 100-year flood events. Afforestation in these areas is projected to enhance hydrological resilience through improved water infiltration and riparian stabilization. Overlap between UHI hotspots and flood-prone industrial suburbs in the southeast underscores the need for adaptive species selection (e.g., *Alnus glutinosa* for flood tolerance, *Tilia cordata* for heat resistance) to address compounding climatic stressors.

Low and medium priority areas dominate northern and peripheral regions, where established forests, woodlands, and semi-natural grasslands sustain robust carbon sequestration and air purification services. Northern deciduous and coniferous stands, integral to Duisburg's carbon storage capacity, exhibit minimal greening urgency due to mature canopy cover and low anthropogenic disturbance. Low-density suburbs in northwestern transition zones, though classified as low priority, retain potential for ecological connectivity enhancements, particularly in fragmented grasslands and shrublands that could serve as biodiversity corridors.

The analysis highlights a stark dichotomy between urbanized cores and peri-urban peripheries, emphasizing the inverse relationship between urbanization intensity and greening feasibility. Industrial and densely populated zones demand immediate intervention to counterbalance pollution, thermal stress, and social inequities, while northern forests and floodplains require conservation to maintain existing ecosystem services.

The prioritization framework highlights the necessity of context-specific afforestation strategies:

Industrial and Urban Cores: Deploy compact green infrastructure (e.g., street trees, green roofs) to address space constraints and maximize microclimate regulation.

Floodplains: Prioritize riparian buffer zones with hydrophyte species to synergize flood mitigation and carbon sequestration.

Social Equity Gaps: Target high-density residential areas with limited green space access to align ecological benefits with community health outcomes.

This spatially explicit assessment provides a foundational assessment for optimizing greening interventions, ensuring alignment with Duisburg's climate resilience targets and sustainable urban development goals.

4.6. Final Suitability Map

4.6.1 Final Greening Suitability and Afforestation Priority

The final greening-need based afforestation suitability map, as shown in figure 11, integrates greening need priority with afforestation suitability, refining the areas where afforestation can be most effectively implemented or can be initiated. Out of the 44.23 km² initially identified as suitable for afforestation, only 19.4 km² falls under the high-priority category, highlighting constraints due to land-use limitations, urban infrastructure, and other exclusion criteria.

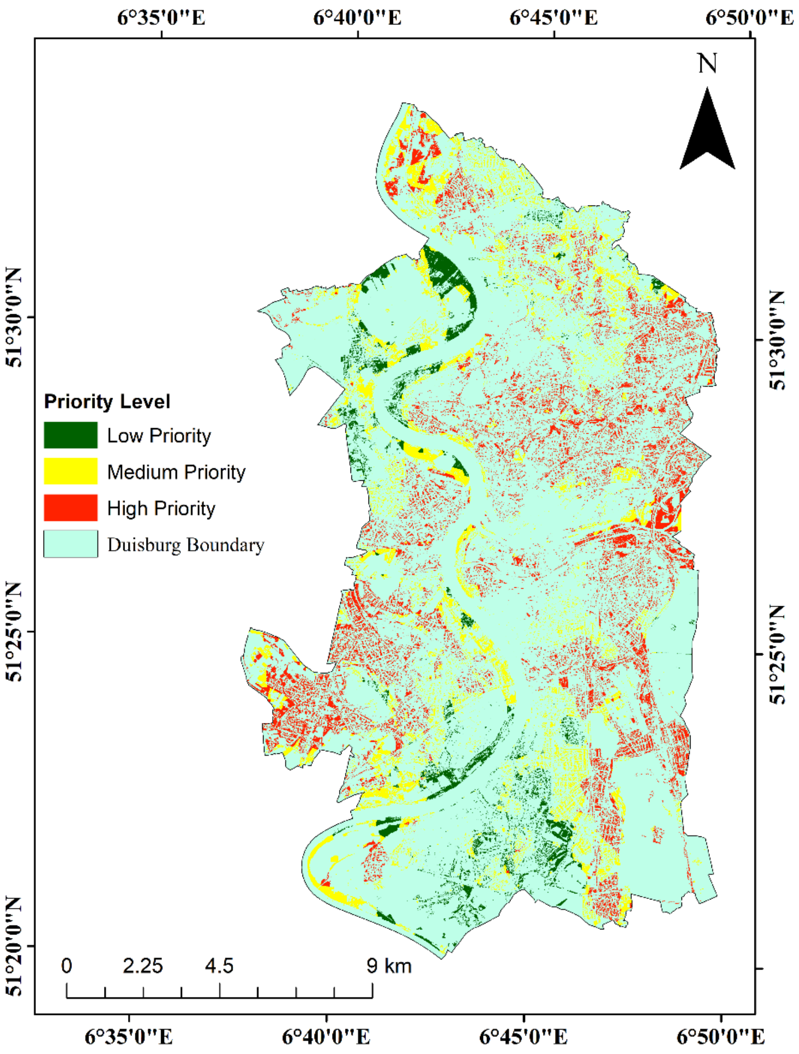


Figure 11: Greening need-based priority levels for afforestation suitability

High-priority areas are predominantly concentrated in the central, southeastern, and western industrial and residential zones, where urban heat island (UHI) effects, poor air quality, and flood risks coincide. The southern industrial belt and southeastern neighborhoods, which previously emerged as hotspots in the need-for-greening analysis, remain critical zones for intervention. These areas experience high levels of NO_2, $PM_{2.5}$, and PM_{10}, making them essential targets for air quality improvement through tree planting. Additionally, regions adjacent to the Rhine River and other flood-prone areas in the west exhibit high afforestation potential, reinforcing their role in flood protection through improved water infiltration and erosion control.

If all 19.41 km^2 of high-priority land is afforested, the carbon storage potential would significantly increase, providing an additional offset beyond the current 2.52 million tons. However, large-scale afforestation across all suitable zones is unlikely in the short term due to logistical, economic, and land-use constraints. Prioritization should therefore focus on areas where afforestation provides the greatest environmental and social co-benefits.

Prioritization Strategy Based on Key Factors:

Air Quality Improvement: The southeastern industrial corridor must be prioritized due to persistent air pollution from industrial activities. Afforestation efforts should focus on establishing pollution-resistant tree species that act as biofilters for particulate matter and nitrogen oxides.

Flood Protection: The western floodplain areas along the Rhine River hold strategic importance in reducing surface runoff and mitigating flood risks. Tree planting in these areas will enhance infiltration and stabilize riverbanks.

Urban Cooling & Social Well-Being: High-density residential zones in the central and southern parts of Duisburg, including Rheinhausen and Hochfeld, require immediate greening interventions to counteract extreme heat and address green space shortages. Green corridors and urban parks in these areas will enhance both livability and climate resilience.

The results indicate the need for a phased afforestation approach, prioritizing areas where greening offers immediate climate adaptation, mitigation, and social benefits. Future implementation should target a balance between carbon sequestration and localized environmental improvements, ensuring that afforestation efforts maximize their impact in Duisburg’s most vulnerable areas.

CHAPTER 5
DISCUSSIONS

5 Discussions

5.1 Interpretation of Results

The findings of this study provide interesting insights into the potential for carbon sequestration through nature-based solutions (NBS) in Duisburg, a heavily industrialized city. The analysis shows that Duisburg's current carbon storage capacity is approximately 2.52 million tons, accounting for only 9% of the city's annual carbon emissions. This emphasizes the limited but significant role of terrestrial ecosystems in offsetting anthropogenic emissions. The northern and northeastern regions, dominated by deciduous and coniferous forests, emerged as the primary carbon sinks, while urbanized and industrial areas in the central and southeastern parts of the city contributed minimally to carbon storage.

The afforestation suitability analysis identified 44.23 km² (19% of the total land area) as suitable for tree planting. However, only 19.41 km² of this area was classified as high-priority for afforestation, highlighting the challenges posed by land-use constraints, urban infrastructure, and competing priorities. The high-priority zones are concentrated in the central, southeastern, and western regions, where urban heat island (UHI) effects, poor air quality, and flood risks are most evident. These areas represent essential targets for greening interventions that can simultaneously enhance carbon sequestration, mitigate environmental stressors, and improve social well-being. Priority levels map was created just as a baseline like where to start, starting with where there is need for greening will increase the potential of carbon storage and also will provide significant climate and social benefits.

The study's results align with global climate strategies that emphasize the integration of NBS into urban planning to achieve carbon neutrality. By identifying spatially distributed areas for afforestation, this research provides a roadmap for utilizing under-represented green spaces to enhance Duisburg's climate resilience. However, the findings also highlight the need for complementary strategies, such as renewable energy adoption and industrial emission reductions, to address the city's carbon deficit comprehensively.

5.2 Comparison with Literature

The results of this study are consistent with previous research on urban carbon sequestration and the effectiveness of NBS in mitigating climate change. For instance, studies in Shenzhen, China, and Nador City, Morocco, have demonstrated that urban greening can significantly enhance carbon storage while delivering co-benefits such as improved air quality and biodiversity conservation [13], [20]. Similarly, the use of the InVEST model for carbon storage assessment aligns with findings from other temperate regions, where the model has been successfully applied to quantify ecosystem services and inform land-use planning [19].

However, this study also introduces several innovations. Unlike previous research that often focused on rural or less industrialized areas, this study addresses the unique challenges of urban-industrial contexts, where land availability and ecological conditions are limited. The integration of multi-criteria analysis (MCA) to prioritize afforestation sites based on environmental, climatic, and social indicators represents a different approach that bridges the gap between ecological potential and human needs. This methodology builds on the work of

[46], who emphasized the importance of stakeholder engagement in urban greening projects but extends it by incorporating spatially explicit data to guide decision-making.

The findings also contrast with studies that have primarily focused on large-scale afforestation without considering local constraints. For example, while research in Rajasthan, India, identified 40% of the state as suitable for afforestation [23], this study highlights the limitations of such approaches in densely urbanized and industrialized settings like Duisburg. By focusing on high-priority areas, this research provides a more realistic and actionable framework for urban greening.

5.3 Practical Applications

The results of this study have several practical implications for urban planners and policymakers in Duisburg and similar industrial cities. First, the identification of high-priority areas for afforestation provides a clear roadmap for targeted greening interventions. These areas, which include the southeastern industrial corridor, central residential districts, and western floodplains, should be prioritized for tree planting to maximize environmental and social benefits.

Second, the study highlights the importance of integrating NBS into broader climate strategies. For example, afforestation in flood-prone areas can enhance flood resilience by improving water infiltration and stabilizing riverbanks; while greening industrial zones can mitigate air pollution and reduce urban heat island effects. These co-benefits highlight the potential of NBS to address multiple environmental challenges simultaneously.

Third, the findings emphasize the need for context-specific afforestation strategies. In densely urbanized areas with limited space, compact green infrastructure such as street trees, green roofs, and vertical gardens can provide significant ecological benefits without compromising urban functionality. In contrast, peri-urban and riparian zones offer opportunities for large-scale afforestation projects that enhance carbon sequestration and biodiversity connectivity.

Finally, the study calls for the development of policies that support the implementation of NBS. This includes incentives for private landowners to participate in afforestation initiatives, regulations to protect existing green spaces, and funding mechanisms to support urban greening projects. By aligning ecological goals with economic and social priorities, policymakers can ensure the long-term sustainability of afforestation efforts.

CONCLUSIONS

Conclusions

This study explored the role of nature-based solutions (NBS), particularly afforestation, in mitigating industrial carbon emissions in Duisburg. To achieve these following questions were answered.

Question 1. Which carbon storage (CS) model is most suitable for evaluating emissions in heavily industrialized regions like Duisburg, based on literature?

A comprehensive literature review of carbon storage models was conducted, leading to the selection of InVEST as the most suitable tool for assessing emissions and sequestration potential in urban-industrial contexts. InVEST model was chosen due to its ability to integrate spatial data, simulate land-use changes, and quantify ecosystem services. Compared to other models, it provides a spatially explicit representation of carbon storage, making it highly effective for urban-industrialized contexts.

Question 2. How much carbon emissions do Duisburg produce, and what is its current carbon storage capacity?

Duisburg’s current carbon storage capacity is estimated at 2.52 million tons, which accounts for only 9% of its annual carbon emissions (24 million tons). This highlights a large carbon imbalance, demonstrating that the city's existing green spaces and terrestrial ecosystems play only a minor role in offsetting emissions. Given the dominance of industrial activities in the region, the gap between emissions and sequestration capacity highlights the need for additional carbon offsetting strategies, including afforestation and broader emission-cutting measures.

Question 3. Where are the high-potential areas for afforestation in Duisburg?

To determine where afforestation could be implemented, this study employed exclusion criterion to identify high-potential areas for afforestation within Duisburg. The results indicate that 19% of the city’s land area is suitable for afforestation. Although land availability is a major limitation in industrial cities, strategic greening initiatives can still be implemented in these identified locations to enhance carbon sequestration while providing additional ecological benefits.

Question 4. Can afforestation in Duisburg effectively counterbalance industrial carbon emissions?

Despite the identified afforestation potential, planting trees alone cannot fully offset Duisburg’s industrial emissions. Even if afforestation were maximized across all suitable areas, carbon storage (5.5 million tons out 24.5million tons) remains insufficient to neutralize the city's high emissions output. This finding emphasizes the need for a multi-faceted approach to emission offsets and cuts, integrating afforestation with policies aimed at industrial decarbonization, renewable energy adoption, and enhanced carbon capture technologies.

In addition to estimating afforestation potential, this study also prioritized areas based on greening needs using indicators such as climate change mitigation (e.g., flood risk, urban heat island effects), environmental factors (e.g., air pollution, proximity to industrial emitters), and social well-being (e.g., population density, accessibility to green spaces). This prioritization ensures that if afforestation efforts are to be implemented, they can begin in locations where afforestation provides the greatest environmental, social, and climate benefits. The analysis identified 19.41 km² as high-priority zones, offering policymakers a practical starting point for urban greening initiatives.

While this study provides valuable insights, several limitations should be acknowledged. The use of static land cover data (2023) may not fully capture the dynamic nature of urban landscapes, potentially affecting the accuracy of the results. Future research could incorporate real-time or near-real-time remote sensing data to enhance the precision of carbon storage estimates and afforestation suitability assessments. Additionally, legal and landownership constraints were not considered, which may have overestimated the feasibility of afforestation in certain areas. Integrating land tenure and policy restrictions into future models would offer a more realistic assessment of afforestation potential.

Another limitation is the lack of stakeholder engagement, which could impact the acceptability and practicality of the proposed afforestation strategy. In future studies, including input from local communities, policymakers, and industries would enhance the alignment of afforestation efforts with socio-economic and political realities.

Despite these limitations, this study successfully demonstrated that urban afforestation could enhance carbon sequestration and provide co-benefits, including improved air quality, reduced urban heat island effects, and enhanced flood resilience. The integration of geospatial technologies and multi-criteria analysis proved to be a cost-effective and innovative framework for guiding afforestation initiatives in urban-industrial settings. However, other nature-based solutions (NBS), such as wetland restoration and green infrastructure, were not evaluated, despite their potential to complement afforestation efforts and further enhance urban resilience.

To build upon this research, future studies should explore the socio-economic feasibility of afforestation, including cost-benefit analyses, funding mechanisms, and policy integration. Expanding the scope to incorporate additional nature-based solutions and stakeholder-driven approaches could provide a more comprehensive understanding of urban climate mitigation. Additionally, investigating the long-term impacts of afforestation on biodiversity, ecosystem services, and community well-being would offer deeper insights into its role in sustainable urban planning. Addressing these gaps will help develop more holistic and actionable strategies for enhancing climate resilience in industrial cities like Duisburg.

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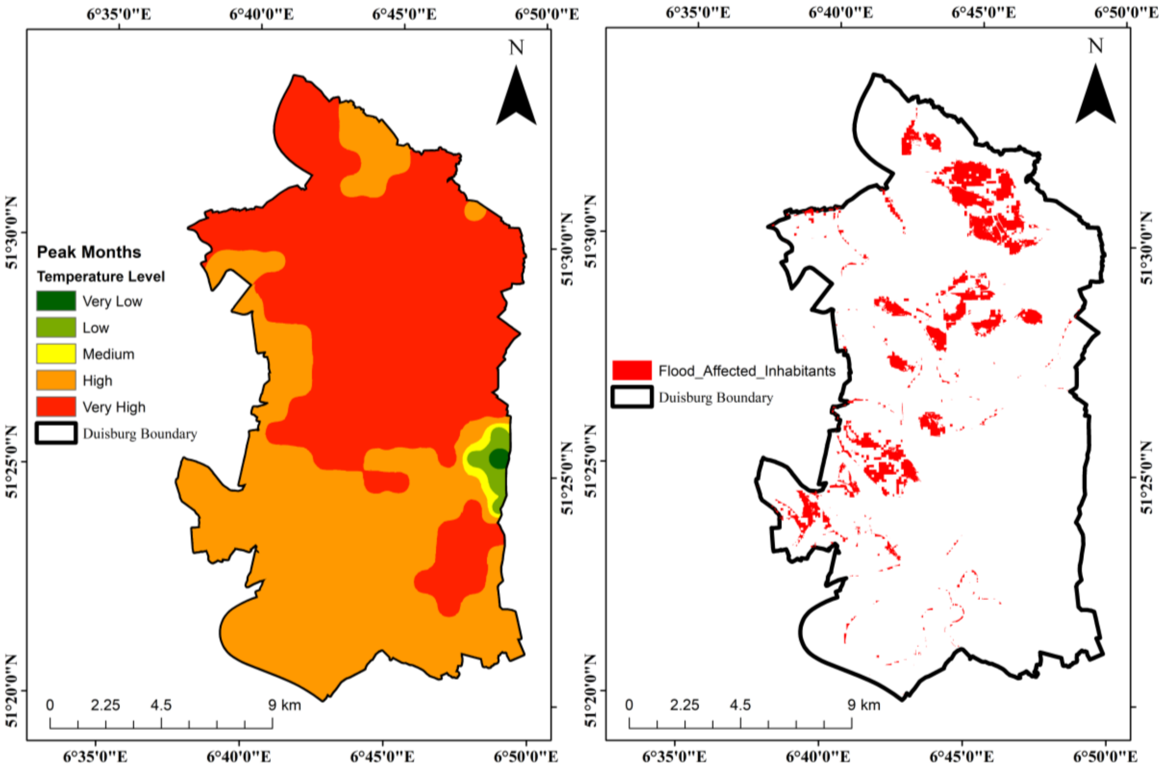
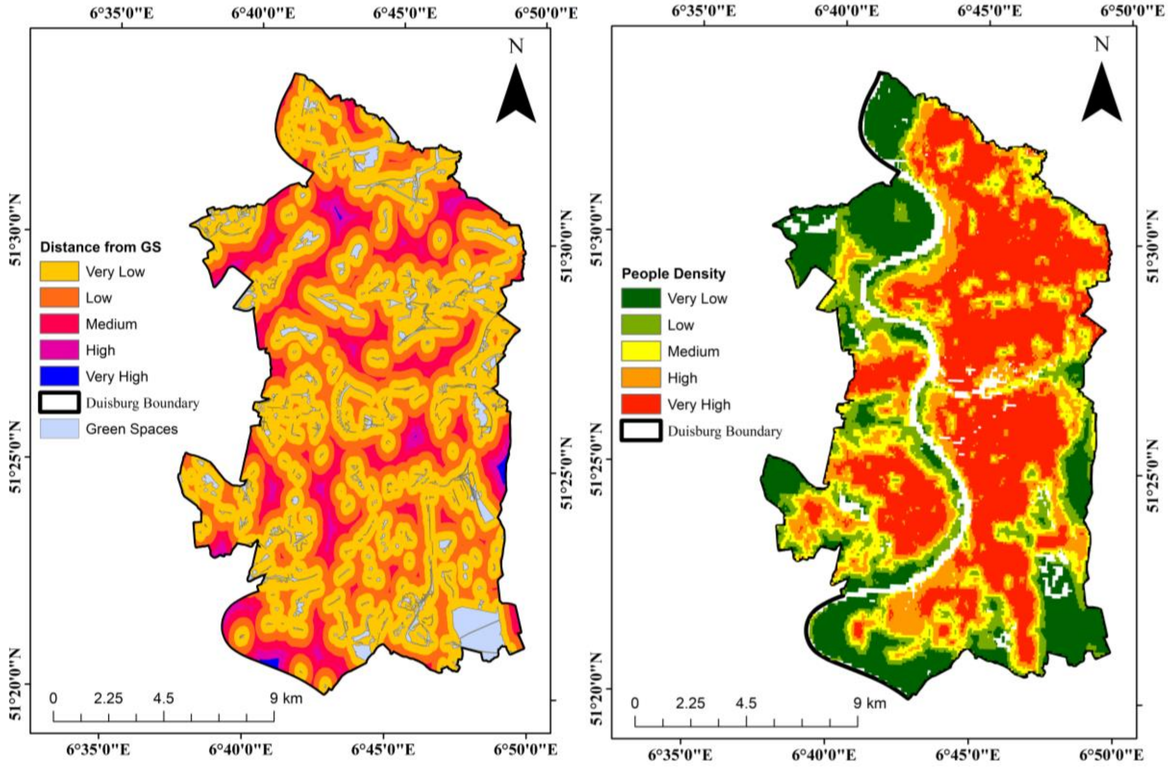
ANNEXES

Annexes

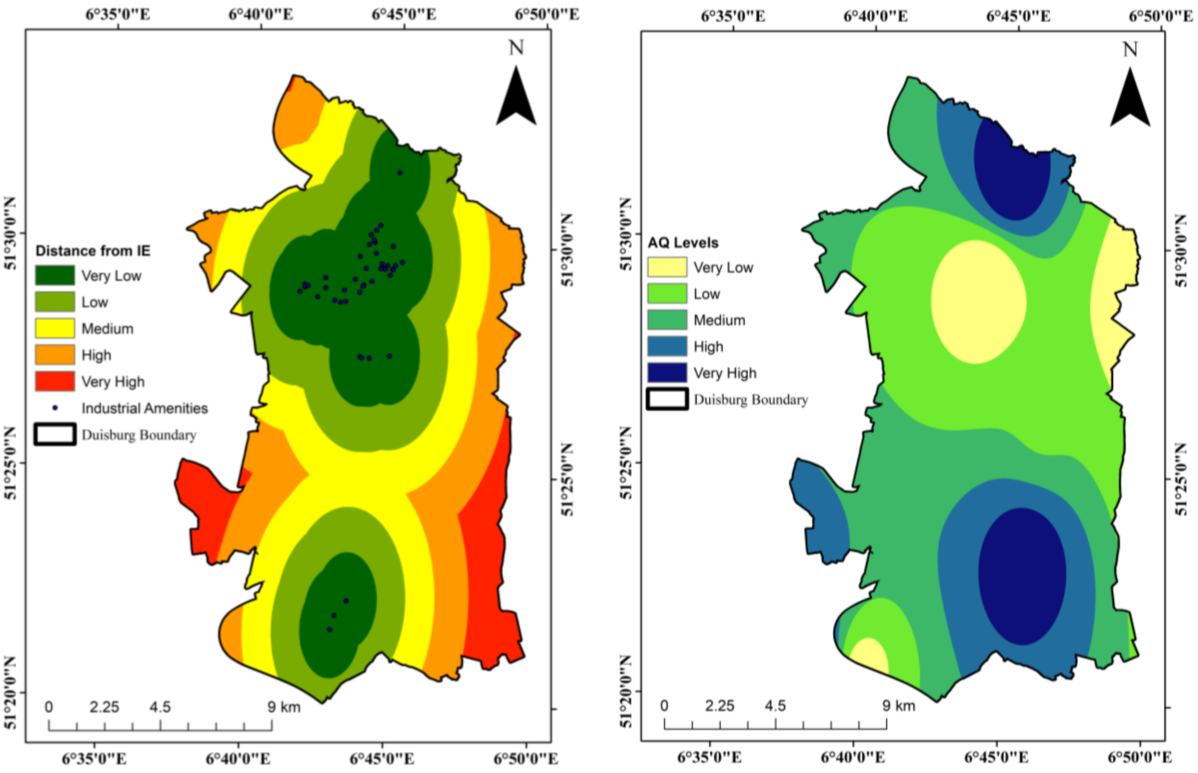
1. Individual Indicators Maps



Figure; Climate Change Mitigation Layers (a) Peak months temperature levels (b) Flood risk zones



Figure; Social Well-being Layers (a) Distance from Green Spaces (b) People per pixels density



Figure; Nature Indicators Layers (a) Distance from Industrial Emitters (b) Peak months Air Quality

2. Current and Potential Carbon Storage Charts

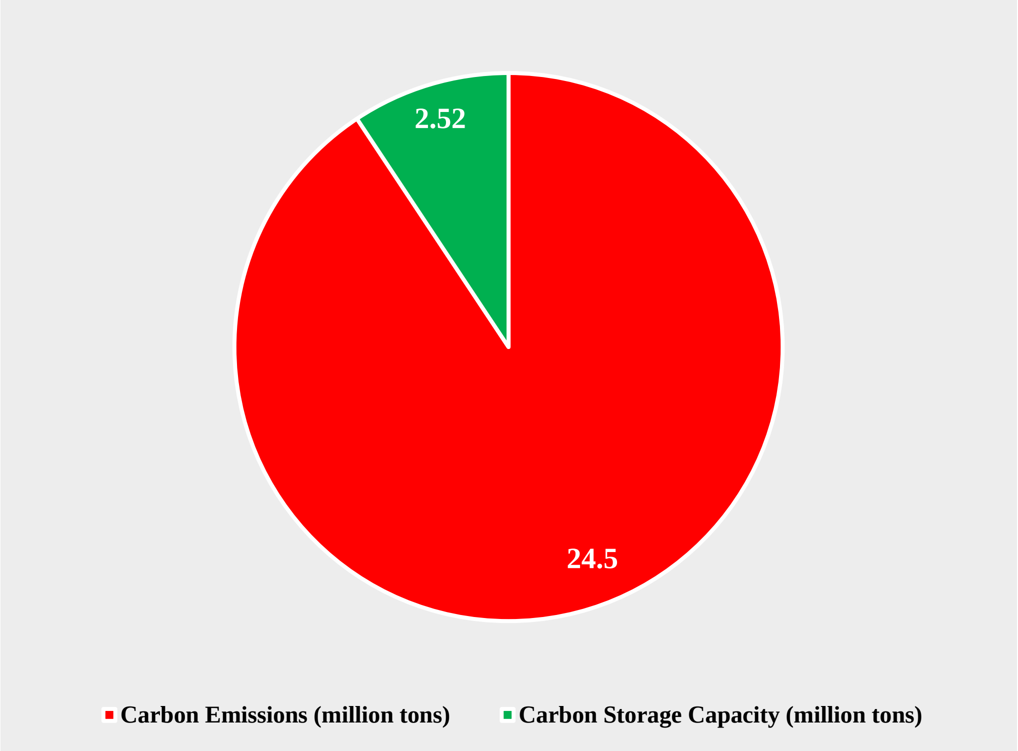


Chart 1 Duisburg's Current Carbon Emissions and carbon offsets (2023) based on current landcover and calculated using InVEST model

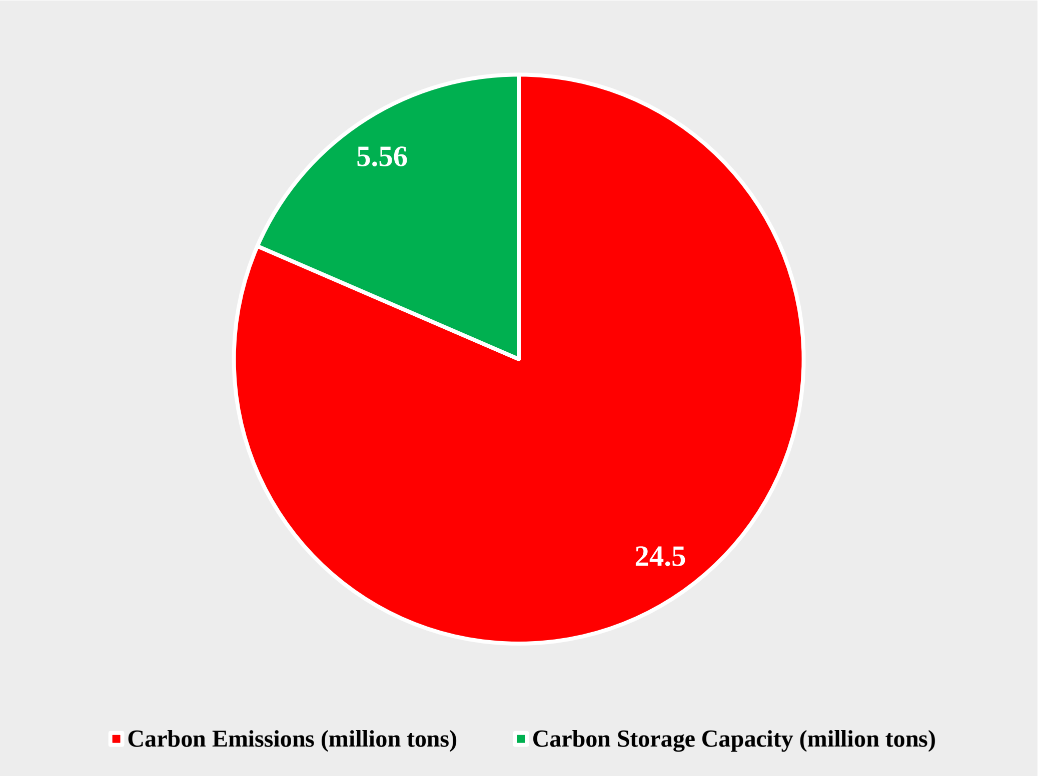


Chart 2 Duisburg's Carbon Emissions (2023) and Potential carbon offsets based on potential (assumed afforestation suitable as mixed forest) Landcover and calculated using InVEST model