DOCTORAL THESIS

Management of Urban Public Spaces: Challenges and Future Directions from a Municipal Perspective

Kristiina Kupper

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for doctoral or equivalent academic degree.

Kristiina Kupper

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signature

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Linnaliste avalike alade korraldus. Probleemid ja tulevikusuunad omavalitsuse vaateses

KRISTIINA KUPPER

TALTECH KIRJASTUS

Contents

List of Publications

The list of author's publications, on the basis of which the thesis has been prepared:

I **Kristiina Kupper**, Nele Nutt, Minea Kaplinski-Sauk. 2025. Data from Urban Tree Surveys of the 19th-21st Centuries as Input for Planning the Maintenance of Historical Tree Stands. Case Study of Kaarli Puiestee in Tallinn, Estonia. Baltic Forestry, 31 (1).

II Nutt, N.; Salmistu, S.; **Kupper, K**.; Kotval, Z. 2024. Assessing age-friendliness of contemporary urban outdoor places in Estonia. *Quality in Ageing and Older Adults*, 25 (3), 204−219, August 2024.

III Laura Mrosla, Henna Fabritius, **Kristiina Kupper**, Fabian Dembski, Pia Fricker. What grows, adapts and lives in the digital sphere? Systematic Literature Review on the Dynamic Modelling of Flora and Fauna in Digital Twins. *Ecological Modelling*, 504 article 111091, January 2025.

Author’s Contribution to the Publications

Contribution to the papers in this thesis are:

I The author was the corresponding author of the article responsible for the research concept and data collection, working out the initial methodology. She wrote the manuscript and was solely responsible for the conclusions. The co-authors advised her on the research focus and gave her valuable feedback on the manuscript.

II The author was the co-author of the article responsible for the research concept, data collection, and formal analysis. She compiled diagrams and summarized photographic materials, and was also responsible for writing the manuscript.

III The author was the co-author of the article responsible for writing, reviewing and editing the article. She was in charge of composing the original draft, validation, methodology, formal analysis, data curation, and conceptualization.

1 Introduction

Belief systems that separate humans from nature have evolved alongside economic and technological progress. However, humanity remains fundamentally dependent on the biosphere, which is not external to society or the economy but forms the foundation upon which all civilization depends on. Today, humanity is the dominant force shaping the Earth's system—driving climate change, biodiversity loss, rising inequality, and reduced resilience to unexpected challenges (Folke et al., 2021). In order to navigate a future marked by rapid change and uncertainty, building resilience is essential. However, traditional, efficiency-driven development models are insufficient. Instead, resilience strategies—such as fostering diversity, redundancy, adaptive governance, and social learning—are necessary to respond to tipping points and sustain human societies (Steffen et al., 2018).

Global urbanization is one of the defining demographic trends of recent decades. Since 2007, more than half of the world's population has lived in urban areas, and projections suggest this share will rise to 66% by 2050, when over six billion people are expected to reside in cities (United Nations, 2025). Urban growth is closely linked to economic development, access to employment and education, and the availability of public services. However, rapid urbanization also generates significant challenges, especially in high-density cities, where access to public spaces, green areas, and adequate housing is often limited, and where social and environmental pressures are intensifying (United Nation, 2025). Changes in urban land cover threaten biodiversity and reduce ecosystem productivity by diminishing habitat, biomass, and carbon storage. Although cities were historically compact, over the past 30 years their land area has expanded at twice the rate of population growth (Seto et al., 2012).

Climate change presents growing challenges for contemporary cities. Its impacts are being felt more severely and earlier than previously anticipated, particularly in the form of extreme weather events such as heatwaves, droughts, wildfires, intense rainfall, floods, and storms (Folke et al., 2021). Public green spaces and vegetation are essential to mitigating climate impacts and supporting urban quality of life. Urban greenery reduces heat island effects, supports biodiversity, absorbs rainfall, and enhances ecological stability. However, poor maintenance, pressures of urban development, and inadequate monitoring have increased the vulnerability of these green infrastructures to climate stressors.

Climate change also intersects with demographic trends and public health. As cities experience aging populations, the need for inclusive and climate-resilient outdoor environments, becomes increasingly urgent. Public spaces that support mobility, shade, and social interaction are critical to maintaining the health of older adults. Micro-scale adaptations—such as shaded seating, green corridors, and cooling shelters—are vital for thermal comfort, as shown in urban case studies (II; Tousi et al., 2025).

A growing body of evidence shows that parks and green spaces provide substantial benefits, including improved health outcomes and reduced healthcare costs. These benefits are closely tied to accessibility and quality. Equity in access to such spaces is critical, as disparities persist in who benefits from urban greenery (Cohen et al., 2022).

1.1 Relevance of the Research Topic and Justification for the Choice of Topic

The Estonian state has adopted several strategic documents to address these trends and challenges, aiming to ensure a high-quality living environment and to adapt to global changes.

One such document, **Estonia 2035**, outlines the country's long-term development priorities and was adopted by the Estonian Parliament on 12 May 2021. Developed through an inclusive co-creation process involving nearly 17,000 participants, the strategy defines five equally important goals. Three of these are particularly relevant to this dissertation: (1) Estonia is home to smart, active, and health-conscious people; (2) society is open, caring, and cooperative; and (3) the country provides a safe, high-quality living environment responsive to diverse needs.

Some of the key identified development needs include the aging population and Estonia's growing demographic reliance on migration. These trends call for coherent policies and supportive environments across sectors such as education, health, and family support. The strategy emphasizes the need for longer working lives and dignified aging. As Tallinn's population continues to grow, Estonia 2035 calls for a knowledge-based, balanced approach to urban development.

In relation to health, the strategy acknowledges the need to prepare for the impacts of climate change on well-being and living conditions. It highlights concerns about biodiversity loss, rising obesity and physical inactivity, increased mental health issues, and a growing elderly and disabled population—challenges that require more accessible and inclusive environments. Biodiversity loss, habitat fragmentation, and the need for improved soil protection are also recognized. Given that nearly 70% of Estonians live in urban areas, the strategy underscores the importance of both private and public spaces in ensuring quality of life. It promotes densification of historic urban centers and enhanced spatial literacy through better data and digital services.

In the realm of governance, the strategy points to the importance of efficient human resource use, particularly in the light of a shrinking working-age population. It advocates for reducing administrative burdens and integrating research-based evidence into policymaking. Innovations in digital technology and real-time data exchange are seen as essential tools for enhancing governance. The vision for spatial development in Estonia 2035 emphasizes accessible and comfortable physical, mental, and digital environments that preserve both biodiversity and cultural heritage. It also stresses innovation and knowledge use within governance structures and calls for improved quality and accessibility of local government services.

Estonia's broader digital strategy complements Estonia 2035, aiming to create a digitally empowered public sector. Despite Estonia's reputation as a digital pioneer, the strategy notes that the complexity and limited user value hinder many services. In the increasingly competitive global environment, service quality is a decisive factor. Advances in digital technology offer opportunities to redesign services using intelligent solutions. A guiding principle of Estonia 2035 is the pursuit of optimal decisions through shared knowledge and collaboration. By 2030, Estonia aims to ensure that all government decisions are based on high-quality, timely, and interoperable data. However, challenges remain, including uneven data literacy, fragmented datasets, inconsistent metadata, and poor lifecycle management. These issues limit the reuse of data and the realization of the "once-only" principle. The potential of linked data to improve service delivery remains underutilized. In order to address this, the strategy calls for strengthening the science of data and capacities for governance, and fostering innovation through collaboration with academia and startups. Similar goals are outlined in Estonia's digital transformation roadmap for the public sector.

Recognizing the interdependence of environmental, economic, and social systems, the Estonian Parliament also adopted the **Environmental Strategy until 2030** on 14 February 2007. While this strategy focuses primarily on energy and emissions, its treatment of climate change is not explored further in this thesis. The strategy also acknowledges the growing importance of urban forests and biodiversity. While nature conservation has traditionally focused on protected sites, current approaches emphasize the need for preserving habitat networks and cultural landscapes. Biodiversity is positioned as essential to well-being, and the strategy promotes public awareness of nature's benefits. It also endorses evidence-based decision-making, advanced modelling tools, and cross-sectoral cooperation.

Key challenges for the future include land-use change and landscape fragmentation, which threaten biodiversity. To address this, the strategy proposes protecting habitats throughout the national territory—not just in designated conservation zones. A balanced approach to forest management that considers ecological, social, and economic factors is promoted, including the development of a forestry monitoring system to support informed decisions. In landscape management, the goal is to preserve multifunctional, coherent landscapes, including governance systems outside protected areas to support suitable habitats and the survival of species. Finally, the strategy aims to ensure a healthy external environment that supports public health, with spatial planning and environmental governance playing a key role in mitigating health risks.

1.2 The Aim of the Study

A review of the development strategies of the Republic of Estonia and the City of Tallinn reveals several shared challenges, including urbanisation, adaptation to climate change, excessive bureaucracy, fragmentation of green and habitat networks, and issues concerning the quality of existing information systems and data, as well as their usability in decision-making. A standard solution identified across these documents is the utilisation of information systems and data to support informed decision-making, which requires the one-time collection of necessary data—using a range of technologies—followed by continuous updating, cross-utilisation, and the integration of different information systems.

The benefits of open space and public parks within the built environment are recognized by scholars and practitioners alike. Benefits range from physical to emotional, and social to economic. As such, municipal governments are actively engaged in creating and maintaining public parks and green spaces within city limits.

Sustainable management and planning of public space increasingly rely on data-driven approaches that integrate both ecological and social dimensions. While digital twins and 3D models are becoming more common in urban planning, the integration of urban green infrastructure, dynamic ecological elements, and user-centered needs remains limited. The core problem lies in the lack of suitable data, inconsistent data quality and accessibility, and insufficient consideration of diverse user group needs.

This doctoral thesis aims to explore how data-driven models and digital twins can support the sustainable planning and management of public space, with a focus on embedding ecological complexity, green infrastructure, and the diverse requirements of urban users into planning processes. The study investigates the types of data and modelling techniques required, the challenges related to data quality and availability, and how different user groups—including urban planners, green space professionals, and citizens—perceive and utilize such data in the design and governance of public environments.

1.3 Research Questions

A critical question that arises is: what is needed to manage the city's public greenery?

RQ 1: To what extent is the data on urban green infrastructure collected sufficient and reliable to support management of public spaces?
1.1 What types of data on urban greenery, particularly urban trees, have been collected and preserved in the past, and how accessible and usable have these datasets been for management?
1.2 What challenges have emerged in using historical greenery data for long-term monitoring and decision-making in public space management?

RQ 2: To what extent has existing data been utilized in the creation of inclusive public spaces in Estonia, and what design shortcomings—particularly in relation to universal design principles—could have been avoided through more effective data use?

RQ 3: How can the digital twin, as a tool, enable evidence-based decisions for public space management?
3.1 What types of data and modelling techniques are required to integrate dynamic ecological information into digital twins of public space, and what challenges arise in this process?
3.2 What are the challenges and opportunities of using greenery in the digital twin for the management of urban public spaces?

1.4 Methods Used to Answer Research Questions

A threefold methodological framework was employed to examine public green space management across historical, contemporary, and future contexts:

- Historical Methods in Publication I included archival research, which was carried out using historical maps, photographs, and dendrological surveys to reconstruct the landscape history of Kaarli Boulevard in Tallinn. Data were sourced from national and city archives, libraries, museums, and private collections. Although valuable, the materials were fragmented, inconsistent, and often incomplete, requiring critical evaluation.
- Contemporary Methods in Publication II conducted fieldwork in ten Estonian town centers that were redeveloped under the "Great Public Space" program. When evaluating spaces as age-friendly parks, ten design principles (e.g., accessibility, safety, contact with nature) were adapted. A binary scoring system and team-based analysis produced detailed assessments of inclusivity and usability, especially for older adults.
- Future-Oriented Methods consisted of a systematic literature review (PRISMA framework) that examined the role of digital twins in Publication III. Major database searches yielded 38 relevant studies, which were categorized into thematic areas (e.g., forest modelling, ecosystem preservation, microclimates, agronomy). Content analysis identified data challenges, gaps in interoperability, and opportunities for adaptive, evidence-based governance.

1.5 Theoretical and Practical Novelty of the Thesis

A review of the content of the national and Tallinn development policy documents discussed in the Introduction chapter reveals that their sole explicitly shared objective is the use of necessary data, ensuring its currency, archiving, cross-utilisation, and, through these measures, the reduction of bureaucracy and the facilitation of data-driven decision-making.

This thesis provides new theoretical perspectives on how data-driven approaches can support the sustainable planning and management of urban public green spaces. It expands the conceptual understanding of how diverse data types—historical records, spatial datasets, ecological indicators, and user feedback—can be integrated to reflect the dynamic and multifunctional nature of green infrastructure in cities. The research contributes to urban studies and digital twin development by exploring how living systems and social inclusivity can be represented in digital models for better decision-making.

From a practical standpoint, the thesis identifies systemic barriers to using existing data for long-term monitoring, inclusive design, and adaptive management of public green areas. It highlights the fragmented nature of datasets, the lack of standardisation, and missed opportunities for interoperability. By examining use cases in Estonia and conducting applied evaluations, the research offers actionable recommendations for improving data governance, enhancing inclusivity through universal design principles, and embedding ecological complexity into digital platforms. These contributions support urban planners, landscape managers, and municipal decision-makers in designing more resilient and inclusive public spaces.

The topic of this thesis has been addressed in the following publications:

- Kristiina Kupper, Nele Nutt, Minea Kaplinski-Sauk. 2025. Data from Urban Tree Surveys of the 19th-21st Centuries as Input for Planning the Maintenance of Historical Tree Stands. Case Study of Kaarli Puiestee in Tallinn, Estonia. BALTIC FORESTRY, 31 (1), 793. DOI: 10.46490/BF793.
- Mrosla, Laura; Fabritius, Henna; Kupper, Kristiina; Dembski, Fabian; Fricker, Pia, 2025. “What grows, adapts and lives in the digital sphere? Systematic literature review on the dynamic modelling of flora and fauna in digital twins” Ecological Modelling, 504, 111091. DOI: 10.1016/j.ecolmodel.2025.111091.
- Nutt, N.; Salmistu, S.; Kupper, K.; Kotval, Z. 2024. “Assessing age-friendliness of contemporary urban outdoor places in Estonia” Quality in Ageing and Older Adults, 25 (3), 204−219. DOI: 10.1108/QAOA-05-2024-0033.
- Tallinn, Tiina; Pent, Elle; Tuulik, Tiina; Abner, Olev; Kupper, Kristiina, 2024. Book “Parks and green areas of Tallinn” Tallinna Keskkonna- ja Kommunaalamet.
- Fabritius, Henna; Tuulik, Tiina; Kupper, Kristiina; Mrosla, Laura; Nummi, Pilvi; Prilenska, Viktorija; Yao, Chaowen. 2023. “Varying Data on Urban Trees Complicates Meeting User Needs for Digital Twins of Urban Green Infrastructure” CUPUM 2023 conference proceedings: The 18th International Conference on Computational Urban Planning and Urban Management, Montreal, QC, Canada, 20-22 June 2023. Center for Open Science, 1−14.
- Allik, Martin; Mrosla, Laura; Fabritius, Henna; Kupper, Kristiina. 2022. “Urban Digital Twins as a tool for multi-species approach in planning” AESOP Annual Congress Space for Species: Redefining Spatial Justice - Book of Abstracts: AESOP Annual Congress 2022. Space for Species: Redefining Spatial Justice, Tartu, Estonia, July 25-29. Tartu, Estonia: AESOP Association of European Schools of Planning, 148.

- Kupper, K. 2014. Master thesis “Necessity and compiling of the development plan for green areas” Tartu College of Tallinn University of Technology
- Kupper, K. 2012.Bachelor thesis “Comparison of various research methods of allees according to the example of the avenue on Vanapargi street in Pärnu” Tartu College of Tallinn University of Technology

In addition, the development of public space in Tallinn, plans for its management, the necessary data sets and future trends have been presented at the following conferences:

- Tartu X planning conference, Tartu 15-16. Mai 2025 “There is no question - nature belongs in the digital world also!”
- Swedish Annual Tree Conference 2024, Kingdom of Sweden, Gävle 6-7 November 2024 “New city strategy” Tallinn 2035””
- Cities and Parish Days, Tallinn 12-13. April 2023. Kristiina Kupper, Andres Maremäe “Public urban space, connecting greenery and people through digital twin”
- UPE13, International Urban Planning and Environment Congress, Tartu, Estonia, 29 July-01 August 2022. Kristiina Kupper “Comparison of different tree research methods in Pärnu Vanapargi avenue”
- AESOP, Association of European Schools of Planning, Tartu, Estonia, 25-29 July 2022. Kristiina Kupper “Preservation and exhibition of the bastion zone and the Old Town of Tallinn using a digital twin”
- 5th International Conference Urban E-Planning, Portugal, 7-10 September 2021. Kristiina Kupper, Martin Allik, Henna Frabritius “Review of Digital Twins used for Urban Green-Blue Infrastructure”

2 Background

2.1 Description of the Study Area

The Republic of Estonia, with Tallinn as its capital, is located in Northern Europe on the shores of the Gulf of Finland and the Baltic Sea. The area of Tallinn is 159 km², and as of 1 June 2025, the city had a population of 460,986 (*e-population register*), accounting for 33% of the national population. Greenery covers 55.5% of the area of Tallinn, and 22.2% of it includes publicly accessible green and landscaped areas. The largest category entails forest land, which encompasses a total of 3,121.44 hectares.

In Tallinn, the ratio of vegetation-covered area (including both private and public green spaces, measured in square metres) per capita has been decreasing. In 2005, the indicator was 231.4 m² per resident (*Tallinna haljastu tegevuskava aastateks 2013–2025, 2013*) However, by 2023, it had declined to 192.96 m² per resident (*TAR*), which represents a reduction of 38.44 m² per person.

Tallinn is a city with a long history, having been granted town rights in 1248. Its landscape is diverse—in addition to its coastal location, the city is traversed by a river and includes several lakes as part of its water features. A significant green area is formed by an island located in the bay. The city's topography is further enriched by bogs and the North Estonian Klint that runs through the urban area.

The history of urban greenery in Tallinn dates back to the medieval period (Tallinn et al., 2024), when the city had three public gardens: the Rose Garden (Roosiaed), the Parrot Garden (Papagoiaed), and the Old Garden (Ammuaed). Records from the 16th century provide the first evidence of private gardens located beyond the city walls, which evolved from orchards into ornamental gardens. In the 17th and 18th centuries, green spaces were established as protective zones for the city's bastions; thus, the formation of the Ringpuiestee began—its remnants now form some of Tallinn's main streets.

In the 18th century, Peter I founded the baroque park of Kadriorg. During the 19th century, urban greenery became associated with public hygiene and health concerns: green zones were established around the bastion belt (Figure 1), and the first public parks were created in Toompea, the Falgi area, and along the city esplanades. The development of Kaarli Boulevard also dates from this period. Green areas in the Old Town, such as the Danish King's Garden and Kitse Park, emerged later. By the end of the century, new parks were laid out in suburban garden districts, including in Nõmme.

Park development continued in the 20th century: throughout the 1920s and 1930s, centrally located green areas and forest parks were introduced in residential garden suburbs. After World War II, many ruins were transformed into parks, contributing to the design of the so-called "green cross." Cemeteries around Tallinn were converted into public parks.

During the 1950s to 1980s, green areas were systematically developed in new housing districts. Following the restoration of independence, a number of smaller parks and green spaces were added alongside new developments. Forested areas have also played a significant role. In the 20th century, these forest zones were established through targeted planning, reaching over 36,000 hectares by the 1990s. Nevertheless, as of 2012, only about 1% of Tallinn's total area was municipally owned forest land, despite the city's efforts to bring forest areas into municipal ownership. In summary, the development of greenery in Tallinn reflects a long and multi-layered history, in which green spaces and forests have played a vital role in shaping the city, enhancing the quality of the urban living environment, and preserving natural heritage.

Figure 1. Development of the bastion zone – top map from 1825 (Tallinn, et al. 2024)) and below an extract from a 2025 orthophoto (Land and Spatial Development Board).

In addition to its diverse landscape, Tallinn is a city of significant nature conservation value. The urban environment is characterized by exceptional ecological diversity, encompassing a wide range of landscapes and ecosystems, including forests, meadows, coastal areas, and marine habitats. These environments are vital for the preservation of numerous plant and animal species, some of which have become rare elsewhere in Europe (*Tallinn European Green Capital 2023 application*, 2023). In the context of population growth, access to green spaces is of increasing importance, serving essential ecological, social, and recreational functions.

The city contains 61 officially designated parks and 131 registered green areas, offering diverse opportunities for both nature conservation and the well-being of residents.

The ecological and functional diversity of urban greenery is further reflected in the high proportion of protected areas—approximately 19.5% of Tallinn's territory (3,106.8 hectares) is under protection at either the national or local level. Nearly one third of this consists of green areas under local protection, which underscores the city's commitment to preserving natural values and strengthening ecological networks.

Over the past decade, residential developments in Tallinn have covered approximately 3% of the city's total land area, and around 70% of this development was realized through the densification of the existing urban fabric. This pattern has manifested in construction on individual vacant plots and the subdivision of larger land parcels into smaller development units. In the central district, the population has increased by approximately 25% during the same period, corresponding to more than 13,000 new residents. This population growth has been achieved primarily through a more compact spatial structure, while public green areas have been preserved. In new urban developments, green spaces are planned only to a limited extent, while pressure to build on existing green areas, including forests, is increasing. The most significant changes over the past decade have occurred in the districts of Pirita and Haabersti, where vegetated areas decreased by a total of 167.8 hectares between 2012 and 2020, averaging a loss of 21 hectares per year (*Kliimaneutraalne Tallinn. Tallinna säästva energiamajanduse ja kliimamuutustega kohanemise kava 2030*, 2021).

The responsibilities, organization, and relationships of local governments, including the City of Tallinn, other municipalities, and the state, are defined by the Local Government Organisation Act (*Kohaliku omavalitsuse korralduse seadus*, 1993). This legislation establishes key principles of local governance, including autonomous decision-making, legal compliance, citizen participation, accountability, transparency, protection of rights, and the efficient provision of public services. The Act mandates that municipalities organize a wide range of local services, such as social welfare, elderly care, cultural, sports, and youth programs; housing and utilities management; public order; waste management; water supply and sewerage; spatial planning; public transportation; and the construction and maintenance of roads. Additional responsibilities may be assigned through other legislative acts. Municipalities are also required to prepare a development plan and a budget strategy to guide cross-sectoral development. The development plan must analyse environmental and demographic trends, identify key challenges and opportunities, and define strategic goals along with the necessary actions to achieve them.

At the end of 2020, the Tallinn City Council adopted the city's new development strategy "Tallinn 2035" (Arengustrateegia Tallinn 2035, 2025). The document sets out the city's vision—Tallinn, Green World City. The whole idea of the vision is strongly linked to greenery and the green transition. It sets out six strategic objectives and fourteen areas of action through which the city aims to achieve its goals.

The 'Cityscape' strand contributes to the strategic objectives 'A Friendly Urban Space', 'A Healthy Tallinn Moves', 'Green Turnaround' and 'A Home that Starts at the Street'.

In addition, one of the activities in the Urban Governance Action Programme is data-driven governance. In explaining this, the availability and use of key data, the one-off collection of data and the principle of collecting data on an as-needed basis are described as important. For this work, the principle that the city makes and explains decisions in a data-driven way is important. The development of a 3D model of the city (the digital twin) and the availability of information for decision-makers in order to make management decisions are identified as lines of action.

One of the principles for the implementation of the Urban Landscape policy area is to build on the integrity of the green life cycle. The action programme for this area is the Smart Green Life Cycle (Figure 2), and the action line is the intelligent management of green spaces and the collection and management of data on them.

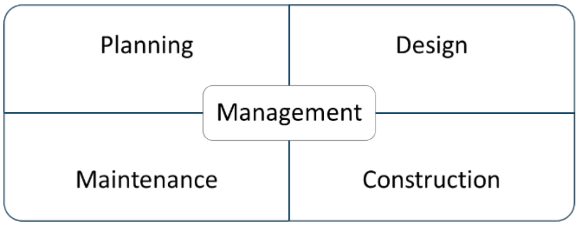

Figure 2. Life cycle of greenery.

The need for data for decision-making or management to implement the Tallinn strategy is described in several places. Data, as decisions need to be based on them, are also necessary for the quality of the city's green life cycle management set out in the Urban Governance Action Programme. One of the principles of data collection is that only the necessary data are collected.

In order to address environmental challenges, the Tallinn City Council adopted the *Environmental Strategy of Tallinn until 2030* on 16 June 2011 (*Tallinna keskkonnastrateegia aastani 2030*, 2011). This strategy sets long-term sustainability goals and outlines actions to ensure a high-quality living environment and responsible use of natural resources.

Biodiversity and Urban Greenery

The strategy highlights that, while Tallinn contains valuable protected and green areas, insufficient research on ecological conditions and connectivity poses risks to biodiversity. The absence of systematic monitoring has resulted in a fragmented understanding of nature’s condition. Ecosystem services are often overlooked during decision-making, and biodiversity data remains scattered. Conservation efforts are mainly formal and weakly enforced.

The city’s green areas—including forests, parks, residential greenery, street vegetation, and cemeteries—are unevenly distributed and vary in quality and connectivity. Many spaces have been neglected and underfunded. Key issues include undervaluation of greenery, inadequate maintenance and restoration, and insufficient data on optimal greening levels. Green infrastructure is often excluded from urban design, and new green areas are rarely planned. Current development further limits public access and fragments the green network.

Urban Planning and Environmental Considerations

Urban densification, particularly in the city center, has reduced space for greenery and contributed to suburban sprawl. Environmental impact assessments are conducted, but their influence on planning decisions remains limited. Car-centric planning has led to environmental degradation and further loss of greenery. Detailed plans frequently alter land use without adequate environmental consideration. However, there is growing recognition of the importance of early-stage environmental assessments and the protection of natural areas.

Strategic Vision for Greenery

The strategy envisions treating urban greenery as infrastructure on par with built systems. Green areas should be cohesive, well-maintained, and promote a healthy, biodiverse urban environment. Strategic goals include maintaining environmental quality, promoting public health, and preserving biodiversity through a functional green structure. Key measures include:

- conducting biodiversity inventories and drafting action plans;
- improving the maintenance of green infrastructure;
- enhancing environmental monitoring and awareness;
- integrating habitat protection into planning;
- developing area-based assessments and a greenery development plan.
- strengthening information systems and improving forest and park management; and
- increasing street greenery diversity and quality.

The strategy also emphasizes the need for updated regulations, professional training, and public engagement to support effective green space management.

Climate Change and Resilience

In order to further address climate change, the Tallinn City Council adopted the *Climate-Neutral Tallinn: Sustainable Energy and Climate Adaptation Plan until 2030* on 3 June 2021 (*Kliimaneutraalne Tallinn. Tallinna säästva energiamajanduse ja kliimamuutustega kohanemise kava 2030*, 2021). Aligned with the Tallinn 2035 strategy and the European Green Deal, the plan aims to achieve climate neutrality by 2050 while enhancing green infrastructure, biodiversity, and public health. Over the past 40 years, average temperatures in Tallinn have risen steadily, and the number of annual heatwaves has doubled. Although precipitation has not increased significantly, the growing extent of impermeable surfaces has caused urban flooding and stormwater management issues. The green network remains fragmented and unevenly distributed. If current development volumes proceed as planned, a substantial reduction in greenery is expected, including a projected 10% decline in tree canopy coverage—leading to reduced ecosystem services.

The plan considers global trends such as urbanization, migration, technological advancements (e.g., AI in urban planning), and open data to enhance decision-making. It calls for both new and existing solutions in transport, construction, energy, and land use, which include:

- green roofs and vertical greenery;
- increased tree planting;
- public awareness campaigns; and
- adaptive land use to improve the resilience of infrastructure.

Compact development can free land for nature, while impervious surfaces can be used for stormwater buffering, benefiting biodiversity. Key climate risks identified include heatwaves, heavy rainfall and flooding, and the spread of pathogens. Land use regulation plays a central role in adaptation, particularly through green space requirements and limits on impervious surfaces. Priority actions include:

- expanding public green spaces and street greenery;
- applying minimum green area ratios in master plans;
- introducing the green factor concept and pilot areas;
- promoting permeable surfaces;

- researching climate-resilient plant species; and
- implementing strategies to mitigate the urban heat island effect.

Ecosystem and Biodiversity Protection
The plan underscores the importance of biodiversity and cohesive green networks for resilience. It calls for improved ecosystem data and monitoring through cost-effective, innovative methods like automated and image-based systems. Key actions include:

- mapping habitats and species;
- assessing green space connectivity and light pollution;
- engaging citizens in biodiversity mapping and pilot projects.

Under the Local Government Organisation Act, municipalities can prepare sectoral development plans. Tallinn adopted its first *Urban Greenery Development Plan* in 2005, followed by the *Tallinn Urban Greenery Action Plan 2013–2025* (Tallinna haljastu tegevuskava aastateks 2013–2025. 2013.), led by the author of this doctoral thesis. This plan supports the broader *Environmental Strategy until 2030* and the *Tallinn 2035* strategy, focusing on urban greenery, nature conservation, and spatial planning.

Current Conditions and Key Challenges
Analysis reveals a decline in vegetated areas: between 2005 and 2012, 273.85 hectares of green space were lost, and 169.7 hectares of impervious surface were added. Challenges include:

- inadequate greenery in heritage areas;
- privatization of municipal green spaces due to land reform;
- biodiversity loss and degraded green infrastructure;
- poor condition of protected parks and limited species monitoring;
- ineffective Urban Greenery Information System due to data quality issues;
- underfunded park renovations and aging street greenery;
- limited expert involvement in planning and maintenance;
- fragmented governance and unclear responsibility for greenery; and
- chronic underfunding of maintenance and reconstruction.

Vision for 2025 and Recommended Actions
The 2025 vision presents Tallinn as a green, diverse, and aesthetically pleasing city supported by robust green infrastructure. Six long-term goals have been set:

- coordinated governance;
- a unified, transparent information system;
- systematic and well-funded maintenance;
- diverse and biodiverse urban landscapes;
- healthy, attractive living environments; and
- recognition of greenery as vital to urban life.

The implementation plan includes 101 actions: several are aligned with this doctoral thesis. Key recommendations:

- conduct governance analysis;
- improve the greenery information system to enable public input;
- create a public tree inventory;
- develop service level methodologies for maintenance;
- ensure district-wide consistency in maintenance commissioning;
- draft management plans for key parks and allees;
- develop a web-accessible database on habitats and species;

- promote universal design and assess mobility for people with special needs;
- monitor and manage plant diseases; and
- reconstruct parks and renew tree alleys.

The digital development of the City of Tallinn is guided by the forthcoming strategic document Digital Tallinn 2035, which builds on the digital objectives set out in the broader Tallinn 2035 strategy. The document focuses on two primary programme areas: human-centred service design and data-driven governance, along with the Smart City programme targeting the business environment. It is also aligned with the national Digital Agenda 2030, extending the concept of a digital state to address urban challenges.

While Tallinn's digital services are internationally recognized, an untapped potential to integrate more knowledge and solutions from the private and academic sectors into urban governance remains. Technologies such as chatbots, sensors, and real-time data enhance the delivery of public services. However, several challenges persist, including the partial implementation of information systems—many still rely on external tools for data collection or processing—and insufficient funding for development. Moreover, city systems depend heavily on national registries. Clear agreements are needed around open data management, data quality, storage, and inheritance to reduce administrative burden and ensure data accuracy. A critical issue concerns spatial data, particularly the lack of standardized rules for their collection, management, and use. One of the city's main IT priorities is to ensure access to high-quality data and facilitate its use to support data-driven decision-making and the automation of workflows.

In the environmental sector, the goal is to display current or real-time data on digital maps to enable environmentally sound, location-specific planning and project development. Digital construction and digital twins can enhance environmental protection by improving data interoperability, scenario modelling, and impact assessment—provided green infrastructure and protected species data are integrated into the system. In urban landscape planning, the objective is to base development and maintenance activities on the integrated spatial data, which requires linking various sectoral systems, such as the Tallinn City Repair, Maintenance and Landscaping Information System (HHHIS), Information System for Processing Permits for Excavation Work in Tallinn, Temporary Street Closures and Other Road Maintenance Work in the Area (OpInfo), and the Tallinn Spatial Data Register (TAR), to ensure all public space elements are represented. Digital construction and digital twins also enable more accurate spatial planning. A key issue in urban planning is the fragmentation of spatial data and the constant need for updates. By 2035, the city aims to make both surface and subsurface data readily accessible and to use digital tools more extensively for public engagement. The application of digital construction and digital twins is expected to improve the quality of spatial decisions and accelerate building permit procedures. In the domain of city governance, these tools will also support the green transition by enabling better planning for climate adaptation and mitigation—for example, modelling urban heat islands and flooding, or planning for greenery and infrastructure.

The vision of Digital Tallinn is to become an innovative and efficient city that integrates physical and digital environments, supports the green transition, fosters innovation, and enables data-driven governance. A key principle is that all digital services are based on prior service design, and new solutions are developed only when they add real value and are user-friendly. Cooperation with the national government is essential to leverage state-maintained data systems effectively. The city follows a "collect once, use many times" principle—gathering only necessary data with a clear understanding of its purpose, users, and timing.

Under the Data-Driven Governance programme, the city emphasizes the need for up-to-date and well-structured overviews of data and metadata. Information systems must be interoperable and comply with the national interoperability framework. Spatial data should be used effectively to generate value and support decision-making, with best practices applied to data collection and use. Data should be collected purposefully and automatically to avoid redundancy while maintaining quality and timeliness. Key actions include mapping and harmonizing duplicate datasets across systems, updating the TAR, and piloting new solutions in collaboration with universities. Reducing spatial data fragmentation and integrating it with non-spatial data are also strategic goals.

In digital construction and digital twin deployment, the objective is to digitize the city's construction and urban development processes. The Building Information Model (BIM) and digital twins are central to this transformation. By 2035, Tallinn aims to make data-driven decisions, enable seamless collaboration across planning and related sectors, and implement projects efficiently. Planned actions include developing a digital construction concept, creating an integrated data environment, advancing automated data collection, building forecasting tools using digital twins for early risk detection, and gradually transitioning to BIM-based planning and permitting.

Under the Smart City Programme, the city seeks to embed innovation into urban management and service development by 2035, which involves both technological advancement and broader change management. The city commits to agile development and collaborative models with universities and businesses. Automated system checks will reduce manual workloads, enabling more substantive decision-making and improved procedural efficiency. Priority activities include adopting new technologies, collaborating with universities to build digital expertise, raising awareness of new solutions, developing methodologies to integrate AI into service infrastructure, and systematically reducing digital waste.

2.2 Availability and Use of Urban Data

Strategic planning documents such as Tallinn 2035 and the Tallinn Digital Twin development framework emphasize the importance of data-informed decision-making. Effective urban management requires reliable, up-to-date information on vegetation growth, condition, required maintenance, and replacement planning. Accurate data is essential for efficient urban resource management. Both national and municipal information systems are used to manage public spaces. A key national platform is the Geoportal of the Estonian Land and Spatial Agency, which consolidates spatial data through a range of thematic map applications—including Land Information, Historical Maps, Engineering Geology, Legal Restrictions, Folklore Maps, Nature Conservation, and Urban Heat Islands. This publicly accessible tool is widely used by municipal staff, planners, architects, and landscape designers to obtain baseline spatial data.

Statistics Estonia also provides critical demographic information, such as population size, age and gender distribution, and temporal trends—essential inputs for future public space planning. These datasets are integrated into the Geoportal via thematic layers, such as a forest felling map that visualizes permitted logging activity by county and forest type. For construction-related data, the national Building Register serves as a centralized platform for managing and disseminating information about buildings in all stages—planned, ongoing, or completed. The register is publicly accessible and supports local governments in processing building-related documentation, including technical specifications and legal records. Tallinn offers around 600 public services, of which about two-thirds are e-services accessible via digital channels like self-service portals, tallinn.ee, mobile apps, or email. All services are uniformly documented in the Tallinn Service Database, which also serves as a gateway to digital services. In order to support these services, the city operates nearly 60 information systems and 35 data registers (Digitaalne Tallinn 2035, 2025).

In Tallinn, public green space data is distributed across multiple databases or collected in line with city regulations. One key repository is the Tallinn Spatial Data Database (*TAR*, s.a.), which supports the centralized collection, management, and sharing of spatial data within the city. TAR ensures seamless cooperation between systems and users, minimizes data duplication, and facilitates timely access to current information via standardized formats. It also underpins the production of the official Tallinn city map. The TAR metadata catalog includes information on public green areas (Table 1). However, from the perspective of this doctoral research, limitations include infrequent data updates and insufficient integration with other systems, which hinder effective data renewal.

Another important system is the HHHIS. Developed to support public procurement and monitor maintenance quality, HHHIS allows residents to access information about service areas, report issues, and submit complaints. It is a process-oriented system designed to improve workflow efficiency in public space management. Despite its utility, the system is hindered by the complexity of data entry and updates. Missing data cannot be easily added, preventing the initiation or management of corresponding tasks.

A third relevant document is the City Government's regulation, Procedure for Greenery Inventory (*Haljastuse inventeerimise kord*, 2020). This regulation aims to identify the locations of valuable and protected vegetation, as well as invasive species that threaten ecological balance, in order to guide decisions related to construction and infrastructure. The inventory must cover all areas affected by construction—public or private—where existing greenery might be impacted. Results are included in relevant planning and construction documentation and consist of tabular data and visual representations. Each object is assigned an ID number and categorized according to value classifications outlined in the regulation, enabling informed decisions in spatial planning and design to protect valuable vegetation. Inventory reports are stored in the Tallinn Planning Register or the National Building Register.

The author of this doctoral dissertation co-authored the updated version of this regulation. Under the earlier version, inventories were submitted in PDF format, containing a drawing and an unstandardized table of inventoried objects. The revised regulation requires submission of tabular data in Excel and drawings in both CAD and PDF formats, enhancing compatibility with existing spatial databases. However, one notable shortcoming persists: while the drawings include tree canopy extents (as polygons), they do not contain point data representing trunk locations. This omission hinders the ability to link graphical and tabular data effectively, suggesting a need to revise the technical requirements. From an information systems perspective, the structure and content of tree inventory datasets present a further challenge. A single tree may appear in three different databases, each assigning slightly different geographic coordinates. This undermines data consistency and complicates integration and usability across platforms (Table 1).

Table 1. Compares tree-related data contained in the TAR, HHHIS and the greenery inventory reports.

Data	Tallinn City Repair, Maintenance and Landscaping Information System (HHHIS)	Tallinn Spatial Data Register (TAR)	Procedure for Greenery Inventory
General data			
ID	X	X	X
Location (address)	X	X	X
Type of tree (deciduous, coniferous)	X		
Species name in Estonian and Latin, variety	X	X	X
Type of tree (street, park, alley)	X		X
Age in years (0-10, 20-60, 60-unspecified)	X		
Height in meters (0-5, 5-10, 10-15, 15-20, 20-25, over 25)	X	X	
Tunk diameter (cm)	X		X
Crown diameter (m)	X	X	X
Trunk height (m)	X		X
Conditions of the tree (very good, good, satisfactory, bad)	X		
Value class (I, II, III, IV, V)	X		X
Specialness (under nature protection, commemorative, remarkable copy)	X	X	
Inspection time	X		
Planting data in addition to General data			
Time of planting	X		
End of warranty period	X		
Seedling origin (country, nursery)	X		
Notes on the seedling	X		
Data on the place of growth (volume of growing soil, bearing growing medium, origin of soil)	X		
Irrigation system (existing/ non-existing)	X		
Support (support poles existing/ non-existing, metal or wooden)	X		
Trunk protection (yes or no)	X		
Mulching (yes or no, deciduous or conifer mulch)	X		
Data of an existing tree, in addition to General data			
Root system (13 differences)	X		
Stem (17 differences)	X		
Crown (10 differences)	X		
Notes	X		X
Symbol 3D (unspecified, yes, no)		X	

Among the three, HHHIS provides the most detailed information, as it is specifically designed for the management of public spaces. It includes data on both existing and newly planted trees, as well as records of completed maintenance activities. TAR contains basic tree attributes, such as whether a tree is deciduous, coniferous, or a fruit tree. The inventory reports focus on detailed parameters of existing trees. As shown in Table 1, all three systems share overlapping fields—such as tree ID, type, species/variety, trunk diameter, and canopy extent—revealing significant redundancy across the datasets.

2.3 The Intersection of Personal Motivation and Professional Experience in Defining the Research Focus

The author of this thesis has over 30 years of professional experience in the management of public greenery, ranging from the organisation of maintenance for various landscape elements and the implementation of reconstruction and replacement projects for the preparation of strategic planning documents. While working as the city gardener in Pärnu, she came to understand that the efficient organisation of daily maintenance tasks in public space requires appropriate digital tools. However, such tools are only helpful if reliable data exist about what is present or growing in the public realm.

Upon taking the position of city landscape architect for the City of Tallinn, the author's first assignment was to develop a strategic document for public greenery. During the initial analysis of the existing situation, it became evident that although the city had created a Tallinn Green Areas Information System (HIS) and made it available for use by the city districts, the data were not usable, which was due to inconsistency in data updates—some districts updated information as changes occurred in the public space, while others did not use the database at all. As a result, although the system technically contained data, they could not be used for meaningful analysis.

An analysis of greenery development in Tallinn revealed that many parks had been reconstructed in the past decade, yet the work remained incomplete in approximately half of them. Often due to overly ambitious design projects: once the reconstruction tender was carried out, it turned out that the city lacked sufficient funds to implement the whole project. Consequently, only part of the park would be rebuilt, and in the following year, resources would shift to a different green area.

While moving through the city, the author also observed that several recently reconstructed areas were already experiencing maintenance issues—both in terms of vegetation and infrastructure. Tallinn City Government uses a budget planning tool called the 'product card', which, according to municipal regulations, records the proportion of green space maintained to standard and the proportion maintained below standard. In principle, this enables the city to identify funding gaps in green area maintenance. However, questions arose about the origin of the figures used in these product cards. It turned out that each city district had independently defined what and how to maintain, with some figures dating back as far as 2005, when the original HIS was established. These figures formed the basis for annual budget increase requests, yet there was no clarity on the actual scope and intensity of maintenance, nor on the efficiency of resource use.

While preparing the strategic greenery document, the author came to the conclusion that in order to improve the overall quality of green space management, every stage of the greenery life cycle (Figure 2) needs quality enhancement. In the example of half-completed park reconstructions, this would have meant using the existing natural conditions more effectively, aligning design ambitions with available construction budgets, and considering future maintenance needs.

All of the above prompted the idea of redeveloping the HIS to meet practical needs better. However, it became clear that the existing system was outdated and had been developed in stages without a coherent goal. As a result, the City of Tallinn made the decision to create a new integrated information system—covering HHHIS, to consolidate all information related to public space and to support the full range of functions required for its maintenance, such as preparing procurements and monitoring service quality. One of the features developed in this system was a public reporting tool, enabling residents to report problems directly related to the urban environment. For efficiency, the reports would be forwarded directly to the responsible official and their service contractor, thus avoiding the need for phone calls or emails.

Participating in the industrial PhD programme has provided a valuable opportunity to examine the challenges of urban greenery management critically and to propose at least one potential pathway toward more effective governance. One possible solution for better collection and cross-use of data related to landscaping emerged while working on the creation of dynamic models of trees, shrubs, and growth types within the Green Twins project. The solution for Tallinn to achieve its development goals would be as follows:

The elements of public green areas can be divided into natural and artificial environments; the natural components are further categorized into individual plants and plant groupings. Plant identification is based on taxonomy and includes the species name (including the Latin name) and, where applicable, the cultivar designation. For plant communities, site types are used for characterisation, following in Estonia the classification developed by Paal (Paal, 1997).

The artificial environment of public green areas includes elements such as roads, fountains, lighting fixtures, benches, and waste bins. These elements can already be managed within BIM (Building Information Modelling) environments and digital twins, and in Tallinn, such components are geolocated within the municipal HHHIS. Upon reviewing the CCI (Construction Classification International) classification system used in BIM environments in Estonia, it becomes evident that codes for artificial structures have been defined, as greenery and trees are included under natural elements. However, there is currently no coding scheme for the identification of planting material. Since most construction projects include both natural and built elements, it is not possible to fully implement such projects in BIM without accommodating natural components.

To bring natural and artificial elements into the digital domain, including data collection, it is essential first to identify each object and assign it a unique identifier (ID). For natural components, this must also include the Estonian and Latin names of the plant. As a first step, it is necessary to develop an extension for the CCI coding system to cover both plants and site types. In the context of public space management, it is sufficient if the codes for plant species comprise the family, genus, species, and cultivar components. For site types, Paal's classification provides a suitable basis, as it already includes codes for various site types. According to this classification, in addition to forest, meadow, mire, cliff, dune, and sandy vegetation types, urban environments also include ruderal and lawn site type communities.

During the GreenTwins project, site type classification in the test areas revealed a challenge related to the categorisation of parks and orchards. In collaboration with experts, it was concluded that the site type "park" should be further divided into three subtypes: dry, moderately moist, and wet.

Once CCI coding systems have been developed for plants and site types, they can be integrated into BIM environments or the city's digital twin. By examining the stages of the green infrastructure life cycle alongside the use of CCI codes (Figure 3), it becomes possible to incrementally collect accurate data and apply it consistently across different phases of the green space life cycle. Compared to other cities, Tallinn benefits from a regulatory advantage through the existence of the local ordinance "Procedure for Greenery Inventory", which requires the preparation of a vegetation inventory for any area subject to a planning or design process prior to the development of the respective plan or project. As a result of this requirement, the city obtains accurate data regarding the presence and condition of existing vegetation, which can then be utilized throughout subsequent planning, design, and management processes.

In the City of Tallinn, spatial data are collected, stored, and managed within the TAR. A review of the metadata catalogue and data structure of the register—including tree-related information (Table 1)—reveals that the available data and their level of precision are insufficient for managing the green infrastructure life cycle. Furthermore, there is currently no cross-utilisation of data between TAR, HHHIS and the results of greenery inventories.

A situation has emerged in which, for example, adding or removing a tree from the map may require the involvement of up to three different individuals, even though accurate data are already available in the inventory reports or derived from service requests in the HHHIS (e.g., tree removal orders). Since the Tallinn base map is generated based on TAR, it does not require precise data. However, for the purpose of managing public spaces, the city requires more detailed information, which can technically be generalized for mapping purposes (e.g., different forest site types may be displayed collectively as "forest" on the map).

The coding system developed for plants and site types can be applied across municipal institutions, such as the Tallinn Botanic Garden. The data collection and cross-utilisation framework illustrated in Figure 3 helps eliminate redundant data gathering and entry, and enables the city to make decisions based on continuously updated, high-quality information.

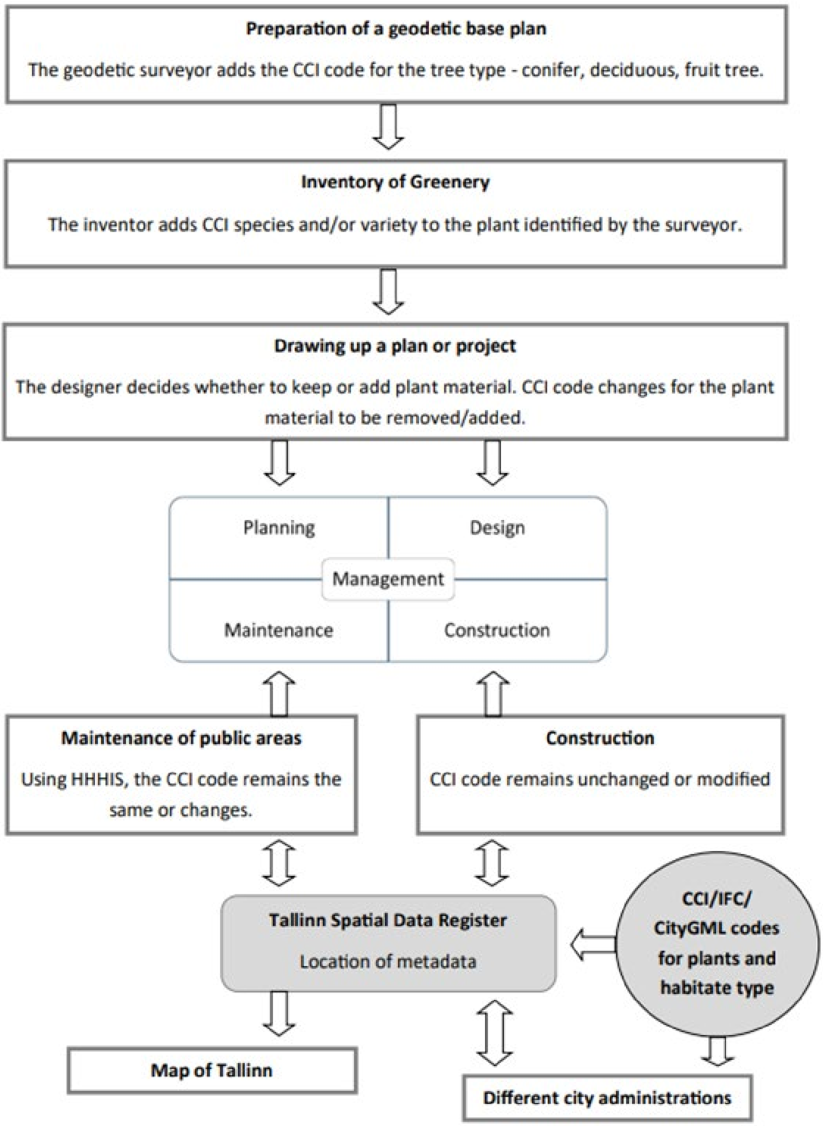

Figure 3. Possible solution for the movement of data related to landscaping in Tallinn.

2.4 Literature Review

The purpose of public green spaces in the city is not just to provide aesthetics, but they have an important connection to the health of citizens. The simplest links are between green spaces and physical health (Eichinger et al., 2015; Roemmich et al., 2018), but there is also evidence of a strong link between green space use and mental health (Gidlow et al., 2016; Wood et al., 2017) that foster social cohesion and community belonging (II; Peters et al., 2010) through exposure and participation. Natural environments support environmental health through air quality and climate adaptation (Cohen et al., 2022). Studies show the economic links and benefits between the existence of green spaces, their accessibility and the health of the population (Bedimo-Rung et al., 2005; Buckley & Brough, 2017).

Urban planning needs to strike a balance between densification and the preservation of public green spaces to design a city that is resilient to climate change (Heidt & Neef, 2008; Krueger et al., 2022). One of the challenges posed by climate change is the loss of biodiversity (Biodiversity Strategy for 2030. 2025) and with it a decline in the quality of life in cities (McKinney, 2008; United Nations, 2015). Public green spaces will enable the city to better cope with flooding from heavy rainfall (Cohen et al., 2022) and mitigate the effects of heat waves and islands (Depietri et al., 2012; Krueger et al., 2022).

Cities compete to attract people, workers or businesses. One of the advantages for the competitors is the availability and quality of public green spaces (Trust for Public Land, 2024).

The creation, reconstruction, and management of public spaces require fundamental data: where spaces are located, what they consist of, and the characteristics they exhibit (I). Over time, the methods of data collection and record-keeping have undergone significant transformation. Earlier efforts relied on manual surveys and static records (I), whereas today, advancements in technology have enabled more dynamic, high-resolution, and real-time data acquisition (III). With these developments, data has become a powerful tool in informing and enhancing the management of public spaces through evidence-based decision-making (Biljecki et al., 2015; Galle et al., 2019). It supports real-time monitoring, diagnostics, and forecasting, enables realistic behavior in simulations and ensures continuous bidirectional synchronization between the physical environment and its digital twin (Grieves & Vickers, 2017).

In working with data, it is crucial to collect only what is necessary and to ensure its potential for cross-functional use (I). However, as technical capabilities continue to evolve, a key question persists: what types of data will be needed to fully leverage emerging technologies (III; Zhang et al., 2021)? Data collection frequencies also vary considerably, ranging from near real-time or continuous acquisition using technologies such as Radio-Frequency Identification (RFID), Internet of Things (IoT) devices, and the Global Positioning System (GPS) (III), to periodic annual updates (Tanhuanpää, 2016) and irregular ad hoc inputs (I; Mongus et al., 2021).

The design of urban space must consider the multiple layers—technical, environmental, and social—that have developed over time. Longitudinal data is therefore essential for navigating these complexities and enabling informed planning and intervention (I). Moreover, diverse datasets are necessary to ensure urban spaces are inclusive. Understanding who the future users are and anticipating their needs is a critical component of the planning process (II).

An increasing number of research articles are being published on digital twins (III). As a relatively new and evolving technology, digital twins are often described as 3D or digital models. In this thesis, the term digital twin refers to the concept described by Kritzinger (Kritzinger et al., 2018; III), where synchronization between the physical and digital worlds is achieved either through manual data input or the use of automatically collected data.

Initially introduced in industry and manufacturing (Grieves & Vickers, 2017), digital twin technology has since expanded into various other domains, including agriculture (Purcell & Neubauer, 2023; Pylianidis et al., 2021), forestry (Hejtmánek et al., 2022), urban environments (Ferré-Bigorra et al., 2022; Lehtola et al., 2022), ecology (Trantas et al., 2023), and biodiversity (Khan et al., 2024; Sharef et al., 2022).

Experts from a range of disciplines contribute to the development of digital twins. These include professionals in landscape architecture (Luka & Guo, 2021), urban planning

(Shu et al., 2022), geoinformatics, computer science (Shu et al., 2022), as well as representatives from agriculture (Majore & Majors, 2022), agronomy (Skobelev et al., 2022), forestry (Buonocore et al., 2022) citizen engagement and education (Harrington et al., 2021).

The integration of vegetation into digital twins is an emerging trend (III). Within the context of the greenery life cycle (Kupper, 2014), digital twins can support the management of urban public spaces. For example, they can be used to generate dynamic tree models that incorporate species-specific characteristics (Gobeawan et al., 2018, 2019, 2021), to monitor and maintain tree or forest attributes (Mongus et al., 2021; Tanhuanpää, 2016), and to address issues related to tree root systems (Luka & Guo, 2021).

When examining digital twins of greenery, the user base is notably diverse. Dynamic models are utilized by researchers (Shu et al., 2022), municipal authorities (García-Granja et al., 2020), architects, landscape architects, urban planners (Fabritius et al., 2023; Fernández-Alvarado et al., 2022), as well as by citizens (Johannsen et al., 2021) and learners (Harrington et al., 2021).

Based on written sources, the founding of Tallinn can be traced back to 1219 (Alttoa et al., 2019). However, the history of the city's public green spaces extends even further, with origins in the medieval period (Kala et al., 2019; Tallinn et al., 2024). The evolution of Tallinn's urban form has long involved the preservation and use of varied landscapes, as evidenced by historical maps dating back centuries (Raid, 2011). A particularly significant example is the bastion belt surrounding the Old Town, which, along with associated defensive structures, has been preserved as an integral part of the city's green heritage (Vilbaste & Kenkmaa, 1965).

The first extensive written overview of public green areas in Tallinn, including photographic documentation, was published in 1932 (Viirok, 1932). Since then, the Tallinn Botanic Garden has played a leading role in conducting multi-scalar assessments of the urban environment. Key efforts include evaluations of urban ecosystem health (*Tallinna ökosüsteemide seisund*, 1981) and planning studies for areas such as the Old Town (*Uurimistöö Tallinna Vanalinna haljasalade planeerimiseks*, 1982) and Lasnamäe's residential greenery (*Uurimistöö Lasnamäe elurajooni haljastuse planeerimise aluste kindlaksmääramiseks*, 1983). In 1996, the city established guiding principles for developing a coherent green space system (Levald, 1996), advocating for a holistic and interconnected approach that aligns with Tallinn's structural, cultural, and natural heritage. These principles emphasize responsiveness to recreational and demographic needs while remaining flexible and compatible with regional development strategies.

Studies on Tallinn's woody vegetation have become increasingly granular, tracking spatial patterns and botanical diversity across districts. In 1991, researchers documented 637 woody plant taxa in the city; this number rose to 840 by 1996 (Sander et al., 1991, 1996). Subsequent investigations have examined the composition and distribution of urban flora in specific districts and neighborhoods, including the Old Town (Sestakov, 1986), Toompea (Kukk, 1996), the Süda and Kalamaja areas (Elliku & Tarand, 1986), the Nõmme forest (Ploompuu & Soekov, 1996), and suburban manor sites within city limits (Tamm, 1986). A significant update to this line of inquiry was the 2021 survey of the bastion green belt, aimed at identifying preserved landscape architectural and ecological values (AB Artes Terrae OÜ, 2020). Complementary studies have explored the development, condition, and spatial configuration of Tallinn's urban forests, providing management recommendations grounded in ecological assessment (Pärn, 1990; Pärn & Martin, 1996; Ratas, 1986; Rauk, 1996).

Parallel research efforts have examined the condition and health of Tallinn's trees, including assessments of vitality, disease, and age structure (Normet, 1986b, 1986a). Given that the planting dates of older specimens are frequently undocumented, methods for estimating tree age have been developed (Sander & Läänelaid, 2008). Other studies have investigated the health and species composition of trees along central streets (Tarand, 1986), while specific attention has been given to the historically significant tree alleys surrounding the Old Town (Tamm, 1981). Notably, species-level studies have included work on ornamental cultivars such as the Chinese poplar 'Fastigiata' (Populus simonii) (Sander & Eensaar, 1990).

The topic of tree felling and replanting has also received long-standing attention. Research has documented both the spatial distribution of tree removal and the underlying motivations (Sander, 1986). In 1991, Reinvald proposed a method for the economic valuation of trees, which later informed the city's current regulation on compensatory planting (*Raie- ja hooldusլõikusloa andmise kord*, 2021). Meanwhile, Tallinn joined the "Pesticide-Free Towns" initiative in 2018 (*Pesticide Free Towns*, s.a.), building on earlier efforts to understand species interactions in urban planting schemes (Kruus, 1986). A recommended list of tree and shrub species suited to urban conditions, first published in 1991 (Aaspõllu, 1991), was updated and institutionalized through the city's planting guidelines (*Avalikule alale puude istutamise kord*, 2011).

Other aspects of Tallinn's vegetation have also been studied, including vertical surfaces and herbaceous plant communities. For instance, the number of climbing plant species used in the city rose from two to thirty-three over time (Elliku, 1986), while multiple investigations have addressed patterns in herbaceous flora and plant community succession (Saar, 1986; Saar & Zernask, 1986; Zernask & Liik, 1986).

However, lifecycle management of urban greenery remains underdeveloped as a field of academic research. Although the Urban Greenery Design and Construction Handbook (Tuul, 2006) addresses elements of public space design, it largely omits maintenance considerations. A more practice-oriented guide (Jürisoo et al., 2014) offers definitions, typologies, and maintenance guidance for green spaces, but does not provide an overarching framework for the organizational management of maintenance activities.

Recent attention has turned to climate resilience and its implications for urban planning in Tallinn. The Tallinn Urban Heat Island Mapping 2021 study underscores the growing importance of mitigating urban heat risks, particularly as climate change is projected to increase the frequency and severity of heatwaves. By the end of the century, such events could lead to an estimated 1,000 premature deaths annually, primarily concentrated in Tallinn due to urban density (Sammul et al., 2015). One of the main contributors to the urban heat island effect is artificial ground cover, and between 2014 and 2021, related conditions have worsened in districts such as Haabersti, Mustamäe, Lasnamäe, and the Central District (Sepp & Sagris, 2021).

Closely related to these environmental concerns is the digitalization of urban planning processes. Studies have shown that building lifecycle data and digital infrastructure are vital for improving urban governance. Effective planning requires that facility management data be reintegrated into the early design and planning stages, a feedback loop made possible through open data and digital twin systems. Nevertheless, this bidirectional flow remains poorly implemented. Most existing research isolates lifecycle phases, contributing to inefficiencies and data loss. A more integrated alternative involves the adoption of a central digital twin—a real-time data hub that enhances transparency, regulatory compliance, and operational efficiency throughout a building's lifecycle. By drawing on public registers, digital twins can support accurate and timely planning, construction, and maintenance processes. However, significant barriers remain, particularly in integrating legacy data with newer digital systems (Raitviir & Lill, 2024).

Recognizing the potential of digital tools in managing urban green infrastructure, a recent survey involving Tallinn city officials identified eight key user groups of digital green infrastructure models—including planners, landscape architects, and citizen activists—each with distinct but overlapping needs (Fabritius et al., 2023). Some stakeholders require simulation models for plant growth and environmental response, grounded in localized empirical data. Others prioritize seasonal visualization or real-time updates, which depend more on robust data structures than on forecasting. Overall, dynamic, data-driven approaches are increasingly recognized as essential for inclusive, adaptive, and evidence-informed urban planning.

Tallinn city officials participated in a survey regarding the use of a digital twin (Fabritius et al., 2023). The study identifies eight main user groups of digital urban green infrastructure models—such as planners, landscape architects, and citizen activists—with overlapping but varied needs. Many needs require simulation models for growth and environmental response, relying on localized empirical data. Others, like seasonal visualization or real-time updates, need better data structures but not predictions. Overall, dynamic, data-driven models are key to informed and inclusive urban planning.

3 Methodology

This chapter presents methods in three focus areas corresponding to the published articles and explores appropriate data needs, usage and analyses for past, present and future outdoor spaces.

3.1 Methods for Studying Historical Areas

To explore historical public urban spaces, historical sources were consulted to gather information on the establishment and development of specific sites. For areas such as parks, squares, streets, and villages, historical maps served as particularly important research tools. Many Estonian scholars specializing in outdoor spaces and landscapes (Kaplinski-Sauk et al., 2023; Nurme, 2019; Nutt, 2008) have relied on historical map materials preserved in the National Archives. These cartographic sources provide crucial spatial and locational information regarding features such as buildings, roads, and tree stands.

This dissertation focuses on Kaarli Boulevard, located in central Tallinn, as the selected historical case study. Relevant maps were sourced from the Estonian Historical Archives, the National Library of Estonia, the Tallinn City Archives, and the Tallinn City Museum. In addition to maps, photographic materials were analysed to clarify aspects that were unclear or missing from the maps.

Photographs were obtained from the Estonian Historical Archives, the Estonian History Museum, and historical newspapers. While these materials offered insights into the origin, location, and spatial development of the site, dendrological information was analysed through existing tree inventory studies. As one of Tallinn's oldest alleys, situated in the city's historical core, Kaarli Boulevard has drawn considerable attention over time. It was assumed that numerous dendrological surveys conducted during the Soviet period would provide valuable information and allow for the reconstruction of the site's landscape history. These materials mainly were handwritten and dispersed across various archives and libraries (e.g., Tallinn Botanic Garden, Tallinn City Government) or preserved in private collections (e.g., by the study's author or their descendants). Consequently, compiling these materials was time-consuming. Upon review, it became evident that, despite promising titles, most studies were not comprehensive inventories. Instead, they focused on select features, such as the diameter of the largest tree or records of tree removal during tunnel construction. Based on the materials collected, an overview of the historical development of Kaarli Boulevard was constructed.

More recent studies, housed in the Tallinn City Government archives, are more detailed and contain tree-level data. However, inconsistent methodologies prevent these studies from being used for longitudinal analysis. Some assessments were subjective and dependent on the individual author's experience and knowledge, resulting in varying evaluations (e.g., the health condition of certain trees was reported to have improved over time).

Their titles guided the preliminary selection of written sources. Sources chosen for further analysis included keywords such as: vegetation, trees, trees in the city centre, felling, and tree stands. The analysis focused on discussions of Kaarli Boulevard, tree health, and influencing factors. During dendrological studies, the date, author, and methods used were documented. Since inventory reports often contain both textual descriptions and site plans with tree ID numbers, it was possible to associate descriptions with individual trees in the field. In the final stage, all relevant data on the condition of trees along the boulevard were analysed to assess whether these datasets could support accurate monitoring of individual tree health. The structure of tree-related data in the city was assessed based on the HIS, HHHIS and Greenery Inventory Procedures.

In summary, while historical public spaces have garnered considerable attention, the number of suitable sources was lower than initially expected, and their quality varied significantly. Furthermore, the historical record is incomplete, requiring researchers to be critically evaluative and mindful of informational gaps.

3.2 Methods for Studying Contemporary Public Spaces

Historical methods are not applicable to newly constructed public spaces. For contemporary areas, fieldwork proved to be the most effective research method and was accordingly employed in this study. Field investigations were conducted on site with the aim of evaluating how well newly developed public spaces meet the needs of the target population.

The study focused on ten Estonian town centres that were redeveloped under the "Great Public Space" architecture programme, initiated to celebrate the Republic of Estonia's centenary. The competition, held between 2014 and 2017 across 15 towns, aimed to revitalize central public urban spaces by 2020. Ten completed sites—squares and/or streets—were selected for evaluation. In preparation, a fieldwork methodology was developed, including a checklist and evaluation criteria. Given Estonia's aging population, especially in rural and small urban areas, the central research question was whether these newly developed public spaces accommodate the needs of older adults.

The method Placemaking for an Aging Population: Guidelines for Senior-Friendly Parks (Loukaitou-Siders et al., 2014) was adapted to the Estonian context and supplemented with age-friendly city principles (Gamme & Anne Berit, 2020). Ten design principles were used: control, choice, safety and security, accessibility, social support, physical activity, contact with nature, aesthetics, and sensory enjoyment. A binary scoring system was applied: "1" (yes), "0" (no), or "NA" (not applicable). Assessments were carried out during the summer by two landscape architects. Results were analysed through team discussions. Field data were recorded in tables, supplemented with notes and photographs, and entered into an Excel spreadsheet for analysis. Comparative analysis identified the most problematic thematic areas. Although time-intensive, this method produced accurate and comprehensive insights, making it well-suited for evaluating contemporary public spaces.

3.3 Methods for Studying Future Public Spaces

To investigate the future of urban spaces, this study examined how data-driven tools and digital twins can support sustainable planning and management—particularly by integrating ecological complexity and diverse user needs into urban decision-making. A systematic literature review was conducted following the PRISMA 2020 framework (Page et al., 2021).

In the first stage, search terms were defined. Given the relative novelty of the digital twin concept, "3D city model" was used alongside "digital twin" to capture relevant studies not labelled explicitly as such. Additional keywords included: biodiversity, ecology, greenery, green area, green infrastructure, species, urban landscape, vegetation, and wildlife. The ambiguous term "green" was excluded. Searches were conducted on 18 May 2022 and 28 February 2023 across three databases: Web of Science, ScienceDirect/Scopus, and Google Scholar. Google Scholar results were downloaded using the "Publish or Perish" software (Harzing, 2010), and the top 250 results were selected for further analysis. Articles were time-limited to appear after 1.01.2015.

After removing duplicates, the remaining records were compiled in Excel. Non-English entries, videos, and websites were excluded. Studies discussing 3D models with digital twin characteristics were retained. The analysis proceeded in three stages: title screening, abstract screening, and full-text analysis using the web-based software Atlas.Ti.

A total of 38 articles were selected for in-depth review. In order to answer the research questions, the following aspects were analysed: annual publication trends, authors' countries, disciplinary focus, and potential user groups. Articles were categorized into the following areas:

- trees and Forest Modelling;
- natural Environment and Ecosystem Preservation;
- virtual Interaction and Education;
- vegetation-related Microclimates and Aerobiological Exposure Risk;
- open-Field Agronomy;
- controlled-Environment Agronomy; and
- vegetation Data and Information Management.

Content analysis, performed using Atlas.Ti and a code system based on the research questions revealed how data are collected and used, existing challenges, instances of cross-application, and the types of models developed and by whom. Although time-consuming, this systematic review provided a comprehensive understanding of the digital twin concept, its current state, and its potential applications in future urban space governance.

This doctoral study employed a range of methods to analyse the management of public green spaces across historical, contemporary, and future contexts. Despite the breadth of the approach, several methodological challenges emerged, affecting the usability of data and the generalisability of results. Historical data—such as tree inventories and maps—were fragmented, often incomplete, and lacked standard formats or spatial references. Fieldwork on contemporary public spaces was time-consuming and relied on expert assessments, introducing a degree of subjectivity. In the forward-looking analysis, conceptual ambiguity and a lack of standards in modelling ecological information digitally became apparent. Data interoperability was limited, with no common framework in place.

The main barrier was the lack of institutional collaboration and data harmonisation, which hindered evidence-based decision-making. Nevertheless, the study identified key data gaps and proposed directions for improved urban public space management.

4 Results and Discussion

This chapter outlines the study's principal results, discussing how they respond to the research questions and contribute to existing knowledge on sustainable public space management and digital tools.

RQ 1: To what extent is the data on urban green infrastructure collected sufficient and reliable to support management of public spaces?

The case of Kaarli puiestee shows that data on urban trees has been collected over time through maps, photos, and dendrological surveys. However, this data is scattered across archives, varies in format, and is often difficult to access. Methodological inconsistencies and subjective assessments limit comparability between surveys, making it challenging to use historical data for long-term monitoring or management decisions.

RQ 1.1 What types of data on urban greenery, particularly urban trees, have been collected and preserved in the past, and how accessible and usable have these datasets been for management?

The research question is answered in Article I.

Results

The case of Kaarli Puiestee in Tallinn provides a valuable longitudinal view into the ways urban tree data has been collected, stored, and applied over time. This boulevard, situated in the heart of the city, has been the focus of repeated dendrological and planning investigations, making it one of the most well-documented public green areas in Estonia. The historical and contemporary records related to this site reveal the richness, diversity, and complexity of urban tree data collected over more than a century.

Data sources identified in the study include:

- Historical maps and photographs from the 19th and 20th centuries provide visual and contextual information about tree locations and planting schemes.
- Written reports and site plans from Tallinn Botanic Garden and city departments, some dating back to the Soviet period, often include descriptions of species, planting intentions, and changes due to urban infrastructure projects.
- Dendrological inventories were conducted in various periods, particularly in 1999, 2003, 2011, and 2021. These more recent surveys document individual tree data, such as species, trunk diameter, crown width, and visible health indicators. Each inventory differed in scope and method. While earlier surveys focused on aesthetic and compositional elements, later reports incorporated more structured data collection, including technical health assessments using resistographs and tomographs. Most importantly, trees were given unique identifiers and mapped with increasing spatial precision.

Despite these improvements, data were not consistently collected using consistent methods. The indicators used to assess tree health or structure varied across inventories. In some cases, trees identified as declining in one survey were later considered in good health, suggesting inconsistencies in assessment protocols or subjective judgment. Furthermore, some data exist in digital format (e.g., Excel tables or PDFs), but earlier inventories are still in analog form—stored in scattered locations such as the Tallinn City Archives, Tallinn Botanic Garden, municipal offices, or even in private collections.

Discussion

The findings highlight both the potential and the limitations of historical and contemporary urban tree datasets for supporting sustainable public space management in Tallinn. The city has a long-standing tradition of urban greenery documentation, particularly for prominent public spaces like Kaarli Puiestee. The continuity of inventories and planning documents provides a rare opportunity for longitudinal analysis of tree growth, composition, and health in an urban context.

However, the usability of these datasets for practical management remains constrained by several factors:

- Data fragmentation: Information is dispersed across different formats, storage locations, and institutional domains, making it difficult to access or synthesize in a timely manner.
- Lack of standardization: Variations in methods, indicators, terminology, and technologies used across inventories hinder long-term comparison and integration into digital systems.
- Limited interoperability: Although Tallinn has developed modern information systems (e.g., TAR, HHHIS), these systems operate almost entirely independently from historical inventory records. As a result, valuable longitudinal data are underutilized in current maintenance or planning activities.
- Incomplete digitization: Much of the older data remains in physical archives or in formats not easily integrated into geospatial or analytical tools, which undermines their potential use in digital twin applications or other forms of dynamic modelling.

The article also underscores a tension between the growing capacity for tree-level monitoring and the need for institutional coordination. While contemporary technologies allow for increasingly detailed data collection, these efforts must be harmonized through shared protocols and infrastructure to realize their full value. Improving the accessibility and usability of tree data requires a multi-pronged approach: comprehensive digitization of legacy records, development of shared metadata standards, and creation of interoperable systems that link planning, maintenance, and monitoring functions. These actions would support more evidence-based urban management and could serve as a foundation for integrating ecological data into broader digital twin environments.

RQ 1.2 What challenges have emerged in using historical greenery data for long-term monitoring and decision-making in public space management?

The research question is answered in Article I.

Results

The evaluation of historical data usage for long-term urban greenery management revealed multiple technical and organisational barriers. Methodological inconsistencies across time periods were evident; the tree surveys lacked standardized assessment criteria, especially in evaluating tree health. This inconsistency hinders the ability to track vegetation change longitudinally.

Furthermore, incomplete or selective data collection reduced the value of inventories as comprehensive baselines. Many assessments only focused on a subset of trees—often those affected by nearby developments—rather than documenting entire stands. Spatial ambiguity also emerged as a significant issue. While some surveys included basic spatial diagrams, these were often not aligned with official geospatial systems, making it challenging to match historical trees with current digital twin environments or GIS platforms.

From a governance perspective, the absence of a unified data policy and cross-departmental coordination created institutional silos. Data remains difficult to retrieve, often stored in incompatible formats or held in non-municipal repositories. There is also a legal gap regarding ownership and responsibility for archiving and updating historical greenery data.

Finally, the records are not systematically integrated into municipal data systems. For example, the tree-level information from dendrological inventories is not directly connected to the TAR or the HHHIS, even though these platforms are used to manage ongoing greenery maintenance.

Discussion

The findings indicate that Tallinn's urban greenery data, particularly for tree populations, offers valuable historical insight, but its current applicability is hindered by inconsistent recording practices and insufficient standardisation. The challenges identified illustrate how historical data, while rich in content, is complex to utilize effectively for ongoing urban greenery management. The lack of methodological coherence between surveys prevents reliable tracking of change, which is especially problematic for planning interventions in culturally or historically valuable sites like Kaarli Puiestee, where decisions must balance conservation and ecological functionality.

This gap reflects broader issues in urban environmental data governance: decentralized collection practices, minimal investment in digitisation, and limited alignment with modern data infrastructures. There is a missed opportunity to leverage past data for longitudinal ecological monitoring and predictive maintenance of urban green infrastructure. To move forward, public administrations would benefit from systematic efforts to recover, digitize, and harmonize these records. Incorporating such data into dynamic digital platforms—like city digital twins—could transform fragmented historical surveys into usable intelligence for adaptive green space management.

Spatial referencing gaps further limit the operational use of historical data in contemporary planning tools that rely on precise geolocation. Without accurate mapping or consistent identifiers, integrating old data into BIM or GIS systems becomes technically cumbersome and error-prone. From a systems perspective, the challenges point to the need for institutional reform. Historical data use requires not only technical tools but also policy frameworks that ensure systematic archiving, versioning, and interdepartmental data sharing. Furthermore, developing interoperability standards for legacy and modern data formats is essential to bridge temporal gaps. Ultimately, while historical greenery data holds significant value for understanding long-term ecological and management trends, it requires careful curation and digital translation to become actionable in present-day decision-making contexts.

RQ 2: To what extent has existing data been utilized in the creation of inclusive public spaces in Estonia, and what design shortcomings—particularly in relation to universal design principles—could have been avoided through more effective data use?

The research question is addressed in Article II.

Results

The article assessed ten contemporary public urban spaces developed through the "Great Public Space" programme in Estonia, using a structured age-friendliness assessment tool. Findings show that although most spaces performed well in general design and cleanliness, they only partially met the specific needs of older adults.

On the positive side, all spaces were clean, well-maintained, and equipped with diverse seating options. These features are particularly significant for older adults, as they support resting, enhance feelings of safety, and allow for extended time spent outdoors. Most spaces also included varied greenery—such as trees, shrubs, perennials, and flowerpots—which offered aesthetic and sensory benefits and supported interaction with nature. Pavement materials were generally non-slip, contributing to physical safety. Central locations and adjacent public institutions further enhanced usability for all age groups, including seniors.

However, only a limited number of sites provided design elements explicitly aligned with the principles of universal or age-friendly design. Notably absent were schematic maps or directional signage to support navigation—an important element for those with mobility or cognitive challenges. Exercise equipment suitable for older adults was missing from all locations, while public restrooms were limited or absent entirely. While younger age groups were accommodated through features like playgrounds or sports facilities, older users were typically left with passive activities such as sitting or watching. Opportunities for quiet recreation—such as sensory installations, reading nooks, or shaded areas—were also scarce.

Discussion

The findings suggest that while the public spaces built under the "Great Public Space" initiative incorporated general design improvements, there was a lack of detailed attention to inclusive planning based on empirical user data—particularly concerning older adults, which highlights a gap in the application of universal design principles. A key issue was the top-down design process and the lack of meaningful community engagement. While competition-based design may foster innovation, it often fails to reflect the lived experiences and daily needs of users—especially those from vulnerable groups such as the elderly. As the article notes, participatory planning—an essential component of age-friendly design—was largely absent. Consequently, critical user data that could have informed better outcomes remained unused.

Moreover, design continuity issues were identified. Several projects deviated from their original plans during construction, with age-friendly elements potentially lost due to cost or oversight. This fragmentation highlights the need for stronger integration of age-friendly guidelines not just in design, but also in implementation and maintenance stages. The lack of basic infrastructure, such as restrooms and exercise features, reveals a broader underestimation of older adults as active public space users. These oversights could have been mitigated through systematic data collection on user demographics, behaviours, and preferences—data which is often either missing or unused in Estonia's urban development processes.

In conclusion, the study underscores the importance of embedding inclusive, evidence-based approaches into public space design. Better use of data—collected through participatory methods, statistics available to the public and post-occupancy evaluations—could prevent many of the shortcomings observed and lead to more universally accessible, age-inclusive environments.

RQ 3: How can the digital twin as a tool enable evidence-based decisions for public space management?
Digital twins enable real-time simulation of ecological and user-related processes, supporting informed and adaptive governance. Their practical application requires high-quality, interoperable data, yet challenges such as data fragmentation, lack of standards, and limited ecological modelling persist. This research question is answered in Article III.

RQ 3.1 What types of data and modelling techniques are required to integrate dynamic ecological information into digital twins of public space, and what challenges arise in this process?
The research question is answered in Article III.

Results
The systematic literature review revealed that while digital twins (digital twin is defined as a dynamic system that enables continuous, bidirectional automatic data exchange, allowing real-time interaction and feedback between the physical entity and its digital counterpart (III)) of urban systems are increasingly incorporating green infrastructure, the modelling of dynamic ecological processes—such as plant growth, phenological cycles, or biodiversity interactions—remain underdeveloped. Most current models rely on static representations or simplified indicators (e.g., indices or tree canopy size) rather than on continuous and responsive simulations of ecological change. Data inputs predominantly include remote sensing data (satellite and drone imagery), point cloud scans (e.g., LiDAR), and urban tree inventories. However, there is little standardisation across case studies. Only a limited number of projects incorporate real-time or sensor-based data, and very few accounted for long-term ecological feedback. The types of modelling techniques identified include rule-based simulations, parametric growth models, environmental response models (e.g., light, temperature), and increasingly, machine learning algorithms.

The systematic literature review reveals that integrating dynamic ecological information into digital twins of public space requires a wide array of data types and modelling techniques. The most common data types include:

- remote sensing data (e.g., LiDAR, UAV imagery, satellite data);
- in-situ sensor data (e.g., soil moisture, temperature, air quality);
- biodiversity and functional trait data;
- crowdsourced or citizen science contributions; and
- geospatial data (e.g., point clouds, GIS layers).

Regarding modelling, both mechanistic and data-driven models are used to simulate ecological phenomena. Mechanistic models draw on established biological functions (e.g., plant growth or evapotranspiration), while data-driven models—often using machine learning or AI—allow dynamic updates based on real-time data streams. Additionally, 3D plant models and visualisation tools are increasingly applied to represent vegetation with spatial and morphological accuracy.

Discussion
Despite technological advances, significant challenges hinder the effective integration of ecological data into urban digital twins. These include:

- Data heterogeneity: inconsistent formats and variable spatial/temporal resolutions complicate model harmonisation.

- Interoperability gaps: ecological datasets often lack alignment with built environment standards such as IFC or CityGML.
- Lack of standard protocols: diverse data sources require harmonisation to support meaningful integration into predictive models.
- Computational complexity: high-resolution and high-frequency data place computational demands on systems, limiting their responsiveness and scalability.

A critical bottleneck is the limited ecological understanding that underpins models; without robust empirical grounding, projections risk oversimplification or misrepresentation of dynamic ecological processes. To enable meaningful simulation of vegetation responses, models must be calibrated with locally contextualized ecological data, which is often missing or incomplete.

RQ 3.2 What are the challenges and opportunities of using greenery in the digital twin for management of urban public spaces?
Addressed in Article III.

Results
Several challenges were identified regarding the use of greenery in urban digital twins. A central issue is the technical complexity of integrating botanical data into spatial modelling systems (e.g., BIM, GIS) that were not initially designed for biological entities. Spatial referencing inconsistencies, limited historical records, and varying levels of detail across datasets hinder interoperability. Furthermore, the dynamic nature of plant systems presents difficulties for model calibration and validation, especially in the absence of continuous ecological monitoring.

However, the review also highlighted substantial opportunities. Incorporating greenery into digital twins enhances the ability to model urban microclimates, simulate stormwater absorption, evaluate habitat connectivity, and guide adaptive maintenance strategies. For instance, simulations of tree growth and canopy shading can be used to optimize pedestrian comfort or assess heat island mitigation potential. The review showed growing interest in leveraging DTs for participatory planning and monitoring, with some projects engaging citizens to validate vegetation data or report maintenance needs.

The reviewed literature identifies greenery as a particularly challenging component in digital twins due to its living, growing, and reactive nature. Challenges noted include:

- Limited inclusion of non-static biological components in digital representations.
- Scarcity of species-level data and plant functional traits required for realistic simulations.
- The low frequency of longitudinal ecological monitoring, making predictive modelling difficult.
- Difficulty linking ecological services (e.g. shade, cooling, biodiversity) to specific vegetation elements in digital platforms.

Despite these limitations, opportunities emerge through advances in:

- sensor technology and real-time environmental monitoring;
- AI-driven modelling techniques (e.g., predictive maintenance, stress detection);
- cross-disciplinary collaborations that integrate ecology, informatics, and urban planning; and

- development of closed-loop digital twins capable of feedback-based ecosystem management.

Discussion

The integration of dynamic ecological information into digital twins is both a technical and conceptual challenge. The review confirmed that digital twin development in the urban ecological domain is still at an early stage, with fragmented approaches and minimal standardisation across data structures or modelling methodologies. The dominant reliance on static datasets and one-time inventories limits the responsiveness and usefulness of digital twins for evidence-based public space management. From a planning and governance perspective, this fragmentation reflects broader issues in urban environmental data governance—including siloed data collection practices, unclear ownership, and insufficient institutional collaboration. Digital twins that aim to support green infrastructure must evolve toward more open, modular, and interoperable architectures. For this, standardized ecological data formats and cross-sector data exchange protocols are critical. The use of greenery in DTs is particularly promising for improving the adaptiveness of public space management. By simulating vegetation response to stressors (e.g., drought, pruning, compaction), municipalities can plan interventions more proactively. However, this potential remains untapped mainly due to technical constraints and a lack of suitable ecological metadata. Future development efforts should therefore focus on the inclusion of physiological plant parameters, modular growth libraries, and interface tools that allow landscape architects and maintenance workers to interact with living systems digitally. Nevertheless, several conditions must be met:

- ethical data governance and privacy safeguards (especially with citizen-sourced data);
- institutional support for systematic data archiving and versioning;
- standardisation across sectors to ensure data interoperability and long-term usability; and
- user-centred design to ensure digital twin applications meet the actual needs of landscape managers, planners, and citizens.

The shift toward automated and AI-enhanced data collection offers promise to close existing data gaps. However, the transition from static models to adaptive ecological twins will require iterative calibration, ongoing data collection, and strong cross-domain collaboration. The Tallinn and Helsinki-based GreenTwins project, referenced in the article, provides a relevant applied example: by integrating dynamic tree models into the city's digital planning tools, it demonstrated both the practical benefits of visualising growth and the limitations posed by data gaps and modelling uncertainty. It also showed how collaborative development between researchers and municipal departments can help refine use cases and identify realistic thresholds for model complexity and update cycles.

In conclusion, while challenges persist, the strategic integration of ecological data into digital twins offers a powerful avenue for advancing sustainable urban public space management. Ensuring data interoperability, ecological accuracy, and user-centred design are key to unlocking this potential.

5 Conclusion

A growing challenge for cities is coping with urbanization and climate change, alongside competition with other cities for residents. An integral component of a high-quality living environment is an inclusive public space, which supports population health and serves as a habitat for birds, animals, and other living organisms. These issues and objectives are addressed in various development documents of the Republic of Estonia and the City of Tallinn. Achieving related goals—such as reducing bureaucracy, making informed, data-based decisions, engaging the population, and ensuring habitat connectivity—requires the availability of up-to-date, high-quality data.

This doctoral dissertation examines the requirements for effective management of urban public greenery within the framework of sustainable urban development. It focuses on data-driven tools and digital twins, analyzing the reliability, usability, and potential of green infrastructure data to support evidence-based planning and maintenance of public spaces.

Generations of residents have left their mark on the urban landscape, creating features valued for their cultural or natural heritage. However, it is not only officially protected natural landscape elements that are important—any feature that poses no danger can enhance a city's capacity to adapt to change. Old trees are one such example: their canopies slow stormwater runoff, provide shade on hot days, lower urban ground temperatures, and create habitats for numerous species.

The analysis of tree data and the Kaarli Boulevard case study demonstrate that managing valuable trees requires longitudinal data on their health status. The study also found that, even when data exist, they are often difficult to access, as they may be recorded on paper, dispersed across archives (including personal collections), or not preserved at all. Moreover, existing records are often general, descriptive, and—especially in older documents—not linked to specific trees. Renewal or removal of valuable trees in public spaces requires decisions supported by data. Since tree removal attracts high public interest, data-based explanations can help communicate such decisions more effectively.

Public space must meet the needs of all citizens while fulfilling broader city objectives and addressing its challenges. The "Great Public Space" programme, launched to mark the 100th anniversary of the Republic of Estonia, sought to modernize central areas in cities and towns through architectural competitions in cooperation with local governments and the Estonian Association of Architects. Ten central areas were reconstructed by 2023 based on winning designs.

Analysis of the completed projects revealed that while aesthetic and architectural improvements were prioritized, the needs of diverse user groups—particularly older adults—were often insufficiently addressed. This gap persists despite the Estonia 2035 national development strategy emphasizing the growing proportion of older adults in society and the need to consider them in spatial design. In reconstructed outdoor spaces, measures to ensure physical accessibility, comfort, and safety for older adults were applied inconsistently, reflecting a missed opportunity to incorporate user-centred and demographic data during the planning stage.

Technological advances are creating new opportunities for managing public spaces. A systematic literature review indicates that while digital twins are increasingly used in urban contexts, dynamic modelling of ecological processes remains underdeveloped compared to built-environment modelling. Most current systems rely on static vegetation representations and limited ecological data, hindering simulations of growth, biodiversity changes, or environmental feedback.

Integrating nature into the digital domain requires data. While digital twins exist in agronomy and forestry, urban vegetation grows under different conditions, and relevant datasets are scarce. Nonetheless, real-time, sensor-based technologies hold promise for collecting data on urban plants and growth conditions. Beyond improving digital literacy or public engagement, AI-based simulations and geospatial visualization tools in urban digital twins can help residents explore dynamic, plant-specific scenarios—such as whether a tree might obstruct a landmark or traffic signal, contribute to cooling urban heat islands, or maintain habitat connectivity.

Achieving national and municipal strategic objectives often depends on high-quality data. This dissertation examines historical and current datasets, as well as the data needed to integrate emerging technologies. Effective public space management requires digitizing existing datasets—ideally with geolocation—and understanding the context in which data were collected. Digital twin applications for public space also require more detailed and integrated ecological information. Challenges persist, including heterogeneous data formats, a lack of standardization, and limited interoperability between ecological and built-environment datasets.

The dissertation concludes that sustainable and inclusive management of urban greenery depends on consistent, long-term data management practices, inclusive design processes, and modelling tools grounded in digital technologies. To realize the potential of digital twins for adaptive green infrastructure management, cities must address:

- technical challenges – interoperability between systems and cross-utilization of data;
- organizational challenges – strengthening public-sector digital competencies and improving service design; and
- governance challenges – securing funding for system development and maintenance, and creating appropriate legal frameworks.

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Abstract

Management of Urban Public Spaces: Challenges and Future Directions from a Municipal Perspective

This doctoral thesis examines how data-driven approaches and digital twin technologies can enhance the sustainable planning and management of urban public green spaces. The motivation lies in the growing need to integrate ecological complexity and diverse user requirements into municipal decision-making, particularly as cities confront climate change, biodiversity loss, and demographic shifts. The study identifies significant gaps in existing urban greenery data—fragmentation, inconsistent quality, limited spatial precision, and poor interoperability—that constrains long-term monitoring, inclusive design, and adaptive management.

The research introduces novelty by combining historical analysis, contemporary field assessments, and a systematic literature review of digital twins to form an integrated perspective on past, present, and future public space governance. It addresses the problem through three case-based research streams: reconstructing historical greenery data and assessing its management usability; evaluating inclusivity in newly redeveloped public spaces using age-friendly design criteria; and reviewing global practices for integrating dynamic ecological information into digital twin platforms.

Methodologically, the study employs archival analysis of historical maps, photographs, and inventories; fieldwork-based evaluations of public spaces; and a PRISMA-guided literature review of ecological digital twin applications. Results reveal that, although historical inventories offer valuable insights, methodological inconsistencies hinder comparability. In contemporary projects, aesthetic and architectural goals often overshadow systematic use of demographic and behavioural data, limiting inclusivity. Digital twin applications for greenery remain at an early stage, dominated by static models with limited ecological parameters; however, advances in sensor technology, AI modelling, and cross-sector collaboration hold substantial potential.

The thesis concludes that effective and inclusive urban greenery management requires consistent long-term data practices, robust interoperability, integration of universal design principles, and digitally enabled modelling tools. Realising the potential of digital twins will necessitate overcoming technical and institutional barriers, establishing ecological data governance, and fostering collaboration among planning, ecological, and information technology domains. These findings contribute theoretically to urban studies and offer practical recommendations for planners, landscape managers, and policymakers seeking resilient, adaptive public space solutions.

Lühikokkuvõte

Linnaliste avalike alade korraldus. Probleemid ja tulevikusuunad omavalitsuse vaates

Käesolev doktoritöö uurib, kuidas andmepõhine lähenemisviis ja digikaksiku tehnoloogia saavad aidata kaasa linnade avalike rohealade jätkusuutlikule planeerimisele ja korraldamisele. Linnade väljakutsed seoses kliima- ja demograafiliste muutuste ning elurikkuse kaoga on tekitanud järjest kasvava vajaduse põimida kohalike omavalitsuste otsustusprotsessi loodussüsteemide ökoloogiline keerukus ja ruumi kasutajate mitmekesised vajadused. Uurimus toob esile olulised lüngad linnahaljastust käsitlevates andmestikes. Andmete killustatus, ebaühtlane kvaliteet, piiratud ruumiline täpsus ja vähene ristkasutatavus – kõik see takistab pikaajalist seiret, kaasava disaini kasutamist ning linnaruumi andmepõhist korraldamist.

Uurimistöö teaduslik uudsus peitub ajaloolise analüüsi, tänapäevaste välitööde ning digitaalkaksikuid käsitleva süstemaatilise kirjanduse ülevaate ühendamises, et tuua avalikku haldusesse terviklik minevikku, olevikku ja tulevikku ühendav vaatenurk. Probleemi käsitletakse kolme juhtumipõhise uurimissuuna alusel: ajalooliste haljastusandmete taastamine, et selgitada välja, kas neid saab kasutada haljastuse korraldamise otsustes; hiljuti ümber kujundatud avalike linnakeskuste hindamine easõbralikkuse ja kaasava disaini vaatest; ning ülevaade digikaksiku platvormidele dünaamilise keskkonnateabe integreerimise rahvusvahelistest praktikatest.

Metoodiliselt rakendati teadustöö läbiviimisel ajalooliste kaartide, fotode ja inventuuride arhiiviuuringuid, välitöödel põhinevat avaliku ruumi hindamist ja PRISMA-metoodikast lähtuvat kirjanduse ülevaadet keskkonnaandmeid kasutavatest dünaamilistest digikaksikutest. Tulemused näitavad, et kuigi ajaloolised inventuuriandmed pakuvad väärtuslikku taustainfot, on andmete võrreldavus metoodiliste ebajärjepidevuste tõttu raskendatud. Tänapäevastes projektides seatakse esteetilised ja arhitektuurilised eesmärgid sageli demograafilise ja käitumuslike andmete süstemaatilisest rakendamisest kõrgemale. Digikaksikute haljastusrakendused on endiselt varases arenguetapis ning lähtuvad valdavalt staatilistest mudelitest, millesse on integreeritud vaid üksikud keskkonnaparameetrid; siiski pakuvad arengud sensortehnoloogias, tehisintellektil põhinevas modelleerimises ja valdkondadevahelises koostöös märkimisväärset tulevikupotentsiaali.

Doktoritöö lõppjäreldus kinnitab, et efektiivne ja kaasav linnahaljastuse korraldus eeldab järjepidevaid andmehalduse tavasid, tõhusat koostalitusvõimet, universaalse disaini põhimõtete rakendamist ja digitaalselt toetatud modelleerimisvahendite kasutust. Digikaksikute potentsiaali täielikuks elluviimiseks tuleb ületada tehnilised ja institutsionaalsed tõkked, kehtestada linnaruumi keskkonnaandmestiku ülesehitust ja haldamist reguleeriv raamistik ning toetada planeerimise, ökoloogia ja infotehnoloogia valdkondade vahelist koostööd. Uurimistöö tulemused annavad panuse linnauuringute teoreetilisse pagasisse ning pakuvad planeerijatele, linnahaljastuse korraldajatele ja poliitikakujundatele praktilisi soovitusi vastupidavate ja kohanemisvõimeliste avalike ruumide loomiseks

Appendix 1

Publication I
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Data from urban tree surveys of the 19th–21st centuries as input for planning the maintenance of historical tree stands: A case study of Kaarli Boulevard in Tallinn, Estonia

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Abstract

Greenery plays a crucial role in shaping the urban environment and its resilience to climate change. Urban trees are the most noticeable and long-living part of urban greenery, but poor management decisions or negligence pose a significant risk to the health of urban tree stands. To successfully plan the maintenance and renewal of urban trees, we need to be able to assess their condition.

In this study, we examine what data on urban trees are available in Estonia to date, as well as the quality of these data. The study aims to determine whether the available data are sufficient to plan future maintenance and renewal of urban tree stands. As a case study, we examined the available dataset on Kaarli puiestee and assessed its usability.

Kaarli Boulevard (Kaarli puiestee) is one of the most researched historical urban tree stands in Estonia. After examining the available materials, the following concerns emerged: 1) data retrieval is difficult; 2) retrieving the necessary information from the materials is time-consuming; 3) different methods have been used in the surveys, which means that there is no systematic longitudinal study that could be used to monitor changes in the condition of the trees and to assess the impact of different factors.

Planning of future maintenance cannot solely rely on using this existing material as input, because the data is not uniformly comparable. It is therefore essential to improve the quality of the data by making it readily available, ensuring data harmonisation and keeping it up to date.

Keywords: urban trees; historical boulevards; tree surveys; greenery; dendrology

Introduction

Tree stand surveys in Estonia

There is a long history of conducting tree stand surveys in Estonia. In state-protected (heritage, nature conservation) parks, dendrological inventories are a compulsory part of any restoration project (Nutt et al. 2014). Due to the large number of rural parks (Baltic-German manor parks), the number of dendrological inventories has therefore been very high over time (Palm 2011). However, in most cases, the original inventories are limited to collecting the dendrological data and are not followed by subsequent analysis (Nutt and Kubjas 2020).

In recent years, methods and models for determining species composition, authenticity, etc., have been developed based on the data collected in rural manor parks established in the early 19th and early 20th centuries. (Nutt 2013, Nurme et al. 2014, Nutt et al. 2020). Like rural parks, surveys in urban parks have also focused on assessing the health of the trees, measuring their physical parameters and determining their species and/or variety. The survey reports sometimes include site maps.

The history of one of the oldest boulevards in Tallinn

Tallinn's oldest and most valuable stands of trees are situated in the bastion belt surrounding the Old Town. These earthwork bastions were built starting from the middle of the 17th century and retained their importance as fortifications from the middle to the late 19th century. The first written records describing the boulevards surrounding Tallinn bastions date back to the first half of the 19th century (Viirok 1932). The first map to depict the exact location of one of the boulevards is a partial plan of the Esplanade area, drawn up in 1845 (Eesti Ajalooarhiiv 1845). However, at that time, Tallinn was still considered a fortified city, which meant that large-scale greening of the bastion belt became possible only after the Crimean War, in 1857, when Tallinn was excluded from the Russian Empire's list of fortified cities.

During the 19th century and following the example of Vienna, the idea of forming a ring road or *Ringstrasse* around historical town centres spread throughout Europe.

Figure 1. Ring Street (Ringstrasse) around Tallinn Old Town is marked with a yellow line and the location of Kaarli Boulevard is marked with a red line (Land and Spatial Development Board)

These circular roads were mainly constructed on former fortified areas and lined with parks and important representative buildings (Tammet 2003). Following the examples of several German cities, and especially that of neighbouring capital Riga, a similar new representative area was also developed in Tallinn. As shown in Figure 1, Tallinn Ringpuiestee (Ringstrasse) is formed by Kaarli puiestee, Toompuiestee, Põhja and Mere puiestee, and, in the area between Viru and Harju gates, two parallel streets – Estonia puiestee (Estonia Boulevard) and Pärnu maantee (Pärnu Road; historically Jaani Street, built in the 1880s) (Tamla et al 2019/2020). Churches were also built along Ringpuiestee as representative buildings, including the Kaarli kirik (St. Charles Church; built in 1862–1870).

The exact date of tree planting along Kaarli Boulevard is not known, but the city plans of 1849 (Eesti Ajalooarhiiv 1849) and 1856 from Tallinna Linnaarhiiv (TLA 1856) display a boulevard with two rows of trees bisected by a boundary between the properties of the Knighthood of Toompea and Tallinn City Council (Eesti Rahvusraamatukogu 1865). On the 1869 town plan, the boulevard is depicted with four rows of trees (Figure 2) and this is also the date that several sources (Kenkmaa 1965, Kivi 1972, Vende 1990) suggest as the time of planting. However, this contradicts a sample of the outer bark of one of the trees (*Tilia cordata*) collected in 1999, which revealed 168 annual rings, indicating that the tree was about 160–170 years old (Sander et al. 2008). This would place the planting date closer to the middle of the 19th century (1840–50).

Kaarli Boulevard is planted with lime trees. A part of the boulevard nearest to St. Charles Church (Figure 2), which was historically part of the Knighthood of Toompea property, predominantly features the common lime (*Tilia cordata*), a species native to Estonia. The part of the boulevard next to Vabaduse Square is mainly lined with western lime (*Tilia* × *europea*), which is a natural hybrid of the common lime and the large-leaved lime, also known as the Dutch lime, which is not native to Estonia (Sibul 2012). The origin of the seedlings used to plant the trees along the boulevard is unknown. Whilst the common lime tree is native to Estonia, the seedlings may have come from local nurseries that also sold imported plants (Sander 2019).

Current state of Kaarli Boulevard

Estonia has a long history of protecting historical parks with the first legislative act on the topic, the Act on Recreation and Health Resorts (Kohtuministeerium 1925), enacted as early as 1925. Initially, according to the Act, 80 parks were under protection (Viilberg 1931); but by 1982, their number had more than quadrupled to 382 (Nutt et al. 2008). Kaarli Boulevard was placed under national nature protection in 1959 (ENSV MN 1959), but unfortunately, this has not been enough to protect the integrity of the tree stand as Kaarli Boulevard is located right in Tallinn city centre, between two busy roads (Figure 3).

Figure 2. *On the left*: The plan of Kaarli Boulevard (drawn between 1879 and 1881). Excerpt from the plan of Tallinn city centre (TLA 1879–1881). *On the right*: A detail of a 1907 postcard (Eesti Ajalooarhiiv 1849)

Figure 3. *From left to right*: Kaarli Boulevard in 1976 (Vilde 1976), 2009 (Pajula 2009) and 2015 (Gnadenteich 2015). Of the four rows of trees, the health of the trees in the outer two rows has been affected by the widening of the carriageway

Instead of the original single carriageway, there are now two car lanes on each side of the boulevard, since it was widened in 1970 (Tamm 1981). This means that the high daily traffic volume and problems with street maintenance all put the boulevard under significant pressure (Raudi 1986) and have a distinct impact on the health of the trees (Sander 1986).

There are also several underground utility lines: a gas main first constructed in 1953, a sewer in 1978, an underground power cable (exact building date unknown), and power cables laid out in 2014, routed under the boulevard. The lines have been repaired and rebuilt numerous times, adding further damage to the root systems of the trees. Moreover, in 1977–1978, a pedestrian underpass was built at the end of the boulevard adjacent to Vabaduse Square. This underpass biased the groundwater dynamics of the area, which negatively affected the trees.

Materials and method

This study aims to answer the following research questions:

1. What data on Kaarli Boulevard is currently available?
2. What is the quality of this data?
3. Is the existing dataset sufficient for planning the further maintenance and renewal of the tree stand?

The first step of the study was to compile a comprehensive list of all materials that depict or describe Kaarli Boulevard, such as historical maps, photographs, drawings, paintings, and written records, as well as reports of dendrological inventories and surveys. For this purpose, an archival research was carried out in several different archives and collections: the Database for Historical Maps in the Estonian National Archive, the Database of Museums (MuIS), the Photo and Art Collection of Tallinn City Museum, the Photo Collection of Tallinn City Archive, Archive of the Department of Heritage Conservation affiliated with the Tallinn Urban Planning Department, Tallinn Urban Environment and Public Works Department, and Tallinn Botanic Garden Library. When searching, all historical names of the boulevard, Schmiedenpforten-Promenade, Neue Promenade, Brunnenstraße, Petri Boulevard, Karl Marxi Boulevard, and Aleksander Suvorovi Boulevard, were used as reference points.

In addition to archival materials, the authors used various published works, such as "Plans of the City of Tallinn 1634–1989" (Raid 2011), and also interviewed specialists who previously dealt with issues of urban greening and arboriculture in Tallinn. Where possible, references to manuscripts present in published materials were sought out, but in many cases, the original manuscripts have not survived.

In the next step, the collected materials were sorted and analysed. Different types of materials were used in the following manner:

- The maps, which could be used for further analysis, needed to showcase trees as single units so it would be possible to track the number of trees and their position through different periods.
- Historical photographs depicting Kaarli Boulevard either in its entirety or in part were analysed. Although photos cannot be used to count the total number of trees at any given moment, they provide a good input for dating and tracking different infrastructure projects and the extent to which they affected the health of the trees.
- The pre-screening of written records was performed by examining their titles. The texts selected for further analysis had to contain one or several of the following keywords or phrases: vegetation, trees, trees in the city centre, felling, *and* tree stand. The chosen terms were grouped under broader categories such as vegetation, tree stands and trees. A spatial limitation was also applied, focusing on trees in the city centre. Since monitoring changes in tree-lined avenues required information on tree removals, the keyword 'felling' was included. While reading through the texts, the authors concentrated on the parts concerning Kaarli Boulevard, the health of the trees growing there and the factors influencing it.
- While working through the dendrological inventories and surveys, the authors logged the date of the study, the author and the methods used. Since inventory reports and surveys contain both text and site plans, with each tree bearing its identification number, it is possible to link the descriptions with a specific tree on site.

To work out what data is deemed necessary by the City Government to plan the maintenance of trees, we processed the tree data compositions listed in the Tallinn Green Areas Information System (RT 2010) and the Statutes of the Information System for the Maintenance, Improvement and Landscaping Works of The City of Tallinn (RT 2020). Additionally, the Procedure for Inventorying Greenery in Tallinn was studied (RT 2020), which sets out the requirements for submitting inventory data.

In the final step, all relevant data that contained information about the condition of the trees on the boulevard from the previously analysed material was examined to work out if this existing information could be used to reliably track the health of specific trees on the boulevard as required by the City Government. A total of 16 sources were used in the analysis.

Results

The first cartographic references to Ring Boulevard (Ringstrasse) surrounding Tallinn bastion belt can be found in paintings dating back to the first half of the XIX century, showcasing a straight and beautiful boulevard situated to the north of the bastions. These boulevards were planted with poplars, which were heavily damaged during the 1842 storm (Viirok 1932). As decreed by the authorities, the poplars were then replaced by more hardy species such as lime trees. This occurrence may also explain the choice of tree species used in Kaarli Boulevard.

The historical maps that showcase the single trees of Kaarli Boulevard are as follows: 1869 (TLA 1869), 1879 (TLA 1879), 1879/80 (TLA 1879/80), 1880 (Tallinn et al. 2021) and 1885 (TLM 1885). The number of trees (Figure 4) on the boulevard during these years is shown in Table 2.

The texts up until 1999 are of historical value, but do not reflect the overall situation of the trees or the health of individual specimens. In most cases, only the most notable trees are highlighted, but since the textual descriptions are not linked to site plans, they do not provide any information on which tree the facts (dimensions, etc.) refer to. General descriptive information on Kaarli puiestee can be found in the following documents:

- In 1932, a survey entitled "On the Tree Stands of Tallinn" (Viirok 1932) stated that Kaarli Boulevard is part of the Ring Street (Ringstrasse) and that Tallinn has a total of 18 km of boulevards, 63% of which feature lime trees;
- The 1986 article "Trees in the Streets of the City Centre" (Tarand 1986) summarises the tree census data from the years 1974, 1984 and 1985. The species composition of the street trees, the number of trees that grew in different years and the number of trees that died are mentioned, including the fact that 58 trees died due to the construction of the pedestrian underpass across Kaarli Boulevard. In conclusion, it has been noted that lime trees (*Tilia* sp.) are the most common species in the city centre, with 38% of all trees being lime trees;
- Starting from 1981, the Tallinn Botanical Garden carried out health reports of urban trees, using visual assessments of the changes in the foliage and its proportion to the canopy as a point of reference. The results of the survey are presented in the article "On the Health of Urban Trees" (Normet 1986), which, in the case of Kaarli Boulevard, notes that the trees are weakened and that the condition of the lime trees is deteriorating with each year. In addition, it is pointed out that there are several withered trees at the end of the underground pedestrian tunnel (built in 1977–78).
- In 2001, a historical study (Sander 2001) that also included Kaarli Boulevard was carried out. The document contains a description of the development of the boulevard with references to paintings, maps, literature and dendrological inventories. The study mentions a plan from the late 19th–early 20th century, which allegedly shows the number of trees on the boulevard as 99 (rows of 26 + 26 + 24 + 23, respectively). However, it is not clear to which plan this information refers to. Similarly, there is no information on how they counted the number of trees in rows to be 10 + 26 + 24 + 16 or 76 in total, when dendrological inventories carried out in the same year indicate 74 and 77 trees.

The first more accurate records on the number and health of the trees on the boulevard can be found in the 1981 survey "Avenues Surrounding Tallinn Old Town" (Tamm 1981). The number of trees on Kaarli Boulevard is given as 89, with the added note that they are of uniform age but are sometimes beginning to show the signs of disease. It also comments on the change in the number of trees on the boulevard stating that during the first 110 years, 10 trees died, followed by the next 13 ones in more recent

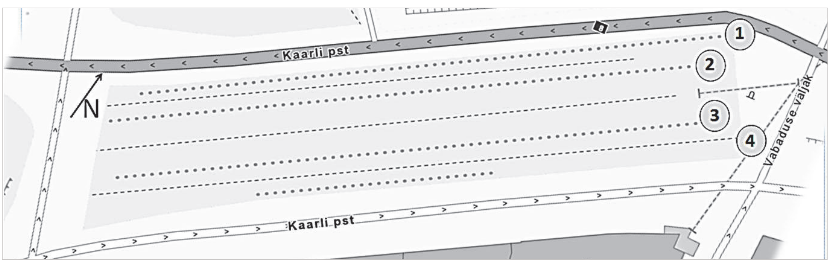

Figure 4. Numbering of tree rows (Land and Spatial Development Board)

decades. The survey also notes that the condition of the trees in the outer rows has significantly deteriorated due to the widening of the streets adjacent to the boulevard. The text also references a previous, but undisclosed, assessment from 1975, which found that of the 89 linden trees on the boulevard, about 50 ones were damaged to varying degrees. Unfortunately, it does not specify which trees the study specifically refers to.

Since 1999, the surveys have become more detailed, giving thorough information on each tree on the boulevard. Several different methods have been used to conduct the surveys (Table 1). The most used assessment method is the visual observation of trees, which has been carried out on five occasions (1999, 2001, 2004, 2014, 2017). Three of the observations have been carried out by the same evaluator (2001, 2004, 2014). A resistograph was employed twice (in 2001 and 2015) to determine the proportion of healthy and damaged wood, and a tomograph was employed twice (both times in 2015) to identify rot, cracks and crevices inside the trees. In addition, a phytopathological study was carried out (2001) using the detection method to assess the damage and the need for detailed examination. Samples collected during the detailed inspection were subjected to laboratory analysis to determine the cause and extent of damage, identify pest infestations and the risk of disease. The data collected during the surveys is linked to a site map and includes the name of the species or cultivar, the physical parameters of the trees (diameter at breast height, height, crown width), value assessment (high value/valuable/important/essential to eradicate or good/average/bad), and comments.

Analysing the total number of trees on the boulevard, indicated on various historical maps and presented in Table 2, we see that the number of trees on the maps varies significantly.

For example, during the two years of 1879–1880, when three different maps were drawn, the total number of trees varied, respectively, as 140/113/167. It is worth noting that the total number of trees on the 1885 map and in the literature relating to 1900 is the same; it is interesting to note that on the 1885 map and in the 1996 dendrological inventory, row 2 still contains 26 trees. Since 1900, according to both literary data and inventory data, the number of trees has been steadily declining, except for one inventory conducted in 2001. Three cases were also noted where the total number of trees and the number of trees in rows presented in the dendrological inventories did not correspond to the data presented in the expert opinion on the organisa-

Table 1. Overview of dendrological inventories

No.	Year	Author	Method	Assessment classes
1	1999	Aaspõllu	observation	high value/valuable/significant/not significant/essential to eradicate
2	2001	Lõhmus and Tamm	observation	high value/valuable/significant/not significant/essential to eradicate
3	2001	Hanso	phytopathological study	
4	2001	Oy PJ Bäckström AB	resistograph inspection	high value/valuable/significant/not significant/essential to eradicate
5	2004	Abner	observation	high value/valuable/significant/not significant/essential to eradicate
6	2014	Abner	observation	high value/valuable/significant/not significant/essential to eradicate
7	2015	Puiden Hoito TS-ympäristöpalvelu Ky	VTA, resistograph and tomograph inspection	very good/good/quite good/poor/dangerous
8	2015	Moon	tomograph inspection	very good/average/poor
9	2017	Möllits	observation	high value/valuable/significant/not significant/essential to eradicate

Table 2. Number of trees on Kaarli Boulevard

	Maps			Literature					Dendrological inventories							
No. of tree row	1869 (TLA 1869)	1879 (TLA 1879)	1879/80 (TLA 1879/80)	1880 (Tallinn et al. 2021)	1885 (Tallinna Linnamuuseum 1885)	1900 (Sander 2001)	1975 (Sander 2001)	1981 (Tamm 1981)	1996 (Helsinki Kaupunki 1996)	1999 (Aaspõllu 1999)	2001 (Lõhmus and Tamm 2001)	2001 (Oy PJ Bäckström AB 2001)	2004 (Abner 2004)	2014 (Abner 2014)	2015 (Puiden Hoito TS-ympäristöpalvelu Ky 2015)	2017 (Möllits 2017)
1	17	39	31	46	26	-	-	-	13	11	10	10	8	7	7	5
2	20	34	31	39	26	-	-	-	26	26	26	26	26	26	26	26
3	20	34	27	38	24	-	-	-	25	24	24	24	24	23	23	23
4	19	33	24	44	23	-	-	-	17	16	14	17	14	14	14	14
In total	76	140	113	167	99	99	89	89	81	77	74	77	72	70	70	68

tion of the future maintenance of Kaarli Boulevard (Aruste 2001). Although observational studies are inevitably subjective (Kupper 2012), the difference in tree numbers cannot be justified.

When analysing the two charters that form the basis of the Tallinn Green Areas Information System (RT 2010, 15 Nov.; RT 2020, 21 Sept.), we found that the 2020 dataset contains 18 more data types than the 2010 one. The new information system describes more options, which reduces the subjectivity of the tree health assessor. For example, when conducting a Greenery Inventory (RT 2020, 20 Jun.), it is now possible to leave comments on trees thanks to the corresponding option; although this is not mandatory and therefore depends on the thoroughness of the assessor.

Discussion and recommendations

Our study highlights a significant gap in systematic urban green space management due to a lack of comprehensive data. In the life cycle of urban green spaces, including the stages of planning, design, construction, and maintenance, wherein maintenance is the longest one, which, in the case of Kaarli Boulevard, lasts more than 150 years. At the same time, maintenance is highly dependent on how well the preceding stages have been carried out. By nature, woody plants are living organisms, and their lifespan, or longevity, depends on many factors. In the case of old boulevards, constant monitoring of the health of their tree plantings is necessary for timely response.

Therefore, carrying out a one-off survey or assessment is insufficient; instead, a long-term systematic monitoring of tree growth and vitality is needed. This, in turn, can be used as a basis for developing an annual maintenance strategy to plan for the replacement of old and diseased trees. Systematically collected data allows costly maintenance work to be optimally organized and expensive replacements to be scheduled well in advance, making it easier to plan municipal budgets. Longitudinal studies are most suitable for this purpose because they allow predictions of future conditions based on systematically collected historical data.

Carefully selecting data collection methods is crucial for conducting a longitudinal study before embarking on the endeavour. The data collected should be able to answer questions about the health of the trees, and data collected at different times should be comparable. In the case of our study site, Kaarli Boulevard, the stand has been assessed using several different methods (Table 1), which are complementary, but do not provide a good overview of long-term trends. We also found that the most commonly used research method for assessing Kaarli Boulevard (visual assessment) is too dependent on the subjectivity of the assessor, and that even the scores assigned to a single tree vary widely. For example, according to our assessments, we found that the estimated health of 38% of the trees on Kaarli Boulevard had improved over the years: trees in 'satisfactory' condition were subsequently rated as 'good' 35 times, and trees in 'poor' condition were subsequently rated as 'satisfactory' 31 times. Such results cannot be used as a basis for making informed decisions. Therefore, the lack of long-term objective data on the health of the trees makes it impossible to plan the future maintenance of these tree stands.

Any data collection should be grounded in real needs, but it should also utilise available technical capabilities. The rapidly developing data analytics domain allows for the rapid collection of large volumes of data, and the collection and storage of data in databases open up opportunities for large-scale analysis. However, here too, the optimum use of resources must be the guiding principle, meaning that any data collection should aim to gather as little as possible and only as much as necessary.

In Estonia, local governments have various functions and powers enshrined in legislation. Among other things, local municipalities are responsible for managing public utilities, maintaining public amenities, spatial planning, constructing and maintaining roads, preparing and implementing development plans, and managing the security of urban spaces. In the case of urban greenery, the municipality is responsible for:

- Organising its maintenance (routine maintenance as well as replacements);
- Budgeting (both maintenance and replacement);
- Drawing up strategic documents indicating a long-term action plan (e.g. large-scale replacement plantings, setting up new green areas);
- Regular monitoring and commissioning of surveys (health of trees, disease and pest control);
- Data collecting, organising, managing and analysing.

To successfully fulfil these obligations, a local municipality needs each urban tree to be characterised by two types of data. Firstly, static data, such as its species, variety, date of planting, and origin, and secondly, dynamic data, which can be further categorised into measurable and descriptive data (Figure 5, Table 3). While the first group of data is collected once at the time of planting, the second group of data is collected over a long period. It needs to reflect regular maintenance activities and health assessments.

Based on our study results and long-term practical experience in urban arboriculture, we propose a list of indicators that fulfil conditions of successful urban tree management, as well as a database structure that is compliant with the municipality's needs.

The general data on trees (Table 3) provides the local government with information on the quantity, species composition, classification, and condition of the tree stands. This can be used for various analyses, as an input in spatial planning or for assessing ecosystem services, but also for communicating with the public or media.

Urban sprawl and deforestation can create heat islands, areas where temperatures can rise to high levels on a hot day, posing a risk to the health of the city's popula-

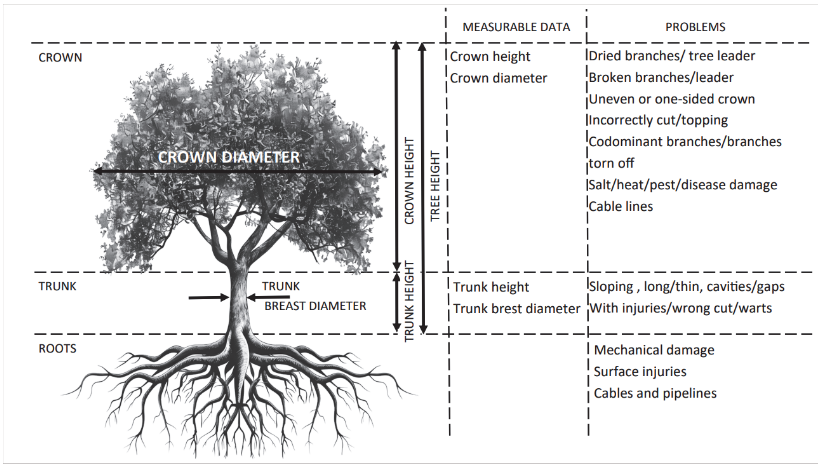

Figure 5. Dynamic data about the tree

Table 3. Data required for tree replacement and maintenance

Data group	Indicator	Necessary for replacements	Necessary for maintenance	Content of the data and its use case
General data	Tree ID	x	x	Needed for identifying a specific tree
	Location of the tree	x	x	Who is responsible for the tree
	Species and variety	x	x	Species-specific growing season, spread of diseases and pests
	Type of tree	x	x	Boulevard, street or park tree
	Condition of the tree	x	x	Overall health assessment
Planting data	Date of planting	x	x	To plan maintenance or replacement
	End of guarantee period	x	x	To plan an inspection
	Origin of the nursery plant	x	x	Climate resilience, disease and pest spread, replacement
	Comments about the nursery plant	x	x	For replacement, maintenance and analysis
	Habitat data		x	Volume and structure of topsoil, origin of planting soil
	Irrigation system		x	For planning maintenance
	Tree support		x	
	Tree trunk guards		x	
	Root protection		x	
	Mulch		x	
Existing tree data	Age of the tree	x	x	To plan maintenance or replacement
	Height of the tree		x	To plan maintenance and analyse cover density
	Tree diameter at breast height			In the absence of more detailed data, can be used to derive the age and size of the tree
	Tree crown diameter			To analyse cover density
	Height of the trunk	x	x	Selection of replacement species/variety and planning the maintenance
	Condition of the roots	x	x	
	Condition of the trunk	x	x	To plan maintenance or replacement
	Condition of the crown	x	x	
Mainte-nance data	Pruning		x	To plan maintenance
	Fitting a support belt		x	
	Cleaning tree cavities		x	
	Removing the damaged part of the trunk		x	
	Supporting the trunk		x	
	Removing soil from the root collar		x	
	Mulching		x	
	Watering		x	
	Fertilising		x	
	Weed, disease or pest control	x	x	Selection of replacement species/variety and maintenance planning, carrying out analysis
	Studies	x	x	To plan maintenance or replacement, carrying out analysis
	Date of inspection	x	x	To plan maintenance or replacement

tion. To prevent and mitigate the occurrence of urban heat islands, canopy coverage ratio analysis is used, which requires information on canopy diameter and tree height. For an existing tree, trunk diameter data is not required. If the planting date is not known, the age and size of the tree can be inferred from it. It is also common practice to ask for a price based on the tree's diameter at breast height when ordering felling.

The data on maintenance (Table 3) shows that most of its operations are necessary to plan on time, as the health and longevity of the tree depend on timely pruning: belated pruning causes significant pruning lesions, weakens the tree and, thus, contributes to the spread of diseases or pests. The various pruning operations are the most extensive part of tree maintenance. The healthier the tree, the more resistant it is to diseases and pests.

On young trees, attention must be paid to the correct development of the crown structure. For example, it is necessary to carry out structural pruning to avoid the emergence of codominant trunks that may subsequently break. At the later stages of a tree's life, crown care, which may involve removing dead, dangerous or malformed branches, thinning the crown or reducing its volume by up to 20%, is crucial in maintaining the safety and health of the tree. In urban conditions, one must also consider the street corridors, as ensuring sufficient room for traffic flow often necessitates raising the tree crowns. Furthermore, tree canopies may need to be maintained in a trimmed form to suit better the limited growing conditions or a design style of a particular park. These activities are also part of maintenance pruning.

Nowadays, pests and diseases that damage trees can spread quickly. To stop both introduced and existing pests, e.g. Dutch elm disease, Asian longhorn beetle, from spreading, it is indispensable to anticipate the development of potential threats and act swiftly with disease control or felling. These data are also necessary for planning tree replacements to avoid pests or the spread of plant disease to new trees.

Comparing the data of different assessments with the health condition of the trees at that given period gives us an understanding of the time scale when felling and/or replacing a particular tree becomes necessary.

Conclusions

The results of our study show that although Kaarli Boulevard is one of the most important historical tree stands in Tallinn, about which a seemingly abundant amount of information has been collected over the years, the available data is not usable as a substitute for a longitudinal survey. Therefore, we must conclude that planning the further maintenance and renewal of historical tree stands in Estonia cannot rely on existing data for the following reasons:

1. Existing studies are scarce, untraceable and/or unavailable.
2. Studies are of very uneven quality. In most cases, study results are presented in the form of descriptive text with numerical data.
3. Different methods have been used in the surveys, which makes it impossible to compare data reliably.
4. The most common evaluation method (observation) is subjective in its essence.
5. The survey materials are kept in different archives, e.g. in Tallinn City Government, Tallinn Botanical Garden, and the archives of the Heritage Board, and are difficult to locate.
6. Some of the materials are in private archives which are not accessible.
7. Not all of the information has been written down in manuscripts or published documents, but can be found only by chance while having conversations with older (often retired) officials.

By their very nature, stands are living communities, and their longevity depends on many factors. In the case of old alleys, constant monitoring of their health is necessary for a timely response. Recording the current state does not provide the needed information in the long term, since the plantation, like a living community, is constantly changing and is not static. It is therefore essential that monitoring of stands is carried out continuously over a long period of time and is based on a common methodology that allows data to be compared and timely decisions to be made that will extend the lifetime of the stand and ensure the safety of the urban environment. In the life cycle of a green space, which consists of the stages of planning, design, construction, and maintenance, the latter is the longest stage, lasting more than 150 years, in the case of Kaarli Boulevard. At the same time, maintenance depends very much on the quality of the preceding stages. When dealing with the life cycle of green spaces, it is crucial to manage the different stages soundly and have the necessary data to make decisions based on analysis.

Since other boulevards also lack comprehensive studies, the problem is not uncommon or limited to Kaarli Boulevard or, in fact, Tallinn; it is systemic to all of Estonian urban historic tree stands. Systematic maintenance and renewal of tree stands, however, requires improved data availability, harmonisation and continuous updating. To achieve this, modern digital systems are an excellent solution, allowing a comprehensive approach to managing data on different historic tree stands.

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Appendix 2

Publication II

Nutt, N.; Salmistu, S.; **Kupper, K**.; Kotval, Z. 2024. Assessing age-friendliness of contemporary urban outdoor places in Estonia. *Quality in Ageing and Older Adults*, 25 (3), 204−219, August 2024.

Assessing age-friendliness of contemporary urban outdoor places in Estonia

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Abstract

Purpose – *This paper aims to explore how recently designed and built urban public spaces in Estonia address the concept of age-friendly environments and consider older adults as users of these spaces. This paper presents the evaluation of public spaces built as a result of urban design competitions in ten small towns of Estonia from 2014 until today.*

Design/methodology/approach – *This study explored and assessed how contemporary urban outdoor places meet the needs of older adults. For this purpose, this study developed an assessment instrument of age-friendly environment principles based on various sources and conducted fieldworks.*

Findings – *This study assumed that the needs of older adults were considered during the design competition and construction, as all towns of competition areas have a significant aging population. The findings suggest that various fundamental principles of universal or age-friendly design are not met, and there are areas of improvement in the inclusive design for all people that supports healthy aging.*

Originality/value – *This study can be used as improvement tool for current places in Estonia and basis for future design projects to make public places more age-friendly, specifically senior-friendly.*

Keywords *Age-friendly environments, Universal design, Built environment, Estonia*

Paper type *Case study*

1. Introduction

Health is a principal factor that influences individuals in their everyday life and the society as a whole. In particular, two urban planning concepts are focusing on health. First, the concept of healthy cities, which focuses on public health, equity and equality, urban design and mobility issues among others. Second, the concept of age-friendly cities and communities has emerged as community development initiative since 2006 in response to a global ageing society with public health as overarching concern.

Focusing on age-friendly communities is highly relevant in Estonia - demographic data shows that in 2021, 27% of the population was over 60 years of age and the number of people over 65 years old were 20% of the population. These proportions increase in time - according to the baseline projections of Statistics Estonia (2019, 2023) people over 65 years old increase to 28% by 2050.

Older adults are very diverse social group - they vary greatly in age, physical and mental capacity and sociocultural differences, similar to younger generations. Research on age-friendly communities suggests that before starting to create or renovate public spaces that are suitable to older adults, engaging older adults who are most likely the frequent users of the space is a good practice (Buffel *et al.*, 2012; Buffel and Phillipson, 2016; Fitzgerald and Caro, 2014; Ma and Joshi, 2021; Menec *et al.*, 2011; Phillipson and Grenier, 2021; Steels, 2015; Zhang *et al.*, 2019). Mitchell and Burton (2006) found that dementia-friendly outdoor environments are places that are familiar, legible, distinctive, accessible, comfortable and safe. The findings have enabled the researchers to provide some preliminary recommendations for

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designers, at all scales from urban design to the design of street furniture, on the criteria to consider in developing dementia-friendly urban areas. Most important and overarching concepts of age-friendly communities for older adults related to physical environment are independence, staying home (ageing in place), mobility, physical activity and physical accessibility (including getting from and to places, usability and quality, places to go) (Bayar and Yılmaz, 2023; Chao, 2019; Gilroy, 2021; Salmistu and Kotval, 2023; Sooväli-Sepping *et al.*, 2023; Van Hoof *et al.*, 2022; Zhou *et al.*, 2023). As pointed out by Wang *et al.* (2022), the quality of open space is more important than accessibility factors for older adults.

The topic of universal design, including principles of age-friendliness has been studied in Estonia for more than 10 years. In addition to analyzing existing outdoor spaces, elderly-friendliness of design projects has also been studied by Sauman (2017) who analyzed the winning entries of the urban design competition "Great Public Space" which was dedicated to the 100th anniversary of the Republic of Estonia held in 2016, with the aim to find out how much designers and city officials consider the needs of older adults in the design process of public areas. This paper has gained a major inspiration from the research by Sauman and led to the development of this study.

This study focuses on identifying the inclusive design elements that are specific to Estonia, based on ten recently built urban spaces and aims to highlight the areas that can be further improved. The purpose of this assessment is not to rank and compare selected contemporary places but point out various design principles and components that are crucial for older adults and showcase the information that can be used as inspiration and insight for further developments to make public places more age-friendly, especially senior-friendly.

Authors of this study assumed that the needs of older adults were considered during the design competition and construction as all towns of competition areas have a significant aging population. Moreover, authors acknowledge the fundamental principle that public spaces are designed for all people and are aware that none of the explored places have been specifically designed for older adults but as intergenerational places.

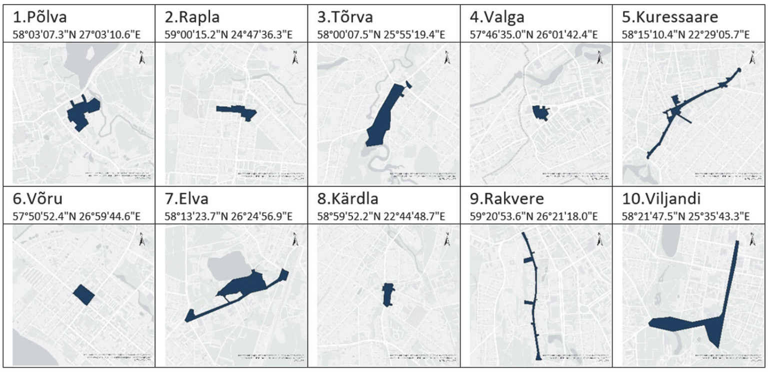
There are various guidelines and toolkits that help to measure age-friendliness of outdoor spaces, from which the most fundamental sources are developed and published by the World Health Organization (Gamme and Anne Berit, 2020; Loukaitou-Sideris *et al.*, 2014; WHO Regional Office for Europe, 2018; WHO, 2007, 2015). For the purpose of this study, we developed an assessment instrument as the combination of these sources and research outcomes by Salmistu and Kotval (2023).

2. Methods

The objects of this research are central squares or streets built on the basis of the winning entries of the Republic of Estonia 100th anniversary architecture program "Great Public Space" which dealt with the design of city centers as one of the important goals of regional policy (Eesti Arhitektide Liit, 2024). Well designed and planned town centers would be pedestrian-friendly spaces that foster community cohesion, host cultural events and stimulate business. The competition took place in 15 cities in 2014–2017 with the aim to reconstruct centrally located public urban spaces by 2020 at the latest. The program was initiated by the Association of Estonian Architects and the organizing team of "The Republic of Estonia 100." Currently the program is continuously reshaping urban space in various small towns in Estonia.

The selection criteria for contemporary urban public spaces explored in this study are: first, they are selected to the project of Great Public Space (i.e. they constitute the most contemporary built urban spaces in Estonia designed through competition) and second, they have been implemented. As a result, ten public spaces were selected as shown in Figure 1.

Figure 1 Configuration of the project areas (all in same scale and orientation)



Notes: Selected places differ in sizes and configuration. map sources: esri community maps contributors, estonia environment agency, estonian land board, esri, HERE, garmin, GeoTechnologie, Inc, METI/NASA, USGS
Source: Figure by author

Majority of the architectural competitions for the selected public places took place in 2015. Some implemented projects (e.g. Tõrva, Valga, Elva) have received the annual prize of landscape architecture that is considered the highest prizes in the profession in Estonia.

Configurations of the areas vary from solid squares to linear and polyhedral shapes, as shown in Figure 1. According to the aim of the project "Great Public Space," mostly central urban spaces (town centers) have been developed (Kärdla, Rapla, Tõrva, Valga, Võru), but also town centers with accompanying main street have been redesigned (Kuressaare, Viljandi and Elva). In one case, only the main street in Rakvere (historic street, linear urban space) has been developed and one new central area next to the town center in Põlva was created.

2.1 Assessment method

To assess selected public spaces, authors developed an assessment instrument based on the guidelines "Placemaking for an Aging Population. Guidelines for Senior-Friendly Parks" (Loukaitou-Sideris *et al.*, 2014) and we adapted it to the specifics of Estonia and elaborated with complementary age-friendly cities' principles (Gamme and Anne Berit, 2020; Public Health Agency of Canada, 2015; Salmistu and Kotval, 2023; Sawyer and Bright, 2007; WHO, 2007, 2015; WHO Regional Office for Europe, 2018).

Similarly to the guidelines by Loukaitou-Sideris and colleagues, we structured our assessment into ten subcategories (design principles), which are control, choice, safety and security, accessibility, social support, physical activity, contact with nature, aesthetics and sensory delight. We developed an assessment instrument with various topical questions in each subcategory to assess the age-friendliness of contemporary urban public places in Estonia, and the convenience and suitability of the public areas for older adults. During the site visits, either "1 for Yes" or "0 for No" was marked after each question on the questionnaire. If the question was not applicable, NA was marked in the table. For example, if there were no stairs in the area then the question about handrails of stairs did not apply. For partially met questions, decisions were made based on team discussion. If necessary, the comments box was filled with clarifying information. The evaluation matrix can be seen in Table 1.

Fieldworks were conducted from August through September 2023 by the team of professional landscape architects. Two researchers visited each area independently to validate the collected data. This ensured that the information observed and documented was as correct as possible as subjective nature of observations cannot be fully eliminated. In addition, a large amount of photographic material was collected, which made it possible to validate the necessary aspects later. During the analysis, we first compared all topics in general, and then the questions within the categories by topics.

In terms of assessing the category of contact with nature, it is important to note, that most explored public spaces have been designed as open squares following the competition guidelines (i.e. not as parks or green areas *per se*), which may have set the limitations assessing greenery and green infrastructure (e.g. use of large trees). Also, although the primary assessment guidelines used in this study refer to parks, we have considered these principles universal to all public spaces.

3. Assessment

3.1 General results

First, it is important to note, that components listed and assessed in this study are valued by most users but are particularly significant and beneficial for older adults who often do not have other satisfactory options to be physically active and exercise, make and keep social connections, or enjoy nature. Our research showed that the least attention in the built urban spaces has been paid to the topics of "control" and "choice." The most attention has been paid to the topic of "aesthetic and sensory delight." The topics of "safety and security" and "contact with nature" have been given some attention. At the same time, a little attention has been paid to the topic of "social support" as well as to the topic "physical activity."

The analysis carried out by topics demonstrates the shortcomings and limitations of urban spaces more precisely, which are described in the following sections.

3.2 Control and choice

Based on the guidelines for senior-friendly parks (as urban spaces), control refers to persons' real or perceived ability to determine what they do, to affect their situation and how they engage with other people and the surroundings (Loukaitou-Sideris *et al.*, 2014). A sense of control is particularly important to older adults with diminishing physical or cognitive abilities. Orientation is particularly important for seniors who may suffer from cognitive impairments.

The topic "control and choice" was assessed the weakest. The assessment shows a lack of overview maps of the area that would facilitate orientation. For instance, for older adults, it is important to find a restroom quickly. In general, there is also a lack of signs that would make it easier to navigate in the area. Because the mobility of the older adults is diminished, it is important for them to find a shortcut to a required place. The most subjective question in this topic was the assessment of the overall design of the place.

Furthermore, there were limited options for choosing a seat for individuals versus groups (private seating), private versus open (visual separation), in the shade versus in the sun and direct versus circular walkways. As a positive aspect, it can be highlighted that the seats in all areas were clean and tidy (as they are newly constructed areas).

Because observed places are central squares and streets, some noise is unavoidable. The material of the benches was user-friendly, and many benches have backrests, but most benches have no armrests, which would make the bench more user-friendly for older

Table 1 Evaluation matrix

Components	Description	City Põlva	Rapla	Tõrva	Valga	Kuressaare	Võru	Elva	Kärdla	Rakvere	Viljandi
CONTROL	There is a map that makes it easier to find your way around the area; way-finding	0	0	0	0	0	0	0	0	0	0
	There are signs that makes it easier to find your way around the area; way-finding	0	0	0	0	1	0	0	0	0	1
	Clear area design, easy to navigate, easy to understand	0	0	1	0	1	1	0	0	1	1
CHOICE	You can choose between seats (individuals-groups)	1	1	1	1	0	0	1	0	0	0
	You can choose between seats (private-open)	1	1	1	0	0	0	0	0	0	0
	You can choose between seats (in the shade-in the sun)	1	1	1	0	0	0	1	0	0	0
	You can choose between different roads, routes (direct-circular/longer, meandering)	1	1	1	1	1	0	1	0	0	0
ACCESSIBILITY	The surrounding streets do not have a high traffic load (noise, accessibility); [cognitive/subjective assessment]	1	0	1	1	1	0	0	1	0	1
	Heavy trucks (and other heavy traffic vehicles) are not using the surrounding streets and/nor cross the area	1	1	0	1	1	1	1	1	0	1
	The area is easily accessible (crosswalks)	0	1	1	1	1	1	1	1	1	1
	Crosswalks are with the sound (audio traffic lights)	0	NA	NA	0	0	NA	NA	0	0	0
	Crosswalks are with long traffic lights	0	NA	NA	0	0	NA	NA	1	0	1
	In/near the area there is a center necessary for the elderly (municipal government (social worker), clinic, grocery store, pharmacy, library, etc.)	0	1	1	1	1	1	1	1	1	1
	The public transport stop is next to the area	1	1	1	1	1	1	0	1	0	0
	The surrounding sidewalks are barrier-free and wide enough for a walking aids (pushing buggies, rollators), wheelchair	1	1	1	1	0	1	1	1	0	1
	There are benches along the access roads	0	0	0	0	0	0	1	1	0	1
	Ability to use and locate the toilets (in area or surroundings)	1	1	1	1	1	1	0	0	0	0
	There are disabled parking spaces for cars (priority parking)	0	0	1	1	1	0	1	1	0	0
	There are clearly marked setting down points/pick up areas	0	0	0	0	0	0	0	0	0	0
	Texts are at the height of a sitting person (readable from a wheelchair) – ca 70 cm from the ground; information, way-finding	0	0	0	0	0	1	1	1	0	1
SAFETY AND SECURITY	The place is clean and well maintained (there are trash cans, garbage cleared, no graffiti, etc.)	1	1	1	1	1	1	1	1	1	1
	Most of the area (including major roads/walkways) is paved	1	1	1	1	0	0	0	1	0	1
	The area is well lit (there are lights throughout the area)	1	1	1	1	1	1	0	1	1	1
	The area is/can be used by other social groups (teenagers, young people), which indicates the risk of falling (risk by younger generations)	0	0	1	0	1	0	0	1	1	1
	Traffic is regulated to access the area (crosswalks, traffic lights)	1	0	1	0	0	1	1	1	1	1
	Joints btw paving units are not too wide (get stuck, stumble); joints without rounded corners	0	1	0	1	1	0	1	1	0	0
	The area is not/cannot be used by other social groups (drunkards, homeless); there's no nuisance element that limits or eliminates the use of the area	1	1	1	1	1	1	1	1	1	1

(*continued*)

Table 1

Components	Description	City Põlva	Rapla	Tõrva	Valga	Kuressaare	Võru	Elva	Kärdla	Rakvere	Viljandi
	Surfaces are firm and even (e.g. flat without curbs, slopes (less than 2%); slip-resistant [vs loose material; Gravel/cobbles vs stones/asphalt]	0	1	1	1	1	1	1	1	1	1
	Tactile paving is used appropriately (esp. important with dropped kerbs)	1	1	1	1	1	1	1	0	1	1
	Partially inserted handrails at steps, ramps and stairs are *only in one side*	0	0	0	0	0	NA	0	0	NA	NA
	Handrails at steps, ramps and stairs are *only partially inserted*	0	0	0	1	0	NA	0	1	NA	NA
	There are handrails at *all* steps, ramps and stairs *in both sides*	0	0	0	0	0	NA	0	1	NA	NA
SOCIAL SUPPORT	There are seats for communication (placed at right angles, in a circle)	1	1	1	1	1	0	1	0	1	1
	It is good to observe the activities of others from the seats	1	1	1	1	1	1	1	1	1	1
	The area has movable seats (people can move them around themselves)	0	0	0	0	0	0	0	0	0	1
	Seats are also located by the roads, pedestrian walkways (to watch passers-by)	1	1	1	1	1	1	1	1	1	1
	There are tables in the area (for playing chess, eating)	1	1	1	0	0	1	1	1	0	0
	The area has focal points that bring people together (fountain, kiosk); meeting points	1	1	1	1	1	1	1	1	1	1
	There is a notice board	0	0	0	0	1	0	0	0	0	0
	There is an outdoor library or something else that supports socialization	0	1	1	1	0	1	1	1	0	0
PHYSICAL ACTIVITY	The road network is suitable for walking, strolling	0	0	1	0	1	1	1	1	1	1
	There are low-intensity training tools, simple, stationary (permanent)	0	0	0	0	0	0	0	0	0	0
	There are attractive walking paths, e.g. to the fountain, sculpture, pavilion, flower beds, streams	1	1	1	1	1	0	1	0	1	0
	There are roads with nonslip surfaces (rubber)	1	1	1	1	1	1	1	1	1	1
	There are "walking pass markers" (benches, posts, flower pots, etc.); distance measurement	0	0	0	0	1	0	0	0	1	0
	Possibilities to engage in *active activities* (skateboards, bicycles, ball games, petanque, swings, musical instruments, human chess, etc.), functions suitable for older adults, indicates the possibilities for physical activities and inter-generational activities	0	0	1	0	0	0	1	0	0	0
CONTACT WITH NATURE	There are flowers, greenery	1	1	1	1	1	1	1	1	1	1
	Flowers, greenery are mostly in hanging flowerpots or containers	1	1	1	1	1	1	1	1	1	1
	There are large shade trees	0	1	1	0	1	1	1	0	0	0
	Large saplings have been planted	0	0	1	1	0	0	0	1	0	1
	Species that grow large are planted	0	1	1	1	0	0	0	0	0	1
	Multilevel planting has been used to have more flowers	1	1	1	1	1	1	1	1	0	1
	There are calm water elements (streams, ponds)	0	0	1	0	0	0	1	1	0	0
	There are wind chimes, the possibility to water flowers	0	0	0	0	0	0	0	0	0	0

(*continued*)

Table 1

Components	*Description*	*City*									
		Põlva	*Rapla*	*Tõrva*	*Valga*	*Kuressaare*	*Võru*	*Elva*	*Kärdla*	*Rakvere*	*Viljandi*
AESTETIC AND SENSORY DELIGHT	There is a possibility to follow/observe seasonal changes (flowers grow, bloom)	1	1	1	1	1	1	1	1	1	1
	There are things that appeal to stimulate different senses (hearing, touching, smelling, seeing); the design of the area uses sensory interesting elements located at short distances	1	0	1	1	1	0	1	1	1	0
	There is no overabundance of visual elements (causes visual confusion)	0	1	1	0	0	1	0	0	1	0
	Interesting views are used (views to the distance, to landmarks)	0	0	1	1	1	1	1	1	1	1

Source: Table by author

adults. In several cases, the comfort was not achieved due to strange incline of the backrest or the depth of seating surface. Benches were placed in the sun, but there was little or no options of sitting in the shade. It was also not possible to sit in the wind-shade.

3.3 Accessibility, safety and security

The ability to access a destination safely, with ease and without barriers influences people's decisions to visit it. The ease of the journey to and from the destination as well as the ease of movement and orientation while at the public space become particularly important for older adults (Loukaitou-Sideris *et al.*, 2014).

The observed sites are in the middle of towns and are accessible from the surroundings. Access to observed areas was generally regulated with crosswalks from the surrounding streets. Traffic speed limit (30 km/h) and speed bumps were used but there were no traffic lights. In general, it can be stated that the vehicle traffic load is rather low in most areas.

As all selected sites are the main squares (or main streets) of the settlements, municipal buildings, cultural centers, shops, cafes, etc. were located in there, nearby or alongside. There were also public transport stops at more than half of the areas. However, accessible streets mostly did not have benches where older adults could sit either when entering or leaving the area. In those areas where the design solution also included the bordering streets, there were benches for sitting on the side of the street.

The need for safety is crucial for older outdoor space users and concerns about safety may deter them from visiting (Bedimo-Rung *et al.*, 2005). Older adults may become anxious for possible crimes and interactions with particular individuals such as homeless or teenagers on skateboards (Loukaitou-Sideris *et al.*, 2014). One of the major stressors regarding safety and security is the fear of falling. This is also related to crossing roads on busy streets.

All areas were clean, there were trash cans in the areas, there was no graffiti, etc. Furthermore, no other social groups (i.e. drunk people, homeless people) were observed. None of the areas were designed for use only for the older adults, but they were universally designed for all possible users (intergenerational). For example, playgrounds were built for children, skateboard ramps for younger people and cafes for adults. However, there were places where the area for riding skateboards and stunt bikes was in the middle of the square (Kärdla) and were not safe to pass.

In general, the areas were paved with hard surfaces and comfortably usable for the older people (with wheelchair, walker etc.), but the construction quality of several areas (e.g. Rapla, Kuressaare) was poor and the stones were either loose or the joint gaps were uneven which constitutes the high risk of falling.

The results of our study confirm that there are enough benches in all areas, but we observed that a large part of the benches lack armrests that the older adults can lean on when standing up. We also observed the same with handrails on stairs and ramps. Handrails were either missing or only on one side of the stairs. A couple of areas had no stairs making them senior-friendly.

Although tactile pavement was used in all areas, some problems became apparent. First, their use is sometimes questionable as they may lead nowhere and secondly, which is a big issue, movable benches (i.e. movable with special equipment by maintenance crew), trash cans and other street furniture were placed on the tactile paving, which made them very dangerous for people with visual impairment.

3.4 Social support

Social support refers to the human need of wanting to be connected with other people and providing or receiving support by them (Loukaitou-Sideris *et al.*, 2014). Urban spaces and their functions provide opportunities for interactions and socializing with other people – between the peers or intergenerational connections. Activities that take place in urban space help to create sense of belonging and sense of community. Physical space enables people to be part of the community life.

The arrangement of benches in the areas made it possible to observe people passing by and watch the activities of other people on the square while sitting. However, the areas did not have movable benches that could be replaced to desired spots by people. In some areas, the benches were not permanently attached to the ground and although they looked like movable benches, machines were needed to relocate them. The benches which were probably moved by the maintenance workers had ended up on the tactile pathways in some cases.

There are focal points for gatherings in the squares by design. However, we did not observe them fully functioning as ones in the space. Many squares have flag areas, fountains, playgrounds, kiosks, etc. There were cafes by the squares for open-air dining. Also, there are outdoor concrete tables with chairs. Several tables have chessboards drawn on them.

We did not observe notice boards in most of the squares where local people could post notices. There are billboards for companies and organizations to advertise their events.

3.5 Physical activity

Open spaces can encourage physical activity by providing appropriate settings for active recreation and walking (Loukaitou-Sideris *et al.*, 2014). Older adults are more likely than other groups to live sedentary lifestyles and the need of physical exercise becomes more important in later life.

The reluctance of many older adults to get involved in physical activity may be a result of fear because of declining capacities and limited stamina but also because of lack of appropriate spaces and social support for exercise. Research shows that if low-intensity exercise equipment is provided older adults would use them frequently (Loukaitou-Sideris *et al.*, 2014). Nevertheless, walking is the easiest and most common type of physical activity for seniors. Thus, walkability plays a crucial role in urban spaces.

None of the areas had low-intensity exercise equipment for older adults. We also did not see simple motivating tools to support physical activity such as walking markers. In most areas, it is possible to walk along different roads and nonslippery materials are used for the pavement. To increase the attractiveness of the areas, fountains, specially designed bollards, flag squares, greenery (diverse vegetation) and pavilions were used.

3.6 Contact with nature

Open public spaces and parks provide contacts with nature in the city and can offer relaxation and positive experiences as “natural distractions,” defined as “environmental features that promote an improved emotional state in the perceiver, may block worrisome thoughts, and foster beneficial changes in physiological systems” (Loukaitou-Sideris *et al.*, 2014).

Positive results can be seen in the category of contact with nature. All areas have diverse greenery (rich in species), multilevel vegetation which is selected considering the seasons. Although half of the areas have a fountain there are also three places with calm water bodies. The observed places are not necessarily located by rivers or lakes. However, in some cases, this potential (location by the lake) was used very well (Tõrva), but in another case (Põlva), there was no connection to the river bordering the area.

In general, it can be said that the planting material used in urban spaces has become increasingly high quality. The saplings are larger and of better quality, and the effect of landscaping can be felt immediately after planting. However, it can be pointed out that to achieve a future shading effect, the growth height and width of the species must also be considered in addition to the age of the planting material.

3.7 *Aesthetic and sensory delight*

Urban design as a form of art should provide aesthetic experiences as well as stimulate or calm the perceptions of senses. As older people walk at slower paces and cover shorter distances than younger adults, sensory interesting features should be placed at shorter intervals than it would be necessary for spaces designed for the general public. However, there should be a careful consideration of the amount of visual variety to avoid visual confusion and disorder (Loukaitou-Sideris *et al.*, 2014).

Although aesthetic evaluation is subjective in nature, we evaluated four aspects in this category. In general, the results were positive. The presence of greenery was especially good which gives the opportunity to observe the change of seasons. The second positive aspect is the availability of interesting views. In case of some areas, the use of local landmarks such as church towers (Valga) was successfully accomplished.

4. Discussion

4.1 *Positive findings*

In this study, we identified criteria that were met in all (10) observed places. It can be argued that these constitute the strengths of Estonian contemporary urban design considering older adults.

All areas were clean and well maintained, as shown in Plate 1. This is an advantage for centrally located urban spaces. Also, these places serve as representative spaces of the towns (i.e. most important public space in the city). We suggest that this category could be re-evaluated after a couple of years as we observed areas with low construction quality which is related to topics of accessibility and comfort. Also, because these are central spaces in towns, there were no nuisance elements that limited the use of the area such as drunkards or homeless people.

Regarding the seating options, there is variety of seats in the areas. In all areas the seats are placed along the roads, the benches are made of resistant material and provide good places for people-watching. Estonia has four seasons – in winter it is cold, snowy and icy and summers can be hot, sunny and with heavy rains. Springs and autumns are windy and cool or cold and muddy. Thus, it is comfortable to be outside only in summers and seasonal changes make designing outdoor spaces difficult. It is important to note that all areas

Plate 1 Project areas are all well-maintained (example from Elva on the left) and there are benches along the streets to support accessibility (example Kärdla on the right)

Source: Figure by author

provide the opportunity to sit in the sun, however, sheltered areas or seating should be increased for hot and sunny seasons.

The third positive observation we identified is related *to landscaping and greenery* (Plate 2). There is a good diversity of landscaping and greenery (although all spaces were designed with the purpose of creating an urban central square, i.e. open paved areas for large gatherings) - low grass surfaces, slightly higher perennials, bushes, trees as well as hanging flowerpots have been used. In the selection of species decorative features such as flowering, leaf color and fruit ripening have been considered. Thus, the greenery of the areas enables to observe seasonal changes and provides sensory enjoyment.

Fourth, *focal points* have been addressed, such as culture houses, flag squares, fountains which provide great meeting points (Plate 3). However, they do not always function as meeting places but as points of interest to watch or take pictures. Also, we found that pavements are slip-resistant in all areas (no wood/timber was used which becomes dangerously slippery especially in rain but certainly in ice).

Finally, in general, creation and existence of these new urban spaces can be seen as a positive factor *per se* as all cities require updating and revitalizing their spaces and amenities. Moreover, people and their needs, as well as desires and lifestyles change over time, and new urban spaces address these needs more and provide better urban life experiences to people.

4.2 Drawbacks

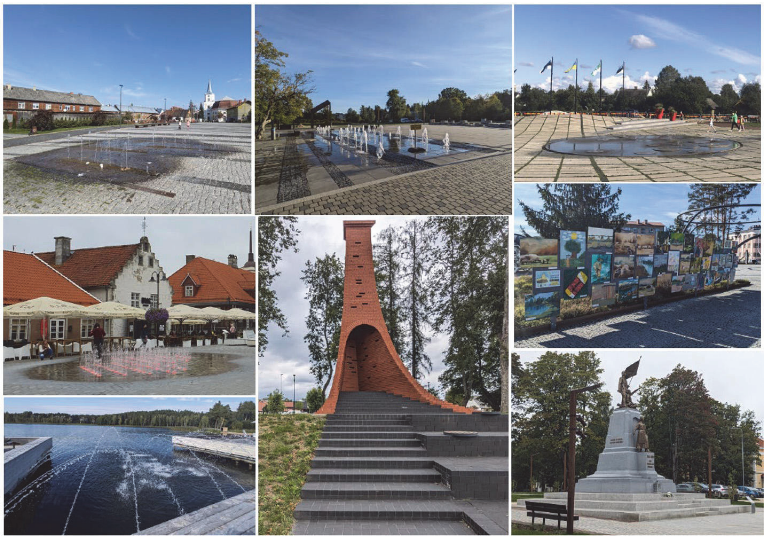
This study identified common shortcomings across all (10) newly constructed urban spaces. It can be argued that these constitute the most crucial weaknesses of Estonian contemporary urban design considering older adults.

The existence of schematic maps of the area which facilitates wayfinding has not been considered in public space design– none of the area met this criterion. In general, there is also a lack of direction signs. Because the mobility of older adults can be limited, it is time-sensitive to find a shortcut to the desired place. It would certainly be important to pay more attention to this without going to the other extreme which results in a public space littered with information noise. Although not identified as a common prevailing deficiency in observed places, the lack of public restrooms in public space is a general issue in Estonia,

Plate 2 Design of the sites makes use of surrounding and existing greenery but also create a variety of new greenery

Source: Figure by author

Plate 3 Water features are widely used as focal points (Valga, Põlva, Rapla, Kuressaare and Elva) but there are also exhibitions (Võru), architectonics (Tõrva) and monuments (Viljandi)



Source: Figure by author

that requires more attention as this can be a great obstacle for older adults going out of their homes from the first place but is very relevant to other generations as well (e.g. in children's playground, people with health-related issues, pregnant women).

Another shortcoming that stood out in all areas is the lack of exercise equipment for older adults. In Estonia, it is not a common idea that older adults want to be physically active as much as they can, beside sitting on benches. Several areas have playgrounds for smaller children, some have skateboard ramps for older children, there are basketball tables, ping-pong tables, but none of the areas had any low-intensity exercise equipment for adults. Consequently, activities for older adults include mainly sitting that allows communication or passive people watching (e.g. seeing children play), or walking. As many older adults take care of their grandchildren, staying around children's playground is another activity.

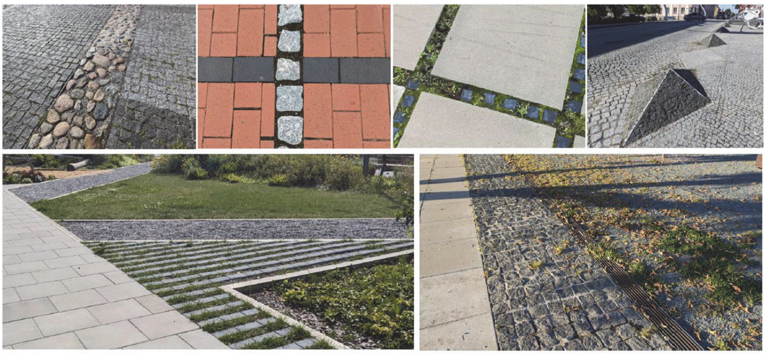
The lack of offering more peaceful activities, such as the sound of wind chimes or borrowing books from outdoor libraries can also be pointed out as a disadvantage. The latter have been used successfully in many places in Estonia but there were no such opportunities in observed places.

Finally, although the implementation and existence of ten novel places have stated as positive aspect in general, the quality or usability always remains as simultaneous factor that impacts the overall satisfaction and usability of the places (Plate 4). For instance, poor quality of stone pavements emerged as one of the most visible drawbacks.

4.3 Meeting the needs of older adults

This study demonstrates most relevant positive aspects and deficiencies considering older adults as users of newly designed urban spaces in Estonia. Consequently, there are more

Plate 4 Different materials in pavements have been used, including widely used cobble stones and monochrome surfaces. In many cases, uneven transitions and gaps between materials were identified



Source: Figure by author

positive aspects than shortcomings observed across all ten places. Nevertheless, there a much more criteria in between that some places addressed well, and some did not at all, which indicates the necessity for further studies. Data of this study demonstrated that there are a lot of possibilities for improvement to adjust the design of the places with the needs of senior users.

Research by Sauman (2017) which analyzed the design competition projects within the project of Great Public Space also identified limitations in the topic of control. At that time (in 2017), three out of four items in the category had issues with providing information to facilitate orientation in the area. Our study suggests that this problem would only increase throughout the construction phase. Although design principles might have been proposed in design phase, some ideas have been cut off in construction stage. Alternatively, this may be the outcome of the fact that the competition works are not built according to the original plan and several ideas that were on paper do not reach to the real space. Thus, good principles may be lost in the implementation process if the designer and client (local governments in this case) are not aware of the needs of older adults as one large segment of final users. Considering the number of older adults in the population, some design principles should be prioritized and followed.

Overall key-finding of this study reveals that the design outcomes completed through urban design competitions do not necessarily reflect the needs and desires of local people as users of the space. Competition and implementation process of these places did not involve public engagement component. As research shows, placemaking occurs or can be initiated through top-down process by professionals (i.e. facilitated placemaking) or bottom-up actions by local people (i.e. lived placemaking) (Balassiano and Maldonado, 2015). Explored urban spaces in this study are examples of facilitated placemaking, whereas placemaking of certain neighborhoods (in residential areas) in Estonia are examples of lived placemaking where residents have actively participated in shaping and designing their local urban spaces (Nutt *et al.*, 2021). Actively involving community members to the design process from the beginning, however, is one of the major key principles of the concept of age-friendly environments (Gamme and Anne Berit, 2020; Ma and Joshi, 2021; Salmistu and Kotval, 2023; Steels, 2015). Consequently, placemaking of these areas has been top-down initiatives, and reflections, assessments and user satisfaction with these places look for future explorations and research.

5. Conclusions

This article explored how recently designed and built urban public spaces in Estonia address to the concept of age-friendly environments and consider older adults as users of these spaces. We explored the design of ten public central squares or streets built in small towns in Estonia during the last decade with the perspective of older adults.

Although design principles and several assessment criteria meet the needs of all age groups, there are components that are more important for older adults, some of them are crucial preconditions to visit public spaces. On a positive note, we can point out that all areas were clean and tidy which increases the sense of security which is extremely important for older adults. All areas have diversity of seating places. Resting possibilities are particularly important for older adults, which increases the time spent outdoors and contributes to enhancing accessibility of public spaces. In addition, it is possible to enjoy greenery in all areas which is particularly important for older adults with limited mobility and physical activity. Also, there are various institutions and public services destinations near the explored public spaces where older adults can communicate and interact with each other. However, the lack of maps to facilitate navigating around the area and the lack of physical exercise equipment for older adults are identified as some shortcomings. The purpose of this assessment was not to rank and compare the places but to highlight various design principles and components that are particularly important for older adults and present information that can be used as inspiration and insight for further developments to make public places more age-friendly. This study can be used as improvement tool for current places and basis for future design projects.

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Appendix 3

Publication III

Laura Mrosla, Henna Fabritius, **Kristiina Kupper**, Fabian Dembski, Pia Fricker. What grows, adapts and lives in the digital sphere? Systematic Literature Review on the Dynamic Modelling of Flora and Fauna in Digital Twins. *Ecological Modelling*, 504 article 111091, January 2025.

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What grows, adapts and lives in the digital sphere? Systematic literature review on the dynamic modelling of flora and fauna in digital twins

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A B S T R A C T

The modelling of flora and fauna is vital for understanding and digitally representing our environment, yet their dynamic modelling in digital twins lags behind human-made inventions like manufacturing and the built environment. The interdisciplinary nature of this research complicates tracking advancements, and no comprehensive overview exists. This Systematic Literature Review (SLR), using the PRISMA method, addresses this gap by analysing studies on dynamic modelling of flora and fauna in digital twins and 3D city models. It covers descriptive metrics and qualitative aspects, identifying key research fields, directions, users, and developers. Additionally, this SLR details on digital twin data, modelling techniques, actuators, user experience with human-computer interaction, and ethical considerations. The findings highlight that the digital twin concept is being increasingly applied to the dynamical modelling of flora and fauna. Moreover, the broad relevance of this research is demonstrated across various fields including ecology, forestry, urban studies, and agriculture, where diverse methods and technologies are used, though progress remains uneven. Currently, precision agriculture is leading the way in automated, bidirectional synchronisation between digital twins and their physical counterparts. Complementing traditional modelling techniques with AI and machine learning where appropriate, expands modelling capabilities. Meanwhile, multimodal interfaces enhance the immersive user experience. Despite these advances, challenges persist in data availability, foundational knowledge, complex interaction modelling, standardisation and transferability, underscoring the need for continued research. Digital twins for the biotic environment show promise in supporting United Nations Sustainable Development Goals 2, 11, 13, 14, and 15. This overview supports researchers and practitioners in developing digital twin applications which include flora and fauna.

1. Introduction

Simultaneously with technological development, the biotic environment is undergoing drastic transformations today (Mottl et al., 2021; Nolan et al., 2018). The increase of the human population is a catalyst for the expansion of human settlements, accelerated urbanisation (McKinney, 2008; Seress and Liker, 2015; Theodorou, 2022) and rising agricultural demand (Kehoe et al., 2017). Further, pollution, overexploitation of biological resources (Shivanna, 2020), monocultural forestry (Liu et al., 2018a), and other human-made influences (Foley et al., 2005; Tscharntke et al., 2012) facilitate habitat loss, causing biotic homogenisation, loss of biodiversity (McKinney, 2008; Seress and Liker, 2015; Theodorou, 2022), and disrupting ecosystem functioning (Theodorou, 2022). The urgency to efficiently address the human-induced negative changes impacting flora and fauna is acknowledged globally, as in the UN Sustainable Development Goals (United Nations, 2015) and in the European Green Deal (European Commission. Directorate General for Communication., 2021). To address these challenges, the conjunction of natural systems and technologies is gaining momentum, driven by unprecedented advancements in science and technology. This can be observed in agriculture (Purcell and Neubauer, 2023), urban green environments (Brkljačić et al., 2020; Galle et al., 2019) and nature overall in variegated manners (Arts et al., 2015; Mohammed, 2016; Nugent, 2018). Nonetheless, the maturity and

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inclusion of biotic elements in the digital sphere, for example (urban) vegetation, still lag behind those of human-made inventions, such as the manufacturing industry or the built environment (Shirowzhan et al., 2020; Xu et al., 2021) and the previously outlined challenges to overcome stay yet unresolved.

However, with the ongoing increase of data availability, computational power and development of digital tools, especially one concept, promising to tackle complex challenges and wicked problems, stands at the forefront of this technological break-through: the "Digital Twin". Digital twins are innovative tools integrating multiple established and emerging technologies, bridging the gap between physical assets and their digital counterparts. They enable (real-time) monitoring, diagnostics and prognostics, realistic behaviour in simulations and a continuous bi-directional alignment between the digital and the physical counterparts (Grieves and Vickers, 2017; Kritzinger et al., 2018; Wright and Davidson, 2020). While some scholars use "digital model", and "digital twin" interchangeably, there are key distinctions between digital models, digital shadows, and digital twins. One of the primary differences lies in the data flow and synchronisation between the physical and digital counterparts, which can be either manual or automatic (Kritzinger et al., 2018) (Fig. 1). For a more detailed definition of a digital twin and its differentiation from a digital model or a digital shadow, see Supplement S1.

Originating in the context of industrial design and manufacturing (Grieves and Vickers, 2017), digital twin applications have transcended industrial confines. Digital twins are now a focus of significant research (Botín-Sanabria et al., 2022) and increasingly applied in fields involving flora and fauna, such as cities (Lehtola et al., 2022), forestry (Hejtmánek et al., 2022), agriculture (Pylianidis et al., 2021), livestock-farming (Jo et al., 2018; Neethirajan and Kemp, 2021), ecology (Trantas et al., 2023) and biodiversity (Sharef et al., 2022). The scales in which digital twins are applied in this context range from local (Taubert et al., 2024) through European-wide (Khan et al., 2024b) to global, aiming at supporting e.g. the Earth's green transition (Bauer et al., 2021). Digital twins are said to hold potential for nothing less than to disrupt the status quo of ecology as a part of its digital transformation (De Koning et al., 2023).

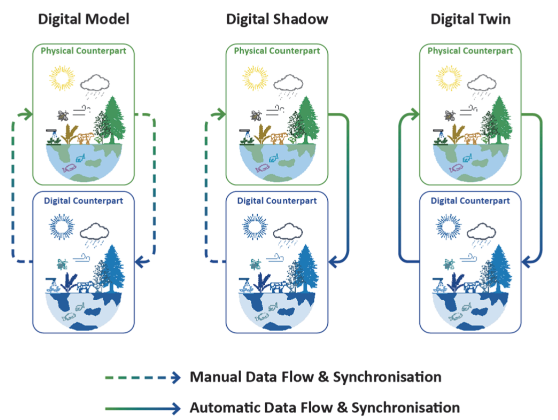

Fig. 1. Conceptual comparison of Digital Model, Digital Shadow, and Digital Twin frameworks as described by Kritzinger et al. (2018) and Botín-Sanabria et al. (2022). Digital models provide static representations of systems with manual data flow and synchronisation (left image, dashed arrows). Digital shadows include unidirectional automatic data flow (middle image, dashed and solid arrows) from the physical counterpart to the digital counterpart. Digital twins incorporate bidirectional automatic data flow (right image, solid arrows), enabling dynamic interactions and feedback between the physical and digital counterparts. This conceptual comparison highlights the progression of modelling paradigms.

1.1. *Aim of this systematic literature review*

While numerous (systematic literature) reviews and overviews exist on related topics e.g. (urban) digital twins (Deng et al., 2021; Ivanov et al., 2020; Ketzler et al., 2020; Lei et al., 2023; Qian et al., 2022; Shahat et al., 2021) and digital twins in agriculture (Purcell and Neubauer, 2023), no comprehensive overview addresses how flora and fauna are modelled in digital twins. This overview is particularly important, as the dynamic modelling of flora and fauna intersects various fields and therefore provides a centralised resource that consolidates the state of the art and facilitates a deeper understanding of the topic across different domains. Consequently, this Systematic Literature Review (SLR) aims to fill that gap and support researchers and practitioners in developing digital twin applications that include flora and fauna.

In contrast to field-specific reviews on digital twins, such as those focusing on e.g. intensive aquaculture (Føre et al., 2024) or livestock farming (Neethirajan and Kemp, 2021), or a framework for data-driven digital twins in ecology (Khan et al., 2024a), this review adopts a broader perspective. It takes a horizontal, cross-sectoral perspective on flora and fauna modelling in digital twins, avoiding segregation e.g. by species, practice, or domain. This approach allows to highlight the diverse fields where flora and fauna models are employed in digital twins and how needs and approaches differ across applications. Such cross-sectoral awareness is particularly valuable for transdisciplinary knowledge pollination and the design of reusable and transferable flora and fauna models. Moreover, it allows to address e.g. standardisation and technical challenges more holistically.

The field of digital twins is heterogeneous encompassing multiple theoretical and conceptual frameworks as well as manifold research approaches. As the meaning of the term digital twin varies greatly across research fields, for this SLR a digital twin was defined as a digital representation (digital counterpart) of a physical counterpart, encompassing variable modelling methods, e.g. 3D and mathematical models and simulations, as well as information updates that can influence both counterparts directly or indirectly. Notably, real-time data is not always indispensable for dynamic modelling of flora and fauna in digital twins, allowing flexible updating frequencies.

The initial aim of this review was to compile and analyse existing knowledge on dynamic modelling (see Supplement S1) of flora and fauna in urban digital twins (UDT). As a result of the three-dimensional nature of urban planning, UDTs are often accessed and interacted with through 3D city model interfaces. Therefore, and due to the novelty of the term "digital twin" in the urban context (Ferré-Bigorra et al., 2022; Shahat et al., 2021), we anticipated that urban digital twins could be, besides the term "digital twin", also be discovered with the search phrase "3D City Model". However, preliminary examinations revealed scant research specifically addressing this nexus. As the implications of urban areas on flora and fauna go beyond city borders (Caldarelli et al., 2023), and as there is potential for knowledge transfer from other domains, the review's scope was expanded to keep matching articles on dynamic modelling of flora and fauna regardless of discipline. Consequently, the focus shifted from city-wide digital twins to dynamic modelling in all disciplines, prompting a complete revision of the research process.

Given the advances in digital twins, and the lack of a concise overview, this review explores, analyses, and synthesises current research, highlighting achievements, identifying gaps, and proposing future directions. It especially covers descriptive metrics and qualitative aspects, identifying key research fields, directions, users, developers, digital twin data, dynamic models, actuators, user experience, and ethical considerations.

While this review aims to provide a broad overview, it is worth noting that the chosen search terms did not specifically target agricultural practices, such as precision farming or livestock modelling. Consequently, agricultural digital twins are not comprehensively addressed in this review.

2. Materials and methods

In this SLR, the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework (Page et al., 2021) has been applied. The detailed review protocol for this study is available upon request.

2.1. Research questions

This SLR was conducted with the aim to answer the following research questions (RQ):

Research question	Question	Addressed in chapter
RQ 1	When, where, for which purposes, in which fields, by whom and for whom are flora and fauna dynamically modelled in digital twins and 3D city models?	3.1 Context and 3.2 Categorisation of Research Topics
RQ 2	What data collection methods are employed, which digital twin data are generated and used and how is the data managed?	3.3 Data
RQ 3	Which modelling techniques and methods are used for which purposes?	3.4 Models
RQ 4	How are flora and fauna represented, and what methods facilitate user-computer interaction?	3.6 User Experience
RQ 5	Which ethical reflections are considered?	3.7 Ethical Considerations
RQ 6	Which fields show research leadership and what are open challenges and future directions in the dynamic modelling of flora and fauna in digital twins?	All Chapters, especially 4. Discussion

2.2. Definition of keywords and search strings

The keyword strings used for the literature search consisted of two parts (Fig. 2). For the first part, the terms "digital twin" or "3D city model" were employed. The term “3D city model” appeared to be the most widely applied for the urban context, and commonly used for reviews by other scholars, such as (Biljecki et al., 2015). Reflecting the initial focus of this SLR, the search term “3D city model” was retained in the search strings because it effectively captured articles consistent with the definition of digital twins, even when the term “digital twin” itself was not used. The term “digital twin” recently emerged across multiple disciplines. Due to its novelty and manageable number of publications across various disciplines, the search term “digital twin” was chosen.

To cover the modelling of flora and fauna, the following search terms were selected after preparatory searches to figure out the most auspicious results: “biodiversity”, “ecology”, “greenery”, “green area”, “green infrastructure”, “species”, “urban landscape”, “vegetation”, “wildlife”. The search terms “flora” and “fauna” were excluded as no applicable new articles were found during the preceding searches. The search for “green” was initially excluded, as the term is too vast.

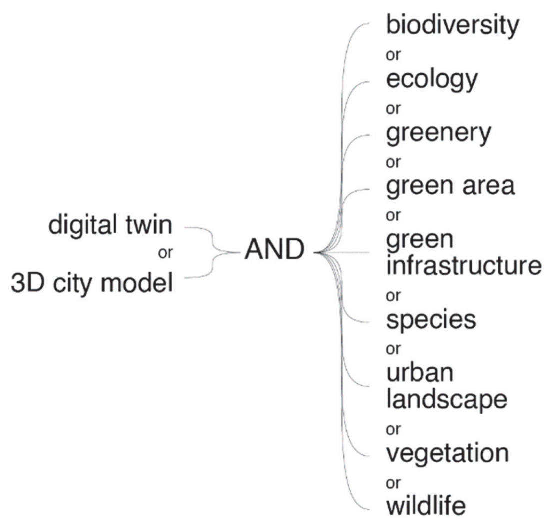

Fig. 2. Combinations of used search terms for the publication collection for the systematic literature review.

2.3. Publication collection

The initial inclusion period for publications was set from 01.01.2015 until May 18th, 2022. To further include topical records published by February 28th, 2023, the literature search was repeated on this date. The literature search for the publication collection was conducted on 18.05.2022 and 28.02.2023 in three pertinent databases (Fig. 3):

1. Web of Science (WoS, www.webofscience.com), the “Core Search” was used.
2. ScienceDirect/Scopus (www.scopus.com). The scope “Article title, Abstract, Keywords” was used for the searches.
3. Google Scholar. Search results were downloaded with the software “Publish and Perish”, as described in (Harzing, 2010). All Google Scholar search results which exceeded 250 publications were ranked by relevance and only the first 250 were included.

2.4. Publication selection

After identifying the relevant literature from three databases, duplicates were culled. Subsequently, the publications were reviewed independently by two reviewers for eligibility in three phases: by title, by abstract, and by full text (Fig. 3). The following inclusion and eligibility criteria were used:

1. Language: Studies where title, abstract and full text are in English were included.
2. Document types: Videos and webpages were excluded; all other document types were included.
3. Topic: Publications were included if they discuss the dynamic modelling of flora and/or fauna within or for future integration into digital twins or 3D city models. For studies identified with either term “digital twin” and/or “3D city model” inclusion was contingent on the study aligning with the definition of a digital twin outlined in Section 1.1: A digital model of a physical counterpart that is capable of incorporating updates (at flexible frequencies) in the virtual counterparts and influencing the physical counterpart either directly or indirectly.
4. Scope: Publications from all disciplines were eligible for inclusion.

2.5. Data analysis

For the analysis of the included articles atlas.ti web software (https://atlasti.com) and Excel sheets were used. Three types of analyses were carried out to address the research questions:

1. Articles were assigned to mutually exclusive categories based on their content e.g. 3.1.1 Time of publication and 3.2 Categorisation of Research Fields.
2. Content lists of topics relevant to the research question were compiled and systematically categorised based on all included

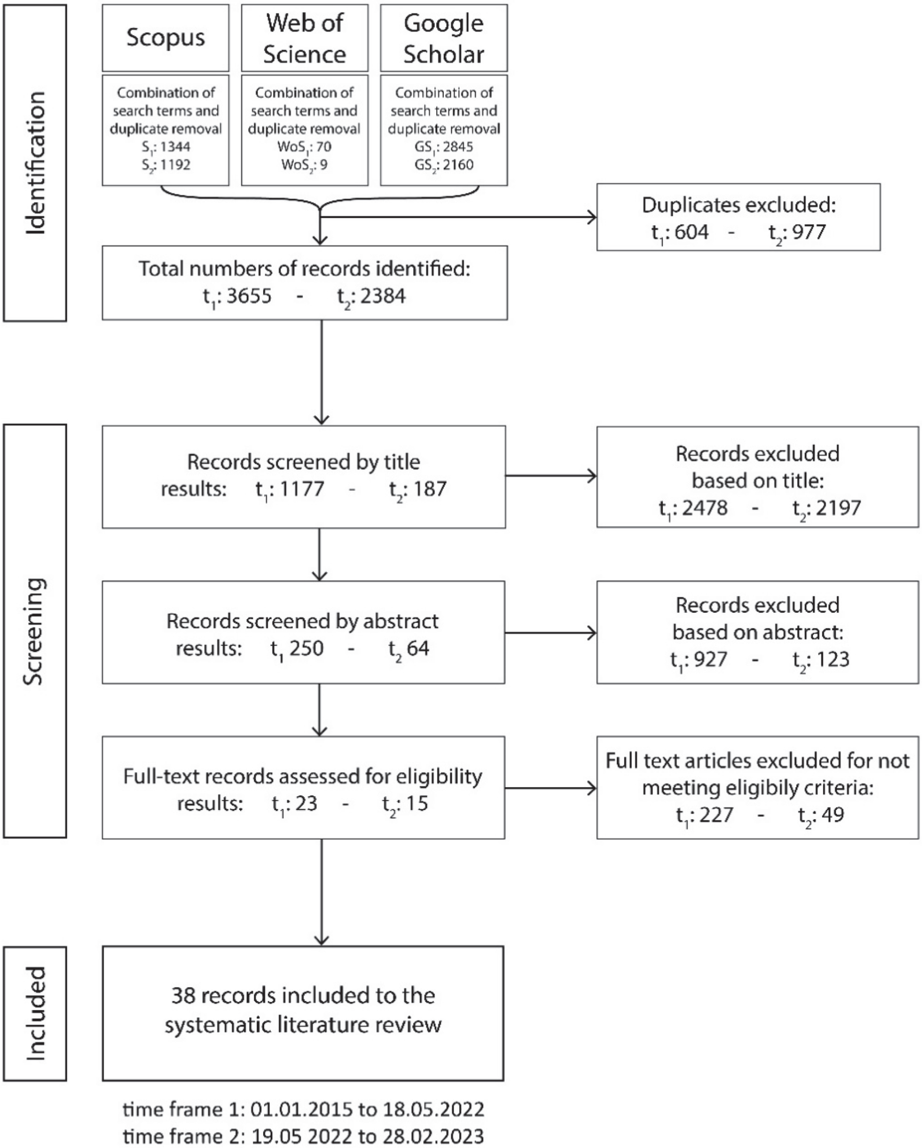

Fig. 3. PRISMA flow diagram (adapted from Page et al. 2021) illustrating the phases of the systematic literature review. It includes the numbers of publications retrieved from the Scopus (S), Web of Science (WoS) and Google Scholar (GS) databases during two data collection time frames (t1 and t2), and subsequently screened and either excluded (right) or included (bottom) in the literature review. Dates of the data collection time frames shown at the bottom of the graph.

articles. Each article could belong to multiple categories, such as "Data" see 3.3.1 and "Models", see 3.4, allowing for comprehensive coverage.

3. Qualitative themes emerging from articles were identified e.g. 3.3.4 Challenges in Data Quality and Availability were added to the content lists of relevant topics. The systematic compilation and categorisation were therefore reiterated.

This review is descriptive in nature and does not include statistical methods, such as meta-analysis. This is due to the heterogeneity of the included studies in terms of their scope, methodologies, and reported outcomes and the lack of quantitative data presented.

3. Results

Out of the total number of 6 039 publications found through the key word search, only 38 publications were eligible for the final inclusion. The included literature was published as journal publications, conference proceedings, congress publications, books, book chapters, master thesis or academic dissertation.

3.1. Context

3.1.1. Time of publication

The number of publications matching the research topic started increasing from 2019 onwards, with a drastic increase of articles containing the search term digital twin (Fig. 4). "Digital twin" ($n = 32$) is considerably more commonly used in the researched context than "3D city model" ($n = 6$). The publications retrieved using the term "3D city model" for this SLR conform to the definition of digital twins. Therefore, subsequent references will solely employ the term "digital twin" for improved readability, except when the context necessitates the differentiation between digital twin and 3D city model.

3.1.2. Spatial distribution of studies by first author affiliation

The largest shares among countries of first author affiliation location were China and Russia ($n = 5$, 13,1 %; Fig. 5).

3.1.3. Developers and users from diverse fields and sectors

The development of digital twins and dynamic 3D-models of flora and fauna is researched by experts from various fields (Shu et al., 2022). The main domains in the selected publications are biology (Shu et al., 2022), agriculture (Majore, 2022; Mishra and Sharma, 2023), agronomy (Skobelev et al., 2020a, 2022a), landscape architecture (Luka and Guo, 2021), urban planning and design (Shu et al., 2022), engineering (Fernández-Alvarado et al., 2021), geoinformatics, computer science, computer graphics (gaming and animation) (Shu et al., 2022), arboriculture, forestry (key forest stakeholders) (Buonocore et al., 2022; Shu et al., 2022), citizen science and education (Harrington et al., 2021).

The selected publications targeted three stakeholder categories:

1. *Academic research*, including research groups from the domains listed in Section 3.1.3, advancing the development and application of digital twins.
2. *Collaboration with other professionals*, e.g. researchers, (small scale) farmers (Johannsen et al., 2021; Klippel et al., 2021; Skobelev et al., 2020a; Zake and Majore, 2022), (political) decision makers (Cirulis et al., 2022; Fernández-Alvarado et al., 2021) and legislators (Mishra and Sharma, 2023) e.g. city authorities (García-Granja et al., 2020; Johannsen et al., 2021), (landscape) architects, engineers and urban planners (Fernández-Alvarado et al., 2021), with the intention of creating e.g. decision support tools or affecting (personal) behaviour (Johannsen et al., 2021).
3. *Engagement with a broader audience*, i.e. stakeholders not directly involved or contributing to the development of the digital tools, such as the general public (Klippel et al., 2021), citizens and consumers (Johannsen et al., 2021), users and learners (Harrington et al., 2021), participants (Cirulis et al., 2022) and non-experts (Harrington et al., 2021).

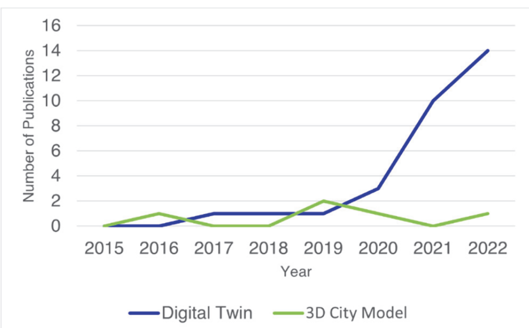

Fig. 4. The number of publications included in the literature review (y-axis) is shown by the year of publication (x-axis) and categorised by the first search term that matched each publication (line color). The year 2023 is excluded from the diagram as it was not fully covered within the literature collection time frame.

3.2. Categorisation of research topics

The dynamic modelling of flora is covered comparably extensively in 34 publications, whereas the publications retrieved through the search process related to fauna modelling appears underrepresented with only four publications. Notably, fauna integration is absent in publications found with the search term 3D city model. A systematic categorisation of the reviewed literature delineates specific domains where dynamic modelling of flora and fauna is employed within digital twins and 3D city models (Fig. 6).

Six publications were found under the search string "3D city model" (Fernández-Alvarado et al., 2021; García-Granja et al., 2020; Kastuari et al., 2020; Tanhuanpää, 2016; Vo et al., 2019; W. Zhang et al., 2022) and the remaining 32 with "digital twin". None of those mentioned both search terms within the same publication.

3.2.1. Flora

The publications treating the dynamic modelling of flora have been structured into six categories aligning with their purposes:

Tree and Forest Modelling: Individual trees, tree groups and trees in forests are the most occurring plants that have been dynamically modelled. The purposes and aims cover the reconstruction of tree skeletons for forest scenario renderings (Wang et al., 2022), the automatic generation and representation of dynamic trees based on physical and biological traits of the respective species (Gobeawan et al., 2021, 2019, 2018) and the immersive representation and projections of forest landscapes for the communication of climate change effects (Klippel et al., 2021). Additionally, dynamic models are used for single tree characteristic and/or forest monitoring, management, maintenance and ecosystem service estimation (Buonocore et al., 2022; Guo et al., 2022; Mongus et al., 2021; Pusztai, 2021; Tanhuanpää, 2016; Wang et al., 2022) as well as the risk assessment including threat assessment through tree growth (Mongus et al., 2021), simulation of forest fire to estimate burning times (Sanchez-Guzman et al., 2022) and for the implementation of early warning mechanisms (Buonocore et al., 2022). Luka and Guo (2021) discuss the roots of trees, whereas most articles focus on above-ground modelling.

Natural Environment and Ecosystems for Preservation Research, Virtual Interaction and Education: Dynamic models of flora have been developed for wetland ecosystems (Lu et al., 2023), bog ecosystems and peatlands (Cirulis et al., 2022), vegetation coverage (Zhao et al., 2022) and a virtual arboretum (Harrington et al., 2021). The purposes of these dynamic models are the monitoring of urban expansion and vegetation coverage (Zhao et al., 2022), the interconnection and mapping of the real and the virtual world (Lu et al., 2023), to foster knowledge dissemination, discussion and for education activities (Harrington et al., 2021). The game-engine based representation of wetland ecosystems (Lu et al., 2023), bogs ecosystems and peatlands (Cirulis et al., 2022) as well as a virtual arboretum (Harrington et al., 2021) had a high emphasis on a (photo-) realistic representation of the environment and e.g. the seasonal dynamic change (Lu et al., 2023). Furthermore they are designed for the user to interact with the 3D virtual environment in immersive ways in real time (Cirulis et al., 2022; Harrington et al., 2021; Lu et al., 2023).

Vegetation-related Micro-Climate and Aerobiological Expose Risk: Dynamic models in this category monitor seasonal variations in tree foliage to evaluate canopy transmissivity for microclimate modelling, focusing on solar radiation distribution (Hofierka et al., 2017), and on aerobiological exposure risks (allergenic potential) emitted by green infrastructure (Fernández-Alvarado et al., 2021).

Open-Field Agronomy: This category refers to agronomical practices in open fields where factors such as climate or soil are not controlled,

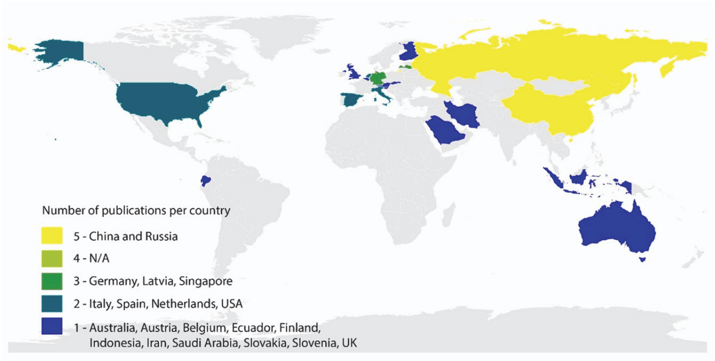

Fig. 5. The number of publications included in the literature review is displayed by country, based on first author affiliation, indicated by country colors on the world map. Countries shown in grey were not indicated as first author affiliation in any of the included publications.

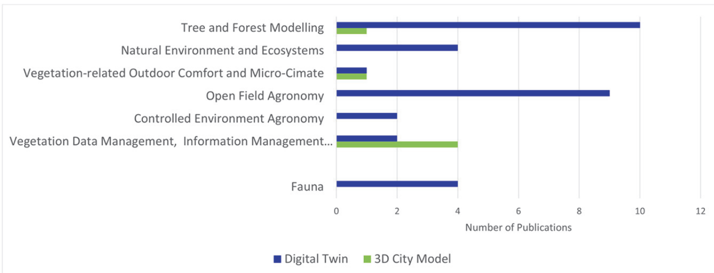

Fig. 6. Number of publications included in the literature review categorised by research focus area (y-axis) and the primary search term used ("Digital Twin" or "3D City Model," indicated by bar color). The x-axis shows the number of publications for each category.

and crops are exposed to natural conditions. Modelled plants encompass grasslands (Purcell et al., 2022), a vineyard (Edemetti et al., 2022), organic potatoes (Majore, 2022), crops (Skobelev et al., 2022b), wheat (Skobelev et al., 2020a), winter-wheat (Skobelev et al., 2022a) and rice (Skobelev et al., 2021). The dynamic plant models and the simulations of their interactions with the environment, such as with soil or atmosphere, aim to improve the economic value, environmental sustainability, and build a basis for plant management and improved decision-making (Edemetti et al., 2022; Purcell et al., 2022; Skobelev et al., 2022b; 2021; Van Evert et al., 2023). These models support plant monitoring, crop management, predictive maintenance, yield forecasting, land use optimisation, and efficient use of resource such as water, fertilizers and pesticides.

The development and use of digital twins in the field of agronomy are more common (Purcell and Neubauer, 2023; Sreedevi and Santosh Kumar, 2020) than reflected in this study. However, Skobelev et al. (2022a) note that the dominant share of these publications primarily focuses on digital twins of the infrastructure facilities, rather than the digital twins of plants, which is the focus of this review.

Controlled-Environment Agronomy: This category is referring to agronomical practices conducted in controlled environments such as greenhouses where e.g. climate, light and humidity are controlled to optimise growth conditions. Publications in this category discuss microclimate control systems and greenhouse crop simulation models (Moin-E-Ddin Rezvani et al., 2021), precision farming and virtual tomato crop use-cases (Knibbe et al., 2022). Both have the purpose to monitor, simulate, predict and regulate the greenhouse itself and the crops.

Vegetation Data Management, Information Management and Modelling: Publications in this category discuss 3D vegetation modelling methods and software, 3D-modelling standards and attribute indicators that are relevant for classifying vegetation (Zhang et al., 2022). More precisely, they discuss dynamic spatial data of trees derived from forest simulations and stored though the Dynamizer in CityGML (Kastuari et al., 2020) and the usage of semantic city models using the CityGML standard for the modelling, monitoring and validating of green façade and roof solutions (Vo et al., 2019). Moreover, parametric trees in Building Information Models (BIM) (Luka and Guo, 2021) as well as the geographic positioning of trees and the integration of an interactive database into a building information model (García-Granja et al., 2020) are considered. Additionally, a Tree Information Model (TIM) as a data exchange platform (Shu et al., 2022) is proposed.

3.2.2. Fauna

Dynamic models of fauna range from the social interactions and behavioural patterns of an abiomimetic robot fish with biological fish (Joordens et al., 2019), to continuous monitoring and assessment of environmental health with smart bat monitors (ultrasonic microphones) (Hudson-Smith et al., 2021), to social-ecological system of urban beekeeping to monitor e.g. the health of bee colonies and anomalies (Johannsen et al., 2021), and to how IoT and digital twins in Precision Livestock Farming (PLF) can improve the health and well-being of farm animals (Mishra and Sharma, 2023).

3.3. Data

Data are one of the key components of digital twins (Zhang et al., 2022a), and therefore an equally indisputable exigency for the dynamic modelling of flora and fauna in digital twins.

3.3.1. Data categories

Following Zhang et al. (2022)'s notion of "Digital Twin Data", data described in the publications are organised here into the six categories based on relevance and frequency in the literature: Physical entity-related data, domain knowledge, virtual model-related data, service-related data, fusion data and connection data (Fig. 7, definition in Supplement S2). Each category is integral to the framework of digital twins, providing a structured approach to assembling optimised digital representation and analysis. Given the extent of the physical entity-related data, a separate list can be found in the Supplement S2.

3.3.2. The rhythm of nature stipulates possible timings and frequencies of data collection

Digital twins of plants necessitate substantial data (Skobelev et al., 2022a). However, since flora and fauna depend on the rhythms of nature, collecting all types of data year-round in uncontrolled environments — such as open-field agriculture or natural ecosystems — is often hindered by natural fluctuations (Johannsen et al., 2021; Majore, 2022). Greenhouse agronomy or livestock farming depend on the lifecycle of the subject of interest in a controlled environment. In contrast, "outdoor" flora and fauna are depending on e.g. the climatic zone, governed by annual cycles, with the life-cycle phases being influenced by both intrinsic biological factors as well as external conditions like weather (Skobelev et al., 2022a). These dependencies can slow data acquisition and knowledge gain compared to digital twins of human-made infrastructures. Moreover, real-time measurement of some system parameters, like plant sugar levels, is not practically feasible (Knibbe et al. 2022).

Frequencies of data collection alike depend on the object of interest, the data collection method, available resources, as well as the modelling approach. In the selected publications, the frequencies of the data collection range from (near) real-time or continuous data collection via e.g. IoT devices, Global Positioning System (GPS), Radio-Frequency Identification (RFID), etc. (Mishra and Sharma, 2023) to regular updates, where data is collected e.g. once a year (Tanhuanpää, 2016), to irregular input data collection (Mongus et al., 2021).

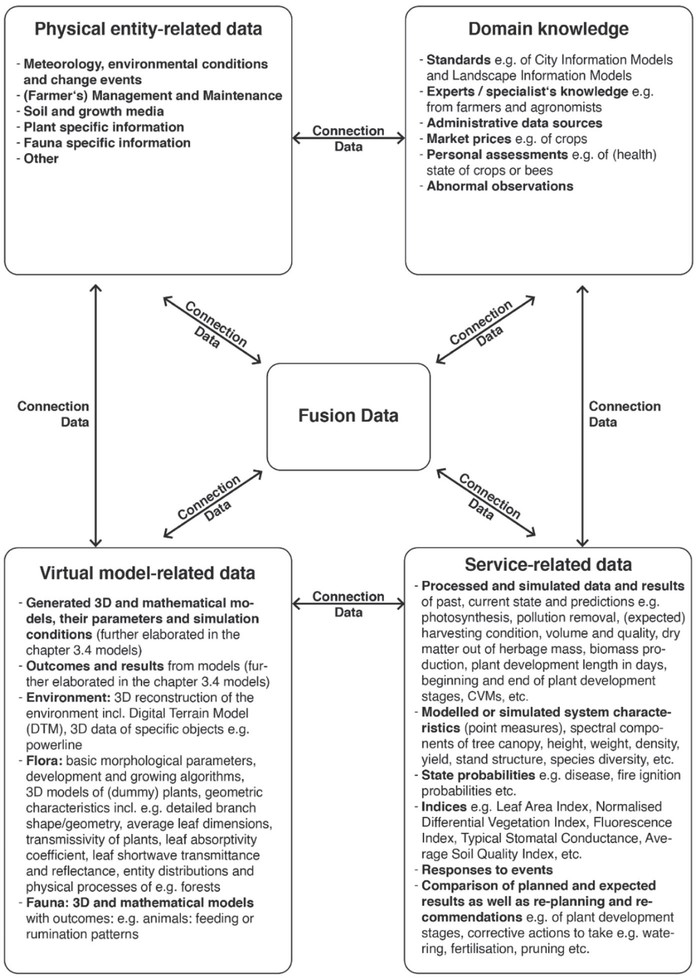

Fig. 7. Data types of flora and fauna models that appeared in the included publications, classified into the six categories of interrelated "digital twin data" types proposed by Zhang et al. (2022). A comprehensive list of the data types in this study that were classified as physical entity-related data, along with a description of the data type classification by Zhang et al. (2022), is provided in the supplement (S2).

3.3.3. Data sources and data collection methods

Data sources commonly include existing databases belonging to the categories “domain knowledge” and “physical entity-related data”, covering e.g. historical data (Zhao et al., 2022). Additionally, data is sourced mainly through the following methods:

Spaceborne and Aerial Observation (SAAO) Methods: Spaceborne and aerial observations methods (SAAO) employed in the selected publications include GPS, Airborne Laser Scanning (ALS) (Gobeawan et al., 2019), multispectral data (Zhao et al., 2022), Light Detection And Ranging (LiDAR) scans from Unmanned Aerial Vehicles (UAV) (Edemetti et al., 2022; Lu et al., 2023), air-borne and satellite imagery (Gobeawan et al., 2018; Zhao et al., 2022) and photogrammetry (Kastuari et al., 2020).

Ground-based Methods: Ground-based data collection methods require physical presence or instruments placed directly at the location or object of interest. These methods are more manifold than the SAAO methods. Terrestrial Laser Scanning (TLS) (Guo et al., 2022; Hofierka et al., 2017; Shu et al., 2022), Mobile Laser Scanning (MLS), LiDAR and other Laser Scanning methods (Gobeawan et al., 2018; Wang et al., 2022) are comparable technologies to the SAAO that are typically used for ground-based vegetation data collection.

Ground-based data collection is in many cases still also carried out manually through inspections, field surveys and measurements (Gobeawan et al., 2018; Hofierka et al., 2017; Kastuari et al., 2020; Lu et al., 2023; Luka and Guo, 2021; Skobelev et al., 2022a). Manual methods are said to be subjective, laborious, time-consuming, less data rich than other methods, and hence, expensive (Kastuari et al., 2020; Li and Wang, 2009; Yuan et al., 2018). Moreover, these methods pose challenges in fields like livestock farming (Mishra and Sharma, 2023), and manual data entry into information systems hinders the timeliness and accuracy of information (Knibbe et al., 2022). Due to e.g. the listed shortcomings, coupled with calls for reduced data harvesting costs, Guo et al. (2022) assert that manual data collection is losing attractivity. As an alternative, GPS systems, diverse sensors and IoT technologies and other mobile technologies now enable continuous data collection and improve accessibility (Hudson-Smith et al., 2021; Mishra and Sharma, 2023; Vo et al., 2019). For the automatic updating and integration of collected (raw) data into digital twin systems, cloud computing (Mishra and Sharma, 2023) or (multi access) edge computing (Edemetti et al., 2022) are employed.

From Raw Data to Insights: Data Mining and Synthetic Data Collection: Data mining methods are applied to extract useful information, e.g. derive the tree canopy from a point cloud (Gobeawan et al., 2018). Moreover, (synthetic) data is created through modelling techniques, which are further described in chapter 3.4 Models.

3.3.4. Challenges in data quality and availability

For meaningful knowledge extraction, high-quality data is paramount, and shortcomings on data affect updating frequencies, the Level of Detail (LoD), e.g. complexity of 3D representations, and accuracy of the digital twins, impeding further progress (Xhafa and Krause, 2021). Researchers cite several reasons for insufficient data coverage for dynamic modelling flora and fauna, including restrictions in availability (Van Evert et al., 2023) and affordability of technologies and infrastructure (Wang et al., 2022), inaccuracies and inadequacies in sensing equipment (Knibbe et al., 2022; Wang et al., 2022), and external factors like obstructions in satellite data collection (Kasampalis et al., 2018; cited by Zake and Majore, 2022). Even when data are available, not all data is equal in terms of quality and relevance. The consequences are particularly evident in machine learning applications within digital twins, which require substantial data to effectively learn and refine conditional probabilities e.g. related to plant states and transitions (Johannsen et al., 2021). Moreover, a key challenge lies in the heterogeneity and diversity of data, requiring standardizing data-sharing protocols across digital twin implementations, including data sources and entity attributes. The proliferation of protocols creates technical debt, interoperability issues, and governance barriers, diminishing the value of digital twins at all scales (Buonocore et al., 2022).

3.3.5. Standards and data management systems

Creating digital twins of flora and fauna requires data aggregation and management. One of the main challenges hereby is to ensure interoperability between different databases, systems and standards (Ketzler et al., 2020; Lei et al., 2023). In the selected publications, data management is in most cases not mentioned nor very precisely described.

Urban Environment: For the urban environment, Building Information Modelling (BIM) (García-Granja et al., 2020) and City Information Modelling (CIM) facilitate information sharing and exchange, enhancing the efficiency and sustainability of planning, design, construction, and management. Additionally, Landscape Information Modelling (LIM) addresses the specific needs of landscape architectural projects, enhancing their planning and execution (Shu et al., 2022). City-wide tree registers, which map trees and model tree-level parameters — such as diameter at breast height, volume, location, species group — are employed for tree information management and storage (Tanhuanpää, 2016).

CityGML is a widely used international open standard for urban environments encompassing aspects such as urban geometry, topology, and semantics while supporting various levels of detail (García-Granja et al., 2020; Kastuari et al., 2020; Vo et al., 2019; Zhang et al., 2022). To prevent obsolescence, CityGML has incorporated a mechanism known as Application Development Extension (ADE) to enable the modelling of additional information, not initially anticipated (Kastuari et al., 2020; Vo et al., 2019). Since CityGML 3.0, the Dynamizer module enables the representation and management of dynamic data — such as time-varying tree heights and simulation results — within the 3D city model (Kastuari et al., 2020).

Agricultural Sector: In the agricultural sector, data pertaining to management activities are traditionally stored within Farm Management Information Systems (FMIS). These systems are available in various commercial versions, many of which lack interoperability. Data entry into FMIS is typically performed manually, leading to challenges in obtaining accurate and up-to-date information. Despite the development of standards for data processing, none have achieved widespread adoption. (Knibbe et al., 2022)

Cross-domain: Geographic Information Systems (GIS) are commonly employed for analysing, simulating, visualising and managing geographic data, e.g. in the creation of a virtual bog ecosystem (BogSim-VR) (Cirulis et al., 2022).

Tree Information Modelling (TIM) facilitates cross-disciplinary knowledge sharing about trees, using a Tree Description System (TDS), which standardises tree descriptions with basic information tags and geometric representations. The high Level of Detail (LoD) of TDS makes it adaptable for various applications, integrating forestry science, Functional Structural Plant Modelling (FSPM) and building environments into a unified platform (Shu et al., 2022).

Application Programming Interfaces (API) allow seamless data interaction and are discussed in various contexts, such as for the graphics in the BogSim-VR (Cirulis et al., 2022), integrating third-party data like weather forecasts (Edemetti et al., 2022; Vo et al., 2019), collecting data from bee hive sensors (Johannsen et al., 2021) and connecting Tree Information Modelling (TIM) to Building Information Modelling (BIM) and GIS (Luka and Guo, 2021; Shu et al., 2022).

3.4. Models

3.4.1. System models

The basis of a digital twin can consist of models with varying complexity and integration levels. These range from single models to multi-scale multi-domain models connecting multiple high-level system models that connect sub-models of various aspects of the physical counterparts into one functional and interactive entity. System models presented in the examined literature vary in their structural complexity, from hierarchical or modular system models with one or more sub-models (Buonocore et al., 2022) to model chains or networks, where outputs of sub-models are used as the inputs of subsequent models (Pusztai, 2021; Skobelev et al., 2020a), to simple input-output models of a key phenomenon of the system (Fernández-Alvarado et al., 2021). Additionally, publications contain digital twins that are collections of unconnected models, bound together mainly by a shared physical system or a common user interface (García-Granja et al., 2020).

3.4.2. (Sub-)model aims and temporalities

System models may include (sub-)models developed for one or more model aims, and hence also for one or more temporalities (Fig. 8). For the categorisation of temporalities and the model categorisation, the three types of analytics techniques — descriptive, predictive and prescriptive models — described by (Roy et al., 2022) are adopted. The granularity and spatial scale of sub-models depend on model aims. For example, plant models vary from large-scale parameters, e.g. tree canopy cover or leaf area index (Cirulis et al., 2022), to tree skeleton models for accurate estimations (Chattoraj et al., 2022). Models of animals can range from e.g. modelling the behavioural state of a (bee) colony (Johannsen et al., 2021) to a model of a cattle's individual heart rate as estimated from the changes of blood flow (Mishra and Sharma, 2023). Sub-model structures also reflect the available data collection tools and frequencies, e.g. whether the available weather data is based on continuous monitoring (Buonocore et al., 2022; Skobelev et al., 2022b) or annual statistics (Mongus et al., 2021).

Descriptive Models: Descriptive models (Fig. 8) in many cases form the foundational layer of digital twins. In most presented publications they summarise (Buonocore et al., 2022) and/or visualise (Gobeawan et al., 2018) current system states based on the collected data. In forestry, agronomy and fauna modelling, descriptive models typically aim for (real-time) system monitoring, change detection and information retrieval, (Johannsen et al., 2021; Mishra and Sharma, 2023; Zhao et al., 2022) with their outputs providing the baseline information required for these purposes. Moreover, those models assist with data exploration, decision-making and manual analysis of intervention needs (Mongus et al., 2021). These models output estimates of e.g. system processes or function, such as greenhouse gas exchange (Edemetti et al., 2022; García-Granja et al., 2020; Guo et al., 2022), current product states, such as tree or forest volumes (Buonocore et al., 2022) or honey in the beehive (Johannsen et al., 2021), developmental stages of crops (Skobelev et al., 2022b), or system performance, such as energy efficiency (Purcell et al., 2022). They may also be designed to output specific variables to support decision-making, e.g. tree health (Pusztai, 2021), forest canopy distance from powerlines (Mongus et al., 2021) or social behaviour of a fish (Joordens et al., 2019).

Detection Models: In digital twins, detection models facilitate (real-time) updates by identifying key system states. This supports in ensuring that the virtual counterpart – based on the provided data and depending on updating frequencies – remains dynamically aligned with the physical counterpart. Image analysis-based detection models are, among others, sub-models of descriptive models, detecting either the presence

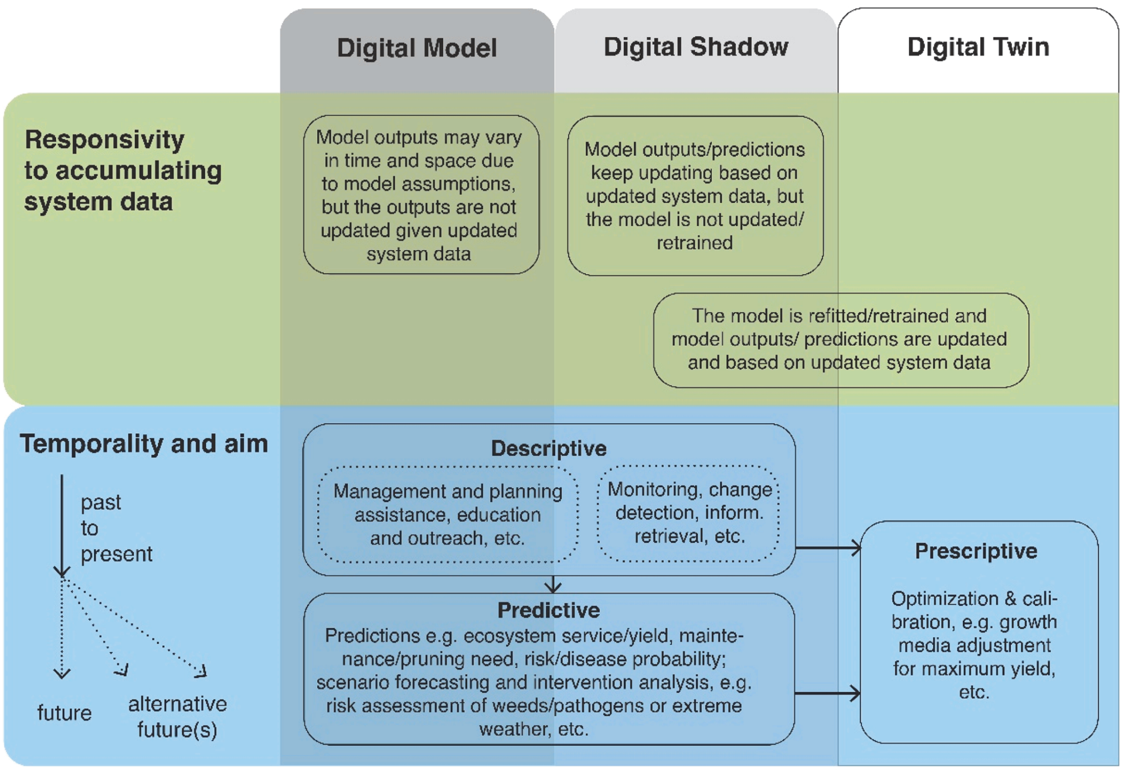

Fig. 8. Aspects of (sub-)models in the included publications, classified according to the type of data flow and synchronisation between the virtual and the physical (columns; for details of the classification, see Fig. 1), responsivity to accumulating system data (green topmost panel), model temporality (light blue bottom panel), and model aim (boxes within the light blue bottom panel). The diagram highlights three primary aims of these systems—descriptive, predictive, and prescriptive—spanning from past to (alternative) futures.

or location of species, phenomena of interest, such as individuals of production animals (Mishra and Sharma, 2023), animal or livestock herds (Majore, 2022), the presence of certain plant species (Chattoraj et al., 2022; Gobeawan et al., 2021) weeds, pathogens (Johannsen et al., 2021), or e.g. indications of fire (Sanchez-Guzman et al., 2022). Sound analysis-based detection models are used to identify the presence of many animal species especially in the context of wildlife monitoring (Hudson-Smith et al., 2021).

Outputs of detection models are used to e.g. analyse animal behavioural stages, stress levels (Mishra and Sharma, 2023), the onset of disease epidemics (Mishra and Sharma, 2023), vegetation coverage (Zhao et al., 2022) or species occurrence and distribution (Lu et al., 2023; Purcell et al., 2022). Furthermore, those models estimate e.g. the expected production performance (Skobelev et al., 2022b), or susceptibility to different environmental hazards (Majore, 2022; Sanchez-Guzman et al., 2022).

Models aiming for system monitoring and change detection also include blockchain technologies to track supply chains and to ensure e.g. the traceability of timber sources (Buonocore et al., 2022) or cattle illness (Mishra and Sharma, 2023). Moreover, descriptive models have been developed for management and planning assistance (Gobeawan et al., 2021; Shu et al., 2022) as well as for public education and outreach (Harrington et al., 2021). These models typically focus on the visualisation of system patterns and processes of interest (Harrington et al., 2021). Along with the progress of time, descriptive models produce a timeline of system states into the past (Harrington et al., 2021).

Predictive Models: Predictive models enhance digital twins by simulating future states of the system. Predictive models (Fig. 8) are used to predict either system characteristics or outcomes at certain time points in the future. Examples include product yield at harvest (Edemetti et al., 2022), the probability of e.g. a pathogen outbreak within a certain time interval (Johannsen et al., 2021), the timing of certain outcomes, such as agricultural product completion, or maintenance/pruning need (Edemetti et al., 2022; García-Granja et al., 2020), or the swarming interval of bee colonies (Johannsen et al., 2021). Plant growth can be modelled using species-specific growth guidelines (Moin-E-Ddin Rezvani et al., 2021; Van Evert et al., 2023), and the structural growth of a plant can be simulated in space using procedural modelling methods (Gobeawan et al. 2018) such as pre-formulated l-system growth rules (Gobeawan et al., 2019). Corresponding data can be collected for predictive modelling of a dairy cow's life cycle phases and structural development (Mishra and Sharma, 2023).

In the case of sparse or sporadic data collection frequencies, predictive models are being used to model the present system state based on data of past system states. Moreover, predictive temporal models are implemented to assess analytical scenarios, such as yield forecasting (Skobelev et al., 2020b) or animal activities (Mishra and Sharma, 2023), and intervention analysis (Fig. 8). These models achieve this by altering the input conditions from real ones, e.g. the harvesting cycle (Majore, 2022; Moin-E-Ddin Rezvani et al., 2021) or the presence of other species (Joordens et al., 2019). These alternative futures can reflect the effects of human interventions or weather events (Skobelev et al., 2022a), for the purpose of analysing e.g. system resilience to extreme weather conditions (Sanchez-Guzman et al., 2022) or the outcomes of changed management (Majore, 2022).

Prescriptive Models: In digital twins, prescriptive models enable real-world interventions by generating actionable insights, which can be implemented through automated feedback loops to actuators or manual decision-making processes, ensuring the physical system adapts dynamically to changing conditions. Precision agriculture, Precision Livestock Farming (PLF) and other production-focused digital twins entail prescriptive (optimisation-calibration) models, where continuously updating system data of the present system state are deployed to evaluate deviations from optimal conditions, e.g. of greenhouse climate or growth media (Moin-E-Ddin Rezvani et al., 2021), beehive humidity (Johannsen et al., 2021) or nutrient intake of animals (Mishra and Sharma, 2023). In some examples robots can then be engaged to automatically modify the conditions of the agricultural system back to the desired optimal state, providing a two-way automated feedback loop between the physical and virtual systems (Skobelev et al., 2022b).

In precision agriculture, predictive and prescriptive models often incorporate elaborate species-specific growth models to simulate crop or timber growth (Buonocore et al., 2022; Skobelev et al., 2022b) or the upcoming animal behaviour (Mishra and Sharma, 2023). Growth models range from simple temporal models that lack interactions with any (spatially varying) environmental predictors, limiting their use to approximate future growth predictions (Luka and Guo, 2021), to highly sophisticated models incorporating e.g. genotype or phenotype effects (Skobelev et al., 2022b) or processes occurring at the level of plant structures (Moin-E-Ddin Rezvani et al., 2021; Shu et al., 2022; Skobelev et al., 2020b) or animal tissue (Mishra and Sharma, 2023).

3.4.3. (Multi) agent-based models

(Multi-) Agent-based models are employed in descriptive models to simulate the spatiotemporal patterns and interactions of individuals of reactive species, such as pollinator insects (Johannsen et al., 2021), (biomimetic robot) fish (Joordens et al., 2019), or as a sub-system for plant growth and development (Skobelev et al., 2022b). When agent-based models are used to visualise the presences and densities of species that are too abundant to be tracked on an individual level, the hypothetical movements and behaviours are simulated based on their tracked presences or densities (Mishra and Sharma, 2023). Additionally, agent-based models are employed in predictive models and scenario forecasting, e.g. to test the effects of alternative rules and regulations (Johannsen et al., 2021).

3.4.4. Visualisation models

Visualisation models are not always embedded in the digital twin, e.g. in applications where monitoring and interventions rely primarily on indicators (Mishra and Sharma, 2023). However, most digital twins include 2D or 3D visualisation models of the physical system, which serve as the basis for their representation in the digital twin's user interface (Chattoraj et al., 2022; Edemetti et al., 2022; Pusztai, 2021; W. Zhang et al., 2022).

In some cases, visualisations are of avail to estimate other parameters of interest from point cloud data, such as tree species (Chattoraj et al., 2022), basal area (Wang et al., 2022) or tree growth (Mongus et al., 2021). Additionally, 3D visualisation models can act as key parts of 3D spatial analyses, e.g. in the case of estimation of green volume (W. Zhang et al., 2022), shadow casting (García-Granja et al., 2020), analysis of object interaction with buildings (Hofierka et al., 2017) or other objects (Mongus et al., 2021).

The current state-of-the-art for generating 3D tree models and species identification from remote sensing data involves reconstructing trees from point clouds and photogrammetry using deep learning (Chattoraj et al., 2022; Guo et al., 2022; Lu et al., 2023; Pusztai, 2021; Shu et al., 2022). Manual 3D modelling by experts is also used, especially for game engine-based digital twins (Harrington et al., 2021; Lu et al., 2023). Additionally, 3D tree models in digital twins evolve over time based on data-driven growth models (Gobeawan et al., 2021, 2019, 2018; Skobelev et al., 2020b).

3.4.5. Model fitting and validation

Mechanistic and Data-Driven Models: Mechanistic and data-driven models are commonly used in the reviewed literature for digital twin systems. Mechanistic models, such as those used for well-studied aspects of the modelled systems, e.g. crop growth, photosynthesis (Moin-E-Ddin Rezvani et al., 2021) or fish tail movement (Joordens et al., 2019), are frequently constructed with mathematical functions known to describe these phenomena. Digital twins also incorporate data-driven statistical models, fitted to data gathered either from the modelled physical or a similar well-studied system (Gobeawan et al., 2021, 2019, 2018). These data-driven models include both state-based and process-based models (Buonocore et al., 2022). Despite advancements, existing mathematical models, including those based on differential equations, statistical data analysis from previous periods, and machine learning approaches, are currently unable to deliver highly accurate plans, e.g. agro-technical, for the entire vegetation period or reliable yield predictions. This challenge arises from the necessity for frequent model retraining, as a range of dynamic factors — such as global climate change, fertilizer application, plant protection products (PPP), and field management techniques — must be continuously accounted for (Skobelev et al., 2021).

Machine Learning (ML) and Artificial Intelligence (AI) Models: ML and AI models represent a specialised subset of data-driven models as they differ from traditional statistical models in their fitting methods and capabilities. For instance, supervised ML methods, such as artificial neural networks, require extensive labelled datasets but can generalise well to similar scenarios. Unsupervised and reinforcement learning techniques, on the other hand, can uncover hidden patterns or optimise decisions in less structured contexts. However, these methods also pose risks, such as overfitting to training data or producing results that lack interpretability, especially when domain knowledge is insufficiently integrated (Rebala et al., 2019). A diverse array of supervised and unsupervised ML methods is used to accurately model phenomena, e.g. those that are non-linear or where understanding the causal relations of phenomena is not essential (Edemetti et al., 2022; Mishra and Sharma, 2023; Skobelev et al., 2020a; Van Evert et al., 2023). Knowledge-driven ML is considered for phenomena where domain knowledge, e.g. procedural rules and constraints could complement the ML approach (Chattoraj et al., 2022). ML methods include e.g. artificial and neural networks (Chattoraj et al., 2022; Mongus et al., 2021). Additionally, ML and AI models are increasingly used in predictive and prescriptive models.

3.4.6. Model responsivity

The responsivity of models to spatial aspects and temporal changes in physical systems varies across publications. Models in digital twins are commonly spatiotemporally explicit, providing different outcomes across space due to i.e. interactions with predefined environmental variables, such as local (micro-) climate (Knibbe et al., 2022; Skobelev et al., 2022a) soil characteristics (Knibbe et al., 2022; Mongus et al., 2021; Skobelev et al., 2022b) or human interventions like pruning (Gobeawan et al., 2021).

However, the presented models are located differently on Kitzinger et al.'s (2018) classification of digital twins, i.e. whether their predictions are automatically updating based on changes in the physical system (Digital Model vs. Digital Shadows vs. Digital Twins). Automatic data collection and processing allows the building of "Smart Cyber-Physical Systems" (Skobelev et al., 2022a), "Smart Digital Twin of a Plant" (SDTP) (Skobelev et al., 2022b) or "Eco-Cyber-Physical Systems" (ECPS) (Majore, 2022), where also the models themselves are automatically calibrated (statistical models) or retrained ((Deep) Neural Networks) along with the accumulation of system data (Edemetti et al., 2022; Johannsen et al., 2021). These models are not yet common in digital twins, as the development of those models is tightly tied to the advances of automatic data collection and processing. Furthermore, the development of AI and ML will support the development of self-learning models (Edemetti et al., 2022; Johannsen et al., 2021).

3.4.7. Model validation and calibration

Regular data collection from the physical counterpart enables ongoing model validation and calibration. This process enhances the accuracy and precision of models beyond their initial construction, which may be based on historical data (Knibbe et al., 2022). For instance, in the case of tree models, field observations are employed e.g. to validate the accuracy of detected risks (Mongus et al., 2021) and to calibrate growth predictions (Guo et al., 2022). Similarly, simulated fish behavioural patterns are validated against the behaviour of real-life fish in corresponding situations (Joordens et al., 2019). The availability of remote sensing data and IoT technologies holds potential for automated model adjustment, further enhancing model fidelity. However, the quality of data is hereby playing a crucial role, as models will only get as accurate as their weakest component. Deficits in input data appearing e.g. due to human error or technical shortcomings, impair the validation and calibration of the respective models and thereby the integrity of their outputs.

3.5. Actuators

Actuators, which automatically transfer outcomes from the digital to the physical world, are key components distinguishing digital twins from digital shadows (Kritzinger et al., 2018). However, only seven out of the 32 reviewed publications found with the search term "digital twin" and none of the articles found with "3D city model" address this aspect. All seven articles discussing actuators are from the field of agriculture. These publications are categorised into "Fauna" for livestock farming (Mishra and Sharma, 2023), "Controlled Environment Agronomy" (Knibbe et al., 2022), and "Open-Air Agronomy" (Edemetti et al., 2022; Majore, 2022; Skobelev et al., 2020a, 2020b; Van Evert et al., 2023).

Besides the benefits attributed to digital twins in general, in agriculture actuators hold potential for addressing challenges in geographically dispersed areas, increasing harvests, and improving animal welfare. Additionally, automated processes could reduce manual labour, freeing up time for other activities (Mishra and Sharma, 2023; Van Evert et al., 2023).

Actuation in digital and precision agriculture is exemplified by autonomous and unmanned machinery like precision planters, spreaders, sprayers, and fully autonomous tractors. However, limitations lie in precision equipment accessibility (Van Evert et al., 2023).

In the case of the digital twins for harvest plants, e.g. tomato plants, high-level guidance on optimal setpoints, such as indoor temperature and pruning rates, is currently provided primarily through consultancy (Knibbe et al., 2022). However, there is potential for automatically relaying the provided decision advice to an actuator (Knibbe et al., 2022; Van Evert et al., 2023). To achieve fully automated control, decision support systems would require control algorithms to automatically calculate and onset the optimal management of inputs and actions (Knibbe et al., 2022).

Future research directions which are not detailed in the analysed literature include developing Eco-Cyber-Physical Systems (ECPS) (Majore, 2022), executive devices for intelligent cyber-physical systems that automate processes like plant growth management (Skobelev et al., 2020a, 2020b), agricultural actuators in vineyards that receive instructions from the digital twin (Edemetti et al., 2022) and robots managing tasks without human intervention for livestock management and precision agriculture (Mishra and Sharma, 2023).

3.6. User experience

3.6.1. Representation

Although it is already possible today to fully automate the connection between the physical and virtual worlds via digital twins, human-computer interaction remains a critical aspect in the development and use of these digital replicas of flora and fauna. The representation and especially the visualisation of the underlying data and models is crucial for helping humans understand vast amounts of digital data, supporting analysis, informs decision-making and behaviours, and fosters data literacy (Gatto, 2015; Rist and Masoodian, 2022; Venkatraman and Venkatraman, 2019).

Representations of flora and fauna in digital twins serve various purposes, primarily aimed at "informing" in the broadest sense. This covers monitoring (Gobeawan et al., 2021; Hudson-Smith et al., 2021; Tanhuanpää, 2016), interpretating simulation outcomes (Purcell et al., 2022; Skobelev et al., 2020a), and providing information, recommendations and data for the decision support (Fernández-Alvarado et al., 2021; Klippel et al., 2021; Skobelev et al., 2020a). The most common form of representation is found to be in 2D maps or 3D, emphasising scientific modelling over photorealistic visualisation. For this purpose, e.g. dummy plants are associated with the plant specific information (Edemetti et al., 2022). However, photorealism is emphasised in specific applications like the virtual arboretum (Harrington et al., 2021) and the virtual scene construction of wetlands (Lu et al., 2023).

Besides the visual representation, Harrington et al. (2021) detail an additional modality in acoustic form, wherein an enhanced multimodal sensory experience, encompassing both visual and acoustic elements, is achieved. Their framework of high information fidelity enables the accurate acoustic replication of the environment, e.g. specific insect and avian populations of each location and season. This approach enhances the accessibility of digital nature experiences for e.g. vision-impaired individuals. (Harrington et al., 2021)

3.6.2. Human-computer interaction

User interfaces form the point of human-computer interaction, representation and communication for digital replicas. Hereby, poor usability can compromise the value of a digital twin by reducing accessibility and practicality (Purcell et al., 2022). Most of the analysed literature does not detail user interfaces, often referring to them generally as platforms or interfaces (Edemetti et al., 2022). Skobelev et al. (2020a, 2022b) describe the development of a specialised user interface, encompassing an ontology editor, a digital twin editor and a multi-agent planning module for their developed SDTP (Smart Digital Twin of Plant). Purcell et al. (2022) propose an interface-driven design focusing on one standardised interface, which can be reused and extended with additional components. This approach simplifies the creation of new interface expansions or services for additional data sources or functionalities. Commonly used interfaces are Graphical User Interfaces (GUIs), 3D, and Spatial User Interfaces, e.g. for virtual city platforms (Gobeawan et al., 2019).

Common mediums for human-computer interaction include Extended Reality (XR), encompassing Augmented Reality (AR) and Virtual Reality (VR) accessed via Head Mounted Displays and controllers (Cirulis et al., 2022; Harrington et al., 2021; Joordens et al., 2019; Klippel et al., 2021; Lu et al., 2023). Additionally, Harrington et al. (2021) connect the VR headset to a treadmill to create a more realistic and immersive physical-virtual environment. Also Cave Automatic Virtual Environment (CAVE) systems, equipped with motion tracking, offer immersive interaction (Lu et al., 2023). Other interaction mediums include PCs (Harrington et al., 2021) with e.g. web browsers (Lu et al., 2023), web applications (Johannsen et al., 2021) and mobile devices such as phones (Skobelev et al., 2020a) or tablets (Cirulis et al., 2022).

The human-computer interaction primarily consists of three main parts:

1. Data input: Users manually input data through tools like online documentation in web applications (Johannsen et al., 2021).
2. Virtual Interaction: Users interact with dynamic models and simulations, involving movement in virtual environments (Edemetti et al., 2022; Harrington et al., 2021; Lu et al., 2023) or altering input variables like pasture and weather to e.g. test or forecast future states of the objects or systems (Purcell et al., 2022; Skobelev et al., 2020b) with real-time updates in the virtual counterparts (Cirulis et al., 2022).
3. Action in Physical Counterpart: Users take action in the physical counterpart based on digital twin information, such as watering crops or feeding colonies. These changes can be manually or automatically (re-) introduced into the digital twin (Johannsen et al., 2021).

3.7. Ethical considerations

Ethical considerations are found in the field of digital twins of agriculture, addressing potential privacy breaches, technology reliability, and the possibility of their misuse (Mishra and Sharma, 2023; Van Evert et al., 2023). Further, Mishra and Sharma (2023) discuss concerns about technologies not aligning with animals' best interests, potential harm to animals, and animals being used solely as data sources. Data-based decision tools in farming raise ethical concerns, particularly regarding shifts in power dynamics between farmers and commercial actors. Often, the data generated are benefiting companies more than the farmers who provide it. Simultaneously, individual farmers may struggle to make the necessary investments to fully benefit from these tools (Van Evert et al., 2023). Knibbe et al. (2022) refer to ethical aspects being discussed in Korenhof et al. (2021) and Van Der Burg et al. (2021).

An emphasis on sustainability and improvements of various aspects, as one of their digital twin development purposes was found in many of the selected publications. In agronomy, aspects such as resource consumption e.g. water (Edemetti et al., 2022) are widely discussed. In this regard it is furthermore prompted that the environmental impacts, including the energy consumption of IT infrastructures and their carbon footprints, need further investigation (Stoll et al., 2019 as cited in Buonocore et al., 2022). The extent to which these concerns are driven by ethical, economic, or other considerations is unclear from the literature.

4. Discussion, future research directions and conclusion

The study of flora and fauna has evolved over centuries, leading to extensive knowledge on the topic. Simple models and simulations are being replaced by complex and highly sophisticated virtual representations which are offering rich, multifaceted insights into the interactions between the biotic and further layers of the digital replicas. As technological advancements continue to accelerate, research in this area is evolving rapidly leading to increasingly heterogenous approaches across different disciplines and applications.

The horizontal, cross-sectoral view on flora and fauna modelling for digital twins allowed this review to highlight the diversity of approaches which are tailored to various developers, disciplines, user groups, and specific purposes, incorporating diverse data, developed and employed models, user experience methods, actuators and ethical considerations. Based on these findings, this review should be regarded as a comprehensive resource showcasing current methodologies and serving as a foundation for future advancements in the diverse fields of flora and fauna modelling in digital twins, rather than as an uniform framework to follow.

4.1. Limitations of this study

Only the scientific publications listed in the three databases Scopus, Web of Science and Google Scholar found with the search strings detailed in the Section 2.2 Definition of Keywords and Search Strings, are covered in this review. It is to be assumed that a more comprehensive perspective on the development of the dynamic modelling of flora and fauna in digital twins could have been gleaned from grey-literature inquiries and with the use of additional search terms. Specifically, for the dynamic modelling of fauna, search terms from domains such as agriculture, precision farming, livestock modelling, and aquaculture could provide further insights. Moreover, only studies with titles, abstracts, and full texts available in English were included in this review. While English is widely used in academic publications in this field, this criterion may introduce a language bias by potentially excluding key studies published in other languages.

4.2. Particular focus areas of fauna models for digital twins

As the systematic literature review approach used in this study resulted in an imbalance of articles for fauna and flora, this chapter discusses particular focus areas of fauna models in digital twins. To provide context and address gaps not fully covered in the reviewed literature, select examples from external sources are provided here.

4.2.1. Mobility

While many challenges of flora and fauna modelling for digital twins are similar, some key differences emerge between these two domains of modelling for digital twins. One critical distinction lies in the mobility of most animal species. Data collection for flora models often relies on remote sensing techniques such as LiDAR or multispectral imaging to capture data on plant structures and growth. In contrast, fauna models often incorporate the movement of either individuals or populations. This requir specific spatial data collection methods, such as the use of GPS collars for wildlife monitoring (De Koning, 2025) or fixed monitoring stations equipped with e.g. camera traps (Sharef et al., 2022) or RFID readers (Mishra and Sharma, 2023).

If digital twins rely on updating data to estimate population sizes or species compositions within defined areas, modelling challenges can arise due to the movement of new organisms into the area after the model has been defined. This issue is particularly pronounced in fauna models, where animal mobility introduces variability in shorter time scales respective to flora. For instance, Convolutional Neural Networks (CNNs) have been applied to classify species in camera trap images (Sharef et al., 2022), while machine learning models have been employed to analyse bird species from sound recordings, addressing the complexities of tracking highly mobile organisms (Ovaskainen et al., 2024).

4.2.2. Responsiveness

Another key challenge of fauna modelling is related to the multiple types of animal responsiveness, which operate often on shorter time scales than vegetation dynamics. Fauna models may need to simulate dynamic physiological processes, sensory responses, cognition, and even emotions to replicate animal behaviour (Føre et al., 2024). Due to these multi-dimensional complexities, AI-driven frameworks are employed to model e.g. livestock behaviour (Neethirajan and Kemp, 2021; Tagarakis et al., 2024), fish feeding (Ubina et al., 2023), and the perception and feeding dynamics of dairy cows (Zhang et al., 2024).

4.2.3. 3D modelling

For digital twins that encompass 3D model representations of living organisms, 3D modelling approaches may diverge between flora and fauna digital twins. Whereas flora models focus particularly on the accurate modelling of individual or species-specific structures and growth, fauna models may need to account also for the dynamic nature of animal responsivity and movement. This is exemplified by the models of tail movement to simulate the swimming dynamics of fish (Joordens et al., 2019). The future opportunities of responsive fauna models are exemplified by the neuromechanical model of a fruit fly *Drosophila melanogaster* (Lobato-Rios et al., 2022).

4.3. Research gaps and outlook

Despite the ongoing progress and due to the novelty of the field and its interdisciplinary nature, many research gaps remain unresolved and are only beginning to be explored. Our review identified several trends and challenges in the dynamic modelling of flora and fauna within digital twins, which are summarised into the following categories.

4.3.1. Insufficient understanding of fundamental details and potential knowledge generation

Despite extensive research, a key challenge remains in the limited understanding of interactions between flora, fauna, and their biotic and abiotic environments, such as plant growth (Skobelev et al., 2022a, 2020b) and animal behaviour (Joordens et al., 2019). Improving the understanding of these biological and ecological processes, and integrating them into dynamic models, will enhance accuracy and predictive capabilities. At the same time, digital twins offer potential by enhancing knowledge generation. However, their utility in ecological applications will remain limited without a strong foundational understanding of the underlying biological and ecological processes, which is essential for improving models of biotic interactions in the environment.

4.3.2. Bottleneck: data

Diverse “Digital Twin Data” (Zhang et al., 2022a) is produced and used for dynamic modelling of flora and fauna as elaborated in chapter 3.3 Data. Despite ongoing debates about the necessity of both – ground-based (Hudson-Smith et al., 2021) and SAAO data collection in form of UAVs (Edemetti et al., 2022), researchers still face challenges highlighted in chapter 3.3.4.

Data challenges are widely recognised as a critical bottleneck in the development of digital twins. Beyond the lack of accurate and available data, bias, interoperability, low operating frequencies of data collection and the inability to fully capture dynamic interactions, additional barriers include data heterogeneity and diversity. Variability in spatial and temporal resolution, measurement methods, and data completeness on e.g. species occurrence and functional trait data, can hinder model integration and reliability. Addressing these issues requires besides standardised protocols, data harmonisation, also efforts to fill gaps in underrepresented regions and taxa.

Furthermore, data fusion, forming another data-related challenge itself, plays a pivotal role in overcoming data heterogeneity, which is being researched e.g. for digital twins in ecology (De Koning et al., 2023). This process involves combining data, referred to as fusion data, see Supplement S2, from sensors (also referred to as sensor fusion), databases, and other sources to create a coherent and unified representation. Robust data assimilation techniques are essential to address the inherent uncertainties in both the data and the mathematical models. Developing standardised and scalable approaches for data fusion and assimilation is crucial to enhance the reliability and accuracy of digital twins, particularly for achieving predictive and prescriptive functionalities. (Liu et al., 2018; Macías et al., 2024) Overcoming these challenges will pave the way for comprehensive monitoring of flora, fauna and their environments. This would allow for realistic digital replicas, continuous recalibration, precise prescriptive models and digital twins’ responsiveness to changes.

To get closer to this aim, on the one hand inaccuracies in data collection need to be addressed and the reliable methods and techniques for this made accessible to a broad audience. Guo et al. (2022) assert that manual data collection is losing attractivity. A shift in data collection methods – transitioning from manual to automated methods – is likewise presented in the literature beyond this SLR, such as in Tuia et al. (2022) or Rozenstein et al. (2024). This shift in the data collection has the potential to support overcoming mentioned shortcomings (Rozenstein et al., 2024; Tuia et al., 2022). Additionally, the listed shortcomings could be approached through the application of AI technologies, such as computer vision and other methods, enabling the automatic quantification of properties from e.g. video footage and other comprehensive data sources. These advancements hold promise to facilitate the mining of previously uncollected data, higher accuracy, more frequent updates, scalability, cost efficiency, non-invasive monitoring, the discovery of hidden patterns, adaptability to new data, customisation and precision, automation of tedious tasks, and the integration of data from multiple sources.

Data availability could be leveraged by incentivised cross-domain data sharing and the application of FAIR (Findable, Accessible, Interoperable, Reusable) (Wilkinson et al., 2016) data principles. Van Evert et al. (2023) examines the EU Code of Conduct on agricultural data sharing, suggesting that similar Codes of Conduct could help prevent only commercial actors from benefiting from data sharing. On the other hand, for the interoperability of data from various sources, data harmonisation and adherence to standards is substantial.

4.3.3. Models becoming dynamic in nature

There is already a plethora of approaches to modelling flora and fauna across various domains. Traditional ecological modelling techniques, such as agent-based and descriptive models, are prevalent and increasingly being coupled with ML and AI methods. Existing and established models could further evolve by integrating continuous data updates, becoming dynamic in nature, and connecting them to the digital twin concept. To drive actions in the physical counterpart, these models must also incorporate mechanisms for decision-making and actuation, enabling their outputs to influence real-world processes. Such developments enhance the accuracy and efficiency of the dynamic models, enabling them to shift from descriptive to prescriptive.

However, while the field of machine engineering is advancing rapidly, particularly in the digital twin sphere, it is essential to recognise the multifaceted intricacies of natural systems. Flora and fauna possess inherent complexities that distinguish them from machines. Over-simplified models, especially in areas such as environmental sustainability, food production, or those involving living organisms, can lead to unforeseen consequences if not carefully considered. Additionally, applying "Good Modeling Practices" (GMP) as outlined by Jakeman et al. (2024) helps to ensure that models are robust, transparent, adaptable, and reliable, enhances their accuracy, usability, and impact across diverse applications. This is particularly relevant, as the developed models may be influenced by human factors including e.g. biases and uncertainties (Jakeman et al., 2024).

Validation for digital twins is imperative but also uniquely challenging due to (real-time) data integration and the – where applicable – autonomous synchronisation with the real world. Key techniques include (dynamic) data validation, model validation, machine learning-based validations, feedback-loop validation, and scenario-based validation. (Hua et al., 2022; Mertens and Denil, 2024)

Additionally, model acceptance by practitioners is often hindered by a lack of trust and the complexity of models. Strengthening collaboration between researchers, extension workers, and advisors and the application of GMPs is essential to maximise the benefits of data and modelling (Van Evert et al., 2023).

4.3.4. Enhancing interoperability, integration, standardisation and transferability

Interoperability between different databases, software, and digital twin instances is not yet fully established, necessitating the development of and adherence to standards and protocols. Implementing Minimal Interoperability Mechanisms (MIMs) (Ketzler et al., 2020) can help address this challenge. Additionally, Application Development Extensions (ADE), such as those in CityGML (Vo et al., 2019), offer a promising approach for integrating flora (Petrova-Antonova et al., 2024) and fauna into existing standards, enabling the modelling of additional information. A modular approach to developing digital twins of flora and fauna would further enhance the transferability and adaptability of research. In some cases, the source-code is being made publicly available. Doing this in a systematic and formalised way also allows for traceability, validation, model auditing (Jakeman et al., 2024) and e.g. the adaptation and further development (Johannsen et al., 2021).

It is important to emphasise that interoperability or the sharing of the models between systems does not guarantee transferability to other contexts. Specifically, models being designed for particular contexts, e.g. geographic locations and environmental conditions, inherit limiting factors which cannot be transferred offhand.

To date, research on digital twins incorporating flora and fauna has, as stated for the agricultural sector by Purcell et al. (2022), largely focused on experimental feasibility, neglecting key design aspects like scalability, reusability, and simulation. As a result, many advanced digital twin examples lack clear, systematic design principles and essential functionality to ensure long-term value (Purcell et al., 2022). Additionally, there are no universally applied methods, standards, or guidelines for developing the software, software architecture and workflows of such (De Koning et al., 2023) which cause inconsistencies and hinder progress (Trantas et al., 2023).

Addressing these gaps and applying GMPs will further leverage the development of digital twins. However, future research should aim to prioritise the development of standardised methods and design frameworks to address the burgeoning fragmentation of developments. Hereby the emphasis should lie on scalability, reusability, and simulation, ensuring both the long-term value and broader adoption of digital twins of flora and fauna.

4.3.5. Accessibility and user experience

Digital twins were initially focused on accurate, data-driven and mechanistic models, but as their use expanded, the need for accessible, user-centred design has become paramount. Digital twins often encompass complex factual situations, data, and domain-specific models which are not directly accessible and interpretable for users with varying expertise levels. As a result, user experience (UX) plays a crucial role in helping users understand content and enabling evidence-based decision making across fields including agriculture, education and policy-making (Trantas et al., 2023). Developers must therefore elicit and capture stakeholder needs (Jakeman et al., 2024) and consider how output are visualised and interpreted by end-users (De Koning et al., 2023). Digital twins involving sensitive information are typically restricted to expert groups. However, for broader outreach such as educational or participatory purposes, digital twins are increasingly being developed without access restrictions (Johannsen et al., 2021). Whether access is restricted or open, to make digital twins accessible and to foster active application of its users, a range of interfaces and devices are employed, as elaborated in Section 3.5.

While digital twins often are based on 2D and 3D visualisations (Chattoraj et al., 2022; Edemetti et al., 2022; Pusztai, 2021; Zhang et al., 2022), current UX emphasises intuitive, multimodal interfaces, frequently incorporating VR/AR to simplify complex data (Deckert et al., 2020; Harrington et al., 2021). Moving forward, UX will prioritise inclusivity, with adaptive interfaces tailored to user roles and expertise. Enhanced multimodal interactions, e.g. voice and gesture control and biometric feedback along with collaborative, multi-user environments will create immersive experiences (Kern et al., 2022), benefiting applications like collaborative work, virtual testing and education. By lowering technical barriers and supporting personalisation, digital twins aim to engage broader audiences, making these tools valuable for both experts and the public across various fields.

To evaluate how well digital twin systems meet user needs, the User Experience–Digital Twin Maturity Model (UX-DTMM) has been developed. This framework is built on the five pillars of experience: visual understandability, usability, convenience, dependability, and delight factors. It can guide improvements by assigning maturity scores to these aspects, helping to optimise digital twin interfaces for better engagement and functionality (Manickam et al., 2023).

4.3.6. Interdisciplinary synergy for advancing digital twins of flora and fauna

The future of this research relies on progress across various fields and close interdisciplinary collaboration. Integrating advancements from pioneering fields like ML and AI to applications will improve the precision of dynamic models for flora and fauna. Additionally, applying expertise from computer science, ecology, biology in domains like e.g. urban planning and agronomy is crucial to transcends isolated disciplines which is accelerating progress toward comprehensive solutions and can be seen as essential to address complex ecological and environmental challenges arising in different domains.

Moreover, leveraging diverse expertise, as e.g. from the examples showcased in this review, enables researchers to address knowledge gaps through cross-disciplinary collaboration, fostering a dynamic environment for the exchange and integration of ideas, methods and models.

4.3.7. Ethical considerations

Ethical considerations in digital twins, particularly in healthcare (Bruynseels et al., 2018; Popa et al., 2021), medicine (Braun, 2021), and the built environment (Ying et al., 2020), are well-established. However, this literature review reveals that ethical aspects of digital twins of flora and fauna have received less attention compared to other fields or technical aspects. Although ethical considerations are gradually gaining relevance in fields like agri-food (Van Der Burg et al., 2021), they are not commonly discussed within digital twins of flora and are sporadic in fauna. Especially within the living environment, addressing issues such as data privacy and potential misuse is essential to ensure ethical and future-proof applications. Tools like the Mepham's Ethical Matrix for food and agriculture (Mepham et al., 2006; cited by Van Evert et al., 2023) can support decision-makers assess the ethical acceptability and regulations of technologies. Given the nascent stage of digital twins of flora and fauna, everyone involved in the development of those technologies should proactively integrate societal values and ethical considerations already early in the research and development phase.

Additionally, with the increasing application of digital twin technologies, these as a whole system as well as its discrete parts, become more prone to cyber threats with widespread consequences (Bissadu et al., 2024; Praharaj et al., 2024). Therefore, the need to efficiently develop and comprehensively employ cyber security measures should be seen as mandatory (Holmes et al., 2021).

4.3.8. Gradualism: from digital models to closed-loop digital twins

In most cases, digital twins are being developed incrementally, building upon existing models (Rolph et al., 2024). This development process typically follows a progression from digital models to digital shadows, and ultimately to autonomous digital twins. Such an approach allows for gradual integration of advanced capabilities, such as continuous data updates and bidirectional interactions, enabling a systematic evolution towards complete mutual influence between the physical and digital counterparts.

To date, digital twins are still abstractions of the physical counterparts, and the full realisation of this concept, along with its inherent logical challenges, continues to be debated, e.g. for urban environments (Batty, 2018). The term "digital twin" is often applied broadly in the literature, encompassing systems with varying levels of capability - from integrating data at variable frequencies with models to fully autonomous, feedback-controlled cyber-physical systems. Systems that do not adhere to the strict definition of digital twins, particularly those lacking automated feedback between the digital and physical counterparts, are on one handmore accurately described as "digital shadows" (Botín-Sanabria et al., 2022; Kritzinger et al., 2018), "prototype digital twins"(Groeneveld et al., 2024; Khan et al., 2024; Lopez et al., 2020) or similar terms, as proposed by researchers. These distinctions help clarify the difference between systems with limited interaction and fully synchronous digital twins that autonomously influence both – the physical and virtual counterparts, a hallmark of closed-loop digital twins. On the other hand, researchers such as Tagarakis et al. (2024) suggest sector-specific definitions for digital twins. While this approach provides contextual relevance, it also contributes to the fragmentation of research around the term "digital twin".

Despite the potential for automated bi-directional information exchange, this capability level remains underexplored in current research. Notably, the agricultural sector being the only one discussing actuators in the reviewed literature, with e.g. precision agriculture (Van Evert et al., 2023) and ECPS (Majore, 2022), leads in fulfilling the closed-loop digital twin criteria. These forerunners provide inspiration for future development in e.g. urban and ecological applications, though not as a universal blueprint.

Regardless of the potential realisation of the digital twin concept, the necessity and appropriateness in every field is to be questioned. A nuanced, context-specific approach is essential, with digital shadows in some cases being more suitable given the current technological state. These tailored approaches ensure digital (twin) technologies are both practical and ethically sound across diverse fields.

4.3.9. Yet underexplored but big potential

This review has demonstrated that the digital twin concept is being developed and applied across diverse fields, including among others ecology, forestry, agronomy, livestock farming and urban sciences. These applications highlight the versatility and potential impact of integrating natural elements and environments into digital twins. Yet, compared to the rampant development, level of detail and application of the digital twin concept in human-made areas such as manufacturing (Semeraro et al., 2021; Tao et al., 2019), cities (Lei et al., 2023; Shahat et al., 2021), engineering (Jiang et al., 2021) and aerospace (Botín-Sanabria et al., 2022; Liu et al., 2021; Phanden et al., 2021), the digital twins of flora and fauna still remain significantly underexplored. However, the development of digital twins for flora and fauna is accelerating and is continuing to do so. Especially in ecology, publications such as from De Koning et al. (2023) and Trantas et al. (2023) give guidance and outlook to the future of digital twins in this field. Further, a multitude of theoretical frameworks, such as digital twins of forests (Buonocore et al., 2022) are currently being developed but are not yet fully implemented. Prototype digital twins, such as those developed within the BioDT project (BioDT, 2024) for e.g. invasive alien species (Khan et al., 2024) and the Digital Twin of the Earth (Bauer et al., 2021; Nativi et al., 2021) are currently being elaborated and tested. These theoretical frameworks and development suggestions are expected to be put into practice and tested soon and together with the already existing protype digital twins going to be refined based on real-world application, feedback and new scientific insights.

Applying theoretical frameworks, refining prototypes, addressing the previously listed challenges and taking proactive steps toward overcoming them offer significant potential for advancing the inclusion of flora and fauna in digital twins. By doing so, this field is expected to make up leeway with the development of digital twins in the pioneering domains.

Ultimately, dynamic modelling of flora and fauna through digital twins offers a transformative approach to addressing complex challenges outlined in the introduction and advancing the United Nations Sustainable Development Goals (SDGs). Future digital twins could enhance biodiversity monitoring and conservation (SDGs 14 and 15), enable precise predictions of climate change impacts (SDG 13), and optimise sustainable agricultural practices (SDG 2). Additionally, they could inform urban planning (SDG 11) by integrating natural habitats into city designs, promoting sustainable living environments and fostering more-than-human approaches to cities.

Declaration of generative AI in scientific writing

Statement: During the preparation of this work the authors used ChatGPT in order to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Laura Mrosla: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Henna Fabritius:** Writing – review & editing, Writing –

original draft, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization, Supervision. **Kristiina Kupper:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Fabian Dembski:** Writing – review & editing, Supervision. **Pia Fricker:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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Data availability

Data will be made available on request.

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