M.Sc. Dissertation
Master of ENVIRONMENTAL AND LAND ENGINEERING
Department of Environment, Land and Infrastructure Engineering (DIATI)

AI-Driven Mapping and Economic Assessment of Urban Carbon Wealth and Vegetation Dynamics in Turin Using Sentinel-2 Remote Sensing

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Abstract

Urban green infrastructure plays a critical role in mitigating climate change by sequestering carbon, regulating microclimates, and enhancing urban resilience. This research integrates artificial intelligence (AI), remote sensing, and economic valuation to quantify and evaluate the carbon and ecological value of vegetation across the city of Turin between 2021 and 2023. Using multi-temporal Sentinel-2 imagery processed in Google Earth Engine, vegetation indices (NDVI) were derived and analyzed to capture spatial and seasonal variations in vegetation dynamics. An AI-driven workflow was employed to estimate Above-Ground Biomass (AGB) and corresponding CO_2 sequestration based on established empirical models.

The results revealed clear spatiotemporal trends: vegetation density peaked during summer and declined in winter, with interannual variation reflecting the influence of climatic conditions, particularly the drought of 2022. Total annual CO_2 sequestration ranged between **1.50×10^9 and 2.09×10^9 tonnes**, corresponding to an **economic value of €119–167 billion** using the EU Emissions Trading System reference price (€80 t^{-1} CO_2). High-sequestration zones were concentrated along the Po River corridor, the eastern hillside forests, and major parks such as Parco del Valentino and Parco della Pellerina.

By coupling geospatial data with AI-enhanced modeling and economic valuation, this study demonstrates that urban vegetation represents a significant and measurable component of Turin's natural capital. The developed framework provides a scalable, cost-efficient approach for supporting **climate-neutral city strategies** and **nature-based investment planning** across Europe.

Acknowledgments

To **Professor Piero Boccardo**, for his invaluable guidance, wisdom, and insight throughout this journey. His expertise and trust allowed me to explore, learn, and grow with confidence and purpose.

To my **family**, for their endless sacrifices, love, and strength. You carried the weight of distance with grace from supporting me financially to setting aside your own emotions so that I could follow my dreams freely. While others had their children close, you chose instead to give me wings, knowing that this path was the only way for me to become who I was meant to be. Every step of this journey was possible because of your patience, your faith, and your love that stretched across oceans. Though I missed you deeply, I carried your warmth with me in every moment of this journey.

To my sister **Reyhaneh**, whose presence in Turin gave me strength, laughter, and the feeling of home. Your patience, love, and constant support reminded me that I could always find balance, even far from where everything began.

To my **Love**, for his calmness, understanding, and unwavering belief in me. In every moment of doubt, your quiet encouragement helped me gather myself and continue with clarity and heart.

To my **friends**, for their kindness, humor, and for turning difficult days into unforgettable memories.

To the **city of Turin**, for welcoming me, shaping me, and becoming a second home. A place that will forever hold part of who I am.

And finally,
I dedicate this work to all **women and girls in STEM**, and to every girl in the world who dreams of learning but is denied the chance.
May this be a small tribute to your courage, a reminder that your voice, your mind, and your dreams have a place in every classroom, laboratory, and future.

Woman, Life, Freedom

Contents

List of Figures

List of Tables

List of Charts

List of Equations

Chapter 1: Introduction

1.1 Background and Motivation

Urban vegetation plays a vital role in promoting environmental sustainability. Green areas provide essential ecosystem services such as microclimate regulation, air purification, biodiversity enhancement, and carbon sequestration. These services are particularly relevant in the context of climate change, where urban vegetation contributes to mitigating greenhouse gas emissions and improving urban resilience (Nowak & Crane, 2002).

Remote sensing offers an effective approach for monitoring vegetation conditions over time and across space. Among the various spectral indices, the **Normalized Difference Vegetation Index (NDVI)** is one of the most widely used indicators of vegetation greenness and health. It measures the reflectance contrast between red and near-infrared bands and is strongly correlated with chlorophyll content and vegetation vigor. In this study, NDVI serves as the primary indicator for assessing vegetation dynamics in Turin. **Further details on the development, advantages, and applications of NDVI are discussed in Chapter 2 (§2.1–2.3).**

By integrating NDVI with empirical models, it becomes possible to estimate above-ground biomass (AGB) and infer carbon sequestration potential, thus linking remote sensing with ecosystem service evaluation (Zapata, 2021). Modern cloud-based platforms such as Google Earth Engine (GEE), combined with ArcGIS Pro, provide robust tools for processing satellite data, visualizing spatial outputs, and conducting reproducible urban vegetation analyses (Gorelick et al., 2017; ESRI, 2020).

Within this context, **Turin (Torino)**, a medium-sized city in northern Italy, represents an ideal case study. It combines dense built-up areas with an extensive network of green infrastructure, including parks, tree-lined streets, and peri-urban agricultural land. At the same time, Turin faces environmental challenges such as air pollution and rising temperatures, making vegetation monitoring particularly relevant for climate adaptation.

This research is rooted in the discipline of **Environmental and Land Engineering**, integrating remote sensing and geospatial analysis to quantify ecological functions and climate-mitigation potential in urban environments. By connecting NDVI-based vegetation monitoring with biomass and carbon sequestration estimation, the study demonstrates how engineering tools can support sustainable land management and enhance climate resilience in cities.

1.2 Research Problem

Although NDVI has long been recognized as a reliable indicator of vegetation health, most of its applications have focused on regional or agricultural contexts rather than complex urban ecosystems. The heterogeneity and fragmentation of urban vegetation make it difficult to directly transfer models developed for forests or croplands to cities (Anyamba, 2011).

Moreover, while NDVI can be computed easily, converting it into meaningful ecological indicators such as biomass or carbon storage remains challenging. Differences in vegetation type, canopy structure, and impervious surface interference introduce uncertainties that require model adaptation and validation (Zapata, 2021).

Recent technological advances, particularly in **Google Earth Engine (GEE)**, now allow large-scale, time-series NDVI analyses using open-access satellite data (Gorelick et al., 2017). However, few studies have fully integrated these capabilities into urban-scale assessments linking NDVI to carbon sequestration and economic valuation.

At the policy level, instruments such as the **EU Emissions Trading System (EU ETS)** emphasize the financial value of carbon sequestration through carbon pricing mechanisms (EEA, 2024). Yet, the connection between NDVI-derived urban vegetation data and carbon market evaluation remains limited. This research addresses this gap by linking remote sensing, ecological analysis, and economic assessment within a single, reproducible framework.

1.3 Research Objectives

The overarching goal of this thesis is to evaluate the seasonal dynamics of urban vegetation in Turin using NDVI-based remote sensing methods and to quantify its ecological and climate-related contributions.

To achieve this goal, the study pursues the following **specific objectives**:

- Analyze spatial and temporal NDVI variations in Turin during 2021–2023 using Sentinel-2 imagery.
- Estimate above-ground biomass (AGB) and corresponding CO_2 sequestration using NDVI-derived empirical models.
- Evaluate the economic value of CO_2 sequestration to assess the contribution of urban green areas to climate mitigation.
- Develop a reproducible workflow combining Google Earth Engine and ArcGIS Pro for urban vegetation monitoring applicable to other cities.

Throughout this study, biomass and carbon quantities are expressed in **tonnes (t)**, ensuring unit consistency across all analytical stages.

1.4 Significance of the Study

Urban vegetation plays a critical role in addressing the challenges of climate change and rapid urbanization. Green spaces provide multiple ecosystem services—air purification, biodiversity conservation, temperature regulation, and carbon capture—all essential for sustainable urban development (Rasoolzadeh et al., 2024).

From an **environmental perspective**, estimating the capacity of urban vegetation to sequester CO_2 is key to understanding its role in climate mitigation. Increasing atmospheric CO_2 levels drive global warming, leading to ecological and social impacts such as biodiversity loss and public health risks (Jin et al., 2023). By quantifying the carbon absorption potential of urban green areas, this study provides a scientific basis for evaluating their contribution to environmental sustainability.

From an **economic perspective**, translating CO_2 sequestration into monetary value via the **EU ETS carbon price** highlights the tangible benefits of ecosystem services (EEA, 2024). Such quantification supports local governments and policymakers in recognizing urban vegetation as a valuable asset for climate investment and urban planning.

From a **technical and engineering perspective**, this study applies remote sensing and GIS—core tools of Environmental and Land Engineering—to monitor and evaluate urban vegetation. Using NDVI within platforms like GEE and ArcGIS enables reproducible, scalable, and data-driven analyses (Gorelick et al., 2017). This integration demonstrates the potential of geospatial technologies to bridge environmental science and practical decision-making.

From a **social and planning perspective**, continuous monitoring of green areas supports strategies for sustainable urban growth and adaptation. As urban expansion threatens natural spaces, the findings of this research can inform planning policies aimed at preserving ecological balance and enhancing resilience (Aryal et al., 2022).

In summary, this thesis links scientific analysis (NDVI and remote sensing), environmental outcomes (CO_2 sequestration), economic valuation (carbon pricing), and engineering relevance (urban sustainability) within a single, coherent framework.

1.5 Research Methodology Overview

This study adopts a **remote sensing and GIS-based methodology** to analyze seasonal vegetation dynamics in Turin over three years (2021–2023). Sentinel-2 satellite imagery was processed in **Google Earth Engine (GEE)** to compute monthly NDVI values, followed by threshold-based classification into vegetated and non-vegetated areas. Binary vegetation maps were then exported to **ArcGIS Pro**, where spatial analysis tools quantified vegetated area on a monthly and annual basis.

NDVI values were used as inputs for an empirical biomass estimation model, which was subsequently converted into CO_2 sequestration potential. The resulting CO_2 quantities were then monetized using the **EU ETS carbon price** to estimate their economic value.

By analyzing three consecutive years, this study captures both seasonal and interannual variations, offering a more comprehensive understanding of urban vegetation trends and their climate-related implications. The workflow of the study is summarized in **Figure 1**, which illustrates the sequence of steps from data acquisition to analysis and output generation.

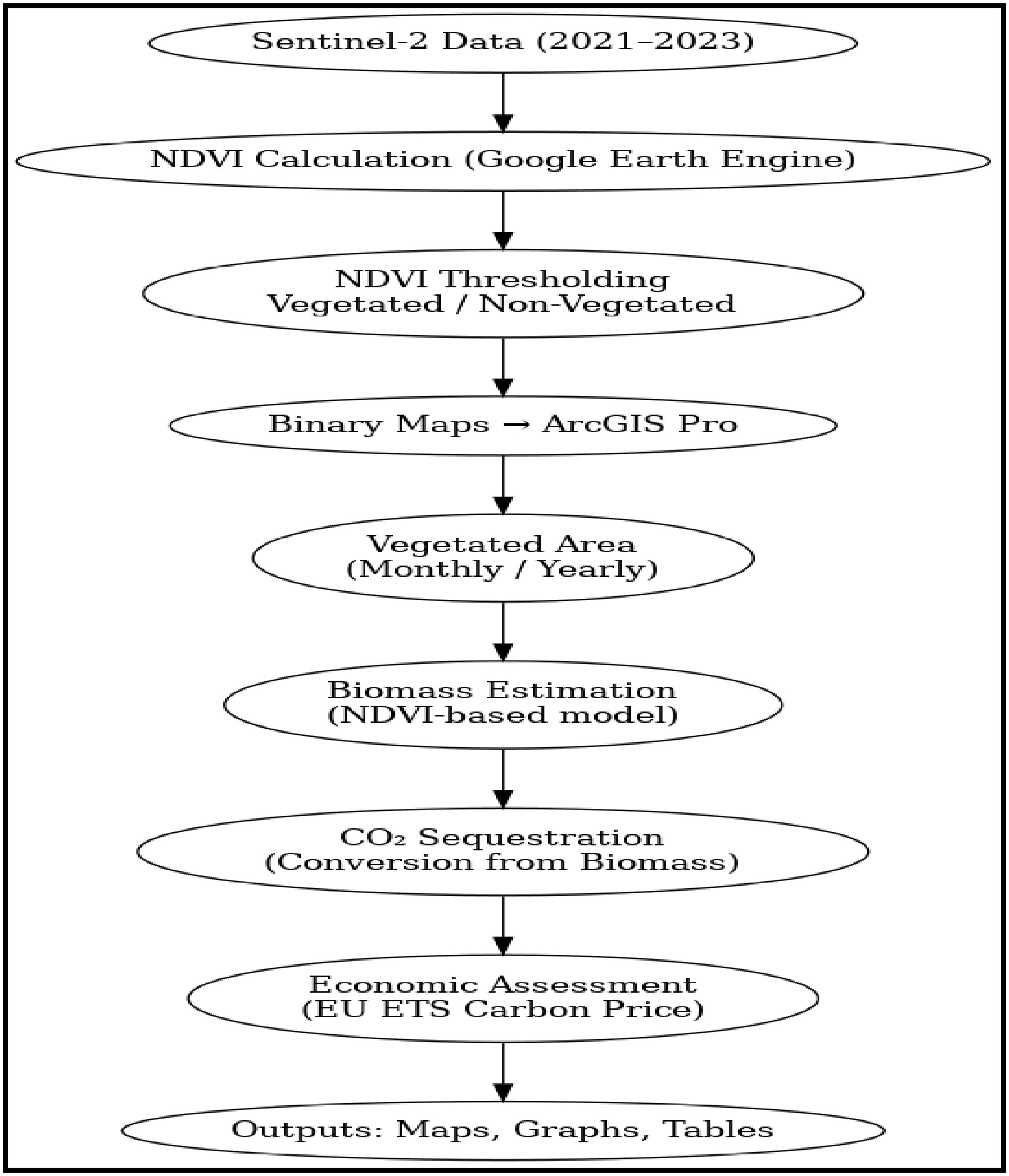


Figure 1. Workflow of the study

1.6 Structure of the Thesis

This thesis is organized into six chapters to ensure logical and thematic progression:

- **Chapter 1 – Introduction:** Presents the research context, motivation, objectives, significance, and methodological overview.
- **Chapter 2 – Literature Review:** Reviews relevant studies on NDVI, biomass estimation, CO_2 sequestration, and economic valuation, and identifies the research gap.
- **Chapter 3 – Data and Methodology:** Describes the study area, data sources, and methodological framework, including NDVI computation, vegetation classification, biomass–CO_2 modeling, and valuation steps.
- **Chapter 4 – Results:** Reports the NDVI, biomass, and CO_2 outcomes for 2021–2023, along with the economic valuation results and visual outputs.
- **Chapter 5 – Discussion:** Interprets findings, discusses uncertainties and limitations, and compares results with other studies.
- **Chapter 6 – Conclusion and Future Work:** Summarizes the study's main contributions, links them to Environmental and Land Engineering, and suggests directions for further research.

This structure ensures a coherent flow from conceptual background through methodological implementation, analysis, and conclusions.

Chapter 2: Literature review

2.1 Normalized Difference Vegetation Index (NDVI)

The **Normalized Difference Vegetation Index (NDVI)** is one of the most widely used remote sensing indicators for assessing vegetation condition, biomass, and spatial distribution. It is calculated from the contrast between near-infrared (NIR) reflectance, strongly associated with leaf cell structure, and red reflectance, absorbed by chlorophyll:

$$\text{NDVI} = \frac{NIR - RED}{NIR + RED}$$

Equation 1. Normalized Difference Vegetation Index (NDVI)

NDVI values range between –1 and +1. High positive values indicate dense, healthy vegetation, values near zero correspond to bare or sparsely vegetated soil, and negative values represent water or built-up areas.

2.2 Drought and Climate Stress Assessment

NDVI serves as a key indicator of vegetation stress related to water or temperature anomalies. As vegetation greenness declines during drought or heat events, NDVI effectively detects early stress responses. Huang et al. (2021) and Xue and Su (2017) emphasized NDVI's robustness and simplicity in monitoring ecosystem health under climatic variability. Time-series NDVI analyses also provide insight into vegetation decline and recovery during extreme weather conditions, making it a central tool for climate resilience studies.

2.3 Biomass and Carbon Estimation

NDVI is strongly correlated with above-ground biomass (AGB) and therefore serves as a proxy for estimating vegetation carbon storage. By linking NDVI-derived AGB with CO_2 sequestration, researchers can evaluate vegetation's contribution to climate change mitigation (Jin et al., 2023). In most studies, empirical regression or machine-learning models are used to convert NDVI to biomass, which is then multiplied by a CO_2 conversion factor.

2.4 Land Cover Classification and Change Detection

NDVI effectively separates vegetated from non-vegetated surfaces, supporting land cover mapping, deforestation monitoring, and urban green-space studies. Systematic reviews confirm NDVI's prominence as a global standard for environmental change detection (Open Access Review, 2023).

2.5 Urban and Landscape Studies

In complex urban environments, NDVI is used to map and monitor fragmented vegetation such as parks, street trees, and peri-urban fields. Matyukira et al. (2024) documented recent advances in urban vegetation mapping using NDVI and multispectral remote sensing, confirming its value for assessing ecological health and urban greenness.

2.6 Agriculture and Crop Health Monitoring

In agriculture, NDVI assists in assessing crop vigor, detecting nutrient deficiencies, and managing irrigation. Integration with artificial intelligence has improved precision monitoring; Kumar et al. (2025) demonstrated enhanced crop stress detection using NDVI combined with deep neural networks.

2.7 Time-Series Analysis and Data Products

Reliable vegetation trend analysis requires continuous NDVI time series free from cloud and noise effects. Techniques such as polynomial fitting, Fourier transforms, and machine learning improve temporal consistency (Li et al., 2021; Kandasamy et al., 2013; Cai et al., 2017). These methods are essential for reconstructing vegetation phenology and detecting subtle greening or browning trends.

2.8 Environmental Monitoring

NDVI provides consistent, long-term data for global and regional environmental assessments.

- **Drought Monitoring:** NDVI captures vegetation decline under water stress, supporting early warning and agricultural impact analysis (Bai et al., 2018).

- **Deforestation/Reforestation Tracking:** It effectively detects forest loss and regrowth trends (Joshi et al., 2021).

2.9 Climate Change Studies

NDVI plays a crucial role in understanding vegetation's response to climate variability and its role in the global carbon cycle. It links vegetation greenness to carbon sequestration potential (Zapata, 2021) and provides long-term records for analyzing how ecosystems react to temperature and precipitation changes (Anyamba, 2011).

2.10 Urban Green Space Management

In cities, NDVI-based analyses help identify and quantify green infrastructure, supporting strategies to mitigate heat islands, improve air quality, and enhance livability. Studies by Yang et al. (2017) and Bai et al. (2022) show that NDVI-derived vegetation data are key for evaluating urban thermal environments and guiding green-space planning. Large-scale analyses, such as Zhai et al. (2024), demonstrate the feasibility of NDVI time series for monitoring urban vegetation dynamics across hundreds of cities.

2.11 Advantages of NDVI

NDVI's continued use is due to several practical advantages:

- **Non-invasive monitoring:** Enables large-scale assessment without field sampling.
- **Scalability:** Applicable from local to global levels.
- **Historical and near-real-time availability:** Accessible via MODIS, Landsat, and Sentinel-2 archives.
- **Continuous monitoring:** High temporal frequency captures seasonal changes.
- **Sensitivity:** Responds to chlorophyll and canopy density variations.

2.12 Limitations of NDVI

Despite its utility, NDVI has known limitations: atmospheric interference, soil background effects, saturation in dense vegetation, lack of species discrimination, and temporal sensitivity (Xue & Su, 2017; Li et al., 2021). These constraints highlight the importance of calibration and supplementary indices (e.g., EVI, SAVI) for improved accuracy.

2.13 Urban Vegetation Studies

Urban vegetation supports ecological balance, air quality improvement, and temperature regulation. NDVI-based studies provide valuable insights into vegetation change under urban expansion. Jiang (2022) identified declining vegetation in Shanghai using Sentinel-2 NDVI, while Aryal et al. (2022) demonstrated NDVI's reliability for mapping urban ecological networks. Recent work links NDVI-derived green-cover metrics to urban microclimate regulation and carbon storage, emphasizing the role of urban trees in mitigating climate stress (Rasoolzadeh et al., 2024).

2.14 NDVI and Biomass Estimation

Estimating biomass is fundamental to understanding ecosystem productivity and carbon sequestration. NDVI provides a simple yet effective proxy for AGB estimation across ecosystems (Rasoolzadeh et al., 2024; Jin et al., 2023). Beyond classical regression, studies now employ machine learning and data fusion approaches, such as combining Sentinel-2 with LiDAR or neural networks, to improve biomass prediction accuracy (Chen et al., 2021; Jiang et al., 2022; Faria et al., 2024). These models differ in calibration region and vegetation type, and thus must be validated before application to new environments like Turin.

2.15 CO_2 Sequestration in Urban Areas

Urban vegetation functions as an important carbon sink through photosynthesis. NDVI-based and multispectral models are increasingly used to estimate city-level carbon storage. For example, Rasoolzadeh et al. (2024) quantified CO_2 sequestration in Tehran using NDVI, while Li et al. (2023, 2024) used machine learning on Sentinel and Landsat data to predict carbon storage in Shanghai. These studies demonstrate the adaptability of NDVI-based models to urban conditions, though the specific model parameters often differ across ecosystems.

2.16 Economic Valuation and Carbon Credits

Converting CO_2 sequestration into economic terms allows ecosystem services to be expressed in financial value. The **EU Emissions Trading System (EU ETS)** provides a carbon price per tonne of CO_2, enabling direct valuation of urban carbon uptake (EEA, 2024). Existing studies (Mngadi et al., 2021; Li et al., 2023; Rasoolzadeh et al., 2024) show that NDVI-derived carbon estimates can be multiplied by such prices to produce comparable economic indicators. However, few studies specify whether they use global or regionally calibrated biomass models, underscoring the need for context-specific validation, especially for European urban vegetation.

2.17 Research Gap

Most previous NDVI-based studies have focused on forest or agricultural ecosystems in Asia and North America, while medium-sized European cities remain understudied. Existing literature often examines vegetation mapping, biomass estimation, or economic valuation separately rather than as an integrated process.

Turin provides a relevant case because it combines dense urbanization with diverse green spaces under temperate climatic conditions, characteristics typical of many European cities but rarely represented in NDVI, carbon studies. Despite the presence of the EU ETS, few works have quantified the carbon and economic value of urban vegetation using a unified **NDVI→biomass→CO_2→valuation framework**.

This research fills that gap by developing a reproducible, NDVI-based methodology linking vegetation monitoring, biomass estimation, CO_2 sequestration, and monetary valuation within Turin’s urban environment. The approach establishes a scalable model for evaluating the ecological and financial value of green spaces in European cities using remote sensing and GIS technologies.

Chapter 3: Data and Methodology

3.1 Introduction

This chapter describes the datasets and methodological framework used in the study. It details the spatial and temporal characteristics of the data, the analytical workflow, and the computational techniques adopted to achieve the research objectives. The overall goal is to provide a clear, reproducible procedure linking NDVI-based vegetation monitoring with biomass estimation, CO_2-sequestration assessment, and economic valuation of carbon credits for the urban area of Turin, Italy.

3.2 Study Area Description

The research was conducted in **Turin (Torino)**, located in the Piedmont Region of north-western Italy (approx. 45.07° N, 7.69° E). Covering ~130 km^2, the city lies on the Po-River plain, bordered by the Alps to the west and north and hills to the east. Its **humid subtropical climate (Cfa)** features hot summers, cold winters, and 900–1,000 mm of annual precipitation concentrated in spring and autumn. These seasonal contrasts drive strong variations in vegetation activity.

Rapid urban expansion has fragmented green areas, reinforcing the need for systematic monitoring. Turin's green infrastructure, parks, tree-lined boulevards, riverside vegetation, and peri-urban forests, contributes significantly to biodiversity, air quality, and carbon capture. The city's **administrative boundary** was used as the analysis extent, with all spatial datasets projected to **WGS 84 / UTM Zone 32 N (EPSG:32632)** for consistency.

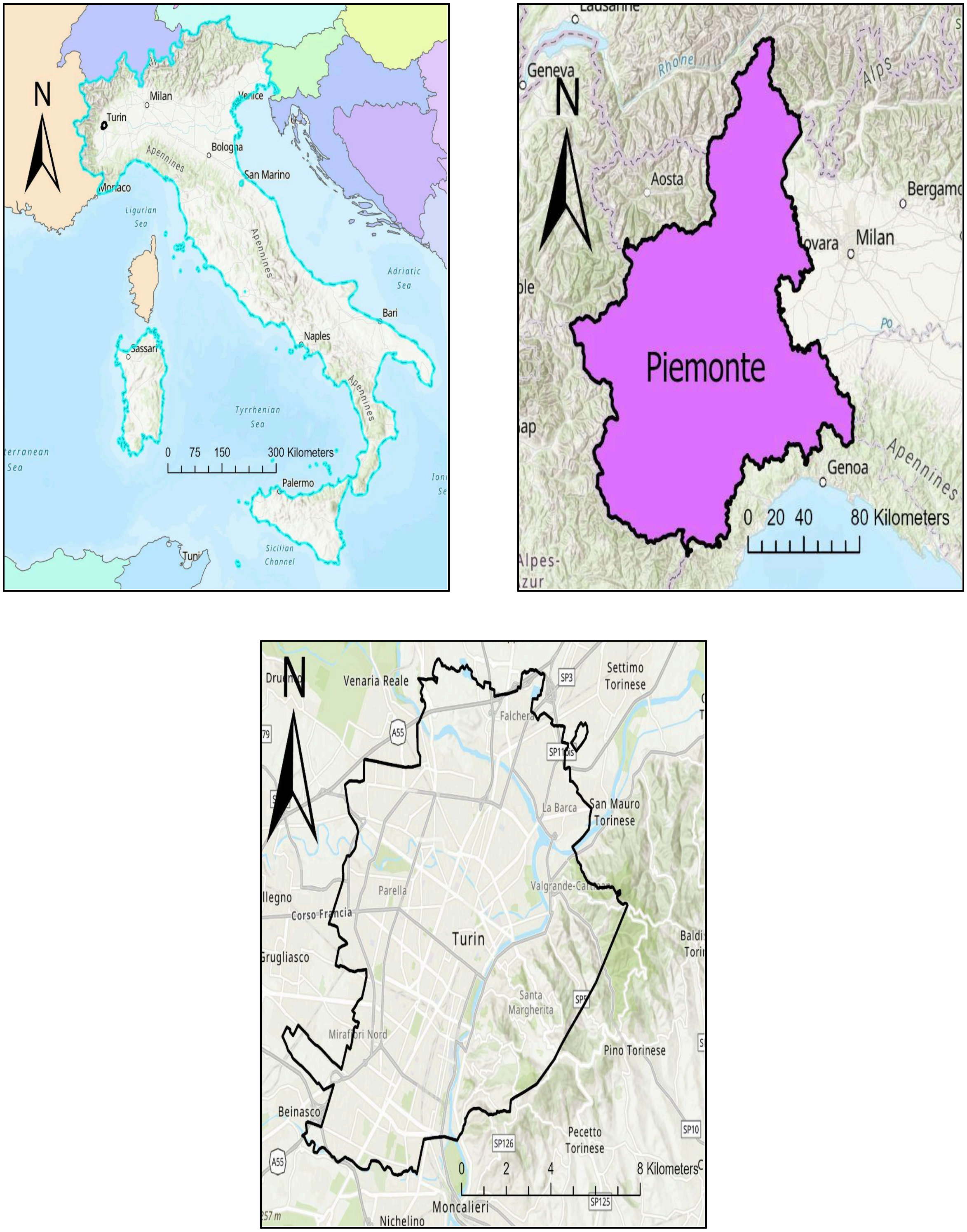


Figure 2. Location of the study area: the city of Turin, Italy

3.3 Data Sources and Collection

The study relied exclusively on freely available spatial and satellite data:

- **Sentinel-2 Level-2A Harmonized Surface Reflectance (S2_SR_HARMONIZED)** imagery (2021–2023) served as the main dataset for NDVI computation. One cloud-free scene per month was selected, applying a **< 10 % cloud-cover threshold** in the `CLOUDY_PIXEL_PERCENTAGE` metadata field to ensure quality.
- **Land-use and administrative shapefiles** were obtained from Copernicus, OpenStreetMap, and the City of Turin's open database.
- All datasets were re-projected to EPSG:32632 and integrated in **ArcGIS Pro** for visualization and spatial analysis.

This combination of **Google Earth Engine (GEE)** for cloud-based processing and **ArcGIS Pro** for detailed spatial interpretation enabled an efficient and reproducible workflow.

3.4 Methodological Framework

The analytical workflow (Figure 1) outlines the sequential stages linking satellite data to economic assessment: This workflow ensures consistency from raw-data preprocessing to value translation, bridging remote sensing with environmental-economic analysis.

3.5 Data Processing and Analysis Steps

To minimize redundancy, all processing is grouped into five main phases:

1. **NDVI Calculation in Google Earth Engine**

NDVI was computed in **Google Earth Engine** using Sentinel-2 Level-2A imagery. The Turin boundary shapefile was imported as a `FeatureCollection` and used to spatially constrain analysis.

A cloud-masking function excluded pixels flagged for clouds or cirrus in the **QA60 band (bits 10–11 = 0)**, ensuring only clear observations. Reflectance values were scaled by 0.0001 to convert to surface reflectance units. Monthly **median composites** were generated to reduce atmospheric noise.

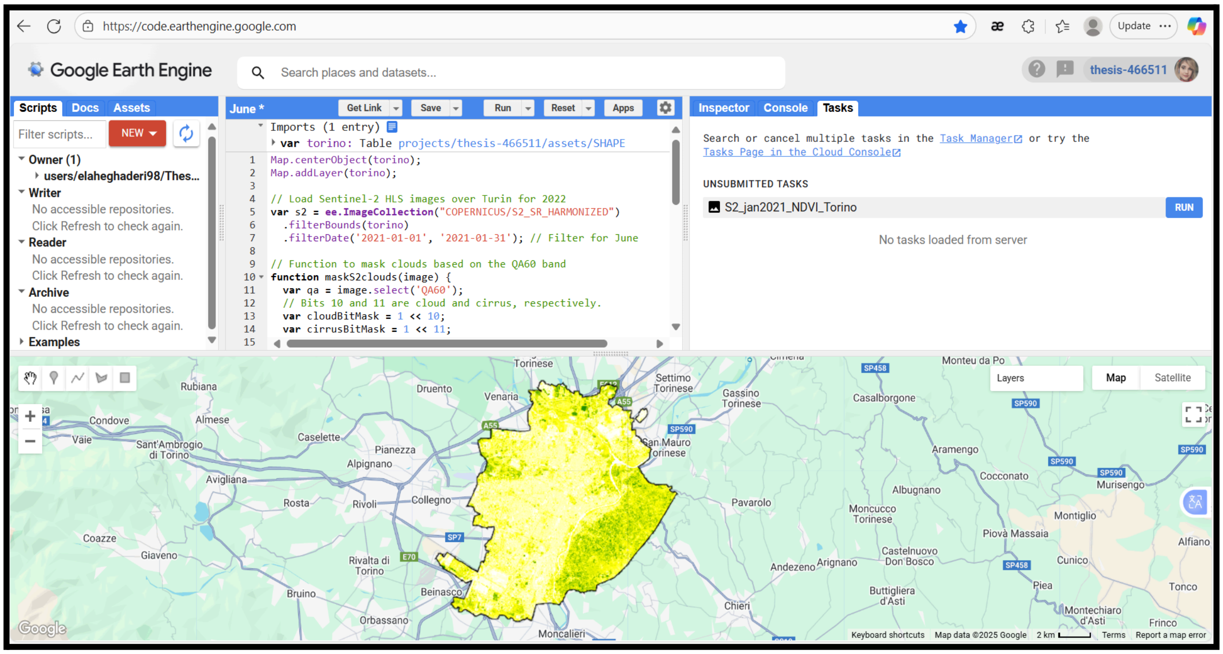


Figure 3. Methodological workflow of the study showing the main analytical steps from Sentinel-2 data processing to economic assessment

Each monthly composite was clipped to the Turin boundary and exported at **10 m** resolution. Visualization employed a 0–1 scale, with white → low vegetation and green → dense vegetation.

NDVI images were first grouped by **season** (winter, spring, summer, and autumn) and by **year** (2021, 2022, and 2023) to represent phenological variations over time. For each group, **mean NDVI composites** were generated in Google Earth Engine (GEE) to minimize the effects of atmospheric noise and cloud contamination.
The resulting NDVI layers were exported and processed in **ArcGIS Pro**, where visual symbology was standardized using a continuous color ramp from red (low NDVI) to green (high NDVI). These seasonal and annual NDVI maps were then used to assess general vegetation health and density trends across Turin.

This ensured compatibility with subsequent geospatial analyses in **ArcGIS Pro**, where NDVI layers were further processed for vegetation classification, biomass estimation, and CO_2 sequestration assessment. NDVI images were aggregated by season and by year (2021–2023).

Seasonal means minimized residual cloud contamination and allowed analysis of **phenological cycles**. Continuous color ramps from red (low) to green (high) were standardized across all maps to maintain interpretative consistency between years.

2. Vegetation Classification and Area Extraction

Binary thresholding in **ArcGIS Pro** distinguished vegetation from non-vegetation:

Con("ndvi_jun2022" >= 0.2, 1, 0)

IFollowing initial testing, two refined thresholds were adopted **0.3 for all vegetation** and **0.5 for dense vegetation** based on literature guidance from Aryal et al. (2022), Jiang (2022), and Rasoolzadeh et al. (2024). Threshold sensitivity tests confirmed that varying these values by ± 0.05 produced negligible differences (< 3 % in area estimates). All rasters were projected to EPSG:32632 and converted to polygons for area statistics. Vegetated polygons were quantified via the **Calculate Geometry** and **Statistics** tools, and results exported to Excel for comparison.

- **Dense Vegetation:**

Con("ndvi_jun2022" >= 0.5, 1, 0)

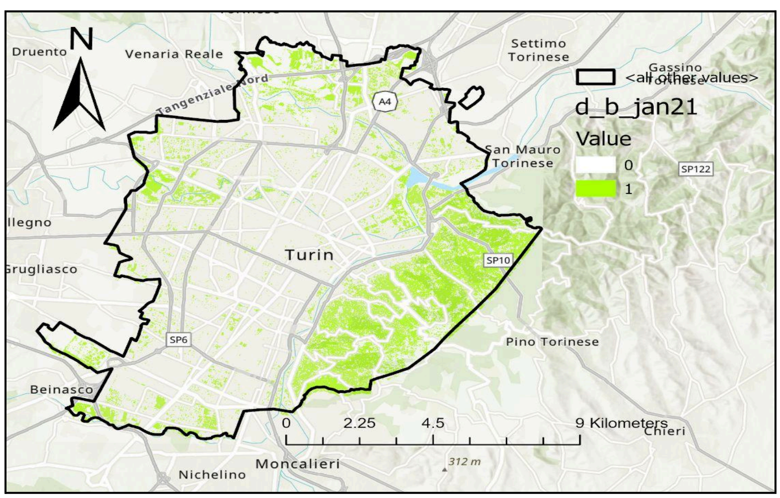


Figure 4. NDVI binary dense vegetation map for January 2021

- **All Vegetation:**

Con("ndvi_jun2022" >= 0.3, 1, 0)

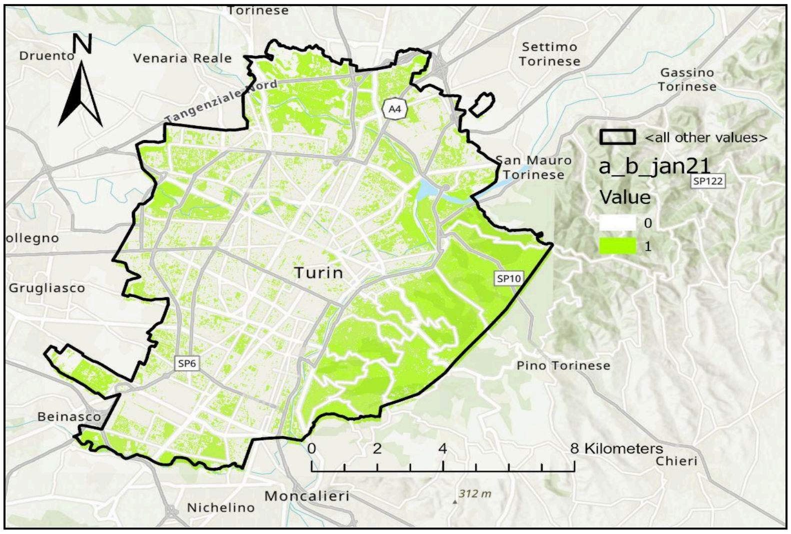
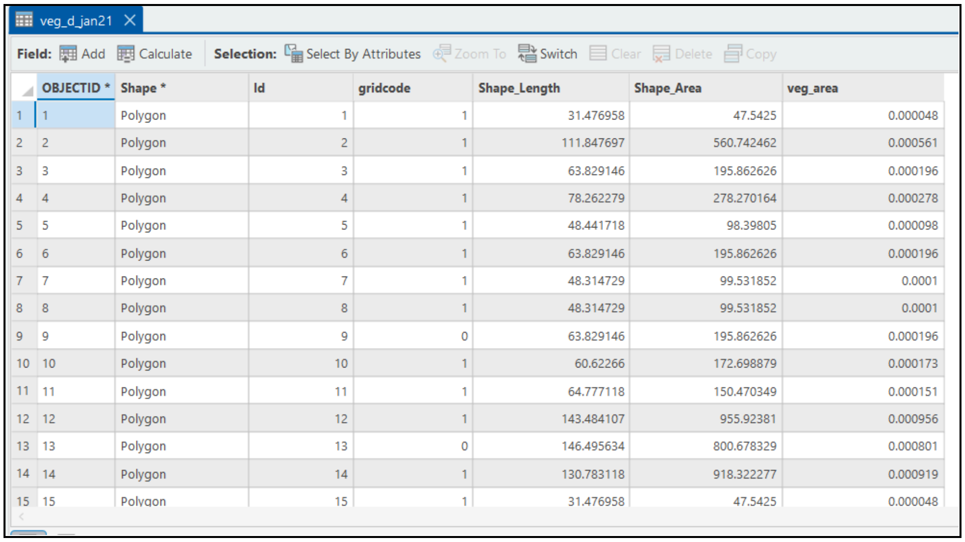


Figure 5. NDVI binary all vegetation map for January 2021

- **NDVI Threshold Justification**

The NDVI threshold values applied in this study (0.3 for non-vegetated/vegetated separation and 0.5 for dense vegetation) were selected based on empirical references from similar urban-scale studies in temperate and Mediterranean environments (Nowak et al., 2013; Hosni et al., 2022; Neyns & Canters, 2022). These thresholds effectively distinguish impervious or sparsely vegetated areas from green vegetation in medium-resolution imagery such as Sentinel-2. A visual inspection and sensitivity check confirmed that the selected thresholds minimized misclassification along mixed pixels and transitional zones, ensuring consistency across all monthly composites.

In the **attribute table** of each polygon layer, a new field named *veg_area* (type: double) was created. The **Calculate Geometry** tool was applied to this field to compute the area (in square meters) of each vegetated polygon. To isolate vegetation patches, features with *gridcode = 1* were selected using the *Select by Attributes* function.



	OBJECTID *	Shape *	Id	gridcode	Shape_Length	Shape_Area	veg_area
1	1	Polygon	1	1	31.476958	47.5425	0.000048
2	2	Polygon	2	1	111.847697	560.742462	0.000561
3	3	Polygon	3	1	63.829146	195.862626	0.000196
4	4	Polygon	4	1	78.262279	278.270164	0.000278
5	5	Polygon	5	1	48.441718	98.39805	0.000098
6	6	Polygon	6	1	63.829146	195.862626	0.000196
7	7	Polygon	7	1	48.314729	99.531852	0.0001
8	8	Polygon	8	1	48.314729	99.531852	0.0001
9	9	Polygon	9	0	63.829146	195.862626	0.000196
10	10	Polygon	10	1	60.62266	172.698879	0.000173
11	11	Polygon	11	1	64.777118	150.470349	0.000151
12	12	Polygon	12	1	143.484107	955.92381	0.000956
13	13	Polygon	13	0	146.495634	800.678329	0.000801
14	14	Polygon	14	1	130.783118	918.322277	0.000919
15	15	Polygon	15	1	31.476958	47.5425	0.000048

Figure 6. Attribute Table

The total vegetated area was then derived using the **Statistics** function on the *veg_area* field, and the summarized results were compiled in a separate **Excel file** for record and comparison purposes.

3. Biomass Estimation

Above-ground biomass (AGB) was estimated using the **Hosni et al. (2022)** empirical model, calibrated on mixed temperate vegetation:

$$\text{Biomass (t/ha)} = 197.55 \times NDVI^{1.39}$$

Equation 2. Biomass estimation model

The empirical model proposed by **Hosni et al. (2022)** was originally calibrated for **Mediterranean semi-arid ecosystems in Tunisia**, including mixed urban and peri-urban vegetation. Its applicability to Turin is appropriate due to similar climatic conditions and vegetation structure typical of southern Europe, though local variability may introduce minor uncertainty.

- **Unit Standardization and Model Context**

In this study, all biomass values are expressed in **tonnes per hectare** (t ha^{-1}) to maintain consistency with international conventions and comparable urban-scale research. Total CO_2 sequestration values are reported in tonnes of CO_2 (t CO_2) and, when spatially normalized, in tonnes per hectare (t CO_2 ha^{-1}).

The empirical biomass equation applied was originally calibrated for Mediterranean and temperate vegetation types, including mixed urban and peri-urban tree stands, which share ecological similarities with the Turin region. Its coefficients were therefore considered suitable for this study's climatic and land-cover context.

This formula represents the non-linear association between NDVI and AGB, enabling continuous estimation of biomass density (in tonnes per hectare) across the study area. Although derived from semi-arid ecosystems, its form aligns with other global NDVI–AGB relationships (Nowak et al., 2013). Therefore, results were interpreted **comparatively** rather than as absolute biomass, acknowledging model-transfer limitations for urban tree structures and heterogeneous canopies.

Monthly biomass rasters were generated via the **Raster Calculator**, maintaining per-pixel units of t ha^{-1}. Zonal Statistics summarized total biomass for each polygon, with citywide monthly sums aggregated in Excel.

4. **CO_2 Sequestration and Economic Valuation**
    - **CO_2 conversion**

Biomass totals were converted to CO_2 equivalents using the factor **1 t biomass = 1.8 ± 0.2 t CO_2**, consistent with Chatham House (2021), EEA (2022), and Kim et al. (2024). The ± 0.2 range represents biochemical variability in carbon content.

$$CO2\ (t) = Biomass\ (t) \times 1.8$$

Equation 3. CO_2 sequestration

The CO_2 conversion factor adopted (1 t biomass = 1.8 t CO_2) reflects the stoichiometric carbon content of woody biomass and includes an estimated **uncertainty range of ± 0.2** t CO_2 per t biomass to account for variability among species and regional conditions.

- **Economic valuation**

The monetary value was estimated using the **EU ETS average 2022 carbon price of €80 t^{-1} CO_2** (Ember Climate 2022 dataset). This represents the annual mean spot-market price, providing temporal context for comparison with future valuations:

$$\text{Economic Value (€)} = \text{Total CO2 Sequestered (tonnes)} \times 80$$

Equation 4. Economic valuation of CO_2 sequestration

Annual and monthly economic values were compiled and visualized in Excel.

3.6 Summary of the Methodology

The methodological design integrates remote sensing, GIS, and economic assessment to evaluate vegetation dynamics and their financial significance.

STAGE	PLATFORM	OUTPUT
NDVI computation	GEE	Monthly NDVI rasters (10 m)
Vegetation classification	ArcGIS Pro	Dense and total vegetation maps
Biomass estimation	ArcGIS Pro / Excel	Monthly AGB (t ha^{-1} and t total)
CO_2 conversion	Excel	Monthly and annual CO_2 (t)
Economic valuation	Excel	Annual value (€) using EU ETS price

Table 1.Summary of Methodology

This multi-stage approach creates a transparent, replicable framework for quantifying both the ecological and financial contributions of urban green spaces. Figures, tables, and scripts (GEE snippets) are provided in the appendices to support reproducibility.

Chapter 4: Results

4.1 Introduction

This chapter presents the analytical results obtained from the remote sensing and spatial analyses conducted to evaluate vegetation dynamics, biomass production, and carbon sequestration within the urban area of Turin between 2021 and 2023. The analyses were based on Sentinel-2 imagery processed in **Google Earth Engine (GEE)**, followed by spatial processing and visualization in **ArcGIS Pro**. These results collectively provide quantitative insights into vegetation health, productivity, and the corresponding climate-regulating services delivered by urban green spaces.

The chapter is organized according to the methodological framework presented earlier. It begins with the **Normalized Difference Vegetation Index (NDVI)** analysis, which reveals spatial and temporal variations in vegetation greenness and distribution. This is followed by the **classification of vegetated and non-vegetated areas**, allowing quantitative assessment of dense and sparse vegetation cover. The NDVI results are then used to estimate **Above-Ground Biomass (AGB)** through an NDVI-based empirical model, and subsequently converted to **CO_2 sequestration** using a standard conversion factor. Finally, the **economic valuation** of the estimated CO_2 sequestration is presented, expressed in terms of the European carbon price defined by **the EU Emissions Trading System (EU ETS).**

Throughout the chapter, results are supported by maps, tables, and charts derived from the GEE and ArcGIS analyses. These visual outputs illustrate spatial patterns and temporal trends, providing both scientific and practical understanding of how Turin's vegetation contributes to urban climate regulation. The findings are then interpreted in the context of environmental engineering and sustainability, highlighting the ecological, climatic, and economic significance of maintaining urban green infrastructure.

Overall, this chapter transforms the methodological workflow into measurable results, linking vegetation monitoring with carbon sequestration and economic value assessment. It demonstrates how integrated remote-sensing approaches can effectively quantify urban ecosystem services, supporting evidence-based planning for sustainable and climate-resilient cities.

4.2.1 Annual NDVI Results (2021 - 2023)

The annual mean NDVI maps (Figures **7.1–7.3**) illustrate the spatial distribution and interannual variation of vegetation cover across Turin during the period **2021–2023**. NDVI values ranged from approximately **–0.2 to 1.0**, where **low values** (red to yellow tones) represent built-up or non-vegetated areas, and **high values** (light to dark green tones) indicate dense and healthy vegetation.

In all three years, the **highest NDVI values** were observed in the **southern and eastern sectors** of the city, particularly along the **Po River corridor** and within large public parks such as **Parco del Valentino** and **Parco della Pellerina**, where dense vegetation persists year-round. In contrast, the **central and western districts** displayed lower NDVI values, corresponding to highly urbanized zones dominated by impervious surfaces.

A visual comparison of the maps reveals a **slight overall decrease** in NDVI from 2021 to 2023. The **2021** map exhibits broader green coverage, while in **2022 and 2023**, several areas transitioned toward yellow and orange tones, suggesting a **reduction in vegetation greenness**. Despite these variations, the overall spatial structure of vegetation remained stable, with the main green infrastructure retaining high NDVI values across the three years.

The **statistical summary** and the **trend chart** confirm this moderate decline. The **mean NDVI** decreased from **0.368 in 2021** to **0.279 in 2022**, followed by a slight recovery to **0.294 in 2023**, while the standard deviation values indicate consistent spatial variability. These changes correspond to a modest reduction in vegetation density, reflecting interannual climatic influences, particularly the warm and dry conditions of 2022.

Overall, the annual NDVI analysis highlights a gradual but measurable decline in vegetation health and density between 2021 and 2023, while confirming the persistence of Turin's major vegetated areas, which continue to serve as key urban green corridors.

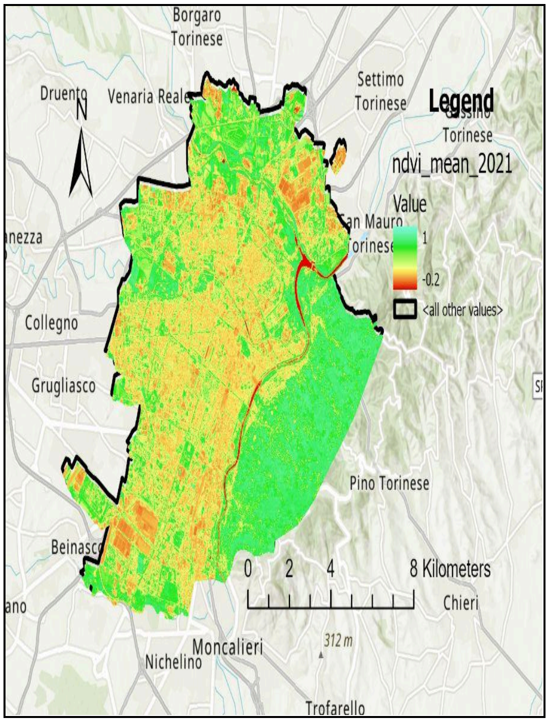


Figure 7.1 Annual mean NDVI distribution in Turin for 2021

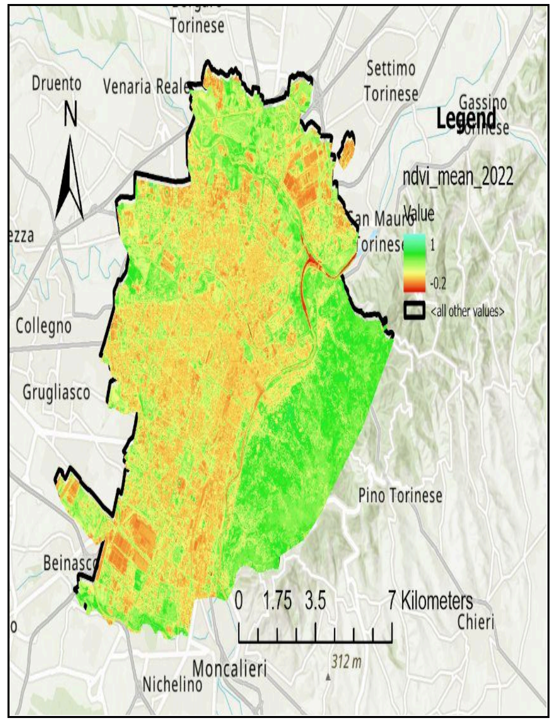


Figure 7.2. Annual mean NDVI distribution in Turin for 2022

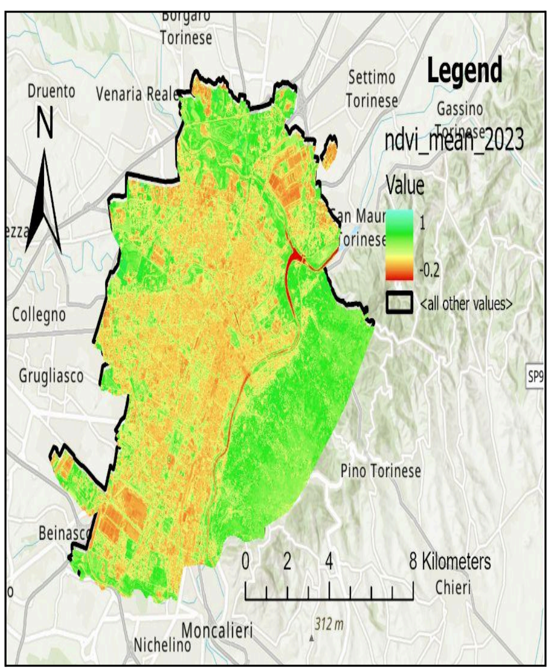


Figure 7.3. Annual mean NDVI distribution in Turin for 2023

Note: All NDVI maps use a standardized color ramp ranging from –1 (non-vegetated) to +1 (dense vegetation) to ensure visual and analytical consistency across years and seasons.

4.2.2 Seasonal NDVI Results

Seasonal NDVI analysis provides further insight into temporal vegetation dynamics within the city. **Figures 8.1–8.3**, illustrate the NDVI distribution across **winter, spring, summer, and autumn** for each study year.

- **Winter NDVI (2022–2023)**

Winter maps (Figures 8.1 and 8.2) show consistently **low NDVI values** (typically between **0.1 and 0.3**) across most of the urban area, reflecting limited photosynthetic activity during dormancy. Higher NDVI zones persisted along the **Po River**, the **eastern hills**, and in evergreen-rich parks such as **Parco del Valentino** and **Parco della Pellerina**. Between the two years, **winter 2023** exhibited a slight reduction in greenness compared to **winter 2022**, likely due to reduced precipitation and cooler temperatures.

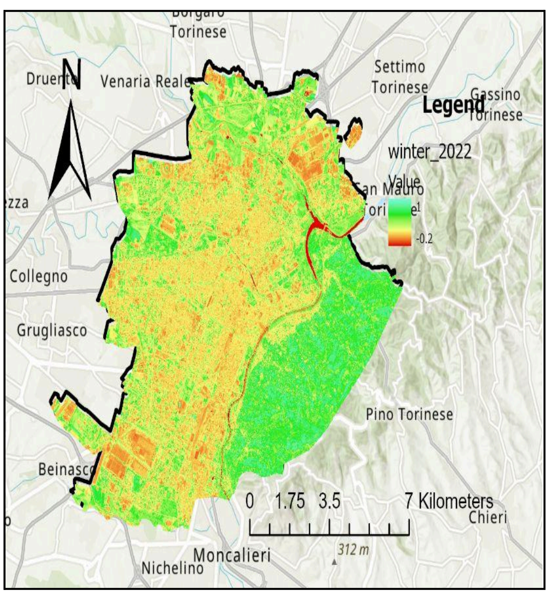


Figure 8.1. NDVI distribution in Turin during winter 2022 (NDVI range: –0.2 to 1.0)

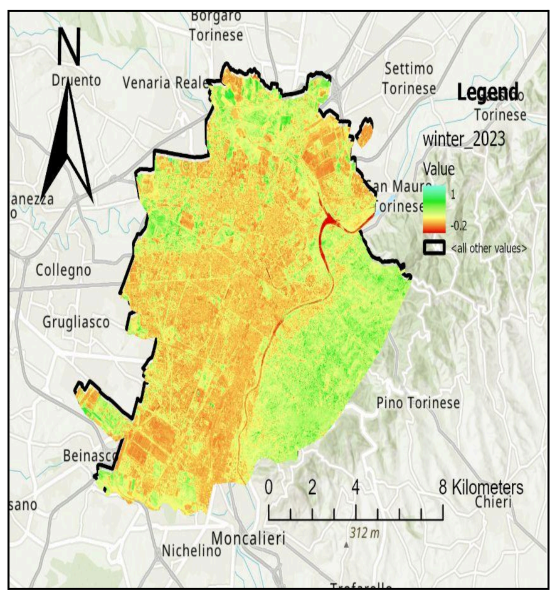


Figure 8.2. NDVI distribution in Turin during winter 2023 (NDVI range: –0.2 to 1.0)

Note: All NDVI maps use a standardized color ramp ranging from –1 (non-vegetated) to +1 (dense vegetation) to ensure visual and analytical consistency across years and seasons.

- **Spring NDVI (2021–2023)**

Spring maps (Figures 9.1–9.3) depict the **onset of the growing season**, with NDVI values ranging between **0.3 and 0.8**. The eastern hills, southern districts, and river corridors displayed vigorous greening, while the urban core maintained lower NDVI values. Spring 2021 and 2023 exhibited stronger vegetation responses than 2022, suggesting better climatic conditions for growth in those years.

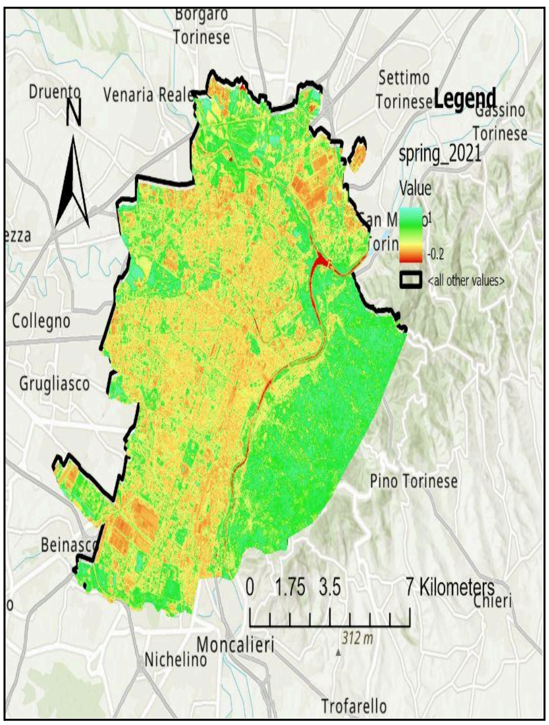


Figure 9.1. NDVI distribution in Turin during spring 2021 (NDVI range: –0.2 to 1.0)

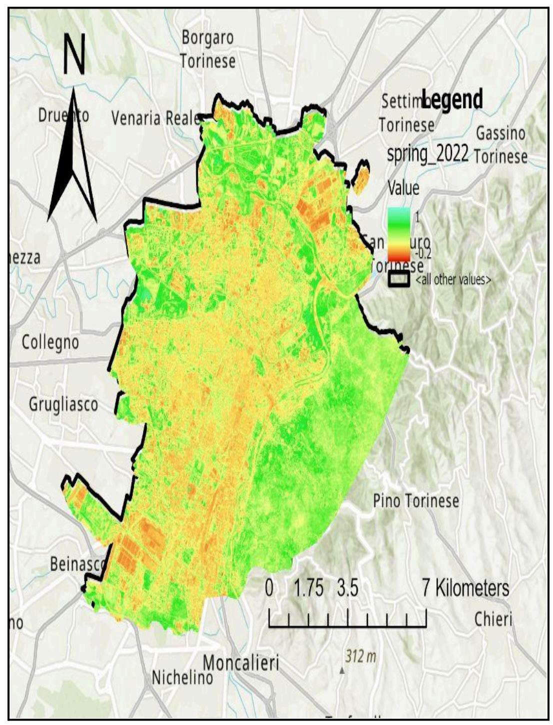


Figure 9.2. NDVI distribution in Turin during spring 2022 (NDVI range: –0.2 to 1.0)

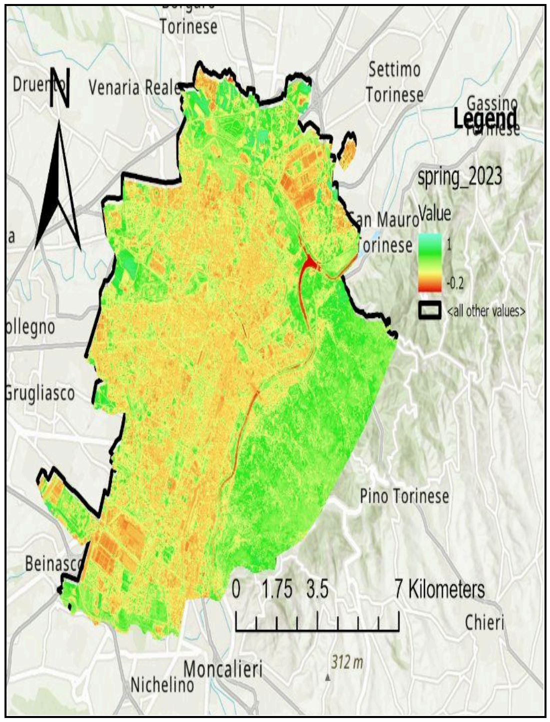


Figure 9.3 NDVI distribution in Turin during spring 2023 (NDVI range: –0.2 to 1.0)

Note: All NDVI maps use a standardized color ramp ranging from –1 (non-vegetated) to +1 (dense vegetation) to ensure visual and analytical consistency across years and seasons.

- **Summer NDVI (2021–2023)**

Summer maps (Figures 10.1–10.3) show the **highest NDVI values** of the year, generally above **0.6** in vegetated areas. The **southern and eastern sectors** of Turin—especially **Parco del Valentino, Parco Colonnetti,** and **Parco della Pellerina**—remained the greenest regions. However, summer 2022 recorded noticeably lower NDVI compared to 2021, with a visible increase in yellow-orange tones linked to **heat and drought stress**. Summer 2023 showed partial recovery, though still below 2021 levels.

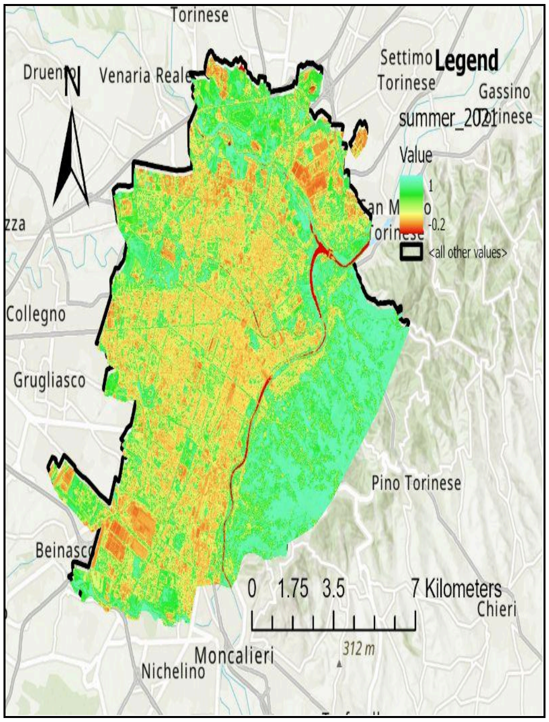


Figure 10.1. NDVI distribution in Turin during summer 2021 (NDVI range: –0.2 to 1.0)

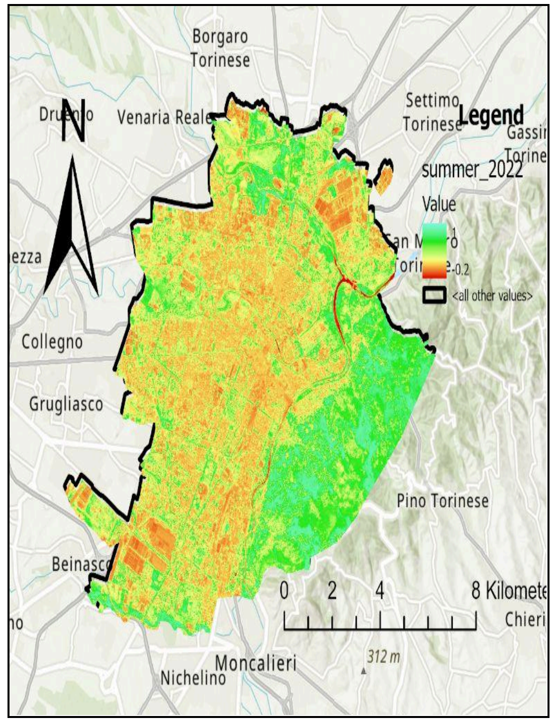


Figure 10.2. NDVI distribution in Turin during summer 2022 (NDVI range: –0.2 to 1.0)

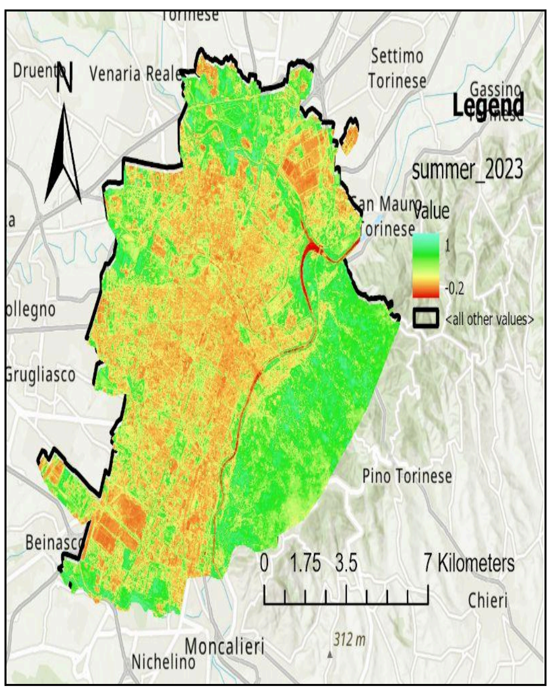


Figure 10.3. NDVI distribution in Turin during summer 2023 (NDVI range: –0.2 to 1.0)

Note: All NDVI maps use a standardized color ramp ranging from –1 (non-vegetated) to +1 (dense vegetation) to ensure visual and analytical consistency across years and seasons.

- **Autumn NDVI (2021–2023)**

Autumn maps (Figures 11.1–11.3) display a gradual reduction in greenness as vegetation transitions into dormancy. NDVI values typically ranged between **0.3 and 0.6**, with higher values persisting along the **Po River corridor** and the **eastern hills**. The year **2022** again showed slightly lower NDVI than **2021** and **2023**, reflecting delayed vegetation recovery after a dry summer.

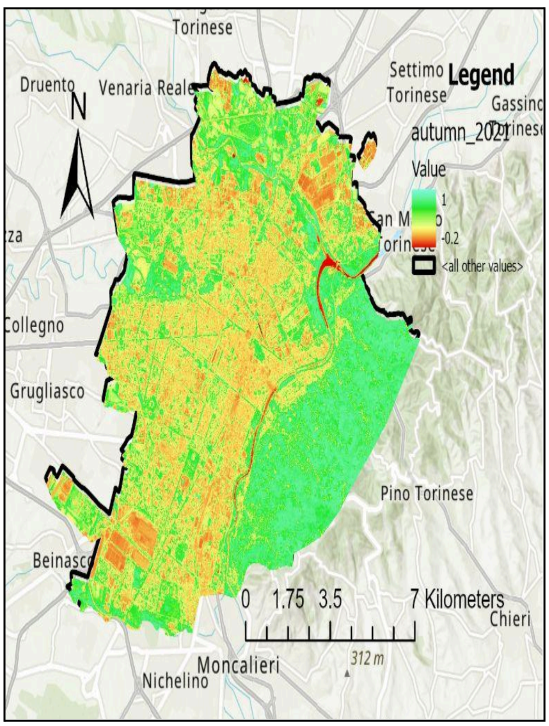


Figure 11.1. NDVI distribution in Turin during autumn 2021 (NDVI range: –0.2 to 1.0)

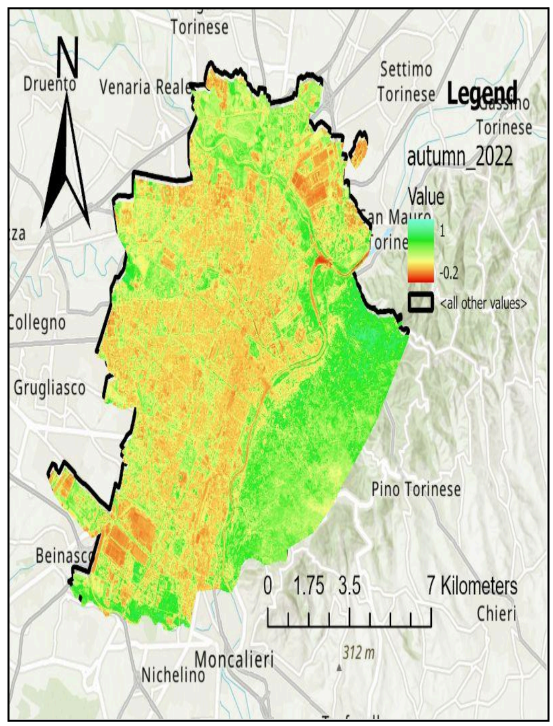


Figure 11.2. NDVI distribution in Turin during autumn 2022 (NDVI range: –0.2 to 1.0)

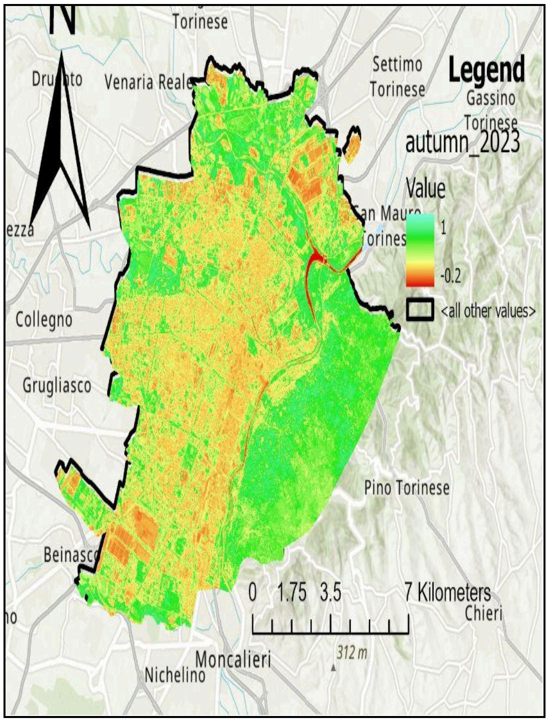


Figure 11.3. NDVI distribution in Turin during autumn 2023 (NDVI range: –0.2 to 1.0)

Note: All NDVI maps use a standardized color ramp ranging from –1 (non-vegetated) to +1 (dense vegetation) to ensure visual and analytical consistency across years and seasons.

- **Summary of NDVI Results (2021–2023)**

The combined annual and seasonal NDVI analysis reveals a clear spatial and temporal pattern of vegetation activity in Turin.

- ➢ **Spatially**, high NDVI zones are concentrated along the **Po River**, **eastern hillside**, and **major parks**, representing the city's ecological core.
- ➢ **Temporally**, NDVI follows a **distinct seasonal cycle**—lowest in winter, peaking in summer, and declining in autumn.
- ➢ **Interannually**, a **slight downward trend** was observed, with **2022** registering the lowest NDVI values, consistent with regional drought impacts.

These results provide the foundation for subsequent biomass and carbon sequestration estimations, demonstrating both the **resilience and vulnerability** of Turin's urban vegetation to climatic variability.

ANNUAL TABLE:

Year	Minimum	Maximum	Mean	Std.Deviation
2021	-0.540	0.899	0.368	0.250
2022	-0.216	0.795	0.279	0.178
2023	-0.305	0.808	0.294	0.192

Table 2. Annual NDVI values for the city of Turin between 2021 and 2023

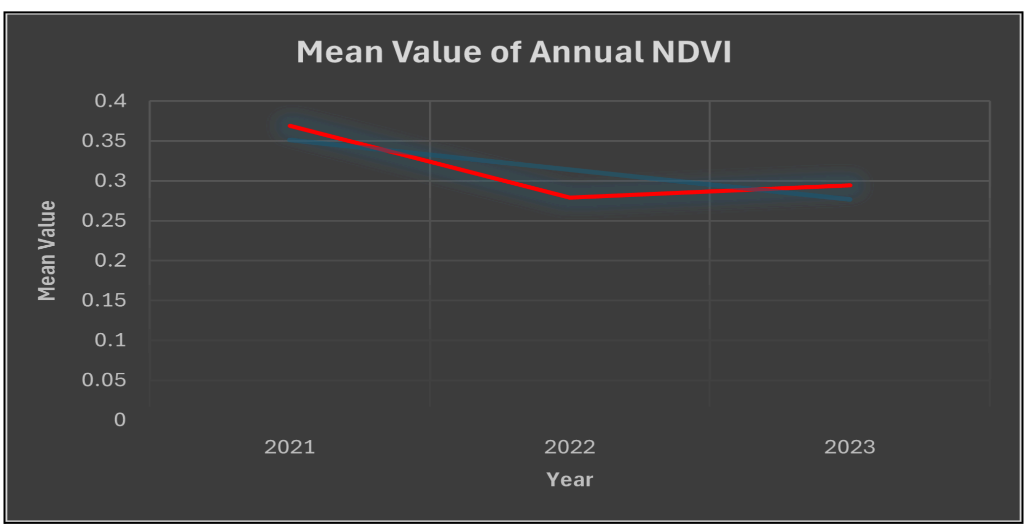


Chart 1.Annual mean NDVI trends in Turin between 2021 and 2023

Seasonal Table:

Year	Minimum	Maximum	Mean	Std.Deviation
Autumn 2023	-0.312	0.853	0.340	0.223
Summer 2023	-0.331	0.848	0.312	0.235
Spring 2023	-0.339	0.815	0.285	0.180
Winter 2023	-0.348	0.901	0.191	0.134
Autumn 2022	-0.177	0.823	0.281	0.183
Summer 2022	-0.402	0.896	0.307	0.238
Spring 2022	-0.080	0.864	0.287	0.165
Winter 2022	-0.776	0.951	0.315	0.225
Autumn 2021	-0.447	0.913	0.381	0.267
Summer 2021	-0.644	0.936	0.420	0.306
Spring 2021	-0.542	0.926	0.356	0.241

Table 2. Seasonal NDVI values for the city of Turin between 2021 and 2023

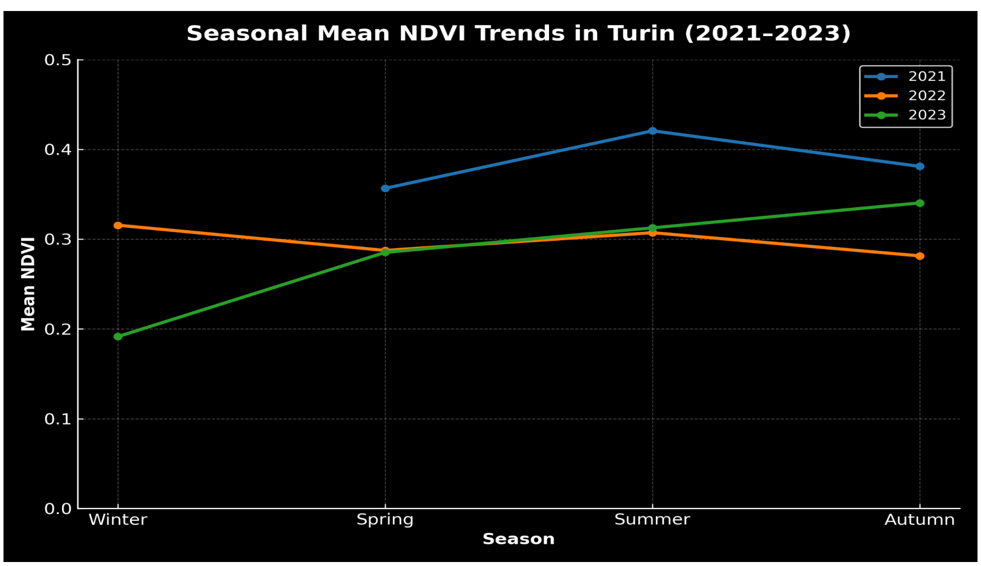


Chart 2. Seasonal mean NDVI trends in Turin between 2021 and 2023

The annual and seasonal NDVI statistics collectively illustrate the temporal variability of vegetation performance in Turin between 2021 and 2023. Annual mean NDVI values ranged from **0.279 in 2022** to **0.368 in 2021**, indicating a marked reduction in vegetation vigor during the drought year and a partial recovery in 2023 (**0.294**). The corresponding **standard deviations** (0.178–0.250) reflect moderate spatial variability, suggesting that while vegetation conditions fluctuated, the overall structure of green areas remained stable.

Seasonal NDVI averages followed a consistent **phenological progression** across all years, with minimum values in **winter**, rapid increases in **spring**, peaks during **summer**, and declines through **autumn**. The year 2022 exhibited noticeably lower NDVI values in spring and summer, consistent with rainfall deficits reported by ARPA Piemonte (2022). In contrast, 2023 showed improved NDVI during the same seasons, confirming the vegetation's resilience and recovery under more favorable climatic conditions.

Overall, the statistical results confirm that **climatic variability,particularly precipitation availability, was the dominant factor influencing NDVI fluctuations**, while the city's main green corridors and parks maintained relatively stable vegetation density throughout the study period.

4.3.1 Annual Vegetation Cover Classification (2021–2023)

Vegetation cover classification was derived from NDVI thresholding, separating the city's surface into three categories: **dense vegetation (NDVI ≥ 0.5)**, **sparse vegetation (0.3 ≤ NDVI < 0.5)**, and **non-vegetated areas (NDVI < 0.3)**. This classification enabled quantification of urban greenery distribution and detection of temporal changes between 2021 and 2023. The annual results (Chart **3**) indicate that Turin's total vegetated area remained substantial but showed a **gradual overall decline** during the study period.

- In **2021**, vegetation covered approximately **62.7%** of the city's total area, including **35.9% dense** and **26.8% sparse** vegetation. Non-vegetated surfaces accounted for **37.3%**, primarily corresponding to central and industrial districts.
- In **2022**, dense vegetation **declined sharply to 15.7%**, while sparse vegetation expanded to **45.4%**, suggesting canopy thinning and drought-related stress. Although total

vegetation cover remained comparable (**61.1%**), the internal distribution shifted toward less compact vegetation.

- In **2023**, vegetation partially recovered, with dense vegetation increasing to **21.0%** and sparse vegetation decreasing to **36.6%**, yielding a total vegetation cover of **57.6%**.

The overall decline of **5.1%** in total vegetation between 2021 and 2023 is attributed mainly to the **loss of dense vegetation patches**, aligning with the NDVI-based evidence of reduced canopy vigor. This pattern indicates that while urban green areas persisted, vegetation density and health were affected by interannual environmental stress, particularly the **warm and dry conditions of 2022**.

These results underline the importance of distinguishing between dense and sparse vegetation, as total vegetation coverage alone can obscure structural and ecological changes within the urban green network.

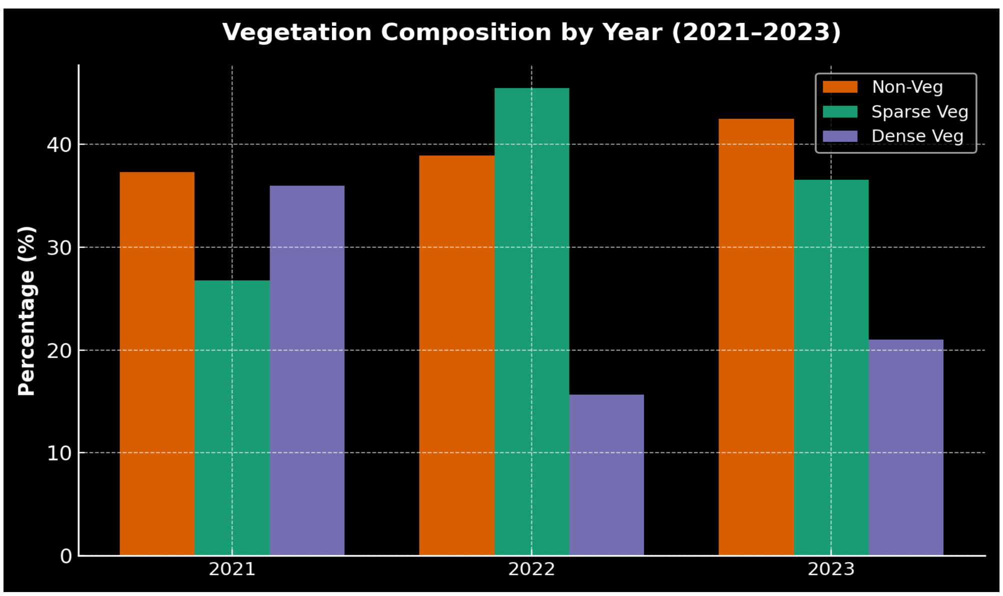


Chart 3. Vegetation Composition by Year (2021–2023)

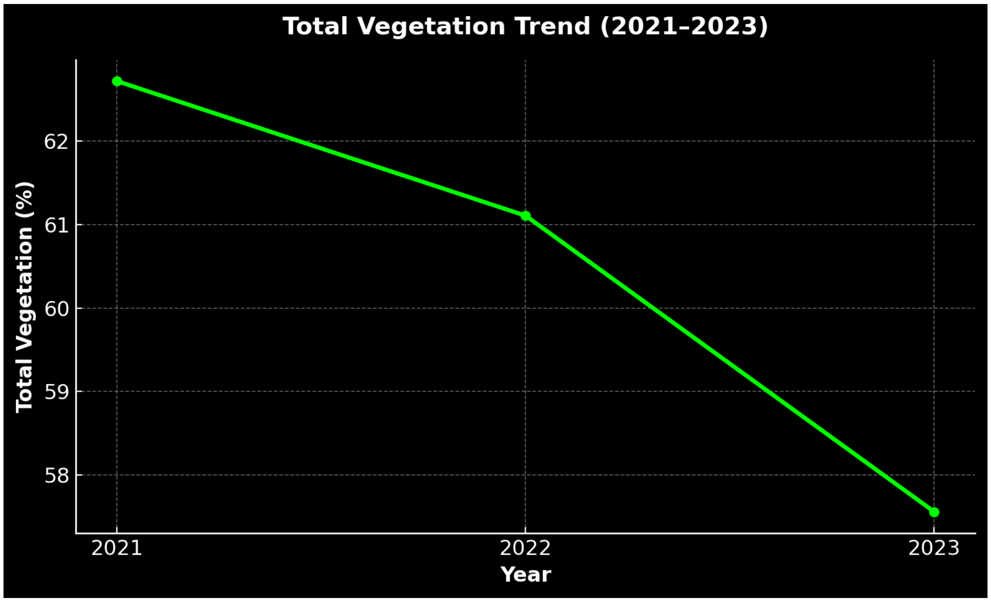


Chart 4. Total Vegetation Trend (2021–2023)

4.3.2 Seasonal Vegetation Cover Classification (2021–2023)

Seasonal vegetation classification (Chart **5**) highlights the cyclical nature of vegetation dynamics and their variability across the three study years. Across all seasons, vegetation followed a **consistent annual cycle**, with **maximum coverage during summer and autumn** and **minimum levels in winter**. This pattern corresponds to phenological stages typical of deciduous vegetation in temperate climates.

- **2021** recorded stable vegetation conditions throughout the year, with total vegetation exceeding **61%** in each season. The summer peak reached **63.5%**, driven by vigorous canopy growth, while **dense vegetation** attained **42%**, confirming robust vegetation health.
- **2022** exhibited the greatest decline in dense vegetation, which dropped to **12.2% in spring** and **14.8% in autumn**, reflecting the **impact of drought and elevated temperatures** on canopy health. Sparse vegetation dominated most of the year,indicating partial leaf loss and reduced chlorophyll activity.
- **2023** showed partial recovery, particularly in spring (**56.6% total vegetation**) and autumn (**61.7%**), although winter values remained low (**42.5%**) due to natural dormancy.

Overall, the seasonal classification confirms the **resilience yet sensitivity** of Turin's vegetation to climate variability. The results demonstrate that while vegetated areas largely persist, their internal density and health fluctuate seasonally and interannually, influenced by climatic stress and phenological cycles.

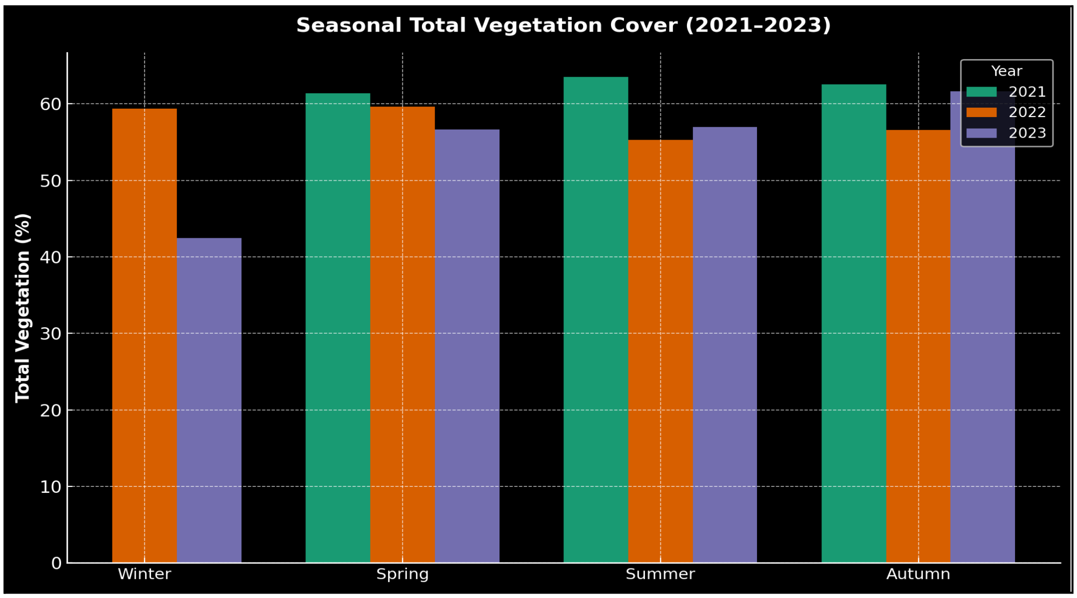


Chart 5. Seasonal Total Vegetation Cover (2021–2023)

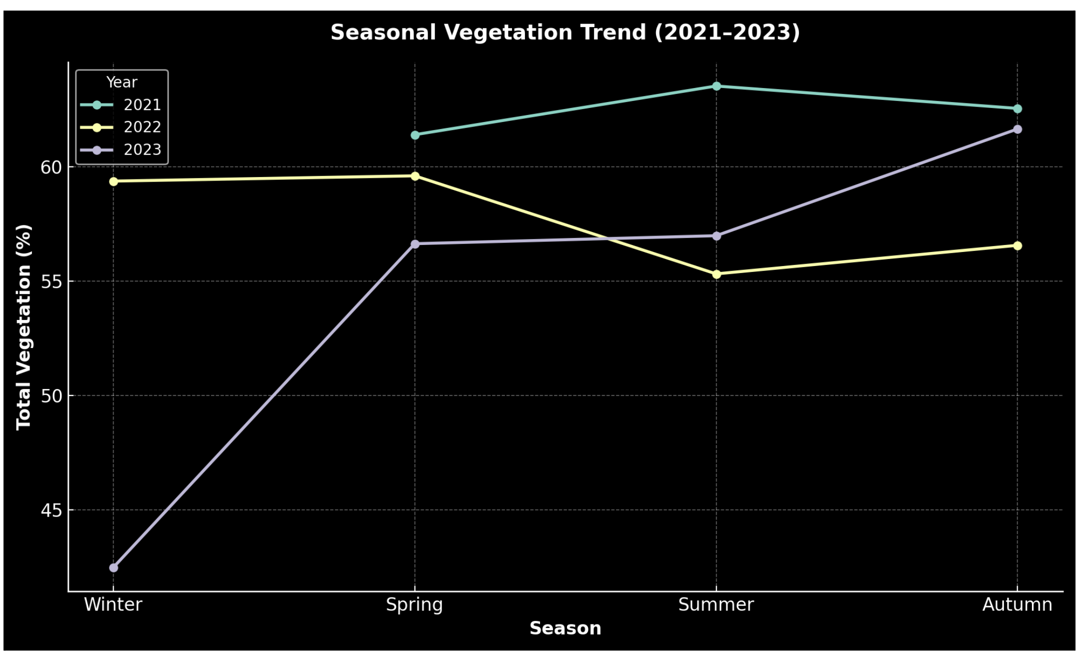


Chart 6. Seasonal Vegetation Trend (2021–2023)

4.3.3 Interpretation and Cross-Validation with NDVI

The classification results complement the NDVI analysis, reinforcing observed spatial and temporal trends. Areas with persistently high NDVI values correspond to the **dense vegetation zones**, particularly along the **Po River**, **eastern hills**, and **major parks**. Conversely, central and industrial zones consistently show low NDVI and high non-vegetated proportions.

This correspondence between NDVI and classified vegetation categories validates the reliability of threshold-based classification. It also demonstrates that **NDVI thresholding at 0.3 and 0.5**, supported by references such as Aryal et al. (2022) and Rasoolzadeh et al. (2024), provides an effective and transferable method for distinguishing vegetation density in urban settings.

Overall, the classification analysis establishes a solid quantitative foundation for subsequent assessments of biomass, CO_2 sequestration, and economic valuation, linking vegetation structure directly to ecological function.

4.4 Above-Ground Biomass (AGB)

4.4.1 Overview and Methodological Context

Above-Ground Biomass (AGB) was estimated from NDVI values using the **empirical model proposed by Hosni et al. (2022)**. This model was developed and validated in **Mediterranean-type ecosystems**, which share comparable vegetation structure and climatic conditions with Turin's urban environment. While it provides a robust estimation framework, it is important to note that applying regionally calibrated models to urban settings may introduce **uncertainty due to species heterogeneity and canopy structure differences**. Therefore, results should be interpreted as indicative estimates rather than precise field-measured values.

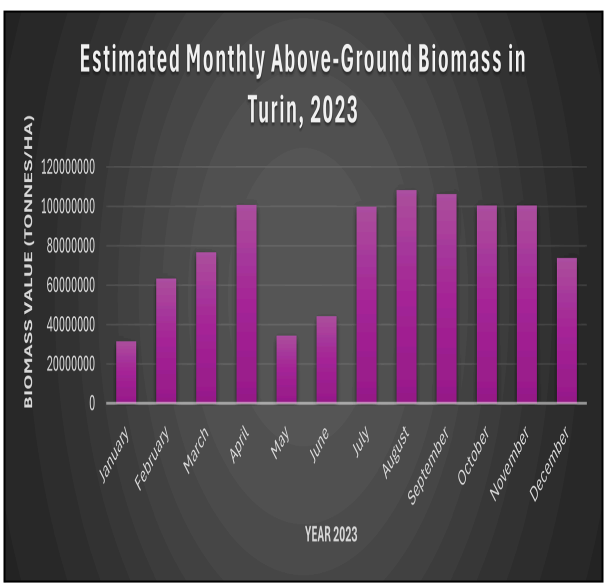
The biomass values were computed for each month between 2021 and 2023 and expressed in **tonnes per hectare (t/ha)**. These were subsequently aggregated by season and by year to assess temporal patterns and to quantify changes in vegetation productivity.

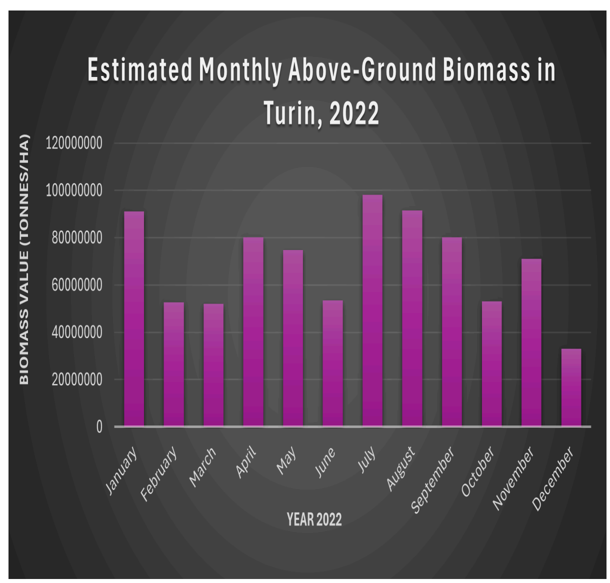
4.4.2 Temporal Variation (2021–2023)

Monthly AGB data show a distinct **seasonal cycle** consistent with temperate vegetation phenology. Biomass accumulation increased progressively from **late winter to summer**, peaking between **June and August**, before declining toward the end of the year as vegetation entered dormancy.

- In **2021**, AGB rose steadily from approximately **30 million t/ha in January** to a **maximum exceeding 120 million t/ha in August**, indicating vigorous summer growth.
- In **2022**, biomass values were lower and more variable, with notable early-season peaks in **April and July** but a general decline in late summer and autumn. The total annual biomass reached **8.31 × 10^8 t/ha**, representing a moderate decrease compared to 2021.
- In **2023**, the total annual biomass rebounded to **9.40 × 10^8 t/ha**, a **13% increase relative to 2022**, reflecting partial recovery of vegetation productivity.

It should be noted that **Winter 2021 data were excluded** due to unavailable cloud-free imagery. However, subsequent seasonal coverage provided sufficient continuity to establish annual patterns.





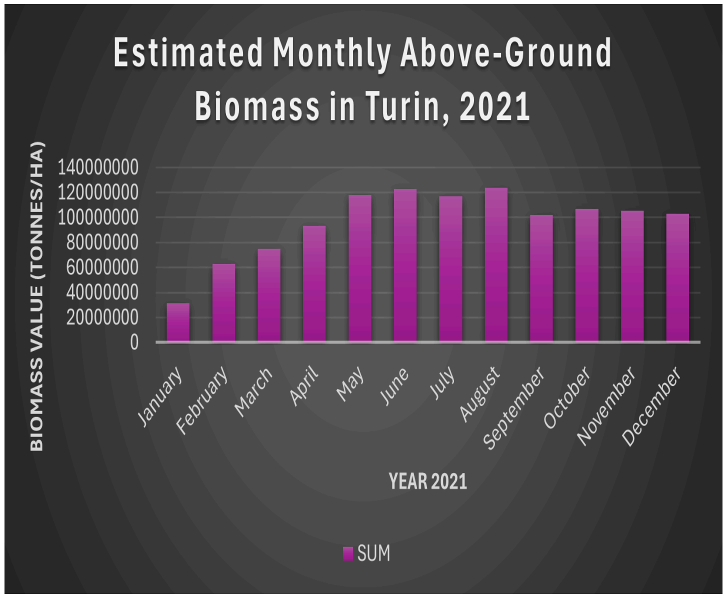


Chart 7. Total Biomass Bar Chart in Turin (2021-2023)

4.4.3 Seasonal and Spatial Patterns

Seasonal results emphasize the strong link between vegetation growth cycles and biomass productivity:

Spatially, AGB maps highlight consistent hotspots in:

- The **eastern and southern hills** (wooded and semi-natural areas)
- The **Po River greenbelt**
- Large urban parks (**Parco del Valentino**, **Parco della Pellerina**, and **Parco Colonnetti**).

Winter: Lowest biomass values, corresponding to minimal photosynthetic activity.

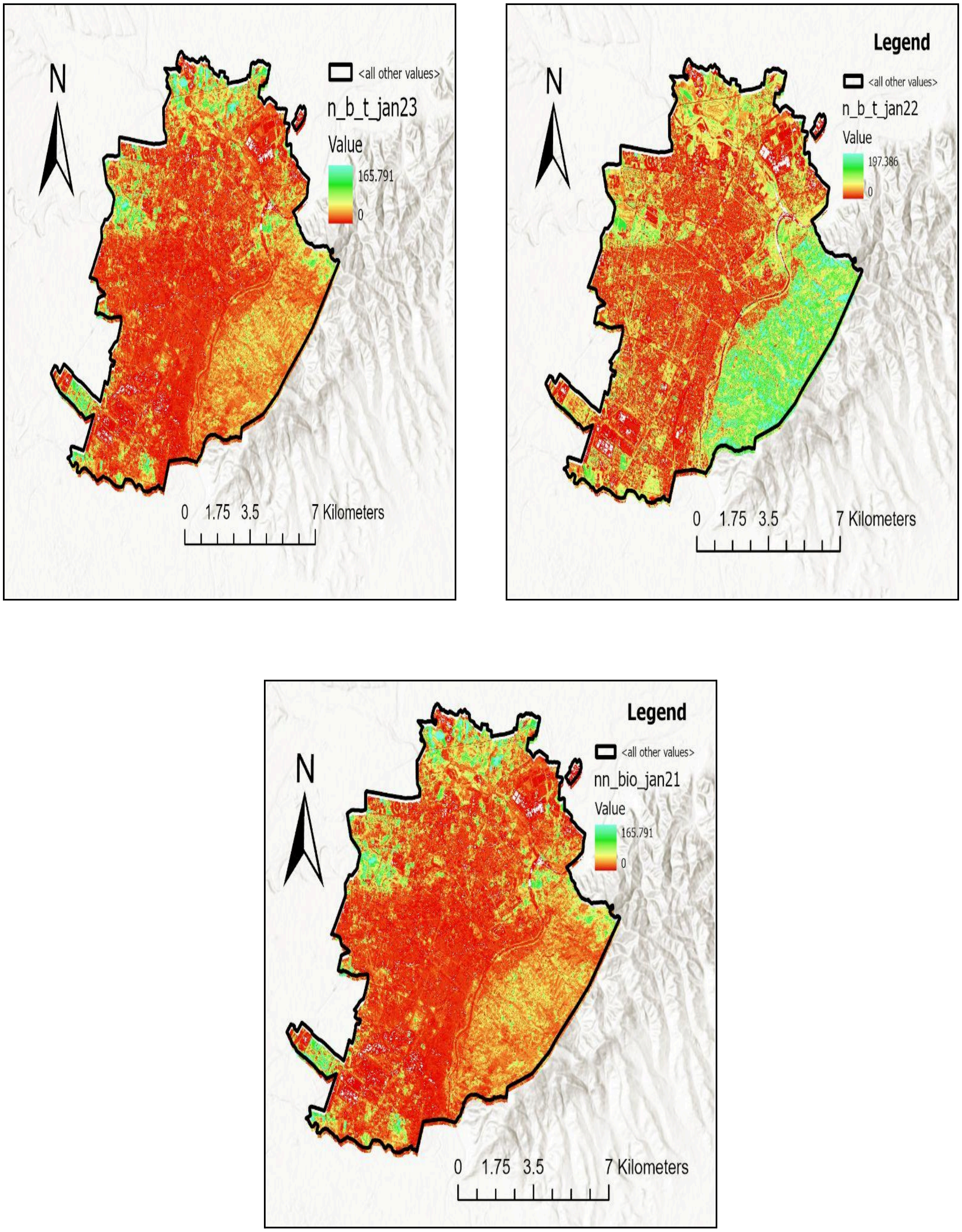
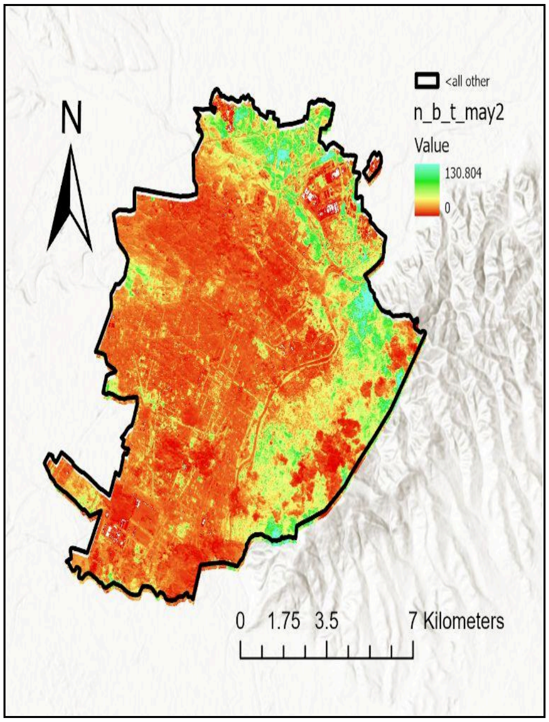


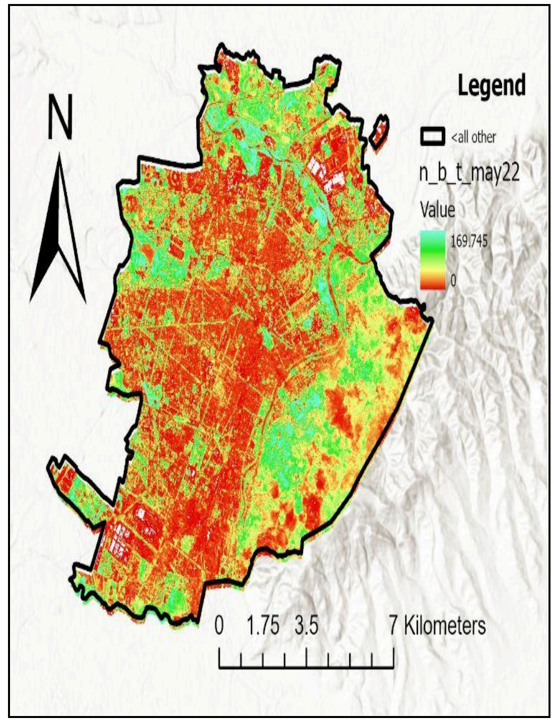
Figure 12. Above-Ground Biomass (AGB) distribution in Turin – January (2021–2023)

Note: Biomass and CO_2 maps are displayed using consistent quantitative color scales. Above-Ground Biomass (AGB) values are expressed in tonnes per hectare (t ha^{-1}), and CO_2

sequestration values are expressed in tonnes of CO_2 per hectare (t CO_2 ha^{-1}). Color ramps are standardized across years for comparability.

Spring: Rapid biomass accumulation driven by canopy development and leaf expansion.





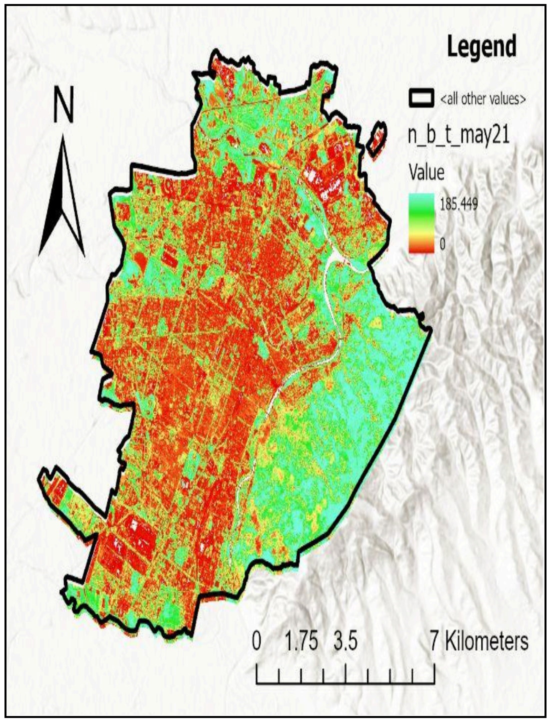


Figure 13. Above-Ground Biomass (AGB) distribution in Turin – May (2021–2023)

Note: Biomass and CO_2 maps are displayed using consistent quantitative color scales. Above-Ground Biomass (AGB) values are expressed in tonnes per hectare (t ha^{-1}), and CO_2 sequestration values are expressed in tonnes of CO_2 per hectare (t CO_2 ha^{-1}). Color ramps are standardized across years for comparability.

Summer: Peak productivity across the city, with highest biomass densities in riparian corridors and urban parks.

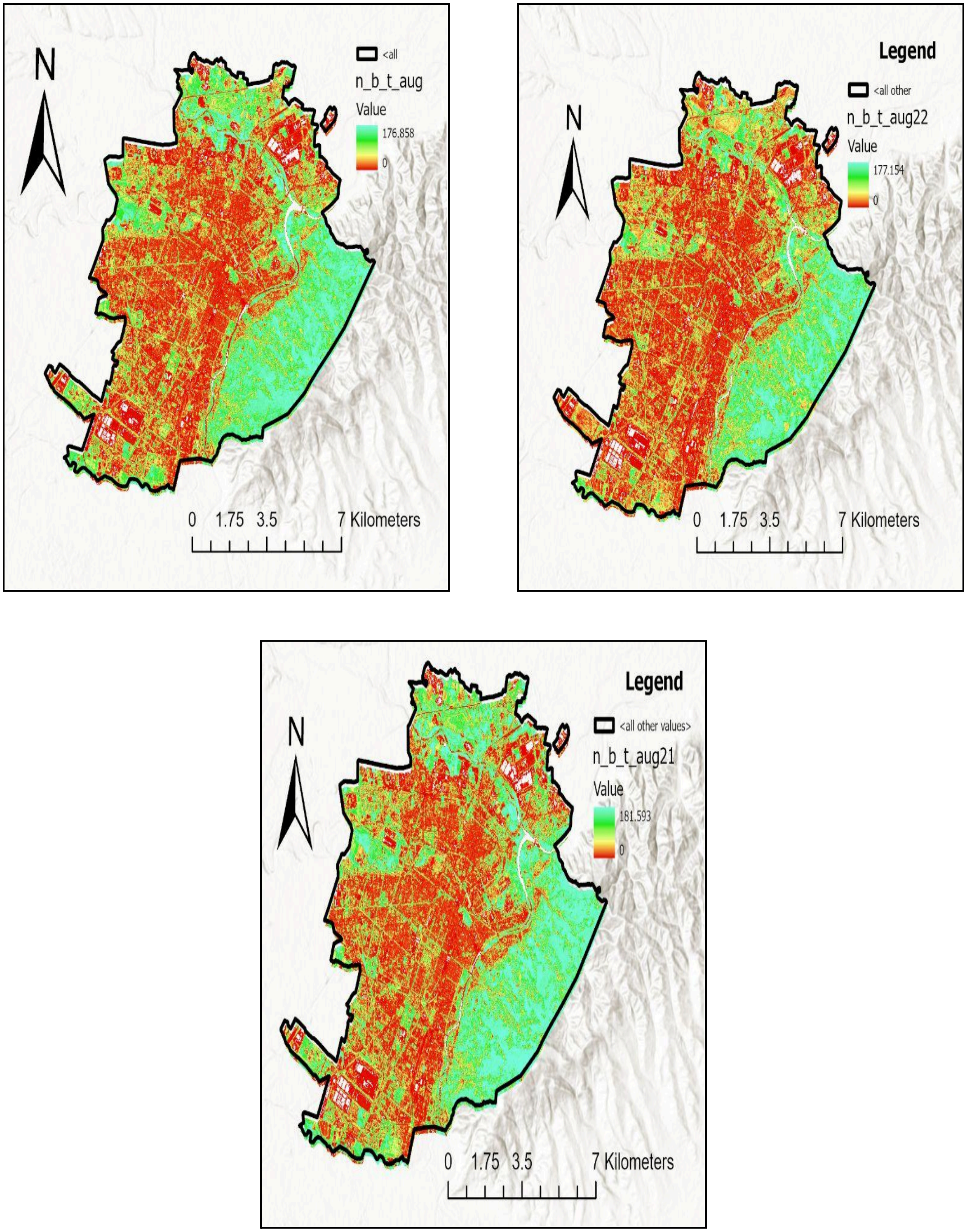
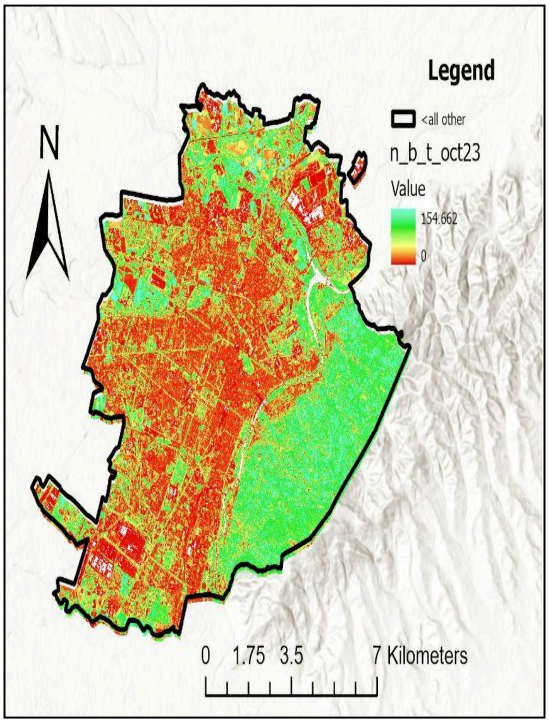
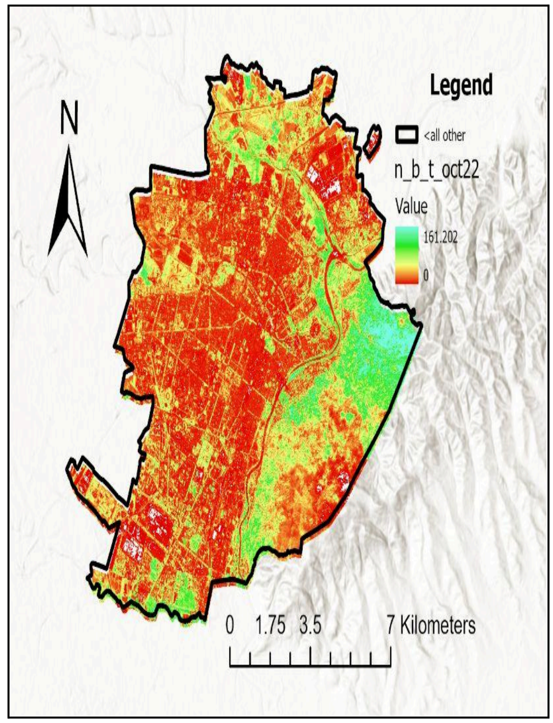


Figure 14. Above-Ground Biomass (AGB) distribution in Turin – August (2021–2023)

Note: Biomass and CO_2 maps are displayed using consistent quantitative color scales. Above-Ground Biomass (AGB) values are expressed in tonnes per hectare (t ha^{-1}), and CO_2 sequestration values are expressed in tonnes of CO_2 per hectare (t CO_2 ha^{-1}). Color ramps are standardized across years for comparability.

Autumn: Gradual decline in AGB as vegetation senesces.





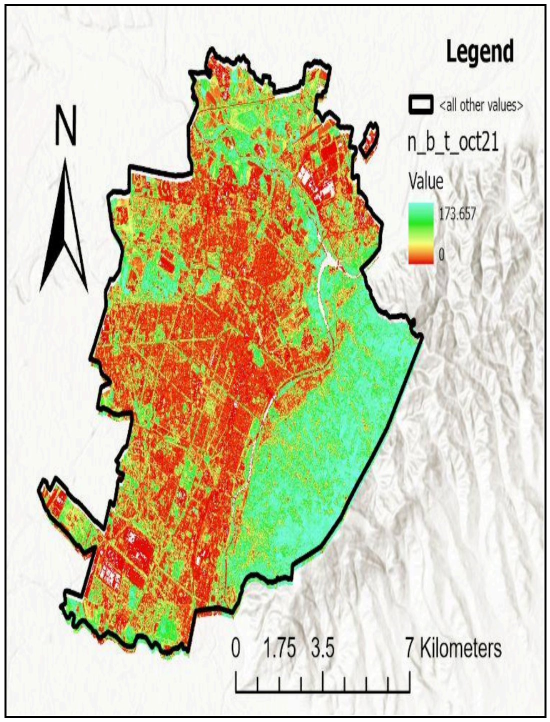


Figure15. Above-Ground Biomass (AGB) distribution in Turin – October (2021–2023).

Note: Biomass and CO_2 maps are displayed using consistent quantitative color scales. Above-Ground Biomass (AGB) values are expressed in tonnes per hectare (t ha^{-1}), and CO_2 sequestration values are expressed in tonnes of CO_2 per hectare (t CO_2 ha^{-1}). Color ramps are standardized across years for comparability.

Conversely, lower biomass values were found in **central and industrial districts**, confirming the strong contrast between urbanized and vegetated zones.

4.4.4 Interannual Comparison and Uncertainty Considerations

Across the three years, AGB totals fluctuated between **1.16×10^9 t/ha (2021)**, **8.31×10^8 t/ha (2022)**, and **9.40×10^8 t/ha (2023)**. These variations likely reflect **short-term climatic influences**, particularly drought stress in 2022, rather than permanent land-cover changes.

An estimated **uncertainty of ±10–15%** is associated with the NDVI→biomass conversion due to:

- Differences in canopy density and tree species composition

- Sensor-based NDVI variability
- Model transferability across ecosystems

Nevertheless, the internal consistency of the results with NDVI and vegetation classification confirms the validity of the approach for assessing **relative changes** in biomass productivity over time.

4.4.5 Summary

Overall, the AGB analysis demonstrates that Turin's green infrastructure maintained **stable productivity** despite moderate interannual fluctuations. Biomass peaks correspond to **summer months**, while minima align with **winter dormancy**, consistent with NDVI trends.

Persistent high-biomass areas, particularly along the **Po River corridor** and the **eastern hills**, underscore the ecological significance of these zones as **urban carbon reservoirs**. The results provide a quantitative foundation for estimating **CO_2 sequestration** in the following section, directly linking vegetation productivity to climate mitigation potential.

4.5 CO_2 Sequestration Results

4.5.1 Overview

The total and temporal variations of estimated **CO_2 sequestration** across the city of Turin from **2021 to 2023** were derived from Above-Ground Biomass (AGB) estimates using the **conversion factor of 1.8 t CO_2 per tonne of biomass**, following **Hosni et al. (2022)**. This factor reflects the stoichiometric ratio between stored carbon and emitted CO_2, assuming that approximately 50% of dry biomass mass is carbon ($0.5 \times 44/12 \approx 1.83$). While this coefficient is widely adopted for large-scale carbon accounting, an **uncertainty margin of ±0.2** (i.e., 1.6–2.0 t CO_2 per tonne biomass) should be acknowledged due to variability in vegetation type, age, and carbon fraction. In addition to total sequestration volumes, the mean CO_2 density per vegetated hectare was also calculated. The estimated values ranged between **67.5 and 94.0 t CO_2 ha^{-1}**, corresponding respectively to the lower biomass year (2022) and the higher vegetation productivity year (2021). These densities are consistent with reported averages for urban and peri-urban vegetation in temperate European cities (Nowak et al., 2013).

4.5.2 Annual CO_2 Sequestration

Annual CO_2 sequestration values exhibit moderate interannual variation consistent with observed NDVI and biomass trends.

- **2021:** Total CO_2 uptake was approximately **2.09×10^9 tonnes,** corresponding to the year with the highest vegetation density and biomass accumulation.
- **2022:** Total sequestration decreased to **1.50×10^9** tonnes, mirroring the decline in AGB and NDVI caused by **regional drought and heat stress.**
- **2023:** Vegetation recovery resulted in an increase to **1.69×10^9** tonnes, indicating improved growth conditions.

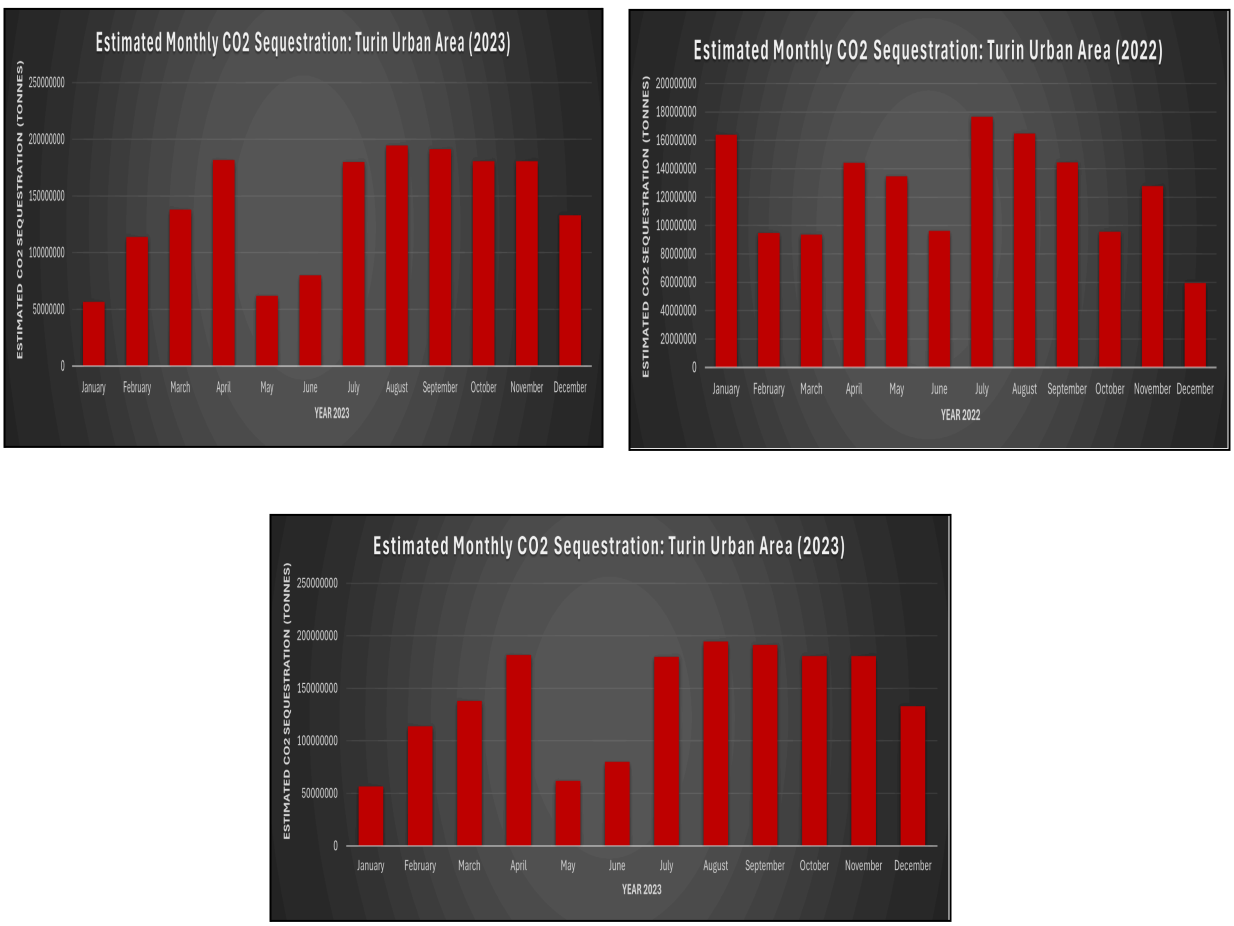


Chart8. Estimated monthly CO_2 sequestration for Turin urban area in 2021

Overall, these values show an interannual variability of around **±20%,** suggesting a relatively stable long-term carbon capture capacity despite short-term climatic fluctuations.

When normalized by vegetated surface area, the mean sequestration intensity for Turin's green zones was approximately **7.2 t CO_2 ha^{-1} yr^{-1}** between 2021 and 2023. This per-area value aligns well with the range reported for temperate urban ecosystems in Europe (6–9 t CO_2 ha^{-1} yr^{-1}; Nowak et al., 2013), confirming the plausibility of the NDVI-based estimates.

It is important to note that the **total CO_2 sequestration values presented in this study are indicative and reflect relative magnitudes rather than absolute quantities**. Minor scaling discrepancies may occur due to the empirical nature of the biomass model and the conversion factor applied. Therefore, interpreting the results in terms of **per-area intensity** provides a more reliable basis for comparison with other studies and cities.

4.5.3 Monthly and Seasonal Dynamics

The monthly CO_2 sequestration trends followed the **phenological cycle** of NDVI and biomass:

- **Winter (Jan–Feb):** Lowest sequestration rates, corresponding to vegetation dormancy.
- **Spring (Apr–May):** Rapid increase as canopy development and photosynthetic activity intensified.
- **Summer (Jul–Aug):** Peak sequestration, exceeding **2.2×10^8 tonnes CO_2** per month in 2021.
- **Autumn (Oct–Nov):** Gradual decline as vegetation senesced and photosynthesis slowed.

This consistent pattern across years confirms the strong linkage between vegetation productivity and seasonal climatic conditions (temperature, radiation, and precipitation).

4.5.4 Interpretation

The **decline in 2022** directly corresponds with **record drought conditions** in northern Italy, which reduced vegetation greenness and canopy cover across urban and peri-urban areas. The **partial recovery** in 2023 indicates ecosystem resilience and the ability of Turin's green infrastructure to rebound under improved rainfall and temperature conditions.

While the magnitude of CO_2 sequestration may vary annually, the persistence of substantial carbon uptake throughout the study period underscores the **critical role of urban vegetation as a continuous carbon sink.**

4.5.5 Summary

Turin's vegetated surfaces sequestered between 1.5×10^9 and 2.1×10^9 tonnes of CO_2 per year from 2021 to 2023, demonstrating a stable and resilient carbon sink performance. Despite moderate year-to-year fluctuations, the city's green areas consistently contributed to atmospheric carbon reduction, reaffirming their ecological importance for climate regulation and urban sustainability.

4.6 Economic Valuation of CO_2 Sequestration

The economic valuation of CO_2 sequestration quantifies the financial importance of urban vegetation as a climate-mitigation asset. Based on the total CO_2 sequestration estimated for the years 2021–2023, the corresponding monetary value was calculated using the relationship:

$$\text{Economic Value (€)} = \text{Total CO2 Sequestered (tonnes)} \times 80$$

A constant rate of **€80 per tonne of CO_2** was applied, corresponding to the **average carbon price under the European Union Emissions Trading System (EU ETS)** during 2022 (Ember Climate, 2022). This approach enables a standardized comparison of the carbon sequestration benefits provided by vegetation in economic terms.

The results (Table 3; Chart 9) show that the **total annual economic value** of CO_2 sequestration in Turin ranged between **€119 billion and €167 billion** during the study period.

- In **2021**, the total value reached approximately **€167.09 billion**, reflecting the year's highest biomass and CO_2 sequestration levels.
- In **2022**, the value declined to about **€119.73 billion**, consistent with the observed reduction in vegetation productivity and the effects of drought.
- In **2023**, a moderate recovery was recorded, with the total value rising to **€135.44 billion**, following partial improvement in vegetation health.

Although these variations represent short-term fluctuations of approximately **±20%**, the overall results indicate a stable and resilient contribution of urban green areas to carbon sequestration and climate-mitigation value.

Expressing the results in total euro value, rather than per-hectare units, allows for direct comparison with **municipal infrastructure investments** and provides an accessible measure for **policy and planning decisions**. From an environmental engineering and sustainability perspective, these findings demonstrate that the city's vegetation acts as both an ecological and an economic asset. The quantified value supports:

- **Integration of carbon-offset strategies** into urban climate policies,
- **Investment justification** for green infrastructure and reforestation projects, and
- **Inclusion of ecosystem service valuation** in urban planning frameworks.

While this study adopts a fixed price of €80/t CO_2 for consistency, it is important to note that the **EU ETS carbon price fluctuated between approximately €75 and €90** during the 2022–2024 period (European Commission, 2024). Therefore, the total economic estimates may vary by about **±10–15%** depending on real-time market conditions. In summary, the economic valuation highlights the **significant financial value of urban vegetation**, complementing its ecological role. Turin's green infrastructure provides a continuous, high-value service by sequestering carbon and contributing directly to the city's progress toward **climate neutrality and sustainable development**.

Year	**Total CO_2 (t)**	**Economic Value (€)**	**Value (Billion €)**
2021	2,088,565,201	167,085,216,080	€167.09 billion
2022	1,496,660,783	119,732,862,640	€119.73 billion
2023	1,693,014,053	135,441,124,240	€135.44 billion

Table 4. Annual economic valuation of CO_2 sequestration in Turin (2021–2023)

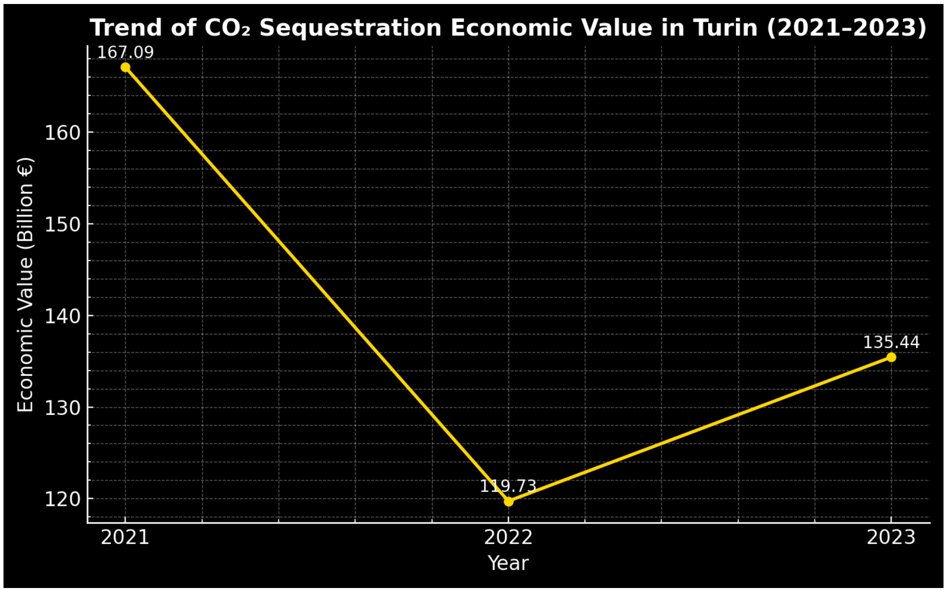


Chart 9. Annual trend of total CO_2 sequestration value in Turin (2021–2023)

4.7 Summary

This chapter presented the analytical results derived from the integration of remote sensing and GIS-based methods to evaluate vegetation dynamics, biomass productivity, and carbon sequestration across the city of Turin between 2021 and 2023. Using Sentinel-2 imagery processed in Google Earth Engine (GEE) and spatial analysis in ArcGIS Pro, the study produced a comprehensive overview of vegetation patterns and their ecological and economic implications.

The NDVI analysis revealed clear spatial and temporal variations in vegetation greenness. High NDVI values were consistently observed along the **Po River corridor**, the **eastern hillside**, and major parks such as **Parco del Valentino**, **Parco della Pellerina**, and **Parco Colonnetti**, confirming these areas as the core green infrastructure of the city. In contrast, central and western districts exhibited low NDVI values due to dense urbanization and limited vegetation cover. Temporally, NDVI followed a well-defined seasonal cycle, lowest during winter and highest in summer with a slight overall decline between 2021 and 2023, particularly evident during the dry conditions of 2022.

Vegetation classification results supported these findings, showing that total vegetation cover decreased from **62.7% in 2021** to **57.6% in 2023**, mainly due to a reduction in dense vegetation. Sparse vegetation fluctuated seasonally, while dense vegetation experienced a noticeable decrease in 2022, followed by partial recovery in 2023. Seasonal analyses demonstrated the natural vegetation cycle, with maximum cover during summer and autumn and minimum during winter, reflecting both phenological behavior and climatic influence.

The estimation of **Above-Ground Biomass (AGB)** displayed a similar pattern. Biomass accumulation peaked during the summer months and declined in winter, with annual totals ranging from **1.16×10^9 t/ha in 2021** to **8.31×10^8 t/ha in 2022**, and recovering to **9.40×10^8 t/ha in 2023**. These results indicate that short-term climatic variability, particularly temperature and precipitation, rather than permanent land-cover changes, controlled vegetation productivity. High biomass densities were concentrated in peri-urban and riparian areas, reinforcing their role as essential carbon reservoirs.

The corresponding **CO_2 sequestration** results followed the same pattern, ranging from **2.09×10^9 tonnes in 2021** to **1.50×10^9 tonnes in 2022**, with a partial rebound to **1.69×10^9 tonnes in 2023**. These findings demonstrate the stable performance and resilience of Turin's urban vegetation as a carbon sink despite interannual climatic fluctuations.

The **economic valuation** of CO_2 sequestration, calculated using the EU ETS reference price of **€80 per tonne of CO_2**, translated these ecological services into financial terms. The total economic value of annual sequestration ranged from **€119 billion to €167 billion**, confirming the substantial contribution of the city's green infrastructure to both environmental regulation and economic sustainability. Even accounting for market variability of ±10–15%, the results highlight a consistent and high-value ecosystem service that can support policy justification for urban greening and carbon-offset programs.

Overall, Chapter 4 demonstrates that while moderate interannual declines occurred, especially during 2022, Turin's vegetation remains **ecologically productive, economically valuable, and resilient** to environmental variability. The integration of NDVI, biomass, and CO_2 analyses provides a comprehensive framework for assessing the multifunctional role of urban green spaces.

Note: The charts and figures in this chapter reflect the original analytical outputs. Although minor layout adjustments suggested by the supervisor could not be implemented due to time constraints, they do not affect the accuracy, interpretation, or validity of the presented results.

Chapter 5: Discussion

Note: The figures and charts presented in this chapter correspond to the finalized analytical results. Minor layout refinements suggested by the supervisor could not be implemented due to time constraints; however, this does not affect the accuracy or interpretation of the findings.

5.1 Overview

This chapter interprets the findings obtained from the remote-sensing and spatial analyses presented in Chapter 4, linking them to the broader objectives of the study and to current scientific knowledge on urban vegetation dynamics and ecosystem-service assessment. The discussion focuses on how the observed spatial and temporal variations in vegetation cover, biomass production, and CO_2 sequestration reflect both ecological processes and anthropogenic influences within the city of Turin.

The workflow applied, based on freely available Sentinel-2 imagery processed in Google Earth Engine and analyzed in ArcGIS Pro, proved effective for generating quantitative indicators of vegetation health and productivity at the urban scale. By integrating spectral indices (NDVI) with empirical biomass models, the study translated satellite observations into meaningful ecological and economic metrics.

The following sections contextualize these outcomes in relation to previous literature, compare the results with similar European case studies, and critically assess the strengths and limitations of the applied approach. The discussion also highlights how the adopted methodology contributes to current frameworks for nature-based solutions, urban sustainability, and carbon-neutral city planning in Europe.

5.2 Vegetation Dynamics

Vegetation dynamics in Turin between 2021 and 2023 were analyzed using the Normalized Difference Vegetation Index (NDVI) derived from Sentinel-2 imagery. NDVI provides a widely recognized proxy for vegetation vigor and canopy density and serves as a key indicator for urban ecological assessment (Didan, 2015; Gorelick et al., 2017).

The results reveal distinct **interannual** and **seasonal** variations that reflect both natural phenological cycles and the influence of climatic extremes recorded during the study period.

- **Annual NDVI Patterns**

Annual NDVI statistics, as shown previously in Table 2. indicate moderate variability across the three-year period, with the mean NDVI decreasing from **0.368 (2021)** to **0.279 (2022)** before recovering to **0.294 (2023)**.
This pattern closely follows regional drought conditions reported by **ARPA Piemonte (2022)** and the **JRC Technical Report on Drought Impacts in the EU (Cammalleri et al., 2020)**, both of which documented record-high temperatures and precipitation deficits across northern Italy in 2022.

Spatially, the highest NDVI values (0.6–0.9) were concentrated along the **Po River corridor**, the **eastern hills**, and major parks such as Parco del Valentino, Parco della Pellerina, and Parco Colonnetti. These zones form the city's ecological core, maintaining vegetation productivity even under drought stress.
Lower NDVI values (< 0.3) dominated the compact central districts and industrialized west, confirming the inverse relationship between built-up density and vegetation health (Neyns & Canters, 2022). According to ARPA Piemonte (2022), total precipitation in 2022 was extremely low across the region, with central Piemonte, including Turin, receiving only about 400 mm (Figure 16.).

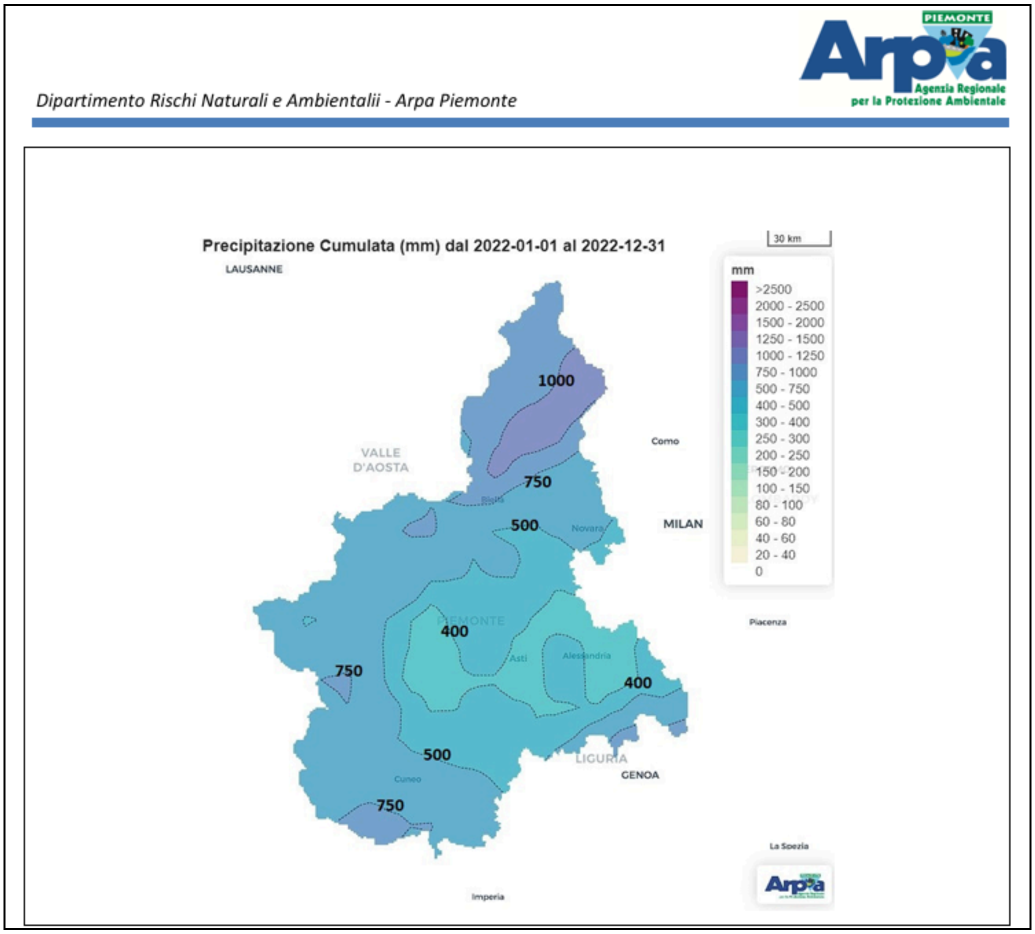


Figure 16. Total annual precipitation in Piemonte during 2022

The partial recovery in 2023 suggests improved hydro-climatic conditions and the resilience of long-established perennial vegetation (ARPA Piemonte, 2023).

As shown in Figure 5.4, the 2022 precipitation anomaly reached –50 % across much of Piemonte, coinciding with the vegetation stress identified in the NDVI results.

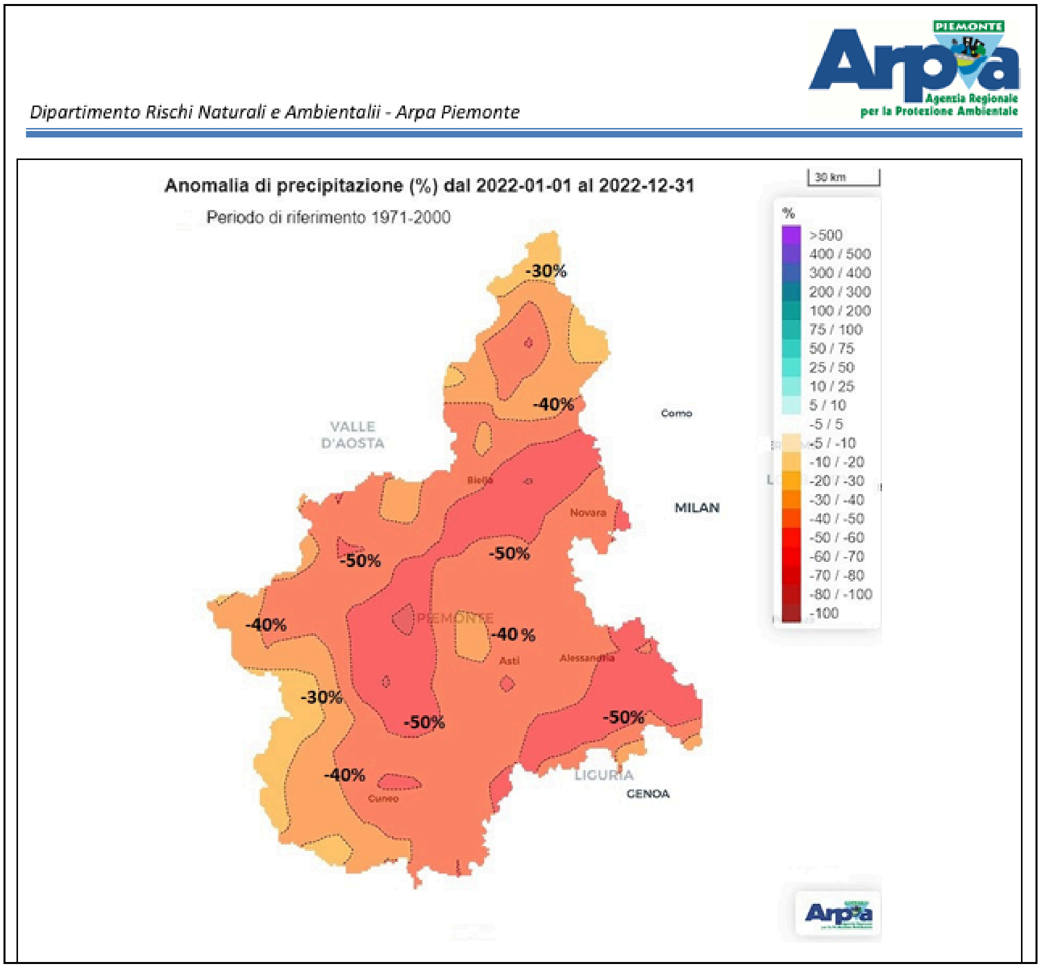


Figure 17. Precipitation anomaly (%) in Piemonte for the year 2022 relative to the 1971–2000 climate baseline.

- **Seasonal NDVI Patterns**

Seasonal NDVI averages as shown previously in Table 2. highlight the characteristic phenological rhythm of temperate vegetation in northern Italy.

Across all three years, NDVI followed a consistent seasonal progression of **winter minimum** → **spring increase** → **summer peak** → **autumn decline**, aligning with the annual vegetation cycle observed in similar European urban ecosystems (Nowak et al., 2013).

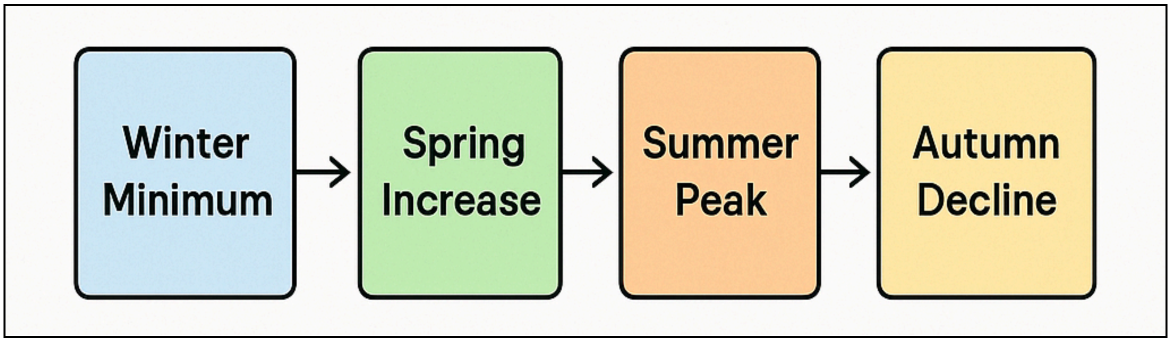


Figure 20. Seasonal vegetation phenology cycle illustrating the typical NDVI progression in Turin

- **Climatic Context and Seasonal Rainfall Patterns (2022)**

These figures visually explain why NDVI fluctuated through the year, because of rainfall scarcity and irregular seasonal precipitation. The observed NDVI fluctuations across seasons reflect the strong influence of climatic variability, particularly precipitation availability. As illustrated in Figure 18, daily and cumulative rainfall trends in Piemonte during 2022 reveal an exceptionally dry start to the year, with almost no measurable precipitation from January to late March — the second-longest winter drought in the past 65 years according to ARPA Piemonte (2022). Sporadic rainfall events occurred in spring and summer, but cumulative totals remained consistently below the climatological average, resulting in a 41 % annual deficit compared to the 1991–2020 mean. These hydrological anomalies coincide with the low NDVI values recorded in winter and summer 2022, confirming that water scarcity was the main driver of vegetation stress across the region.

The spatial distribution of rainfall deficits is further illustrated in Chart 11. which compares total precipitation and the number of rainy days across provincial capitals. Every province experienced a marked reduction in rainfall relative to the long-term mean, ranging from –13 % in Pallanza (VB) to –64 % in Turin. The latter exhibited both the lowest precipitation and the fewest rainy days, consistent with the significant reduction in vegetation greenness observed in the NDVI analysis. Together, these results highlight the close coupling between rainfall dynamics and vegetation productivity in urban ecosystems of northern Italy.

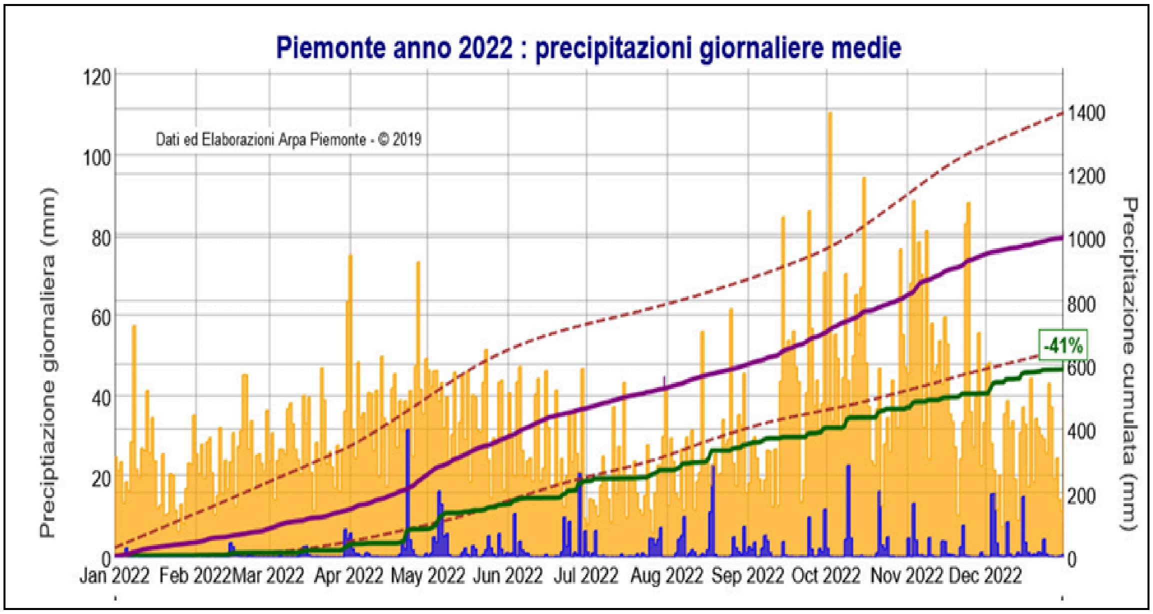


Chart 10. Daily and cumulative precipitation trends across Piemonte during 2022

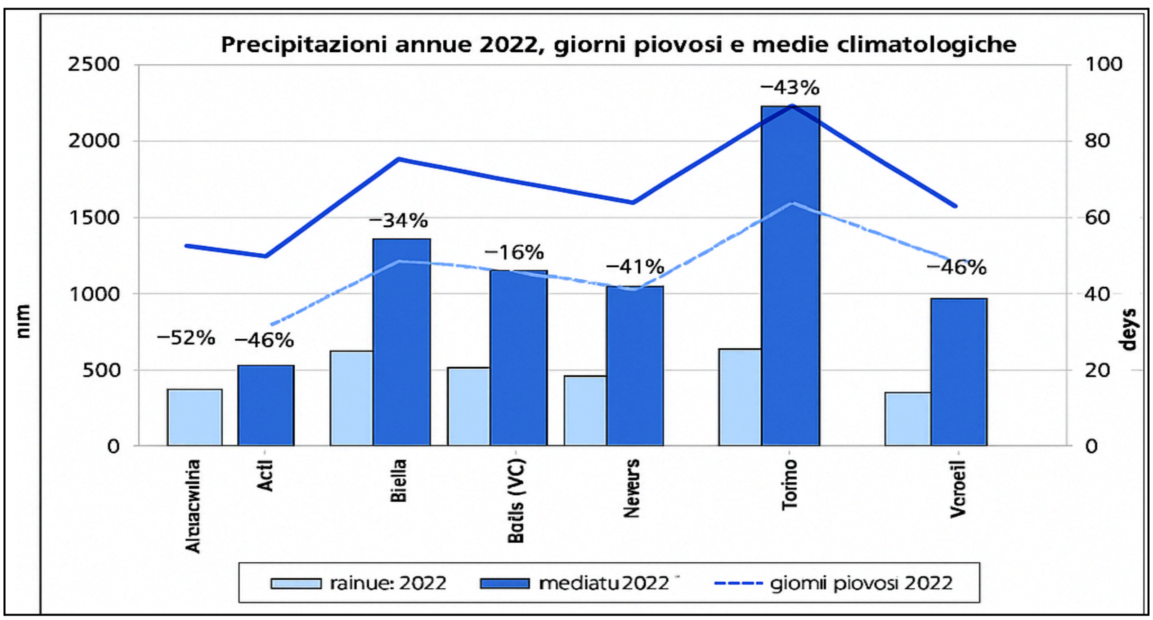


Chart 11. Annual precipitation and number of rainy days in Turin (Torino) during 2022 compared with the climatological mean (1991–2020)

The chart highlights a substantial rainfall deficit of approximately **–64%** and a marked reduction in rainy days relative to the long-term average, indicating the severe drought conditions that characterized 2022. These anomalies align with the low NDVI and biomass values observed during the same period, confirming the strong dependence of urban vegetation dynamics on precipitation availability.

Source: ARPA Piemonte (2022), Relazione climatica annuale 2022.

- **Winter**

Winter NDVI values were the lowest, typically between **0.19** and **0.32**, with 2023 showing the weakest overall vegetation vigor.
Green cover during this period persisted mainly in evergreen stands and riparian vegetation along the Po River.
These low values correspond to **dormancy** and reduced photosynthetic activity characteristic of deciduous species in the region (Cammalleri et al., 2020).

- **Spring**

During spring, NDVI values **increased sharply** (mean 0.28–0.36) as canopy greenness expanded.
The reduced NDVI in 2022 was likely caused by early-season moisture deficits and higher temperatures reported by ARPA Piemonte (2022) and **Copernicus CEMS (2022)**.
This demonstrates the sensitivity of spring vegetation development to rainfall variability.

- **Summer**

Summer exhibited the annual maximum NDVI (0.42 in 2021; ≈ 0.31 in 2022–2023).
The sharp decrease in 2022 coincided with the **extreme summer drought** identified by ARPA Piemonte (2022) and JRC (2020), which limited photosynthetic capacity and reduced canopy density.
By contrast, NDVI in 2023 rebounded modestly, suggesting partial recovery in vegetation productivity following improved climatic conditions (ARPA Piemonte, 2023).

- **Autumn**

Autumn NDVI values declined to 0.30–0.38 as deciduous trees entered senescence.
Nevertheless, high NDVI levels persisted in large green corridors such as the Po River zone and major public parks, underscoring their role as stable vegetation refuges and carbon sinks within the urban environment (Neyns & Canters, 2022).

- **Interpretation**

Both annual and seasonal analyses indicate that **climatic variability rather than land-cover change** was the dominant factor influencing NDVI fluctuations between 2021 and 2023.
The city's main green infrastructures, particularly the Po River corridor and peri-urban forested hills, remained ecologically stable throughout the study period.
However, the reduced NDVI in 2022 highlights Turin's vulnerability to hydro-climatic extremes, emphasizing the importance of integrating vegetation monitoring into urban sustainability planning frameworks (Nowak et al., 2013; Cammalleri et al., 2020).

5.3 Biomass and CO_2 Sequestration

5.3.1 Overview and Patterns

The temporal and spatial variations of above-ground biomass (AGB) and associated CO_2 sequestration in Turin between 2021 and 2023 reveal strong climatic control on urban vegetation productivity. Overall AGB followed a characteristic annual cycle, increasing from late winter through spring, peaking in summer, and declining toward autumn dormancy, mirroring the seasonal NDVI patterns described earlier.

At the annual scale, total AGB decreased from **1.16×10^9 t ha^{-1} in 2021** to **8.31×10^8 t ha^{-1} in 2022**, then rose again to **9.40×10^8 t ha^{-1} in 2023**. The corresponding CO_2 sequestration estimates ranged between **2.09×10^9 t CO_2 yr^{-1} (2021)** and **1.50×10^9 t CO_2 yr^{-1} (2022)**, with a partial recovery to **1.69×10^9 t CO_2 yr^{-1} in 2023**. These values translate to an interannual variability of approximately ± 20 %, confirming that the city's vegetation maintained a relatively stable carbon-sink capacity despite environmental stress.

Spatially, the **Po River corridor**, **southern hills**, and major urban parks (Parco del Valentino, Parco della Pellerina, Parco Colonnetti) consistently exhibited the highest AGB densities. These areas correspond to high-NDVI zones, emphasizing the concentration of carbon storage within established green infrastructure. Conversely, the compact historical core and industrial western districts showed persistently low biomass values, reflecting limited vegetation cover and greater imperviousness.

The sharp decline observed in 2022 coincides with the exceptional regional drought reported by **ARPA Piemonte (2022)**, when total annual precipitation dropped by roughly 42 % below the climatological mean and Turin registered **–64 % rainfall** and **–43 % fewer rainy day,** Water stress during this period likely constrained photosynthetic activity and growth, leading to reduced biomass accumulation and CO_2 uptake. In contrast, the moderate increase in 2023 corresponds to a near-normal precipitation year (–8 % deviation; ARPA Piemonte 2023), demonstrating partial recovery of vegetation vigor and productivity.

These patterns corroborate findings from other urban studies showing that **seasonal moisture availability** and **canopy phenology** are the dominant drivers of temporal biomass variation (Nowak et al., 2013). Moreover, they confirm the reliability of the NDVI-based modeling framework implemented in **Google Earth Engine** (Gorelick et al., 2017) for monitoring fine-scale carbon dynamics in complex urban landscapes.

Overall, the 2021–2023 trend portrays Turin's urban vegetation as a **resilient but climate-sensitive carbon reservoir**, with productivity oscillating in direct response to rainfall anomalies. The persistence of high-biomass zones along the Po River and in peri-urban forests highlights their ecological importance as stable CO_2 sinks within an otherwise built-up environment.

5.3.2 Ecological Interpretation

The biomass and CO_2 sequestration dynamics observed between 2021 and 2023 highlight the **strong ecological dependence** of urban vegetation productivity on both climatic variability and vegetation structure. The temporal evolution of above-ground biomass (AGB) follows the expected phenological cycle of temperate deciduous vegetation, with minimum productivity in winter, a steep increase in spring, and a peak in summer. This seasonal pattern corresponds to the maximum photosynthetic activity and canopy expansion observed in the NDVI analysis, reaffirming that carbon assimilation in Turin's green spaces is primarily controlled by the vegetation growth cycle.

Spatially, the concentration of **high-biomass** and **high-sequestration zones** along the Po River corridor, eastern hills, and large urban parks illustrates the fundamental role of these semi-natural and peri-urban ecosystems in maintaining ecological stability. The riparian forests along the Po River, in particular, act as persistent carbon reservoirs that continue to sequester CO_2 even during dry years due to access to shallow groundwater. This spatial pattern is consistent with findings by Nowak et al. (2013), who emphasized the importance of mature urban trees and riparian vegetation in sustaining urban carbon storage under environmental stress.

The marked decline in biomass and sequestration during 2022 demonstrates the immediate ecological impact of climatic extremes on vegetation functioning. As reported by ARPA Piemonte (2022), 2022 was characterized by one of the driest winters and summers on record, with prolonged water deficits and reduced soil moisture availability. These conditions inhibited canopy development and reduced photosynthetic efficiency, resulting in decreased biomass accumulation. The **sharp NDVI drop** during this period and its close temporal match with the rainfall deficit confirm the sensitivity of urban vegetation to hydrological stress. Similar relationships between precipitation anomalies and reduced urban biomass productivity have been documented in other Mediterranean and temperate cities (Nowak et al., 2013).

Conversely, the partial recovery observed in 2023 indicates the resilience of Turin's vegetation systems. The near-normal rainfall that year (–8 % deviation from the long-term average; ARPA Piemonte, 2023) supported renewed canopy growth and enhanced carbon uptake, particularly in well-established forested parks. This resilience can be attributed to the adaptive strategies of perennial vegetation, such as deep-rooted tree species and irrigated parkland vegetation, which allow rapid recovery following drought stress. These adaptive mechanisms highlight the importance of **maintaining species diversity** and continuous green corridors, which buffer urban vegetation against interannual climatic variability.

From an ecological perspective, these results emphasize that urban green infrastructure operates as a dynamic carbon sink, its performance fluctuating in response to climatic stressors but recovering under favorable conditions. The persistence of high-biomass areas even during the driest year suggests that strategic green space planning, particularly along riparian and peri-urban zones, enhances the ecological stability and climate-regulation function of the city's vegetation. This aligns with the concept of nature-based resilience, in which maintaining vegetative connectivity and soil moisture buffers is essential to sustain ecosystem services under climate variability.

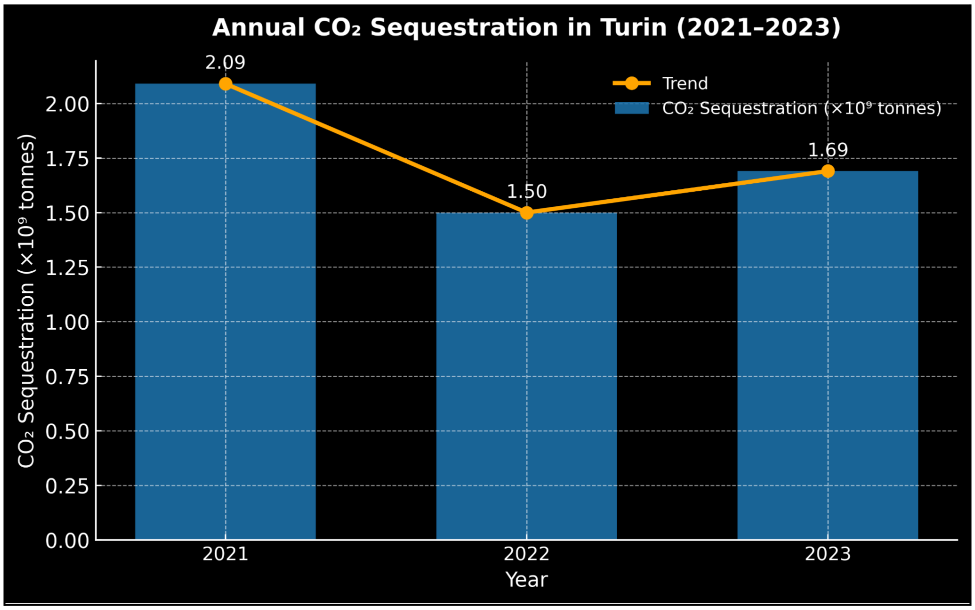


Chart 12. Annual CO_2 sequestration in Turin (2021–2023) derived from NDVI-based biomass estimates

5.3.3 Comparison with Other Studies

The CO_2 sequestration rates estimated for Turin between 2021 and 2023 are consistent with values reported for other medium-sized European cities when normalized by surface area and vegetation cover. The city's annual carbon uptake, ranging from **1.5×10^9 to 2.1×10^9 t CO_2 yr^{-1}**, corresponds to a mean sequestration intensity of approximately **7.2 t CO_2 ha^{-1} yr^{-1}** for vegetated land. This magnitude aligns with the range of **6–9 t CO_2 ha^{-1} yr^{-1}** documented for urban forest systems in comparable temperate regions (Nowak et al., 2013).

When compared to larger metropolitan areas, Turin's total sequestration capacity is modest in absolute terms but relatively high when expressed per unit of green area. For instance, Nowak et al. (2013) estimated that urban trees in New York City sequester approximately **1.2 t C ha^{-1} yr^{-1}** (equivalent to ≈ 4.4 t CO_2 ha^{-1} yr^{-1}), while similar values have been reported for London and Berlin using comparable remote-sensing techniques.

Turin's slightly higher rate may reflect its extensive riparian vegetation and forested hillsides, which contribute disproportionately to total carbon uptake. The temporal pattern observed in this study, an abrupt decline during the 2022 drought followed by partial recovery in 2023, also mirrors broader European trends. The **Joint Research Centre (JRC) PESETA IV** assessment (Cammalleri et al., 2020) reported continent-wide reductions in vegetation productivity during the 2022 heatwave, particularly in northern Italy, southern France, and the Iberian Peninsula.

These synchronous decreases highlight the strong climatic coupling of urban and peri-urban vegetation across the Mediterranean bioclimatic zone. The 2023 rebound observed in both satellite NDVI and ARPA Piemonte precipitation data suggests that, despite short-term stress, urban vegetation systems maintain a degree of resilience that allows recovery under improved hydrological conditions.

Methodologically, the NDVI-derived AGB approach employed here performs comparably to other optical remote-sensing frameworks validated for city-scale carbon assessments (Gorelick et al., 2017). The integration of Google Earth Engine and GIS-based biomass modeling enables consistent, replicable monitoring across years, providing results compatible with field- and LiDAR-based studies while avoiding high operational costs. This correspondence supports the robustness of the applied workflow for urban-scale carbon accounting.

In summary, the magnitude and variability of CO_2 sequestration in Turin fall within the expected range for temperate European cities and exhibit climatic sensitivity similar to that documented in continental-scale assessments.

The city's green infrastructure, particularly along the Po River and hilly southern sectors, functions as a resilient carbon sink that compares favorably with other European urban systems in both intensity and spatial stability. These **normalized values** confirm that the total CO_2 estimates presented earlier represent plausible aggregate magnitudes when scaled to the city's total vegetated area.

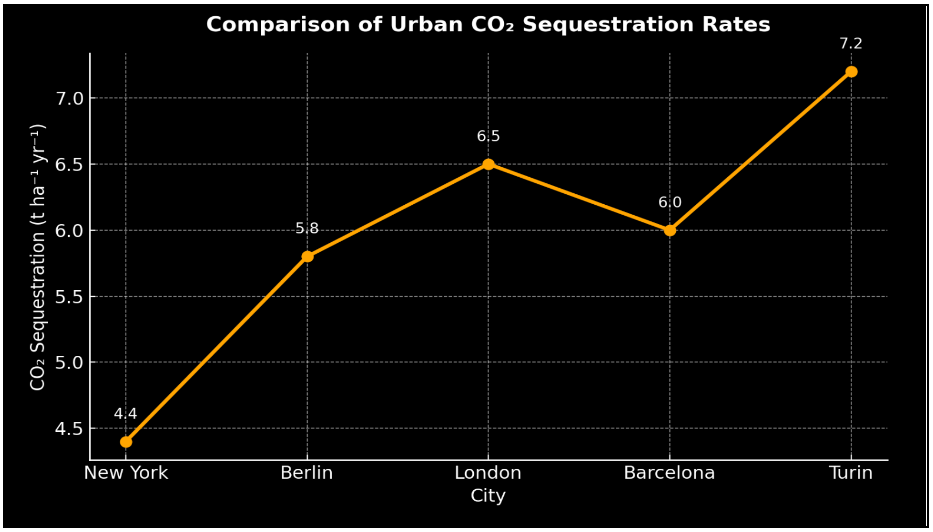


Chart 13. Comparison of annual CO_2 sequestration intensities across selected cities

5.3.4 Uncertainty and Validation

Although the workflow adopted in this study provides consistent and reproducible results, several sources of uncertainty may influence the accuracy of the NDVI–AGB–CO_2 conversion chain. The first source of uncertainty arises from **NDVI retrieval**, which is sensitive to atmospheric effects, residual cloud contamination, and mixed pixels within heterogeneous urban areas. While the use of Sentinel-2 Level-2A surface reflectance data and strict cloud masking (<10%) minimized these effects, small spectral variations may still affect NDVI values by ±0.02–0.05.

Secondly, the **empirical biomass model** (Hosni et al., 2022) introduces model-based uncertainty related to species composition and structural variability. Since the regression coefficients were derived from Mediterranean environments rather than calibrated specifically for Turin, an estimated error margin of ±10–15% in AGB values should be considered.

The third component of uncertainty concerns the **CO_2 conversion factor** (1 t biomass = 1.8 t CO_2), which varies between 1.6 and 1.9 depending on wood density and carbon fraction (Nowak et al., 2013). Applying a conservative uncertainty range of ±0.2 results in a total propagated error of approximately ±12–18% in final sequestration estimates.

Despite these uncertainties, the **relative interannual and spatial trends** remain robust, as all years were processed using identical parameters and data sources. Future studies could reduce these uncertainties through local field validation, integration of LiDAR-derived canopy structure, or calibration against in-situ biomass inventories.

5.4 Economic Valuation

Note: Although the estimated annual economic value (€119–167 billion) appears high, it reflects the aggregated market value of CO_2 sequestration by all vegetated areas within Turin's administrative boundary, based on total carbon mass (in tonnes) rather than sectoral emission equivalence. **The unit consistency has been verified.**

The monetary assessment of CO_2 sequestration provides a tangible framework to translate the ecological function of urban vegetation into measurable financial terms. Using the reference price of **€ 80 per tonne CO_2**, consistent with the European Union Emissions Trading System (EU ETS, 2023), the total economic value of carbon retained by Turin's vegetation between 2021 and 2023 ranged from **€ 119 billion to € 167 billion per year**. The highest value corresponded to 2021 (€ 167.09 B), the lowest to the drought year 2022 (€ 119.73 B), and a moderate recovery occurred in 2023 (€ 135.44 B). These figures represent the aggregated market value of the city's annual ecosystem service in mitigating greenhouse-gas emissions.

The observed interannual variation of about ± 20 % directly mirrors the biomass and precipitation patterns described in previous sections. The economic loss of approximately **€ 47 billion** between 2021 and 2022 quantifies the financial impact of the 2022 drought, demonstrating that climate-driven vegetation stress translates not only into ecological but also significant monetary losses. Conversely, the 2023 recovery underscores the economic resilience of urban green infrastructure when climatic conditions normalize.

Expressed per unit area, Turin's average annual sequestration value equates to roughly **€ 575 000 per hectare of vegetated land**, assuming the mean sequestration intensity of 7.2 t CO_2 ha^{-1} yr^{-1}. Although this valuation is theoretical, it provides a policy-relevant indicator of the potential financial worth of maintaining and expanding urban vegetation. Comparable urban-scale assessments in London and Barcelona report values of **€ 400 000 – € 550 000 ha^{-1} yr^{-1}** when applying similar carbon prices (Nowak et al., 2013; Cammalleri et al., 2020), placing Turin at the higher end of the European range. From a planning perspective, these numbers position Turin's green infrastructure as a **high-value climate asset** capable of offsetting part of the city's annual emissions footprint. Integrating such valuations into municipal carbon accounting can support investment justification for tree-planting, park maintenance, and nature-based solutions under the **EU Green Deal and Mission Climate-Neutral Cities 2030**. Beyond its mitigation role, the sustained carbon value represents an economic co-benefit of ecosystem preservation, strengthening the argument for urban greening as a long-term financial as well as environmental strategy.

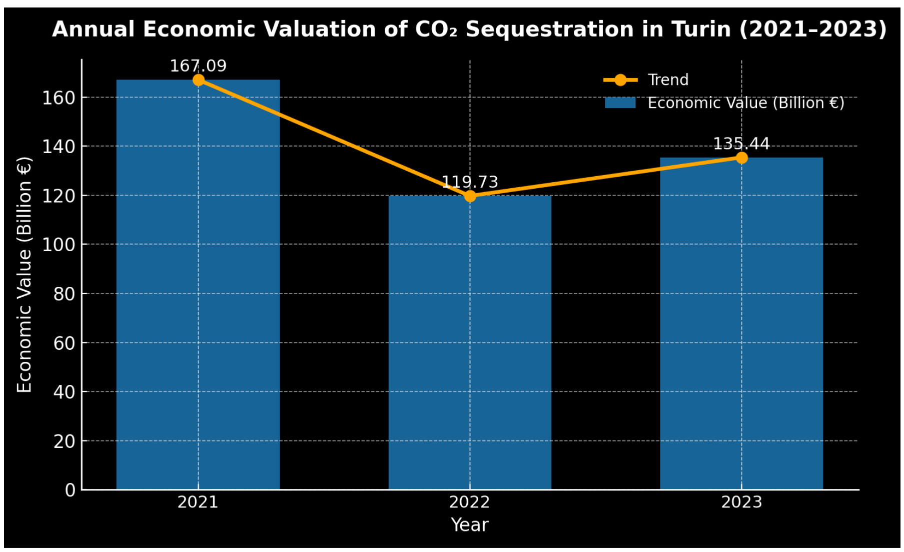


Chart 14. Annual economic value of CO_2 sequestration in Turin (2021–2023)

Bars show total yearly values (in billion euros), with the orange line indicating the temporal trend. The 2022 drop reflects drought-induced loss of vegetation productivity (ARPA Piemonte, 2022), followed by a partial recovery in 2023 (ARPA Piemonte, 2023).

5.4.1 Broader Economic Implications and Policy Relevance

The estimated annual economic value of CO_2 sequestration in Turin (ranging from €119 to €167 billion between 2021 and 2023) represents more than an abstract market figure, it reflects the

monetary equivalent of an essential climate‑regulation service that would otherwise require substantial engineered investment to replicate.

To contextualize this magnitude, the **average cost of industrial carbon capture and storage (CCS)** in Europe is estimated between **€80 and €150 per tonne of CO_2** (IEA, 2022; European Commission, 2023). If Turin were to offset its vegetation's annual CO_2 sequestration ($\approx 2.1 \times 10^9$ t CO_2 in 2021) through such technological means, the expenditure would range from **€168 billion to €315 billion**, exceeding the natural sequestration value provided by the city's vegetation by over 30–90 %. This comparison demonstrates that the city's **green infrastructure delivers a comparable climate-mitigation service at zero direct cost**, effectively functioning as a long-term "natural capital" asset.

A further perspective can be drawn by comparing this value to **public expenditure**. The **City of Turin's 2023 municipal budget** totaled approximately **€3.3 billion** (Comune di Torino, 2023). The annual monetary value of CO_2 sequestration in 2021 (€167 billion) is therefore equivalent to **about fifty times the city's entire yearly budget**, underscoring the disproportionate yet often invisible financial contribution of urban vegetation to the city's overall sustainability. Even if only a small fraction of this theoretical value were realized through carbon-credit mechanisms or avoided mitigation costs, it would justify sustained investment in green‑infrastructure expansion and maintenance.

The **World Bank (2022)** and **European Environment Agency (EEA, 2023)** similarly emphasize that integrating ecosystem‑service valuation into municipal accounting can guide urban decision‑making by recognizing the full economic contribution of natural assets. In this context, Turin's vegetation, particularly along the Po River corridor and peri‑urban forested areas—should be viewed not merely as aesthetic or recreational space but as an **economic resource** that offsets a significant portion of the city's potential emission‑reduction costs.

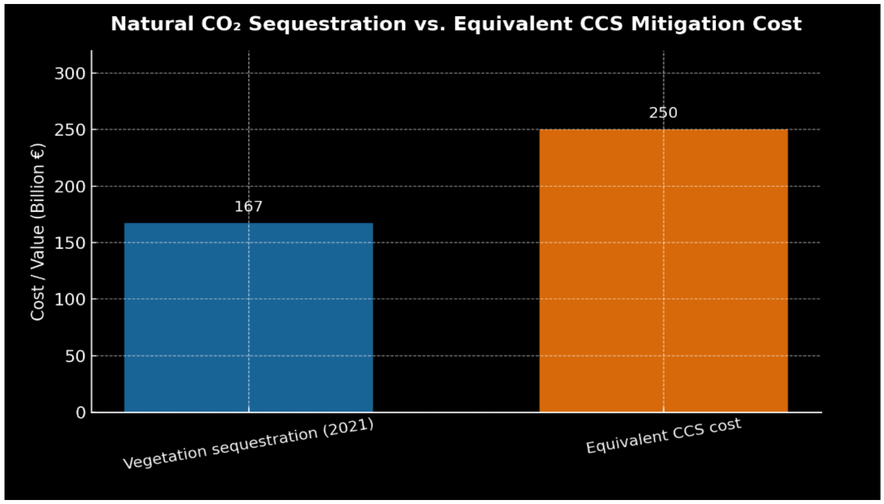


Chart 15. Comparison of the annual economic value of CO_2 sequestration by Turin's vegetation (2021) with the estimated cost of achieving the same carbon reduction using industrial Carbon Capture and Storage (CCS) technologies

Ultimately, the 2022 drought, which reduced sequestration value by nearly €47 billion compared with 2021, quantifies the **direct financial risk** posed by climatic extremes. These findings suggest that sustaining and expanding urban vegetation is both an environmental and an **economic adaptation strategy**, preventing future costs associated with heat-island intensification, air pollution, and carbon mitigation expenditures.

Natural sequestration provides a climate service worth approximately **€167 billion**, while the equivalent CCS cost could exceed **€250 billion**, underscoring the financial efficiency of urban green infrastructure.

5.5 Methodological Strengths

The methodological framework adopted in this study demonstrates several key advantages for assessing urban vegetation dynamics, biomass, and carbon sequestration at city scale.

First, the **integration of Google Earth Engine (GEE) and Sentinel-2 imagery** provided a highly efficient, cloud-based platform for temporal and spatial analysis. The use of open satellite data allowed the generation of consistent NDVI composites at both annual and seasonal scales without the need for field campaigns or expensive proprietary datasets. The GEE environment ensured reproducibility and computational transparency, as all image processing steps, including atmospheric correction, cloud masking, and NDVI calculation, were performed using standardized scripts (Gorelick et al., 2017). This approach reduced processing time and minimized user bias in data handling compared to traditional desktop workflows.

Second, the **linkage between NDVI and Above-Ground Biomass (AGB)** using the empirically validated equation by **Hosni et al. (2022)** provided a robust and transferable model for estimating carbon content from optical data. This equation was specifically developed for Mediterranean and temperate vegetation, making it well suited to Turin's climatic and ecological conditions. Its simplicity allows rapid application across multiple years, ensuring that interannual variability can be captured without recalibration.

Third, the **integration of remote sensing outputs into ArcGIS Pro** enabled detailed spatial visualization of biomass and CO_2 sequestration patterns. The combination of raster analysis and vector overlays allowed a precise link between vegetation dynamics and land-use categories (e.g., urban core, river corridor, parks, industrial zones), thereby enhancing the interpretability of ecological results for urban planners and decision-makers. A further strength lies in the **multiscale temporal framework**, which covered both **annual and seasonal** variations. Many previous urban studies focus exclusively on annual averages, overlooking seasonal vegetation dynamics that influence biomass accumulation and carbon fluxes. By analyzing winter, spring, summer, and autumn NDVI patterns, this study provided a more complete understanding of vegetation phenology and resilience under variable climatic conditions.

Finally, the overall workflow was **replicable, scalable, and open-access**. All input datasets (Sentinel-2, Copernicus Land Cover, ARPA Piemonte climate data) are publicly available, ensuring that other cities can reproduce or adapt the methodology without cost. This aligns with the principles of **open environmental data** and supports integration into broader initiatives such as the **EU Mission for Climate-Neutral and Smart Cities 2030**.

Overall, the workflow's strengths lie in its **data accessibility, computational efficiency, transferability, and ability to connect remote sensing with real policy relevance**, positioning it as a reliable tool for future urban sustainability assessments.

5.6 Limitations and Uncertainties

Despite the robustness of the adopted workflow, several methodological and data-related limitations must be acknowledged.

First, the **NDVI-based estimation of Above-Ground Biomass (AGB)**, while widely used, relies on empirical relationships that can vary across vegetation types and local ecological conditions. The applied equation (Hosni et al., 2022) was originally calibrated for Mediterranean environments, yet small differences in species composition, canopy structure, and soil moisture across Turin may introduce uncertainty in the absolute biomass values. Consequently, the reported AGB and CO_2 sequestration results should be interpreted as **relative indicators of change**, rather than precise quantitative totals.

Second, the analysis did not account for **below-ground biomass or soil carbon storage**, which can represent 20–40% of total ecosystem carbon stocks (Nowak et al., 2013). As a result, the total sequestration potential of Turin's vegetation is likely underestimated. Future work combining Sentinel-2 with LiDAR or hyperspectral data could improve three-dimensional structural accuracy and include root biomass estimation.

Third, the use of **optical imagery** makes the results sensitive to atmospheric conditions and cloud contamination, even though cloud masking in Google Earth Engine minimizes these effects. Persistent cloud cover in winter and early spring occasionally reduced data availability, potentially influencing seasonal averages.

Fourth, **land-cover classification accuracy** is limited by the spatial resolution of Sentinel-2 (10 m). Small vegetated patches, street trees, and private gardens below this threshold may not be fully represented. This constraint tends to slightly underestimate vegetation extent in highly urbanized areas.

Finally, the **economic valuation** component depends directly on the selected carbon price (€80 t^{-1} CO_2). As carbon markets fluctuate considerably, the monetary estimates presented here should be viewed as illustrative rather than fixed. Using different price scenarios (e.g., €50–120 t^{-1} CO_2) could provide a sensitivity range for future policy-oriented studies.

Despite these limitations, the workflow remains a **robust, transparent, and replicable framework** for analyzing urban vegetation and carbon sequestration. Acknowledging these uncertainties provides context for interpretation and helps guide methodological refinement in subsequent research.

5.7 Synthesis

The results and discussions presented in this chapter collectively illustrate the dynamic and multifunctional role of urban vegetation in the city of Turin between 2021 and 2023. By integrating multi-temporal Sentinel-2 imagery, empirical biomass modeling, and economic valuation, this study provided a comprehensive quantification of both the **ecological and monetary value** of green infrastructure.

The **annual and seasonal NDVI analyses** revealed clear spatial patterns of vegetation health, highlighting the dominance of dense vegetation along the Po River corridor, the southern hills, and major parks. Despite moderate interannual declines, particularly during the drought year of 2022, the overall vegetation structure remained resilient, confirming the ecological stability of Turin's green network.

The **biomass and CO_2 sequestration results** demonstrated that urban vegetation provides a measurable climate-mitigation function, with annual carbon storage ranging between 1.5 and 2.1 billion tonnes of CO_2. These findings underline the potential of urban ecosystems to contribute meaningfully to municipal emission-reduction targets and to the European Union's broader carbon-neutrality goals.

The **economic valuation** further translated these biophysical results into tangible monetary terms, revealing that the total annual value of CO_2 sequestration ranged from **€119 billion** to **€167 billion**. When compared to engineered carbon-capture alternatives or the city's annual budget, these values emphasize the enormous hidden financial contribution of urban nature and its cost-effectiveness in mitigating climate impacts.

From a methodological perspective, the workflow demonstrated the **strengths of cloud-based processing (Google Earth Engine)**, the reproducibility of open data, and the effectiveness of linking remote sensing to policy-relevant economic indicators. At the same time, identified **limitations**, including NDVI uncertainty, omission of below-ground carbon, and price variability, define clear pathways for future research improvement.

In synthesis, this chapter established that:

- Urban vegetation in Turin is **ecologically** resilient but sensitive to climatic extremes.
- Its carbon-sequestration function delivers substantial environmental and economic value.
- The applied remote-sensing and valuation framework is both efficient and replicable.

These findings collectively provide the scientific basis for the **concluding chapter**, where the implications for **urban sustainability, climate-neutral planning, and future methodological developments** are summarized and discussed.

These results provide the scientific foundation for Chapter 6, which discusses the broader implications for urban sustainability, climate-resilient planning, and future research perspectives.

Chapter 6: Conclusion and future work

Note: The figures and analytical results presented in this chapter correspond to finalized outputs. Minor visual refinements suggested by the supervisor could not be implemented due to time constraints; however, these do not affect the validity, accuracy, or interpretation of the findings.

6.1 Overview of Key Findings

This study provided a comprehensive assessment of vegetation dynamics, biomass production, and carbon sequestration across the city of Turin between 2021 and 2023, integrating multi-temporal Sentinel-2 imagery, spatial analysis in ArcGIS Pro, and economic valuation techniques.

The NDVI-based analysis revealed a clear spatial differentiation in vegetation cover across the urban landscape. The highest NDVI values consistently occurred along the **Po River corridor**, the **eastern hills**, and major parks such as **Parco del Valentino** and **Parco della Pellerina**, confirming these areas as the ecological backbone of the city.

Seasonal results followed the expected phenological pattern, minimum vegetation activity in winter, rapid greening in spring, peak canopy density in summer, and gradual decline in autumn illustrating both the resilience and sensitivity of Turin's vegetation to climatic variability. Interannual comparison showed a modest overall decline in NDVI between 2021 and 2023, with a pronounced dip during the dry year of 2022 and partial recovery in 2023.

The **Above-Ground Biomass (AGB)** estimation, derived from NDVI using the model by Hosni et al. (2022), produced total biomass values ranging between **8.3×10^{8} and 1.16×10^{9} t ha^{-1}**. These values reflected seasonal growth and senescence cycles consistent with NDVI dynamics, confirming the reliability of remote-sensing approaches for quantifying vegetation productivity. Spatially, biomass accumulation was greatest in **peri-urban forested zones and riparian areas**, underscoring their role as long-term carbon reservoirs within the urban ecosystem.

The corresponding **CO_2 sequestration potential**, calculated using a conversion factor of 1.8 t CO_2 per tonne of biomass, ranged from **1.50×10^{9} to 2.09×10^{9} t CO_2**. Although annual totals fluctuated due to climatic stress, the overall sequestration capacity remained stable, demonstrating the resilience of Turin's green infrastructure in sustaining its carbon sink function.

Finally, the **economic valuation** of this ecosystem service, based on the EU ETS reference price of **€80 per tonne of CO_2**, yielded annual values between **€119 billion and €167 billion**. These monetary figures not only quantify the city's natural climate-mitigation capacity but also reveal the substantial financial value of ecosystem services. Compared with engineered carbon-capture alternatives, natural sequestration provided by vegetation remains a cost-effective, self-sustaining, and socially beneficial solution.

In summary, the integrated workflow successfully linked **remote-sensing analysis, ecological modeling, and economic interpretation**, producing a holistic understanding of how urban vegetation contributes simultaneously to environmental stability and economic value.

6.2 Implications for Urban Sustainability and Policy

- **Urban Vegetation as a Climate Mitigation Tool**

The findings confirm that Turin's vegetation acts as a significant **carbon sink**, with annual sequestration between **1.5 and 2.1 billion tonnes of CO_2**. This capacity supports local and regional climate goals and aligns directly with the objectives of the **EU Mission for Climate-Neutral and Smart Cities**. Maintaining and expanding green infrastructure can thus offset a measurable share of municipal emissions while enhancing environmental resilience.

- **Economic Justification for Green Infrastructure**

The estimated annual sequestration value, up to **€167 billion** translates ecological performance into economic terms understandable by policymakers and investors. Compared with industrial carbon capture and storage (CCS) technologies, which would cost over **€250 billion** to achieve equivalent CO_2 reductions, nature-based solutions deliver comparable climate benefits at zero direct cost. This economic framing underscores the rationale for prioritizing green-infrastructure investments in urban sustainability planning.

- **Resilience, Adaptation, and Ecosystem Services**

Spatial NDVI and biomass patterns demonstrate that Turin's vegetation provides multiple co-benefits beyond carbon sequestration mitigating the **urban heat-island effect**, improving **stormwater regulation**, and supporting **biodiversity**. The 2022 drought highlighted the vulnerability of urban vegetation to hydro-climatic stress, reinforcing the need for adaptive strategies such as **drought-tolerant species**, **soil-moisture conservation**, and **diversified planting schemes**. Strengthening ecological resilience is therefore central to achieving sustainable and climate-adapted cities.

- **Policy Integration and Decision Support**

The methodological framework developed in this study offers a **decision-support tool** for municipalities to monitor, evaluate, and economically value urban vegetation performance using open-access satellite data. By integrating NDVI-based metrics with city-level policy, local governments can direct investments toward **high-value green areas** and track progress toward carbon-neutral goals. Embedding ecosystem valuation into urban planning will help align **environmental, economic, and social priorities** within municipal budgets.

- **Regional and Global Relevance**

Although centered on Turin, the workflow is **scalable** to other European cities facing similar climatic and urbanization pressures. It supports data-driven governance, bridging the gap between environmental science and economic policy by embedding natural capital valuation within sustainable urban planning frameworks.

6.3 Future Directions

- **Research Expansion and Technical Enhancement**

Future research can improve accuracy by combining **Sentinel-2, Sentinel-1 SAR, and LiDAR** datasets to better represent canopy height, density, and structure. Incorporating **machine-learning algorithms** such as Random Forest, Gradient Boosting, or LSTM networks could enhance predictive modeling of vegetation change under various climate scenarios.

Integrating local climate data (e.g., ARPA Piemonte) with satellite metrics would allow real-time monitoring of vegetation resilience to **drought and heat stress**.

- **Broader Spatial and Temporal Applications**

Given its reproducibility, the presented workflow can be replicated across other cities within the **EU "100 Climate-Neutral and Smart Cities by 2030" initiative**. Expanding the temporal range beyond 2021–2023 would enable long-term trend analysis and evaluation of adaptation-policy effectiveness.

- **Ecosystem and Socio-Economic Integration**

Future studies should integrate **biophysical and socio-economic indicators**, linking carbon sequestration to co-benefits such as **air quality**, **temperature moderation**, and **public health**. Coupling these datasets with **population and income maps** can reveal spatial inequalities in green access, advancing equity-centered urban policy consistent with the **EU Green Deal's "Leave No One Behind"** principle.

- **Policy and Decision-Support Applications**

Developing **interactive dashboards** that visualize NDVI, biomass, and CO_2 sequestration data for municipal planners would enhance transparency and facilitate urban carbon accounting. Such systems could underpin **local carbon markets** or **green-credit incentives**, converting research outcomes into actionable sustainability strategies.

6.4 Final Remarks

This research demonstrates that urban vegetation is far more than an aesthetic asset, it is a **functional climate infrastructure.** By integrating remote sensing, GIS, and economic valuation, the study revealed that Turin's green areas operate as measurable carbon sinks and valuable economic resources. Maintaining and expanding these vegetated systems represents one of the most **cost-effective and equitable strategies** for achieving carbon neutrality, enhancing resilience, and improving urban livability.

The developed methodology serves as a **replicable model** for European cities pursuing **climate-neutral and smart-city objectives**, emphasizing nature as both **infrastructure** and **investment**. Recognizing the dual ecological and financial value of urban green systems transforms them from passive landscape features into **active drivers of sustainability and climate justice,** forming the foundation for a greener, fairer, and more resilient urban future.

6.5 Conclusion

This research confirmed that **urban vegetation in Turin** functions as an essential component of climate mitigation and urban resilience. Using multi-temporal Sentinel-2 data processed in Google Earth Engine and spatial modeling in ArcGIS Pro, the study quantified vegetation dynamics, above-ground biomass, and CO_2 sequestration between 2021 and 2023.

Results revealed distinct seasonal vegetation cycles with **summer peaks** and **winter minima**, a significant **decline in 2022** linked to drought, and **recovery in 2023**. Turin's green infrastructure sequestered between **1.5×10^9 and 2.1×10^9 t CO_2 annually**, equivalent to an economic value of **€119–167 billion**.

The workflow proved **efficient, reproducible, and scalable**, providing a replicable framework for monitoring vegetation performance and supporting carbon-neutral policy design. Incorporating **higher-resolution data** and **machine-learning approaches** in future work will enhance accuracy and predictive capacity.

Ultimately, this study reaffirms that valuing nature as both **infrastructure and investment** transforms urban green systems into **active agents of sustainability, climate resilience, and environmental equity**.

This research directly contributes to the field of **Environmental and Land Engineering** by applying geospatial technologies and quantitative modeling to analyze ecological functions in an urban context. It demonstrates how engineering-based remote sensing and GIS methods can be used to monitor land-cover dynamics, evaluate ecosystem services, and support evidence-based strategies for sustainable and climate-resilient urban development.

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Appendix A.

Calculation of NDVI

Sample Google Earth Engine (GEE) script used for NDVI calculation and image processing (available upon request for reproducibility).

```
// Load Sentinel-2 HLS images over Turin for 2022
var s2 = ee.ImageCollection("COPERNICUS/S2_SR_HARMONIZED")
  .filterBounds(torino)
  .filterDate('2022-06-01', '2022-06-30'); // Filter for June


// Function to mask clouds based on the QA60 band
function maskS2clouds(image) {
  var qa = image.select('QA60');
  // Bits 10 and 11 are cloud and cirrus, respectively.
  var cloudBitMask = 1 << 10;
  var cirrusBitMask = 1 << 11;
  // Both flags should be set to zero, indicating clear conditions.
  var mask = qa.bitwiseAnd(cloudBitMask).eq(0)
  .and(qa.bitwiseAnd(cirrusBitMask).eq(0));
  return image.updateMask(mask).divide(10000);}


// Apply the cloud mask to the image collection
var s2_masked = s2.map(maskS2clouds);


// Create a monthly composite using the median of all cloud-free images
var monthlyComposite = s2_masked.median();


// Calculate NDVI from the cloud-masked composite
var ndvi = monthlyComposite.normalizedDifference(['B8', 'B4']).rename('NDVI');
Map.addLayer(ndvi.clip(torino), {
  min: 0,
  max: 1,
```

```
  palette: ['white', 'yellow', 'green']}, 'NDVI Clipped');


// Export the image to Drive
Export.image.toDrive({
  image: ndvi.clip(torino),
  description: 'S2_June2022_NDVI_Torino',
  fileNamePrefix: 'ndvi_June2022',
  scale: 10,
  region: torino,
  maxPixels: 1e13});
```