

Structural integration and dynamic modelling of biodiversity in urban digital twins

Laura Mrosła



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Structural integration and dynamic modelling of biodiversity in urban digital twins

Laura Mrosła

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Urban Digital Twins (UDTs) are increasingly positioned as integrative planning tools for managing the complexity of contemporary cities. Yet despite their expanding adoption across various sectors, most UDT implementations remain strongly human-centred, with biodiversity treated as a peripheral component with limited semantic depth. As cities simultaneously face increasing urbanisation, climate change, and the global biodiversity crisis, there is a growing need for digital planning tools, such as UDTs, that represent ecological information in ways that are dynamic, interoperable, and usable by diverse stakeholders.

This doctoral thesis advances the structural integration and semantic and dynamic modelling of urban biodiversity within UDTs, focusing primarily on flora and, to a lesser extent, fauna. It is structured around three interlinked aims. The first aim is to establish the state of the art in biodiversity modelling in digital twins and to identify user needs for vegetation-aware UDTs through a systematic literature review and action research with practitioners in Tallinn, Estonia and Helsinki, Finland.

The second aim is to develop a conceptual model extending CityGML 3.0 for semantically rich, dynamic vegetation representation.

The third aim is to demonstrate practical approaches and trade-offs for communicating empirical biodiversity data through immersive virtual reality (VR) in a case study in Tartu, Estonia.

The systematic literature review and urban stakeholder user needs analysis reveal three interconnected structural gaps explaining biodiversity's underrepresentation in UDTs: insufficient data infrastructure and standardisation relative to practitioner needs and more mature sectors; misalignment between practitioner needs and the CityGML 3.0 Vegetation module; and limited attention to communication and usability.

In response to these gaps, this thesis presents a comprehensive CityGML 3.0 Vegetation Application Domain Extension (ADE) conceptual model to align semantic vegetation representation with practitioner needs. Iteratively refined from v1.0 to v1.1 through an international participatory stakeholder process, the model provides a standardised semantic framework for structuring and operationalising vegetation data across systems and domains.

Complementing this semantic contribution and enhancing the communicative aspects of biodiversity representation in UDTs, the VR case study at the Jaamamõisa biodiversity restoration site in Tartu, Estonia demonstrates that empirical field inventory data can be translated into communicatively accessible immersive environments. The study reveals a persistent trilemma among modelling fidelity, computational performance, and communicative legibility that requires principled, audience-aware design judgement rather than technical optimisation alone.

By validating the feasibility of flora- and fauna-aware UDTs and providing a transferable pathway from diagnosis through semantic extension to immersive demonstration, this doctoral thesis contributes a foundation for integrating biodiversity into UDTs as a structurally embedded, semantically rich, and communicatively effective dimension of digital urban infrastructure.

Tekijä Laura Mrosła

Väitöskirjan nimi Luonnon monimuotoisuuden rakenteellinen integrointi ja dynaaminen mallintaminen kaupungin digitaalisissa kaksosissa

Artikkeliväitöskirja

Sivumäärä 83

Avainsanat kaupunkien digitaaliset kaksoset; luonnon monimuotoisuus; kasvillisuus; CityGML 3.0; Vegetation ADE; virtuaalitodellisuus

Kaupunkien digitaaliset kaksoset (*urban digital twins*, UDT:t) ovat yhä useammin nousseet esiin integroivina suunnittelutyökaluina, joilla hallitaan nykykaupunkien monimutkaisuutta. Vaikka niiden käyttö on yleistynyt eri aloilla, useimmat UDT-toteutukset ovat edelleen vahvasti ihmiskeskeisiä, ja biologista monimuotoisuutta käsitellään sivuseikkana, jolla on vain rajallinen merkityssisältö. Kun kaupungit joutuvat samanaikaisesti kohtaamaan lisääntyvää kaupungistumista, ilmastomuutosta ja maailmanlaajuisia biodiversiteettikriisiä, tarvitaan yhä enemmän UDT:n kaltaisia digitaalisia suunnittelutyökaluja, jotka esittävät ekologista tietoa dynaamisella, yhteentoimivalla ja eri sidosryhmille käyttökelpoisella tavalla.

Tämä väitöskirja edistää kaupunkien biologisen monimuotoisuuden rakenteellista integrointia sekä semanttista ja dynaamista mallintamista UDT-malleissa keskittyen ensisijaisesti kasvistoon ja toissijaisesti eläimistöön. Se rakentuu kolmen toisiinsa liittyvän tavoitteen ympärille. Ensimmäisenä tavoitteena on kartoittaa biologisen monimuotoisuuden mallintamisen nykytilaa digitaalisissa kaksosissa ja tunnistaa kasvillisuutta huomioivien UDT-mallien käyttäjien tarpeet systemaattisen kirjallisuuskatsauksen sekä Tallinnassa (Viro) ja Helsingissä (Suomi) ammattilaisten kanssa tehdyn toimintatutkimuksen avulla.

Toisena tavoitteena on kehittää CityGML 3.0:aa laajentava käsitteellinen malli, joka mahdollistaa semanttisesti rikkaan ja dynaamisen kasvillisuuden esittämisen.

Kolmantena tavoitteena on osoittaa käytännönläheisiä lähestymistapoja ja kompromisseja empiiristen biodiversiteettitietojen välittämiseksi immerstiivisen virtuaalitodellisuuden (*virtual reality*, VR) avulla Tartossa, Virossa, toteutettavassa tapaustutkimuksessa.

Systemaattinen kirjallisuuskatsaus ja kaupunkialan sidosryhmien käyttäjätarpeiden analyysi paljastavat kolme toisiinsa liittyvää rakenteellista aukkoa, jotka selittävät biodiversiteetin aliedustusta UDT-malleissa: riittämätön tietoinfrastruktuuri ja standardointi suhteessa ammattilaisten tarpeisiin ja kypsempiin sektoreihin; epäsuhta ammattilaisten tarpeiden ja CityGML 3.0:n kasvillisuusmoduulin välillä; sekä viestintään ja käytettävyyteen kiinnitetty vähäinen huomio.

Vastauksena näihin puutteisiin tässä opinnäytetyössä esitetään kattava CityGML 3.0 Vegetation -sovellusalueen laajennuksen (*Application Domain Extension*, ADE) käsitteellinen malli, jolla kasvillisuuden esitys sovitetaan alan ammattilaisten tarpeisiin. Malli on jalostettu iteratiivisesti versiosta 1.0 versioon 1.1 kansainvälisen osallistavan sidosryhmäprosessin kautta, ja se tarjoaa standardoidun semanttisen kehyksen kasvillisuustietojen jäsentämiselle ja käyttöönnotolle eri järjestelmissä ja aloilla. Täydentäen tätä semanttista panosta ja parantaen biodiversiteetin esittämisen viestinnällisiä näkökohtia UDT-malleissa, VR-tapaustutkimus Jaamamõisan biodiversiteetin ennallistamisalueella Tartossa, Virossa, osoittaa, että empiiriset kenttäkartoitustiedot voidaan muuntaa viestinnällisesti helppokäyttöisiksi immerstiivisiksi ympäristöiksi. Tutkimus paljastaa mallinnuksen tarkkuuden, laskennallisen suorituskyvyn ja viestinnällisen ymmärrettävyyden välisen jatkuvan trilemman, joka vaatii periaatteellista, kohdeyleisön huomioon ottavaa suunnittelupäätöstä pelkän teknisen optimoinnin sijaan.

Vahvistamalla kasvi- ja eläimistöä huomioivien UDT-mallien toteutettavuuden ja tarjoamalla siirrettävän polun diagnoosista semanttisen laajennuksen kautta immersiviseen esittelyyn tämä väitöskirja luo perustan biodiversiteetin integroimiseksi UDT-malleihin rakenteellisesti upotettuna, semanttisesti rikkaana ja viestinnällisesti tehokkaana ulottuvuutena digitaalisessa kaupunki-infrastruktuurissa.

Autor Laura Mrosła

Doktoritöö pealkiri Bioloogilise mitmekesisuse struktuurne integreerimine ja dünaamiline modelleerimine linnade digitaalsetes kaksikutes

Artiklitel põhinev doktoritöö

Lehekülgede arv 83

Märksõnad: linnade digitaalsed kaksikud, looduslik mitmekesisus, taimestik, CityGML 3.0, Vegetation ADE, virtuaalne reaalsus

Linnade digitaalseid kaksikuid (*urban digital twins*, UDT-d) käsitletakse üha enam terviklike planeerimisvahenditena, mis aitavad toime tulla kaasaegsete linnade keerukusega. Hoolimata nende ühe laialdasemast kasutuselevõtust erinevates sektorites, on enamik UDT rakendusi endiselt tugevalt inimkesksed ning looduslikku mitmekesisust käsitletakse neis kõrvalise komponendina, mille semantiline sügavus on piiratud. Kuna linnad seisavad samaaegselt silmitsi üha süveneva urbaniseerumise, kliimamuutuse ja ülemaailmse elurikkuse kriisiga, kasvab vajadus digitaalsete planeerimisvahendite järele, nagu UDT-d, mis esitavad ökoloogilist teavet dünaamilisel, koostalitlusvõimelisel ja erinevate huvirühmade jaoks lihtsasti kasutataval viisil.

Käesolev doktoritöö edendab linnade loodusliku mitmekesisuse struktuurilist integreerimist ja semantilist ning dünaamilist modelleerimist UDT-des, keskendudes peamiselt taimestikule ja vähemal määral loomastikule. Töö on üles ehitatud kolme omavahel seotud eesmärgi ümber. Esimene eesmärk on kaardistada elurikkuse modelleerimise hetkeseis digitaalsetes kaksikutes ja selgitada välja kasutajate vajadused taimestikku arvestavate UDT-de järele, kasutades selleks süstemaatilist kirjanduse ülevaadet ja Tallinna (Eesti) ning Helsingi (Soome) praktikutega läbiviidud tegevusuuringut. Teine eesmärk on arendada kontseptuaalne mudel, mis laiendab CityGML 3.0 standardit ning võimaldab taimestikku semantilisel rikkalt ja dünaamilisel kujutada. Kolmas eesmärk on Tartus (Eesti) tehtud juhtumiuuringu kaudu tutvustada praktilisi lähenemisviise ja nendega kaasnevaid kompromisse empiiriliste elurikkuse andmete edastamisel immerstiivse virtuaalreaalsuse (VR) kaudu. Süstemaatiline kirjanduse ülevaade ja linnakeskkonna kasutajate vajaduste analüüs toovad esile kolm omavahel seotud struktuurset lünka, mis selgitavad loodusliku mitmekesisuse alaesindatust UDT-des: ebapiisav andmetaristu ja standardiseerimine võrreldes praktikute vajaduste ning arenenumate sektoritega; praktikute vajaduste ja CityGML 3.0 taimestiku mooduli vaheline mittevastavus; ning piiratud tähelepanu informatsiooni edastamisele ja kasutatavusele.

Nendele puudustele reageerimiseks esitab käesolev väitekirj tervikliku CityGML 3.0 taimestiku rakendusvaldkonna laienduse (*Application Domain Extension*, ADE) kontseptuaalse mudeli, et viia taimestiku visuaalne esitus kooskõlla praktikute vajadustega. Mudel pakub standardiseeritud semantilist raamistikku taimestiku andmete struktureerimiseks ja rakendamiseks erinevates süsteemides ja valdkondades. Mudelit täiustati iteratiivselt versioonist 1.0 versioonini 1.1 rahvusvahelise osalusprotsessi kaudu, mille käigus töötasid koos erinevad sidusrühmad.

Täiendamaks seda semantilist panust ja täiustamaks loodusliku mitmekesisuse esitamise kommunikatiivseid aspekte UDT-des, näitab Tartus Jaamamõisa elurikkuse taastamise alal läbi viidud VR-i juhtumiuuring, et välitöödest saadud empiirilisi inventuurandmeid on võimalik esitada immerstiivsete keskkondade kaudu. Uuring toob esile järjepideva trilemma modelleerimise täpsuse, arvutusvõimsuse ja kommunikatiivse selguse vahel, mis nõuab tehnilise optimeerimise kõrval põhimõttekindlat ning sihtrühma arvestavat disainilahendust.

Tõendades taimestikku ja loomastikku arvestavate UDT-de teostatavust ning pakkudes ülekantavat lähenemisviisi, mis ulatub diagnoosist semantilise laiendamise kaudu immerstiivse esituseni, loob käesolev väitekirj aluse loodusliku mitmekesisuse lõimimiseks UDT-desse kui struktuuriliselt sisselõimitud, semantilisel rikkasse ja kommunikatiivselt tõhusasse digitaalse linnainfrastruktuuri mõõtmesse.

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**Structural integration and
dynamic modelling of biodiversity
in urban digital twins**

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Declaration:

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

Laura Mrosła

signature



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**Bioloogilise mitmekesisuse struktuurne
integreerimine ja dünaamiline modelleerimine
linnade digitaalsetes kaksikutes**

LAURA MROSLA



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Pursuing a PhD alongside constantly changing “background noise”, from moving to a new country during a global pandemic to experiencing war in Europe, was challenging. Yet, what shaped my PhD journey most, beyond this backdrop of constantly needing to adapt to a “new normal”, was the support, wisdom, and encouragement of many people around me. In this section, I attempt to acknowledge their invaluable contributions with words, though I already know they fall short of expressing how I truly feel.

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List of Publications

This doctoral thesis is based on the following publications:

- I. Mrosła, L.;** Fabritius, H.; Kupper, K.; Dembski, F.; Fricker, P. (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
- II. Petrova-Antonova, D.; Malinov, S.; Mrosła, L.; Petrov, A. (2024).** Towards a Conceptual Model of CityGML 3.0 Vegetation ADE. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Volume XLVIII-4/W10-2024 - 8th International Conference on Smart Data and Smart Cities (SDSC), 4–7 June 2024, Athens, Greece, 155-161. DOI: 10.5194/isprs-archives-XLVIII-4-W10-2024-155-2024
- III. Mrosła, L.;** Petrova-Antonova, D.; Malinov, S.; Fabritius, H. (2026). Urban Vegetation Semantics in CityGML - Key stakeholder survey findings and Vegetation ADE development. *International Journal of Applied Earth Observation and Geoinformation*, 146, 105043. DOI: 10.1016/j.jag.2025.105043
- IV. Fabritius, H.; Mrosła, L.;** Kangassalo, P. (2025). Empirical Data Meets Immersive Design – Lessons learned from 3D Modelling a biodiversity intervention site for Virtual Reality. *Confluence - Proceedings of the 43rd Conference on Education and Research in Computer Aided Architectural Design in Europe (eCAADe 2025)*, Ankara, 1-5 September 2025, Volume 2, 591-600. DOI: 10.52842/conf.ecaade.2025.2.591

Other Publications

V. Fabritius, H.; Tuulik, T.; Kupper, K.; **Mroska, L.**; Nummi, P.; Prilenska, V.; Yao, C. (2023). Varying Data on Urban Trees Complicates Meeting User Needs for Digital Twins of Urban Green Infrastructure. The 18th International Conference on Computational Urban Planning and Urban Management, CUPUM 2023, 20-22 June 2023, McGill University, Montreal, Canada.

These publications satisfy the doctoral publication requirements stipulated by both Aalto University, Finland, and Tallinn University of Technology (TalTech), Estonia, in terms of both quantity and quality.

Author's Contribution

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

The author of this doctoral thesis served as the first and corresponding author for this publication. She conceptualised the study by formulating the research idea and designing the methodology, performing data curation, and analysis. She was responsible for project administration, resource management, and supervision throughout the work. Additionally, she prepared the original manuscript draft, the rewriting, reviewing, and editing, and created the visualisations. Laura Mrosła managed the submission, review and publishing process.

Publication II: Towards a Conceptual Model of CityGML 3.0 Vegetation ADE

The contribution of the author of this doctoral thesis to this publication was in co-writing and revising the publication. This publication was developed based on the work published as: Petrova-Antonova, D.*; Mrosła, L.*; Malinov, S. (2024): CityGML 3.0 Vegetation ADE Proposal. DOI: [10.5281/zenodo.13906830](https://doi.org/10.5281/zenodo.13906830), where the author of this doctoral thesis is co-first author (*shared first author) and responsible for domain expertise and technical documentation, attributes refinement, conceptualisation, writing, visualisation, review and editing.

Publication III: Urban Vegetation Semantics in CityGML - Key stakeholder survey findings and Vegetation ADE development

The author of this thesis served as first author and corresponding author. She contributed to the study through investigation and the development of the research methodology. She was responsible for data curation and analysis and data model development. Laura Mrosła prepared the original manuscript draft, and is responsible for writing, review, and editing, and the creation of the visualisations. She also performed validation tasks, managed project administration, and oversaw the allocation of resources. Laura Mrosła also managed the submission, review and publishing process.

Publication IV: Empirical Data Meets Immersive Design – Lessons learned from 3D Modelling a biodiversity intervention site for Virtual Reality

The author of this thesis contributed to the original draft writing, and subsequent manuscript revisions. Her active involvement in the study encompassed conceptualising the Biodiversity Game, project management, contributing to herbaceous plant photography and billboard design, coordinating voice recording and implementation, facilitating stakeholder communication, design and formulation of the game-internal

information on biodiversity and interventions, and conducting user testing with iterative refinement of the Biodiversity Game. Laura Mrosła presented this work at the 43rd eCAADe Conference (Confluence) at the Middle East Technical University in Ankara, Turkey in September 2025.

Author's Contribution to Other Publications

Publication V: Varying Data on Urban Trees Complicates Meeting User Needs for Digital Twins of Urban Green Infrastructure

The author of this thesis contributed to writing the original draft and revising the manuscript. She participated in the collaborative action research activities, including workshops, polls, questionnaires and interviews. Laura Mrosła wrote the introduction of urban digital twins and co-wrote the role of urban vegetation/biodiversity in them and the future-oriented part of the discussion of vegetation's role in UDTs. She co-formulated the research questions and research setting and co-wrote the interpretation of the results.

List of Abbreviations

ADE	Application Domain Extension
AI	Artificial Intelligence
API	Application Programming Interface
CM	Conceptual Model
GIS	Geographic Information System
GML	Geography Markup Language
JSON	JavaScript Object Notation
LiDAR	Light Detection and Ranging
LoD	Level of Detail
UAV	Unmanned Aerial Vehicle
UDT	Urban Digital Twin
UML	Unified Modelling Language
URI	Uniform Resource Identifier
UX	User Experience
VR	Virtual Reality
XML	Extensible Markup Language

1 Introduction

Cities are undergoing rapid transformation under the combined pressures of ongoing urbanisation, climate change, and biodiversity loss. This drives the need for planning tools capable of capturing interactions between built, social, and ecological systems in a coherent way (Audusseau et al., 2024; Li et al., 2024; Urban et al., 2024). In this context, Urban Digital Twins (UDTs) are increasingly promoted in both research and practice as high-fidelity, data-driven representations of cities that support simulation, analysis, and decision-making across multiple sectors (Abdelrahman et al., 2025; Lei et al., 2023). Yet, despite their growing institutional uptake and increasing technical sophistication, most UDTs in practice remain strongly human-centred. Biodiversity, understood in this thesis in accordance with the standard ecological definition as encompassing genetic, species, and ecosystem diversity (United Nations, 1992), is routinely treated as a marginal or simplified element rather than as a semantically explicit, temporally dynamic, and decision-relevant dimension of urban environments (Westerlaken, 2024; M. Zhu & Jin, 2025). This marginalisation is particularly evident in how flora and fauna, the two ecological components at the centre of this dissertation, are represented, or more precisely underrepresented, within operational UDT systems. Even where these appear, they typically take the form of static two-dimensional layers, generic three-dimensional objects, or post-hoc visualisation elements bearing limited semantic information (Dimitrov & Petrova-Antonova, 2021; Lei et al., 2023; Mroska et al., 2025; Ortega-Córdova, 2018; Pantazatou et al., 2024). Such representations are inadequate for monitoring ecological change, communicating management interventions, realistically representing the natural world to a broader audience, or projecting future scenarios. However, these are tasks of growing importance as biodiversity loss accelerates and nature-based and biodiversity-aware urban planning gains wider policy traction (European Commission. Directorate General for Environment., 2021; Tzachor et al., 2022; Westerlaken, 2024). A significant part of the problem resides in the data standards that underpin UDTs. Data standards employed for UDTs, such as the City Geography Markup Language (CityGML), provide an important basis for structuring urban information and ensuring interoperability across systems and organisations (Kolbe et al., 2021). CityGML defines classes and attributes for a wide range of urban objects and already includes a Vegetation module (Kutzner et al., 2020), but in its current form, this module

offers limited semantic depth (Fabritius et al., 2023; Pantazatou et al., 2024; Petrova-Antonova, Malinov, et al., 2024).

This publication-based dissertation responds to these interrelated challenges by advancing the structural integration and dynamic modelling of flora and fauna within UDTs, synthesising five peer-reviewed publications into an integrated research programme. The programme begins with the diagnostic groundwork: a systematic cross-domain assessment of the current state of dynamic flora and fauna modelling in digital twins and related 3D city models (Publication I), complemented by an empirically grounded analysis of user needs and data availability for urban vegetation in specific Nordic-Baltic European city contexts (Publication V). Together, these two studies establish the evidence basis, identifying gaps in data availability, semantic standards, and representation capacity, that directly motivates and shapes the contributions that follow. Building on this foundation, the dissertation advances along two complementary lines of development. On the semantic side, it presents the development and iterative stakeholder refinement of a CityGML 3.0 Vegetation Application Domain Extension (ADE) conceptual model (CM). It is designed to represent urban vegetation in a more semantically explicit, dynamically updateable, and interoperable way within UDTs (Publications II and III). On the communicative side, it demonstrates how empirical biodiversity data from a real-world urban intervention site can be translated into a performance-constrained immersive virtual reality (VR) environment, with the VR demonstrator serving as the perceptual and communicative complement to the semantic modelling work. Where the ADE structures ecological information for machine-readable interoperability, the VR environment renders that same ecological reality accessible and tangible for diverse human audiences (Publication IV).

The cumulative design of this research gives rise to four claims that exceed the scope of the individual publications and constitute the dissertation's central argument.

First, the persistent underrepresentation of flora and fauna in UDTs is not attributable to any single technical deficiency but reflects a cluster of mutually reinforcing constraints spanning data availability, semantic interoperability, practical usability, and representational realism. Addressing this systemic condition requires coordinated progress across all these dimensions, with progress in only one dimension alone merely relocating rather than resolving the systemic bottleneck. Second, CityGML 3.0 can be extended through a Vegetation ADE CM to address identified user needs by incorporating structural components, temporal dynamics, and management information required for vegetation-aware UDT applications, thereby enabling the interoperable representation of semantic vegetation data. Crucially, such a model can be developed in a standards-compliant manner that is responsive to diverse stakeholder requirements across international

contexts. Third, semantic and immersive approaches address different but complementary barriers to biodiversity representation in UDTs. A performance-constrained VR environment grounded in empirical data demonstrates that ecological reality can be rendered communicatively accessible to non-specialist audiences, closing a representation gap that semantic modelling alone cannot address. Fourth, by connecting these strands in a cumulative research design, the work validates the conceptual and methodological feasibility of biodiversity-aware UDTs for urban contexts and provides a transferable pathway for integrating flora and fauna more systematically into UDTs.

These advances lay a standards-compliant foundation for biodiversity-aware UDTs, providing a transferable pathway for ecological data to move from peripheral visualisation towards semantically structured, dynamically updateable, and communicatively effective representation within UDTs.

1.1 Main research objective, aims, and research questions

The overarching research objective of this dissertation is:

To advance the structural integration and semantic and dynamic modelling of biodiversity in urban digital twins, with a primary focus on flora and a more limited treatment of fauna.

This objective is pursued through three interlinked research aims and associated research questions (RQ) which follow a cumulative progression from foundational diagnosis (Aim 1), through standards-level semantic data model development (Aim 2), to demonstrative immersive application (Aim 3). Specifically, Aim 1 establishes the status quo through a systematic literature review and user needs assessment, Aim 2 develops a stakeholder-validated conceptual data model (CityGML 3.0 Vegetation Application Domain Extension Conceptual Model v1.1), and Aim 3 demonstrates the representation of empirical urban biodiversity data in an immersive VR environment. Together, these aims address distinct but related dimensions of existing research gaps.

Research Aim 1: Identify the status quo, gaps and opportunities of dynamic modelling of flora and fauna within digital twins, and user needs for developing digital twins of urban green infrastructure.

This aim establishes the diagnostic foundation of this dissertation, synthesising cross-domain evidence with urban-specific requirements, providing the empirical basis for subsequent semantic and applied work. While Aim 1 and RQ1.1 address flora and fauna across disciplinary domains as a broad evidence base, RQ1.2 narrows to urban vegetation as the primary focus, in line with the thesis scope

established in Section 1.2, where flora is listed as the principal object of study and fauna is addressed only to a limited extent.

Research Aim 1 is pursued through the following research questions (RQ):

RQ1.1: What is the current state-of-the-art documented in scientific literature on dynamic biodiversity modelling across disciplinary domains in digital twins?

RQ1.2: What are the critical gaps in vegetation data models and representational approaches for dynamic modelling that align with user needs for developing digital twins of urban green infrastructure?

RQ1.1 establishes a cross-domain evidence baseline on dynamic biodiversity modelling, clarifying how flora and fauna are currently modelled within digital twin environments and where semantic, data, and representation gaps persist (Publication I). RQ1.2 then narrows this baseline to concrete urban contexts and practitioner needs in Tallinn and Helsinki, specifying which vegetation information is required but currently missing from UDTs and the CityGML standard (Publications I and V). Together, the answers to RQ1.1 and RQ1.2, presented in section 4.1, define the semantic and functional requirements that directly inform the semantic data modelling in Aim 2 (Publications II and III) and guide biodiversity representation in the immersive VR case study under Aim 3 (Publication IV).

Research Aim 2: Develop a standardised, user needs guided, participatorily validated conceptual model extending CityGML 3.0 for interoperable dynamic semantic representation of vegetation in urban digital twins, addressing existing deficiencies.

Informed by Aim 1, this aim translates diagnosed deficiencies into a practical conceptual model for a CityGML 3.0 Vegetation ADE, forming the technical core of the dissertation and ensuring standards compliance across UDTs.

Research Aim 2 is pursued through the following research questions (RQ):

RQ2.1: How can CityGML 3.0 be extended to enable dynamic semantic urban vegetation modelling based on user needs?

RQ2.2: How do stakeholder requirements inform the revision and validation of a practical conceptual model for a Vegetation ADE for UDTs?

Informed by the established baseline and user needs from RQ1.1–RQ1.2 (Publications I and V), RQ2.1 translates identified vegetation-related semantic gaps into a CityGML 3.0 Vegetation Application Domain Extension conceptual model with structural components, management attributes, and temporal dynamics (Publication II). RQ2.2 then validates and refines this conceptual model through

international expert feedback, yielding the ADE v1.1 proposal aligned with international stakeholders' UDT requirements (Publication III). Together, the answers to RQ2.1 and RQ2.2, presented in section 4.2, provide a standards-compliant semantic framework that clarifies pathways for structuring vegetation-related data, informing future UDT integration.

Research Aim 3: Demonstrate practical approaches and trade-offs for immersive VR representation of empirical urban biodiversity data in a performance-constrained environment.

This demonstrative aim applies Aim 1 findings to a case study, exploring VR as a complementary biodiversity communication interface in addition to the semantic-based vegetation representation (Aim 2). It tests practical representation challenges, namely fidelity vs performance vs communication, that highlight limitations in current UDT visualisation approaches.

Research Aim 3 is pursued through the following research question (RQ):

RQ3: What methodological, technical, and communicative challenges arise, and what practical solutions are developed, when translating empirical urban biodiversity data into performance-constrained VR environments for diverse audiences?

In addressing RQ3, this dissertation draws on Aim 1 evidence concerning representation shortcomings and user needs (Publications I and V) to develop workflows to translate field inventories into performance-optimised VR assets, while analysing trade-offs in fidelity, performance, and audience comprehension (Publication IV). This complements Aim 2's parallel semantic work (Publications II and III) by demonstrating how empirical biodiversity data can be rendered communicatively effective in immersive interfaces. Thus, section 4.3 addresses RQ3, closing the research progression by testing practical applicability of earlier insights established in Aim 1.

Table 1 Overview of research gap, contributions to research aims, type of study and in which publication the research gap is addressed.

Research Gap	Research Aim Contribution	Type of Study	Publication
Lack of systematic review of dynamic flora/fauna modelling across digital twin domains despite rapid cross-disciplinary proliferation	1	Review	P I
Limited evidence on the extent to which vegetation data models and representational approaches for dynamic modelling meet user needs of urban green infrastructure representation in UDTs	1	Empirical	P V
CityGML Vegetation module lacks semantic depth for dynamic urban vegetation representation to align with user needs	2	Conceptual	P II
Proposed ADE CM v1.0 requires validation across international stakeholder requirements and use cases	2	Empirical, conceptual	P III
Lack of operational approaches balancing fidelity/performance/communication for immersive urban biodiversity representation in VR	3	Empirical case study	P IV

1.2 Thematic focus, scope and novelty

This thesis is situated at the disciplinary intersection of digital twins, urban planning, biodiversity modelling, semantic data standards, and VR-based immersive representation, with a specific focus on urban environments. Within the broad concept of biodiversity, the focus lies primarily on flora and only to a limited extent on fauna. The thesis deliberately excludes aspects of biodiversity and ecosystems such as fungi, genetic diversity and non-urban landscapes. This thematic focus is chosen for the following reasons: vegetation modelling in UDTs is more technically advanced than fauna modelling, providing a tractable foundation for continued research. Particularly, CityGML 3.0, the primary data standard addressed here, already includes a Vegetation module in its core schema, making an Application Domain Extension a coherent and practically grounded contribution. Fauna is researched in Publication I, where its scarcity in the academic literature on the field of dynamic modelling for digital twins is identified as a structural gap. Moreover, fauna is represented in Publication IV. The thesis does not, however, pursue fauna modelling as a primary research strand. Private sector and proprietary research not reflected in indexed academic literature falls outside the scope of this research. The case study cities of this thesis are situated in Tallinn and Helsinki (Publication V) and Tartu (Publication IV, Figure 1). The empirical work is grounded in these three North-Eastern European urban contexts

and findings may not be directly generalisable or transferable to other contexts with different levels of spatial data and technological readiness, distinct planning governance arrangements, or substantially different urban vegetation types and climatic conditions.

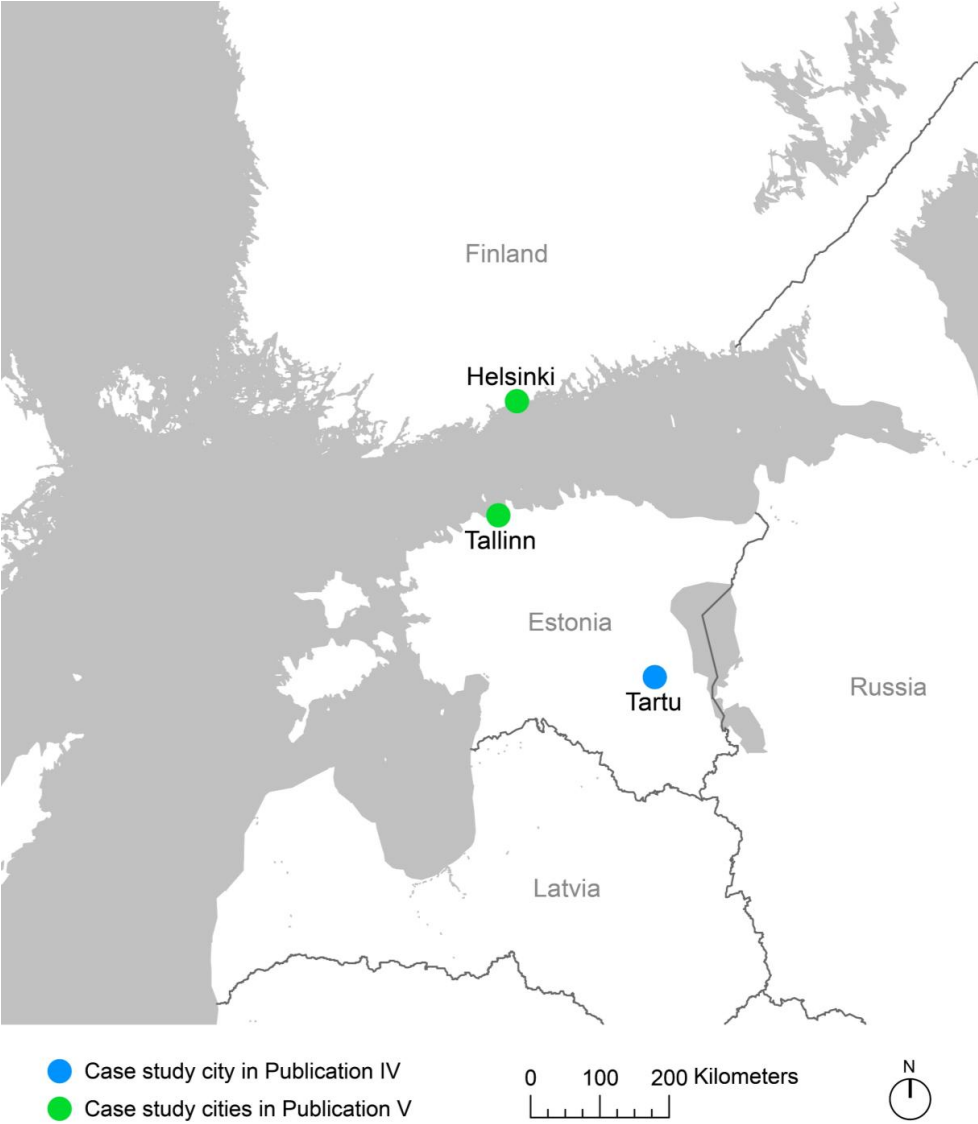


Figure 1 Map of case study city in Publication IV (Tartu in Estonia; blue dot) and case study cities in Publication V (Helsinki in Finland and Tallinn in Estonia; green dots).

Throughout, the scope is conceptual and demonstrative. The thesis presents a CityGML 3.0 Vegetation ADE conceptual model, not a fully implemented technical specification. The VR component in Publication IV constitutes a performance-constrained biodiversity game demonstrator. This thesis does not claim to deliver a fully operational or closed-loop UDT. It establishes and validates constituent technical and methodological components whose integration into such a system represents a next step.

Publication I provides a horizontal, cross-sectoral systematic literature review on dynamic modelling of flora and fauna in 3D city models and digital twins, revealing uneven disciplinary maturity and structural knowledge transfer barriers.

Publications II and III jointly introduce and participatorily refine the first comprehensive CityGML 3.0 Vegetation ADE conceptual model. This proposal enhances semantic depth and supports dynamic vegetation attributes, validated through an international stakeholder survey.

Publication IV documents the translation of empirical field inventory data from the Tartu Jaamamõisa biodiversity intervention site into a performance-constrained VR environment, addressing fidelity and performance trade-offs alongside communicative accessibility.

Publication V contributes an empirically grounded analysis of urban tree data availability and projection-model calibration challenges in Helsinki and Tallinn, linked to practitioner needs for green infrastructure digital twins. Concepts on how to extend the CityGML Vegetation module are proposed.

Across these five publications, this thesis demonstrates that biodiversity integration in UDTs is not only a structural problem but a tractable one. Through a standards-compliant semantic extension, vegetation-related data can be represented in a more structured, dynamic, and interoperable form, and through immersive virtual reality, that biodiversity data can be made communicatively accessible to diverse stakeholders. This thesis is a cumulative research programme connecting cross-domain systematic evidence, standards-level semantic extension, and immersive biodiversity communication within a single coherent argument, providing a replicable trajectory for advancing biodiversity integration in UDTs from peripheral visualisation towards interoperable and communicatively effective ecological representation.

2 Context and motivation

2.1 The biodiversity crisis in relation to urban environments

The global biodiversity crisis is widely recognised as one of the most severe environmental challenges of the twenty-first century (United Nations, 2022; United Nations Statistics Division, 2016). Syntheses by the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) estimate that around one million species are currently threatened with extinction and that most ecosystems have been substantially altered by human activities, undermining ecosystem functioning and resilience (Díaz et al., 2019; Theodorou, 2022). These changes have cascading effects on ecosystem services such as pollination, nutrient cycling and climate regulation (Díaz et al., 2019; Oliver et al., 2015; Weiskopf et al., 2024). This introduces far-reaching ecological, socio, economic and cultural consequences (Arneth et al., 2020; Pörtner et al., 2023; Shivanna, 2020). Scientific assessments converge on the conclusion that contemporary biodiversity decline is overwhelmingly driven by anthropogenic pressures (Keck et al., 2025). The dominant direct drivers being land- and sea-use change leading to habitat loss, fragmentation, and degradation, alongside climate change, pollution, overexploitation of organisms, and invasive alien species (Jaureguiberry et al., 2022; Díaz et al., 2019).

In urban contexts, biodiversity underpins regulating and cultural ecosystem services that are particularly valued, including microclimate moderation, stormwater management, recreation and psychological restoration (Dong Wang et al., 2024). Consequently, safeguarding and enhancing biodiversity in cities is increasingly framed as essential for climate adaptation, public health and long-term urban sustainability (Kabisch & Egerer, 2025; Dong Wang et al., 2024).

This urgency has prompted a series of global and regional policy responses. Internationally, biodiversity loss has been addressed through instruments such as the UN Sustainable Development Goals, particularly Goals 11 and 15 (United Nations, 2015) and the Kunming-Montreal Global Biodiversity Framework (United Nations, 2022). At the level of the European Union, complementary policy responses include the European Green Deal (European Commission. Directorate General for Environment., 2021), the EU Biodiversity Strategy for 2030 (European

Commission. Directorate General for Environment., 2021), and the Nature Restoration Regulation (European Commission. Directorate General for Environment., 2025).

2.1.1 Cities as both drivers and leverage points

Urbanisation is one of the most profound manifestations of global land-use change (United Nations Department of Economic and Social Affairs, 2025). Urban areas already accommodate more than half of the world's population and are projected to absorb most future growth, with urban land cover expanding in extent and intensity. At the landscape scale, urbanisation fragments and isolates habitats (Chu et al., 2022; Seress & Liker, 2015), and simplifies vegetation structure (Lei Zhang et al., 2022). Within cities, impervious surfaces, dense infrastructure and heavily managed green spaces can reduce habitat quality and connectivity and stress sensitive species, frequently leading to biotic homogenisation, favouring generalist, disturbance-tolerant species at the expense of specialists (Newbold et al., 2018; Piano et al., 2020; Ruas et al., 2022). Yet urban environments can also harbour substantial and sometimes unique biodiversity where (semi-)natural remnants, diverse green-blue infrastructure, rewilding and heterogeneous management regimes persist (Finnerty et al., 2025; Ruas et al., 2022; Dong Wang et al., 2024; Wellmann et al., 2025).

Beyond their ecological footprint, cities are key arenas for experimentation with new forms of governance, planning and technology that can address biodiversity loss. Recently, planning in urban environments shifts from “human-centric” to “more-than-human” approaches, recognising ecological needs and more-than-human species and their requirements including health, shelter and food (Kabisch & Egerer, 2025; Sheikh et al., 2023; Van Patter, 2023). Urban living labs, piloting projects and initiatives use cities as testbeds for innovative approaches, interventions and policy instruments, positioning cities simultaneously as drivers of biodiversity decline and as laboratories for its potential reversal (Finnerty et al., 2025; Kabisch & Egerer, 2025; Najda-Janoszka et al., 2025). Realising this potential requires fine-grained, dynamic and actionable knowledge about ecological patterns and processes in cities, as well as integrative tools that connect and represent this knowledge to decision-makers across sectors and scales (Casanelles-Abella et al., 2025). Traditional urban information systems often underrepresent ecological components or lack mechanisms for continuous updating and feedback (Frantzeskaki et al., 2024). Advances in biodiversity-related data collection, modelling, and computational capacity open possibilities for more responsive and systemic approaches, within which digital twins are emerging as a prominent integrative concept (Islam et al., 2026).

2.2 Digital twins

Digital twins are integrative tools that combine multiple technologies to bridge physical systems and their digital counterparts. These digital counterparts are representations of physical entities that incorporate updates at variable frequencies and, in their most capable forms, can influence the physical counterpart indirectly or directly (Grieves & Vickers, 2017; Semeraro et al., 2021; Wright & Davidson, 2020). While there are different definitions of what exactly a digital twin constitutes, they are characterised, in contrast to static digital models, by automated, and ideally bidirectional, data flows between physical and virtual components, enabling e.g. monitoring, diagnosis, decision-support, prediction, and, at the highest levels of maturity, actuation (Haraguchi et al., 2024; Metcalfe et al., 2023; Wright & Davidson, 2020). Originating in manufacturing and product lifecycle management, the concept has been widely adopted in other domains such as engineering, aerospace, and urban planning, though the degree to which full bidirectional automation is realised varies considerably across application contexts (Batty, 2018; Botín-Sanabria et al., 2022; Liu et al., 2021).

2.2.1 Digital twin maturity: A continuum

A foundational conceptual distinction in the digital twin literature concerns the degree to which a digital representation is coupled with its physical counterpart. Kritzinger et al. (2018) propose three idealised categories: a *digital model*, in which all data exchange between the physical and digital counterparts is manual; a *digital shadow*, in which data flows automatically from the physical to the digital counterpart but not in reverse, and a *digital twin* in the strict sense, in which automated bidirectional data flow enables the digital counterpart to influence the physical system. This typology is widely cited and provides a useful conceptual anchor for distinguishing systems with limited coupling from those with full synchronisation (Botín-Sanabria et al., 2022; Kritzinger et al., 2018).

However, the literature increasingly recognises that these categories describe ideal types on a continuum rather than discrete, empirically distinguishable states (Batty, 2018; Metcalfe et al., 2023; Wright & Davidson, 2020). In practice, many systems exhibit intermediate or partial coupling, namely automated data flows in some subsystems but not others, unidirectional automation in some data streams combined with manual inputs in others, such that strict assignment to model, shadow, or twin is often ambiguous. Metcalfe et al. (2023) address this directly by proposing a tiered maturity framework for digital twins in the life and environmental sciences, identifying incremental capability levels from static data-linked representations through to fully autonomous closed-loop systems. Progress towards more capable digital twins is therefore better understood as incremental

maturation along multiple dimensions including data automation, information, model and visualisation fidelity, bidirectionality, and actuation, than as a transition between discrete categories (Haraguchi et al., 2024; Jones et al., 2020; Metcalfe et al., 2023). In practice, the term *digital twin* is applied broadly across this entire spectrum, including to systems that would more precisely be characterised as digital shadows, prototype-digital twin or early-stage digital twins (Botín-Sanabria et al., 2022; Kritzinger et al., 2018; Lecarpentier et al., 2024).

2.2.2 Urban digital twins

In urban contexts, the term urban digital twin (UDT) has been applied to a wide and heterogeneous range of systems, from 3D visualisations to integrated platforms linking city models with real-time sensor data, simulation services, and decision-support interfaces (Azadi et al., 2025b; Lei et al., 2023; Omrany et al., 2025; Weil et al., 2023). Related terms such as “digital twin of a city” (Lehtola et al., 2022), “city digital twin”, “city-level digital twins” (Yan et al., 2025), “digital twin smart cities” (Alvi et al., 2025) and “local digital twin” (Raes et al., 2025), are used partly interchangeably in the literature (Virtanen et al., 2026). Similar to the term digital twin, no fully standardised definition of UDTs is universally applied (Abdelrahman et al., 2025; Lei et al., 2023).

For the purposes of this thesis, a UDT is understood as a digital representation of an urban environment that can incorporate temporal updates and support e.g. scenario analysis and planning decisions affecting the physical city. This definition encompasses both fully automated closed-loop implementations and partial configurations in which data, models, and interfaces are integrated but actuation remains largely human-mediated, a condition that characterises most current UDT deployments, and especially those involving biotic components. In terms of the continuum introduced in Section 2.2.1, this definition intentionally spans the full range from digital shadow to closed-loop digital twin, reflecting the heterogeneity of systems described as UDTs in the literature.

UDTs are best understood not as monolithic systems but as layered, modular architectures - systems of systems - in which multiple subsystems with distinct functions are integrated into a coherent whole (Abdelrahman et al., 2025; Azadi et al., 2025b; Ivanov et al., 2020; Lehtola et al., 2022). The international standard ISO/IEC 30173 Digital twin – concepts and terminology (International Organization for Standardization, 2023) describes a digital twin as comprising five inter-operating elements. These are: i) *Digital twin system*, which in the case of urban digital twins denotes a system that links a target entity (e.g. the physical urban environment) with a corresponding digital entity (e.g. computational models

and datasets) through data connections that keep the physical and digital states synchronised. Such connections can be established through e.g. sensor feeds, Internet of Things (IoT) devices and other information systems (e.g. via Application Programming Interfaces (APIs)). ii) *Services*, covering capabilities such as connection and integration, together with analysis, simulation, visualisation, optimisation and collaboration. iii) *Application domain*, the sector or field in which a digital twin system is deployed (e.g. cities, manufacturing and healthcare). iv) *Infrastructure*, including the software platforms, hardware resources and communication networks that host and operate the digital twin system and its services. v) *System aspects*, such as governance, security, ethics, legal compliance and interoperability within the wider socio-technical context.

2.3 Semantic data modelling for urban environments

UDTs integrate data from heterogeneous sources including municipal databases, sensor networks, remote sensing archives, ecological surveys, many of them using different formats, coordinate systems, attribute names, and classification schemes (Bauer et al., 2021; Lei et al., 2023; Virtanen et al., 2024). To meaningfully integrate these diverse data, geometry alone is insufficient (Sun, 2018): a tree represented only as a point, polygon or 3D model carries no information about its species, age, health status, or role in the urban ecosystem unless that geometry is accompanied by structured, formally defined attributes. Semantic data modelling is the practice of formalising not the shape but the meaning of urban objects. It specifies what classes of objects exist, what properties they carry, how they relate to each other, and how terms are defined consistently across systems (Azadi et al., 2025b; Elhajj, 2026). In urban planning, this matters because it enables machines and human analysts from different disciplines and institutions to share and reuse data without translation, and it allows models to be queried, updated, and combined in ways that geometric files alone do not permit (Kolbe et al., 2021; Psyllidis, 2015). Without a shared semantic layer, data from a municipal tree register, an ecological survey, and a remote sensing analysis of the same urban area cannot be automatically aligned or jointly interrogated, even if all three datasets describe the same physical objects.

In the context of UDTs, semantic data modelling is operationalised primarily through standards that define shared vocabularies, feature class hierarchies, and geometry-attribute relationships for urban objects (Azadi et al., 2025a). Standards-based semantic models allow data produced by different institutions, in different cities, and with different tools to be integrated, queried, and reused without custom translation, a prerequisite for scalable and interoperable UDT applications (Biljecki et al., 2015; Kolbe et al., 2021). CityGML is a widely used open standard for this purpose (Kasprzyk et al., 2024).

2.4 City Geography Markup Language (CityGML)

CityGML is an open international standard published by the Open Geospatial Consortium for representing three-dimensional urban objects with their geometry, appearance, topology, and semantics (Kolbe et al., 2021). Its initial release as CityGML 1.0 was in 2008 (Kolbe, 2009). Since then, the standard has been applied as a basis for semantic 3D city modelling across a range of institutional and national contexts, including urban planning, infrastructure management, environmental simulation, disaster response, and energy analysis (Gröger & Plümer, 2012; Malhotra et al., 2022; Zhao et al., 2025; Zhu et al., 2016). The standard defines feature classes for a broad range of urban object types including *building*, *bridge*, *transportation*, *waterbody*, *landuse*, and *vegetation*, each with geometry representations across multiple Levels of Detail (LoD) and thematic attributes encoding semantic information (Kolbe et al., 2021; Kutzner et al., 2020).

CityGML 2.0 was published in 2012 (Gröger et al., 2012). CityGML 3.0, published in 2021, introduced substantial architectural and thematic revisions (Kutzner et al., 2020). Most significantly for this thesis, it introduced the Dynamizer module, which enables time-series representation of object attributes through sensor feeds, simulation outputs, or observation archives, allowing city objects to be updated dynamically rather than treated as static snapshots (Kutzner et al., 2020). It also introduced a *Versioning* module for tracking change states and planning scenarios over time, and revised its core model to be platform-independent, enabling encoding in GML, CityJSON, and relational databases (Eriksson et al., 2021; Kolbe et al., 2021; Kutzner et al., 2020).

2.4.1 CityGML Vegetation module

The CityGML Vegetation module models urban greenery through two primary feature classes: *SolitaryVegetationObject* for individual plants such as trees and shrubs, and *PlantCover* for areas such as forests or grasslands (Figure 2) (Gröger et al., 2012; Kolbe et al., 2021).

In CityGML 3.0, geometry representations uses *MultiSurface*, *MultiSolid*, with *ImplicitGeometry* for libraries of prototypes (Gröger et al., 2012; Kolbe et al., 2021; Wei Zhang et al., 2022). Semantic attributes include among others *class* (e.g. coniferous tree), *species* (e.g. *Abies Cephalonica*), *height*, *trunkDiameter*, *crownDiameter* for solitary objects, and include *averageHeight*, *minHeight*, *maxHeight* for plant covers, plus *usage* and *function* for both solitary vegetation objects and plant covers (Figure 2) (Kolbe et al., 2021; Wei Zhang et al., 2022).

The Vegetation module was not substantially revised between CityGML 2.0 (2012) and CityGML 3.0 (2021), retaining its conceptual structure and core attributes from the earlier version while other modules, including *Core*, *Building*,

and *Transportation*, underwent significant updates (Kutzner et al., 2020). Critically, while CityGML 3.0's *Dynamizer* module enables time-series representation of object attributes, the existing *Vegetation* module does not include the feature types, attributes, or properties that would be needed to connect vegetation objects with the *Dynamizer* in a semantically coherent way.

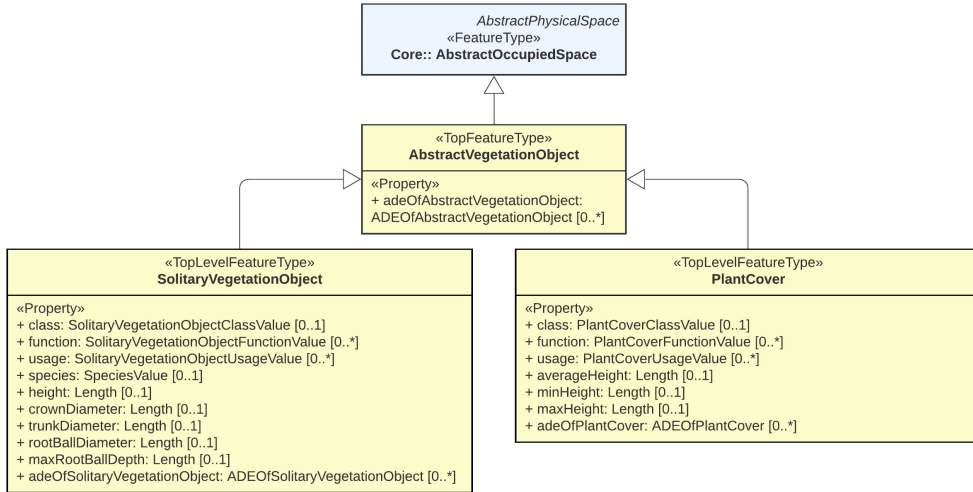


Figure 2 Unified Modelling Language (UML) class diagram of the CityGML 3.0 Vegetation module showing the division of vegetation objects into SolitaryVegetationObject and PlantCover. Adapted from the Open Geospatial Consortium (OGC) CityGML Encoding Standard by Kolbe et al. (2021).

2.4.2 Extending CityGML: The Application Domain Extension mechanism

The CityGML standard explicitly anticipates that its thematic modules will not cover every domain-specific requirement (Biljecki et al., 2018). The Application Domain Extension (ADE) mechanism provides a formally specified pathway for extending any CityGML feature class with additional attributes, associations, and feature types without modifying the core standard schema (Biljecki et al., 2018; Kolbe et al., 2021). CityGML 3.0 extends ADE applicability by defining them as platform-independent conceptual models that can be mapped to multiple encodings, including Geography Markup Language (GML), City JavaScript Object Notation (CityJSON), and relational databases. This is an advance over CityGML 2.0, where ADEs were tied exclusively to XML (Extensible Markup Language) Schema (Kutzner et al., 2020; Kolbe et al., 2021). Extensions are specified as conceptual models in the Unified Modelling Language (UML), conforming to ISO 19109 (General Feature Model) and ISO 19103 (Conceptual Schema Language). This ensures formal interoperability with the CityGML ecosystem and compatibility

with automated encoding generation workflows (Kolbe et al., 2021; van den Brink et al., 2013; Yao & Kolbe, 2017). Unified Modelling Language is the established modelling language for Application Domain Extensions because it provides visual, formally unambiguous specification of class structures and relationships, supports automatic XML schema generation and documentation, and aligns with the ISO 19100-series standards for geographic information (Kolbe et al., 2021; Petrova-Antonova, Malinov, et al., 2024).

The Application Domain Extension ecosystem has expanded substantially since CityGML 2.0, with published extensions addressing building energy performance, subsurface utility networks, noise modelling, urban climate, indoor navigation and cultural heritage, among others (Bachert et al., 2024; Biljecki et al., 2018; Kumar et al., 2017; Su Yang et al., 2024). This body of work demonstrates that the ADE mechanism is a mature and capable pathway for domain-specific extension, and that the most effective extensions are those grounded in user requirements and validated through engagement with the intended user community (Biljecki et al., 2018).

Prior research on extending the CityGML Vegetation module has addressed specific gaps in geometric detail, semantics, and levels of detail, primarily through conceptual models, profiles, and attribute enhancements rather than full Application Domain Extensions. Guerrero Iñiguez (2017) proposed geometric modelling of tree roots with explicit multiple LODs (LOD 0–4) to enable complete subterranean representations, including topologic relationships and semantic attributes like volume and type via a conceptual approach recommending CityGML ADE integration (Guerrero Iñiguez, 2017). Ortega-Córdova (2018) defined custom LOD schemes beyond core standards for urban trees and hedges, emphasising detailed crowns and trunks to improve visualisation and semantic 3D representations (Ortega-Córdova, 2018). Pantazatou et al. (2024) recommended a Swedish national profile for CityGML 3.0 that adds attributes such as popular/scientific tree species names, alongside mandatory measure height, and crown diameter values, without dedicated Level of Detail subdivision, using existing LOD 1–2 points/polygons and deriving as needed. This profile targets ecosystem services like irradiance and noise modelling from 2D/3D data sources via Application Domain Extension-like extensions (Pantazatou et al., 2024). W. Zhang et al. (2022) developed a multi-scale semantic model for trees, shrubs, and ground cover, incorporating above- and below-ground parts plus plant components including branches, crowns, fruits, flowers, roots, across LOD 0 to LOD 4, with six attribute categories, namely class, function, species, height, trunk diameter, and canopy, supported by parametric components in a CityGML-based framework (Wei Zhang et al., 2022). These efforts collectively augment core classes like *SolitaryVegetationObject* and *PlantCover* but remain mostly project-specific, lacking standardised ADEs for biophysical dynamics and broad interoperability.

2.5 Human-computer interaction and immersive representation in UDTs

Urban digital twins require human-facing interfaces to translate complex data and simulation outputs into actionable insights for diverse stakeholders including planners, citizens and domain experts (Luo et al., 2022; Maiullari et al., 2024; White et al., 2021). As outlined in ISO/IEC 30173 (International Organization for Standardization, 2023), digital twin systems comprise five core modules including services such as analysis, simulation, visualisation and optimisation, which are delivered through varied interfaces from web dashboards to immersive environments (Kai Wang et al., 2024; Kung-Jeng Wang & Lee, 2024). In urban contexts, these interfaces range from desktop Geographic Information System (GIS) viewers supporting analytical tasks to augmented and virtual reality (AR and VR) systems enabling immersive, experiential exploration of spatial scenarios and future states (Azadi et al., 2025b; Eilola et al., 2023; Luo et al., 2022; White et al., 2021).

2.5.1 Virtual reality: Definition and relevance for urban planning

Virtual reality (VR) refers to computer-generated three-dimensional environments experienced via head-mounted displays with head-tracked interaction, creating a sense of presence through first-person immersion (Radianti et al., 2020). Unlike conventional desktop visualisations, virtual reality supports immersive, embodied navigation and scale comprehension, making it valuable for communicating spatial relationships and temporal dynamics that are challenging to convey through plans or static models (Bogon et al., 2023; Klippel et al., 2021; Schewenius & Wallhagen, 2024). In urban planning, VR has been applied e.g. to stakeholder engagement, enabling participants to explore proposed developments and assess visual and experiential impacts from pedestrian perspectives (Eilola et al., 2023; Schewenius & Wallhagen, 2024). Research indicates VR improves decision quality by enhancing spatial understanding, while supporting participatory processes through intuitive interaction (Eilola et al., 2023; Evers et al., 2023). However, hardware costs, user discomfort including motion sickness, interoperability and performance demands on commodity devices remain barriers to widespread adoption (Glegg & Levac, 2018; Yirong Yang, 2024).

2.5.2 Immersive environments for biodiversity communication

VR's capacity to render realistic ecosystems positions it as a promising tool for biodiversity representation, where users encounter virtual nature and ecosystem dynamics in navigable scenes (Chandler et al., 2022; Harrington et al., 2021).

Within these immersive capabilities, fidelity, the degree to which virtual representations match real-world referents, emerges as a key design principle (Harrington et al., 2021; Jones et al., 2020). This encompasses information fidelity, the accuracy of underlying ecological data, visual fidelity, photorealistic rendering, and auditory fidelity, realistic soundscapes, which together convey perceptual realism (Harrington, 2023; Lindquist et al., 2020). These sensory dimensions enable multimodal designs that integrate spatialised soundscapes to enhance perceived biodiversity richness and restorative effects beyond visual representations alone (Lindquist et al., 2020; Sarter, 2006).

Effective biodiversity communication requires addressing species literacy gaps among diverse audiences through immersive tools that enhance species recognition and pro-environmental attitudes (Härtel et al., 2025; Hooykaas et al., 2019; Poornesh, 2026). Simultaneously, transparently conveying model uncertainties prevents overconfidence in projections (Trantas et al., 2023), ensuring credible decision-making in VR urban planning contexts.

Urban virtual reality-based biodiversity-centric applications remain limited, with most 3D city models simplifying vegetation to trees or generic grass, underrepresenting herbaceous layers and faunal elements (Baniadam et al., 2025; Hassall et al., 2024; Xu & Wu, 2026). Vegetation in these digital models often derives from semantic data models such as CityGML, which encode geometry and attributes, e.g. species, height, age for instantiation in e.g. game engines and other VR-modelling software via rules-based, procedural modelling (Keil et al., 2021; Rantanen et al., 2023; Thuvander et al., 2022; Zhao et al., 2025). Performance-constrained standalone headsets, such as Meta Quest-series devices, typically favour low-poly static meshes and 2D billboards over complex animated skeletal models to maintain stable frame rates during immersive vegetation visualisation (Ozoliņa et al., 2025). Balancing ecological accuracy with perceptual credibility and real-time performance remains a persistent challenge, as high-detail scenes strain computational resources while low-fidelity representations risk undermining credibility (Chandler et al., 2018).

3 Research setting and methodology

3.1 Research setting

This doctoral thesis was conducted as a joint-PhD (Cotutelle Agreement) between Tallinn University of Technology (TalTech), Department of Civil Engineering and Architecture, Academy of Architecture, and Aalto University, School of Arts, Design and Architecture, Department of Architecture.

The research was embedded within three European projects: GreenTwins and H2020 FinEst Twins, led by the FinEst Centre for Smart Cities at TalTech, and urbanLIFEcircles (LIFE21-NAT-EE-urbanLIFEcircles), coordinated by the City of Tartu with TalTech as partner.

The author has presented this research at various international occasions, including the AESOP Annual Congress 2022 Space for Species: Redefining Spatial Justice (Tartu, Estonia, 2022), Smart City Expo World Congress (Barcelona, Spain, 2023), United Nations Climate Change Conference - COP28 (Dubai, United Arab Emirates, 2023), Tallinn Digital Twin Conference (Tallinn, Estonia, 2023), Urban Digital Twins for a Sustainable Transformation of Cities conference at City Science Lab, HafenCity University (HCU) (Hamburg, Germany, 2025), and the 43rd Conference on Education and Research in Computer Aided Architectural Design in Europe (eCAADe) Confluence (Ankara, Turkey, 2025).

These presentations and project engagements provided critical stakeholder evaluation that iteratively refined the author's work and manuscripts both individually and collectively, ensuring practical applicability and international relevance of the work.

3.2 Applied methods and approaches

This dissertation employs a cumulative research design integrating five publications (Publications I-V) into a cohesive doctoral study. The thesis applies integrated mixed methods, combining qualitative and quantitative approaches across publications (Table 2).

Publication I establishes a cross-domain state-of-the-art baseline on dynamic biodiversity modelling in digital twins and 3D city models through a systematic literature review following Preferred Reporting of Items and Systematic Reviews

and Meta-Analysis (PRISMA) guidelines (Page et al., 2021), identifying semantic, data-related, and representational gaps in digital twins.

Publication V captures user-specific knowledge from Helsinki and Tallinn case studies, unreflected in scientific literature, via action research yielding an urban-focused user needs analysis. Outputs from Publications I and V, including CityGML vegetation semantic deficiencies and prioritised user requirements, directly inform the UML-based conceptual data model development (technical standards extension) in Publication II, yielding the conceptual model for CityGML 3.0 Vegetation ADE v1.0.

Publication III evaluates and refines this model through a participatory stakeholder survey (quantitative Likert scales and qualitative thematic analysis) to ensure alignment with real-world needs and international applicability, resulting in the refined v1.1.

Publication IV employs a case study methodology, developed parallel to the Vegetation ADE (Publications II and III), to translate empirical biodiversity data into performance-constrained virtual reality, addressing gaps identified in I-II and complementing the semantic Application Domain Extension with immersive visualisation.

This cumulative research design logic ensures progression: foundational evidence (Aim 1: Publications I and V) motivates and informs the CityGML 3.0 standard extension (Aim 2: Publications II and III) and the development of an immersive biodiversity-centric VR experience that tests real-world feasibility under constraints (Aim 3: Publication IV).

This methodological integration reflects the thesis's interdisciplinary scope and commitment to bridging theory and practice through multiple complementary research approaches.

Table 2 Research design: Questions, methods, evidence, and publications of the cumulative doctoral thesis.

Research Question	Research Methodology	Evidence Produced	Addressed in Publication
RQ 1.1: What is the current state-of-the-art documented in scientific literature on dynamic biodiversity modelling across disciplinary domains in digital twins?	Systematic Literature Review employing the PRISMA protocol	Descriptive synthesis of 38 studies; status quo and research gap analysis on data, standards, dynamic models, representation and user experience	P I
RQ 1.2: What are the critical gaps in vegetation data models that align with user needs for developing digital twins of urban green infrastructure?	Action research; user needs analysis through interviews and workshops, Scopus literature scan for species growth data	Prioritised user stories and needs; empirical data availability assessment	P V
RQ 2.1: How can CityGML 3.0 be extended to enable dynamic urban vegetation modelling based on user needs?	Requirements analysis and semantic data modelling (UML, CityGML 3.0) for conceptual model of Vegetation Application Domain Extension	Conceptual model for CityGML 3.0 Vegetation Application Domain Extension (ADE) v1.0	P II
RQ 2.2: How do stakeholder requirements inform the revision and design of a practical Vegetation ADE for urban digital twins?	Online stakeholder survey and stakeholder interviews, (Likert scales/open questions), quantitative/qualitative analysis informing the revision of the proposed ADE	Quantitative/qualitative feedback on CM for CityGML 3.0 ADE v1.0; Refined ADE CM v1.1	P III
RQ 3: What methodological, technical, and communicative challenges arise, and what practical solutions are developed, when translating empirical urban biodiversity data into performance-constrained VR environments for diverse stakeholders?	Self-reflective Tartu Jaamamõisa case study: 3D modelling and VR implementation, with user testing and feedback through questionnaires and interviews informing iterative refinement	Optimised immersive VR-demonstrator for biodiversity representation in a use-case; documented fidelity-performance-communication trade-offs and design principles	P IV

The following sections elaborate on the methodological choices made within each publication, describing how the respective methods were implemented within the context of each study. Detailed instruments, protocols, and supplementary material are provided in the appended publications and their supplements.

Publication I presents a systematic literature review following PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Page et al., 2021) that assesses dynamic modelling of flora and fauna across disciplinary domains in digital twins and 3D city models. Keyword search strings combining "digital twin" or "3D city model" with biodiversity-related terms (Figure 3) were iteratively refined with multidisciplinary co-authors.

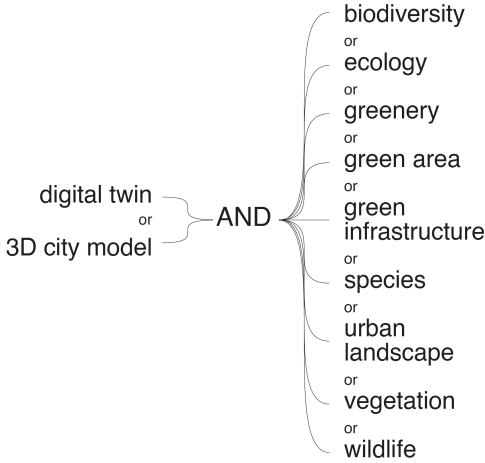


Figure 3 Overview of applied search terms for the publication retrieval for the systematic literature review in Publication I.

Systematic searches across Web of Science Core Collection, Scopus, and Google Scholar (via Publish or Perish software) targeting titles, abstracts, full text, and keywords spanned 1 January 2015 to 18 May 2022, repeated 28 February 2023 for recent publications (Figure 4). The review was limited to studies published from 2015 onwards, as this period marks the emergence of a more consolidated research stream in the field. During the preliminary screening of the literature, no publications prior to 2015 were identified that were sufficiently relevant or methodologically comparable for inclusion.

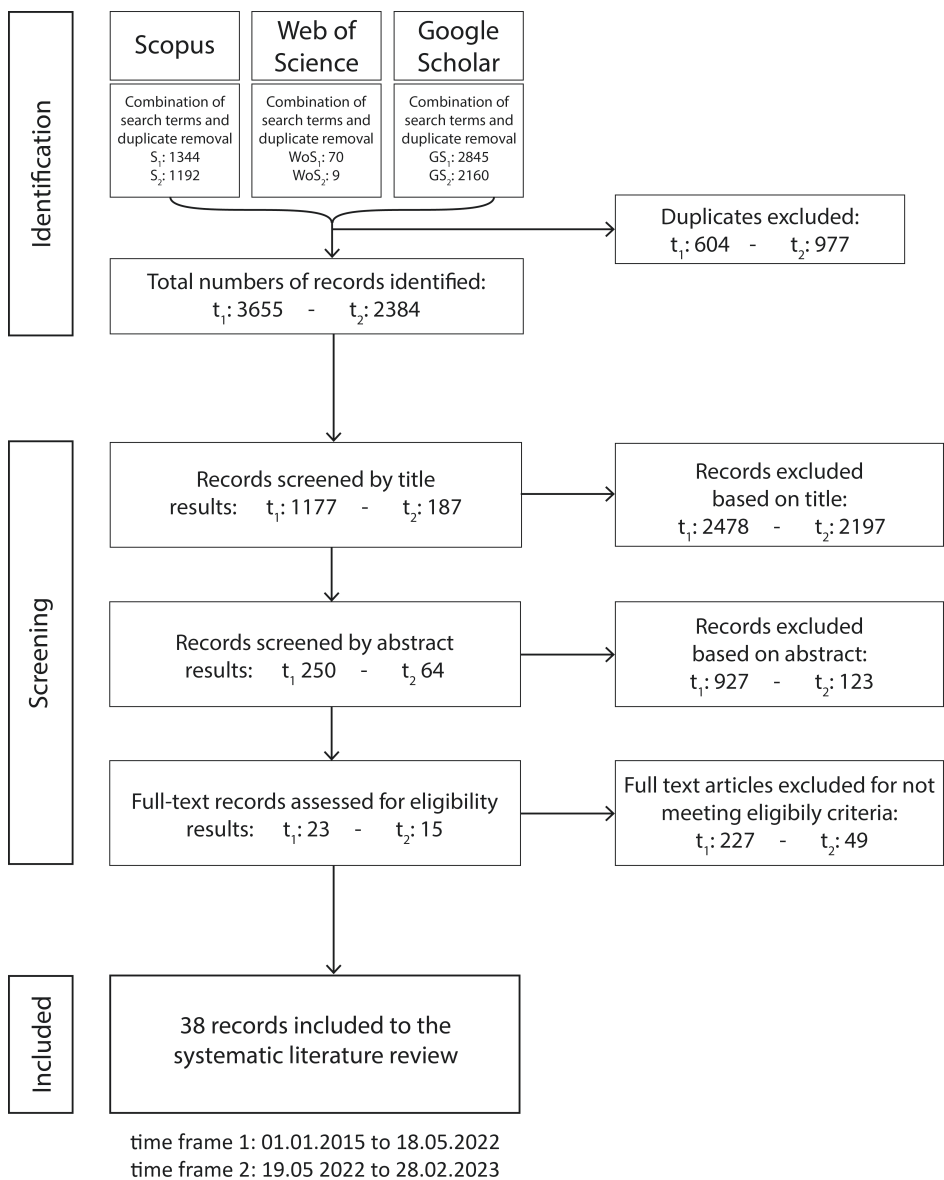


Figure 4 Publication selection process for the systematic literature review presented in Publication I.

Following article retrieval and de-duplication, titles (Stage 1), abstracts (Stage 2), and full texts (Stage 3) were independently screened each by two authors of the publication against predefined inclusion criteria. The criteria to get included encompassed English-language studies (title, abstract, full text) excluding videos and webpages, and including publications addressing dynamic modelling of flora and/or fauna within or for the integration into digital twins or 3D city models where studies aligned with the digital twin definition as a digital model capable of incorporating updates at variable frequencies and influencing the physical counterpart indirectly or directly.

Following the systematic literature selection, a structured content analysis protocol was developed deductively and applied to guide data extraction, capturing application domain, modelling approach(es), temporal dynamics treatment, geographic context, data sources, technical standards, employed representation means, ethical considerations and identified barriers and gaps. Data extraction was conducted collaboratively among co-authors with quality control through iterative feedback and systematic checks. Extracted data were organised in structured spreadsheets and analysed using descriptive statistics and thematic coding done with the software “ATLAS.ti” to identify patterns across disciplines.

Due to heterogeneity of included studies regarding methodologies, scope, reported outcomes, and quantitative data availability, Publication I adopted a descriptive approach without meta-analysis.

Publication II employed a model-driven semantic data modelling methodology to develop a conceptual Application Domain Extension (ADE) for CityGML 3.0's Vegetation module. This approach adapted the framework of van den Brink et al. (2013) while adhering to CityGML 3.0 Conceptual Model Standard Guidelines (Kolbe et al., 2021), ensuring General Feature Model and ISO 19109/19103 standards conformance.

Unified Modelling Language (UML) was selected as the formal modelling language due to its visual expressiveness, unambiguous structure specification, conformance to ISO 191xx standards, and capacity for automated XML schema generation from conceptual models.

CityGML 3.0's *SolitaryVegetationObject* and *PlantCover* were extended via ADE hooks (*ADEOfSolitaryVegetationObject*, *ADEOfPlantCover*), enabling extension with domain-specific data types (*SolitaryVegetationObjectProperties*, *PlantCoverProperties*). New feature types followed CityGML 3.0 core inheritance patterns for associations to relate ADE classes with core types. The CityGML 3.0 Dynamizer module was integrated through dedicated growth classes (*SolitaryVegetationObjectGrowth*, *PlantCoverGrowth*) and management class (*VegetationManagement*) inheriting *AbstractDynamizer* to support temporal

modelling. Domain-specific content was specified through data types, extensible code lists (stereotyped <<CodeList>>), and enumerations (stereotyped <<Enumeration>>), incorporating Uniform Resource Identifier (URI-)referencing for interoperability with external classification systems.

The ADE reused CityGML 3.0 Core module geometries and multi-level-of-detail capabilities without modification, ensuring topological correctness and backward compatibility through syntactic adjustments.

Publication III developed and applied a participatory standards development methodology combining international stakeholder engagement and iterative refinement with technical standards design (Figure 5) to refine the Vegetation ADE proposal from v1.0 (Publication II) to v1.1 (Publication III). A structured online questionnaire was designed so that its sections mirrored the logical components and properties of the proposed ADE, each introduced by concise explanations of underlying concepts and definitions, before respondents evaluated specific elements on semantic clarity and practical applicability. Additionally, respondents were directed to a Technical User Guide hosted on Zenodo (Petrova-Antonova, Mroska, et al., 2024), which introduced CityGML principles, data modelling terminology, and the Vegetation ADE v1.0. For the evaluation of the ADE v1.0 the survey employed 5-point Likert scales and open-ended questions assessing attribute relevance, definition clarity, implementability, code list/enumeration adequacy, geographic/disciplinary applicability, and gaps and missing elements. The English-language, pre-tested survey targeted an interdisciplinary expert audience, and was disseminated internationally between 9 October 2024 and 15 April 2025. All questions were optional to accommodate differing levels of expertise and familiarity with CityGML. Quantitative data from Likert-scale responses were analysed using descriptive statistics, examining scores and response distribution patterns. Open-ended responses underwent thematic coding identifying (in)consistent feedback across respondents, disciplinary-specific or geographically-specific priorities, technical clarification needs, and proposed modifications.

The Vegetation ADE's revision towards version 1.1 followed two guiding principles: preserving full interoperability and compatibility with the CityGML core framework, and managing complexity by implementing only those modifications that were stakeholder-validated and essential for use cases. In line with these principles, properties, code lists and enumerations were adapted, added, or removed to improve semantic clarity, applicability, and inclusiveness across varied urban vegetation contexts, providing the basis for the revised ADE CM v1.1.

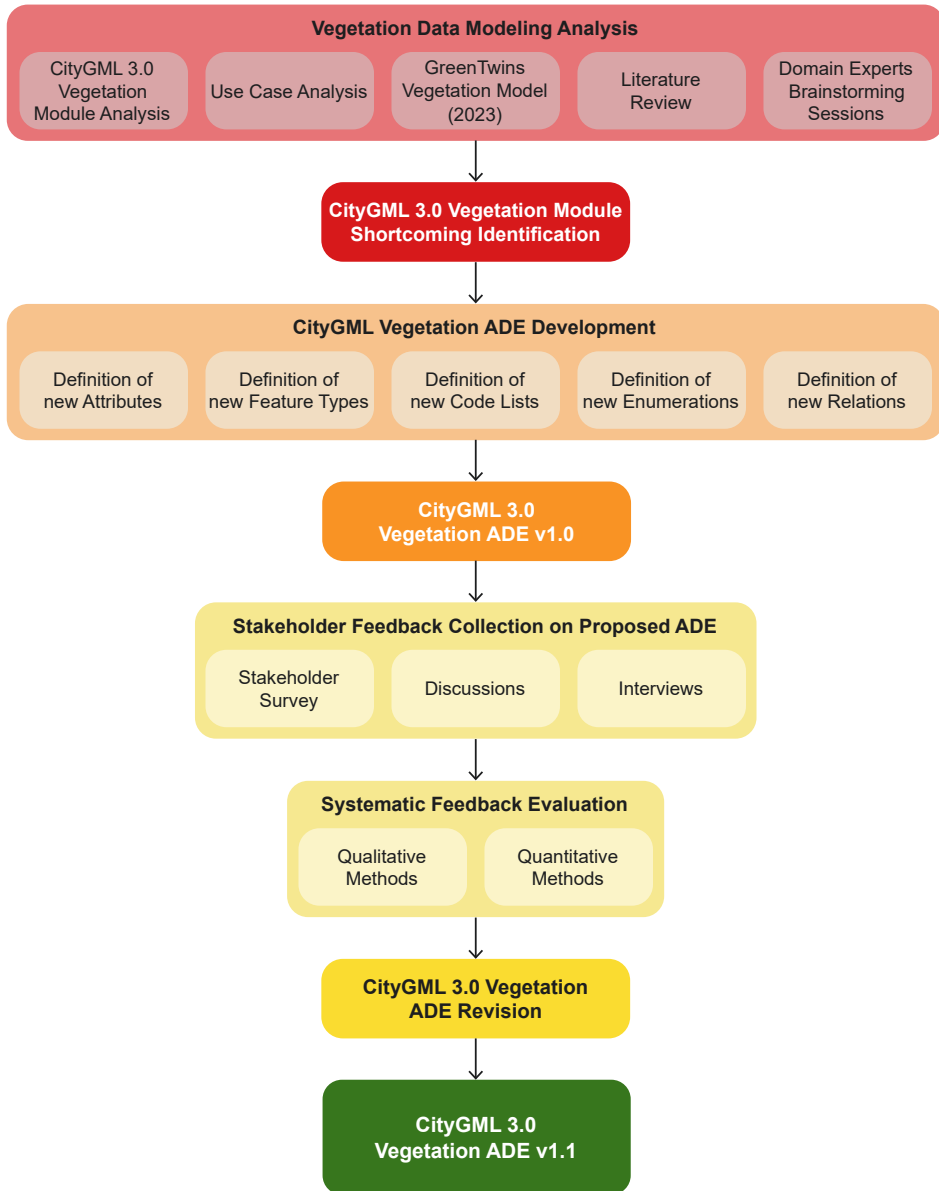


Figure 5 CityGML 3.0 Vegetation Application Domain Extension (ADE) conceptual model development workflow from analysis and shortcoming identification (red) to development of the ADE conceptual model v1.0 (orange), to stakeholder involvement and ADE conceptual model revision (yellow) to CityGML 3.0 Vegetation ADE conceptual model v1.1 release (green) (Publication III).

Publication IV employed a self-reflective case study methodology to examine practical challenges and solutions in 3D modelling urban biodiversity for immersive VR, using Unity for development and Meta Quest 3 for deployment, within the urbanLIFEcircles project's Jaamamõisa stream restoration site in Tartu, Estonia.

Empirical data from 1×1 metre plot sampling, Tartu municipal tree register shapefiles, PlutoF animal occurrence records, and drone imagery underwent geospatial preprocessing through QGIS to Unity coordinate transformation, followed by multimodal integration. This included, e.g., 2D billboards of self-photographed plants, algorithmically growing and height-scaled Unity Asset Store trees matching empirical dimensions, multi-level-of-detail terrain tiling across the 4 km² digital environment and locally recorded soundscapes. Biodiversity-enhancing interventions were modelled based on city expert plans that specified intervention locations, objectives, and temporal states (pre-intervention and depending on the intervention type either immediately post-intervention, one month, one year or 2 to 5 years post-intervention).

Performance constraints were managed qualitatively through pragmatic design decisions e.g. 2D billboards instead of full 3D models, optimised terrain tiling, and hand-placed species aggregations calibrated against site photographs. Formative user testing of the VR environment, followed by structured interviews and questionnaires, iteratively refined noticeability and communicative clarity, establishing fidelity-performance-communication trade-off principles for biodiversity representation.

Publication V implemented collaborative and iterative action research to identify user groups, user needs, and data requirements for urban green infrastructure digital twins in Tallinn, Estonia and Helsinki, Finland, evaluating projection model necessities.

User data were gathered via online workshops, polls, questionnaires, interviews, and co-development sessions with urban planners, landscape architects, ecologists, maintenance staff, researchers, students, IT experts, and citizens. The research instruments targeted to outline current data availability, users' information needs for urban vegetation planning and management, temporal/spatial/species requirements, and barriers. The user needs were codified as user stories, detailed as requirements, and prioritised through voting in joint workshops with GreenTwins team and Tallinn representatives. Each prioritised need was assessed for CityGML extensions or calibrated projection models, specifying required data needs. Pilot area tree inventories integrated field visits, municipal shapefiles, and remote-sensing-derived data. Complementary Scopus literature scans paired pilot species nomenclature with "growth AND urban" operators, filtering proximal geographic studies for growth (height/crown/trunk data) curve suitability.

4 Main results

This chapter synthesises the principal findings from the five publications comprising this doctoral thesis, organised by the three research aims that structure the cumulative research design.

Section 4.1 addresses Aim 1 through a cross-sectoral overview of dynamic flora and fauna modelling in digital twins (Publication I), zooming into the concrete challenges of urban tree data availability and user needs in UDT pilots (Publication V, together establishing the conceptual and operational gaps that motivate the subsequent work.

Drawing on these findings, Section 4.2 addresses Aim 2 by presenting the development and participatory refinement of a semantically rich, interoperable conceptual model for a CityGML 3.0 Vegetation ADE (Publications II and III).

Section 4.3 addresses Aim 3 not as a separate strand but as an additional layer to the semantic modelling work of Aims 1 and 2, examining how empirical biodiversity data can be operationalised as an immersive, multimodal VR representation under practical performance constraints (Publication IV). This extends the dissertation from what is modelled and should be standardised to how biodiversity information can be virtually experienced and understood in an immersive planning interface.

Reading these three sections alongside one another, this thesis traces a progression from diagnosing structural gaps, through developing a standards-compliant data model, to demonstrating how biodiversity information can be made perceptually and communicatively accessible in immersive urban planning interfaces.

4.1 Status quo of dynamic flora and fauna modelling in digital twins and 3D city models

UDTs can and do represent aspects of biodiversity, yet rarely in a form that is semantically rich and temporally dynamic enough to constitute a robust ecological information layer. Moreover, these representations remain insufficiently integrated with planning workflows and communicatively inaccessible to diverse stakeholders, preventing ecological data from becoming a genuinely embedded and decision-relevant component of UDTs. This limitation is the foundational finding of Aim 1

and the motivation for the entire dissertation. The underrepresentation of flora and fauna in UDTs reflects a combination of structural conditions, namely uneven domain maturity, constrained modelling paradigms, data fragmentation, and insufficient attention to representational responsibility. They cannot be reduced to the immaturity of any single technology as the conditions are systemic and mutually reinforcing.

The following subsections establish each of these conditions in turn, drawing on cross-domain and urban-specific evidence, and conclude by articulating how each structural condition directly motivates the research reported in Aims 2 and 3.

4.1.1 Uneven maturity of digital twins of flora and fauna across domains

Dynamic modelling of flora and fauna in digital twins is a rapidly emerging field, but domain context, not technical capability in principle, is the primary determinant of how sophisticated that modelling can become. The unevenness of the field is visible in the composition of the available evidence: an initial systematic search scoped exclusively to UDTs and 3D city models proved unworkable due to the scarcity of eligible publications, requiring scope expansion to dynamic modelling of flora and fauna across all domains. From the resulting pool of 6 039 records, only 38 publications met all inclusion criteria, with the number increasing sharply after 2019, driven predominantly by the term *digital twin* rather than *3D city model* (32 versus 6 publications). Urban vegetation applications represent only a small share of the total, and fauna modelling an even smaller one, appearing in just four publications (Publication I). That even the expanded cross-domain review yielded only 38 eligible publications signals how nascent the intersection of UDTs and dynamic flora and fauna modelling remained at the time of research.

Dynamic modelling of flora and fauna in digital twins spans a spectrum from descriptive models to prescriptive models capable of driving physical interventions, but the distribution across this spectrum is highly uneven.

Publication I states that system models often comprise multiple sub-models serving different analytical aims and temporalities (Figure 6): Descriptive models are foundational and widely used, providing estimates of past and current system states and forming the basis for visualisation and manual decision-making, particularly in forestry, agronomy, and health monitoring of plants and animals. Predictive models extend this by simulating future states, forecasting yields, risk levels such as tree-powerline conflict or disease outbreak, and growth trajectories using species-specific growth functions or procedural plant modelling such as L-systems (Publication I). Prescriptive models, which incorporate feedback loops that adjust physical conditions towards target states, are present almost exclusively in precision agronomy and precision livestock farming. Here, autonomous machinery

can act directly on model outputs towards target states. Actuation is explicitly addressed in only seven of the 38 reviewed publications, all from agriculture (Publication I).

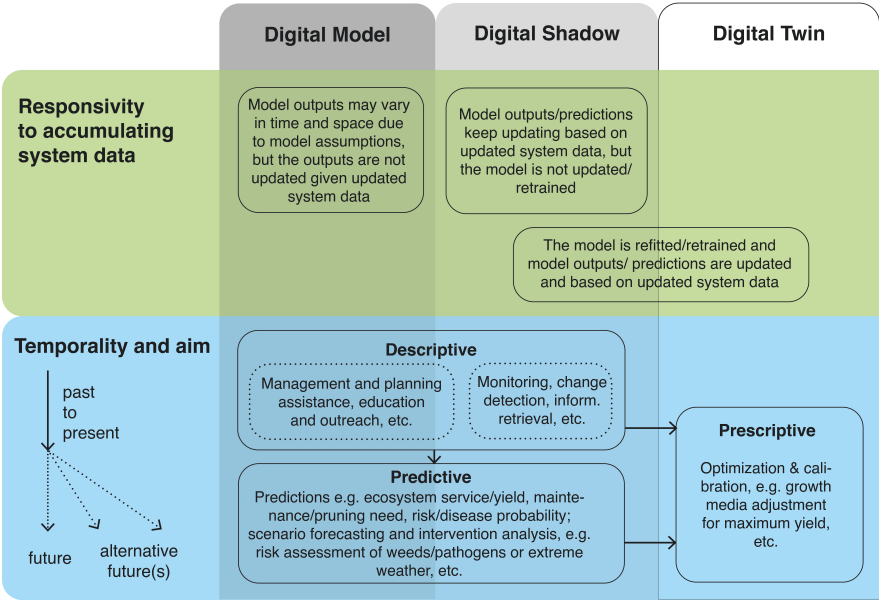


Figure 6 Overview of (sub-)model characteristics presented in the publications forming Publication I, categorised by data flow type and synchronisation between virtual and physical systems (columns; classification adapted from Kritzing et al., 2018), degree of responsiveness to cumulative system data (green, upper panel), model temporality (blue, lower panel), and model purpose (boxes within the blue box, lower panel). The figure illustrates three overarching model objectives, descriptive, predictive, and prescriptive, extending from the past to prospective or alternative future contexts (Publication I).

Across the included publications, the most developed examples of flora and fauna digital twins are found in agriculture, where (near-)real-time sensor data, predictive models, and in some cases prescriptive models with automated feedback to physical actuators are already operational. UDT applications remain mainly descriptive and only in some cases predictive rather than prescriptive and actuation remains underexplored. The implication is that UDTs cannot yet draw fully on an established urban biodiversity digital twin paradigm of their own, but should selectively transfer methods from more mature domains while recognising that urban conditions, data infrastructures, and planning tasks may differ substantially.

The structure of the outlined sub-models is fundamentally conditioned by biological rhythms, annual cycles, seasonal fluctuations, and life-cycle phases, which constrain what can be observed continuously and what must be inferred from

periodic inputs, distinguishing flora and fauna digital twins sharply from those of e.g. manufactured infrastructure (Publication I).

4.1.2 Data availability and variability

Data availability and variability are among principal constraints on credible dynamic flora and fauna modelling in urban contexts. This is not an abstract limitation but one with direct consequences for what predictive and prescriptive models can be built and how reliably they can be calibrated.

The challenge is not simply scarcity of data: data collection methods already span the full spectrum from spaceborne and aerial observation, like satellite imagery and unmanned aerial vehicle (UAV)-based light detection and ranging (LiDAR), to terrestrial laser scanning (TLS), sensor networks and manual field surveys. Categorising this range against the digital twin data taxonomy defined by Zhang et al. (2022) reveals that diverse biodiversity-related data are already in use (Publication I; Figure 7).

The structural problem is one of heterogeneity and temporal constraint. Data sources differ markedly in method, scale, and completeness. Biological life cycles and seasonal rhythms constrain acquisition possibilities in ways that have no parallel in built-environment digital twins. Real-time or near-real-time continuous sensing, well established in controlled environments such as greenhouses or precision agriculture facilities, is less common in open urban settings (Publication I). As a result, data quality, coverage, update frequency, heterogeneity, and standardisation remain persistent bottlenecks that determine not only what can be represented, but how often digital twins can be updated and how reliable downstream models and analyses can be (Publication I). Publication V demonstrates that this is not a general abstraction but a concrete urban problem. Its case study on tree growth data availability for the GreenTwins pilot areas in Tallinn and Helsinki found that suitable empirical growth data was absent from the pilot cities' own databases and literature coverage on tree data was sparse. Data were available for only four of the twenty locally relevant tree species examined. For these species, the available data were inconsistent in terms of measured attributes, environmental context, and methodological approach (Publication V).

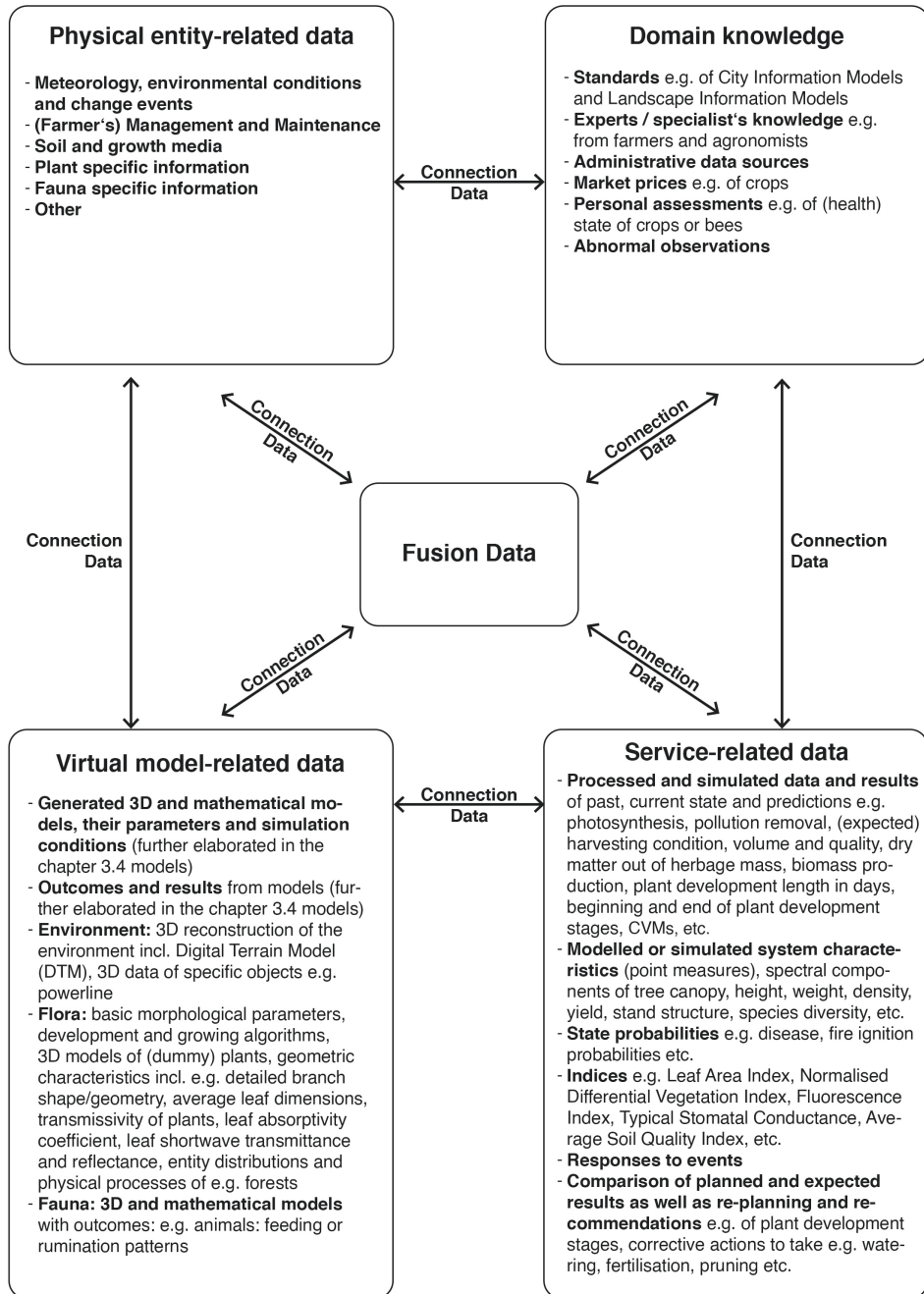


Figure 7 Data types used in flora and fauna models presented in the publications included in Publication I, categorised according to the six interrelated “digital twin data” classes as defined by Zhang et al. (2022) (Publication I).

The implication is that dynamic urban vegetation modelling cannot presently be built on comprehensive, uniform empirical datasets. Even where extensive data streams exist, the challenge is to harmonise them across scales, formats, and domains without introducing severe biases or inconsistencies. Publication I argues that future digital twins encompassing biodiversity will depend on robust data-assimilation and model-calibration pipelines, and on standards that can encode diverse biotic features and processes in interoperable ways.

4.1.3 Urban vegetation: User needs and standards gaps

The critical gaps in vegetation data models for UDTs are not primarily technical deficiencies in isolation; they are due to structural mismatches between what planning-relevant stakeholders need to represent and what current data standards can encode.

Multiple user groups have an active interest in dynamic vegetation models for UDTs: urban planners, landscape architects, real-estate developers, transport engineers, street designers, GIS and city-model specialists, city gardeners, active citizens, urban ecologists and conservation biologists (Publication V). While their specific tasks and perspectives differ, many share a desire to understand how planned and existing vegetation will change over time and under different management regimes, and how these changes will affect e.g., visual appearance, ecosystem services, microclimate, and conflicts with other infrastructures.

From this user research, several prioritised user needs emerge that are directly tied to dynamic modelling of vegetation in UDTs. These include the need to represent: i) how vegetated area management intensity changes affect species composition and visual appearance; ii) how individual trees grow in terms of e.g. height and canopy width, and e.g. when they begin to provide shade or shelter; iii) how root systems develop and interact with constrained underground spaces; and iv) how planned vegetation changes seasonally, e.g. through flowering or leaf shedding. Meeting these needs requires projection models calibrated with empirically grounded, regionally appropriate data (Publication V).

These requirements are not adequately supported by the current CityGML Vegetation module. The module allows basic semantic representation via *SolitaryVegetationObject* and *PlantCover* areas, but lacks attributes for structural components such as crown, trunk, and root dimensions, dynamic properties such as growth trajectories, management history, and biodiversity-relevant semantics such as species composition or habitat type within heterogeneous plant covers. This is not a peripheral limitation: it means that the information needed to connect field observations, projection model outputs, and planning decisions cannot be structured, stored, or exchanged in a standardised and interoperable way. Publication V identifies the need for a formally structured extension of the CityGML

Vegetation module to accommodate the dynamic and management-relevant attributes that projection models and urban green infrastructure management require, providing a direct motivation for Research Aim 2.

From a cross-domain perspective, standardisation, interoperability, and transferability are identified as systemic barriers across digital twins of flora and fauna more broadly, with digital twins commonly configured as bespoke implementations that lack clear pathways for reusing data models or workflows across contexts (Publication I). While CityGML and its Application Domain Extension mechanism are noted as a promising route for structured extension, the current CityGML Vegetation module is described as semantically limited, and the data heterogeneity that characterises urban vegetation sources compounds the challenge of harmonising information across scales, formats, and disciplines.

4.1.4 Usability and truthful representation

The human-facing dimensions of biodiversity-related digital twins, how outputs are represented, for whom, and with what degree of expressed certainty, receive insufficient systematic attention relative to technical and data modelling efforts, with urban applications being no exception. Without explicit attention to user experience (UX) and communication design, including appropriate level of detail or abstraction, digital twins risk becoming expert-only tools or technological showcases. Representation is therefore not just a downstream design concern, it is a substantive challenge: it involves determining how empirically grounded, and appropriately represented biodiversity information can be made usable by diverse stakeholders without becoming misleading.

Across the reviewed literature in Publication I, complex models and high-dimensional data are commonly not readily interpretable by decision-makers, practitioners, or citizens. The dominant forms of representation are 2D visualisations or relatively simple 3D models, prioritising analytic clarity over photorealism or contextual legibility. More visually rich or immersive approaches, such as game-engine-based virtual wetland environments or multimodal virtual arboreta that include species-specific soundscapes, appear only in educational and communication-oriented settings, and represent exceptions rather than the mainstream. In terms of human-computer interaction, Publication I identifies a relative neglect of explicit user experience design and usability evaluation across the reviewed literature. Most publications refer generically to "platforms" or "interfaces" without specifying interaction modes, target user groups, or accessibility considerations. Where user experience is foregrounded, the emphasis tends to fall on communicating model outputs to non-experts through intuitive visual encodings or narrative framing, rather than on decision-support for professional planning contexts (Publication I).

The responsibility for truthful representation can not be deferred until a model is complete: it shapes how past, current and future states should be communicated from the outset. Urban stakeholders require interpretable representations of change over time that support planning decisions, communicate consequences, and reveal conflicts between vegetation and other infrastructures, moving beyond the mere provision of additional data or richer visualisations. Projection models should not convey a false sense of certainty about e.g. future vegetation states. Simulations of change should therefore be grounded in ecological knowledge and calibrated with reliable, context-appropriate empirical data if they are to support credible decision-making rather than mislead it (Publication V).

Ethical considerations including data privacy, power dynamics in data ownership, and animal welfare, were addressed in only a minority of the reviewed publications and remain considerably less developed in flora and fauna digital twins than in domains such as e.g. healthcare (Publication I).

4.1.5 Synthesis for Aim 1

Publications I and V together depict a field advancing rapidly across domains yet stalled at an early stage in urban contexts. Across disciplines, dynamic modelling of flora and fauna is increasingly recognised as critical for representing natural systems in digital twins, with diverse approaches to data handling, modelling, and representation already operational across leading sectors.

Yet the evidence assembled in Aim 1 also exposes structural mismatches specific to urban contexts. Understanding these mismatches is not only diagnostic. Each one points directly to a concrete opportunity for advancement that the subsequent research aims address.

First, domain maturity is unevenly distributed. Precision agriculture already demonstrates prescriptive, bidirectionally coupled twins with automated actuation, while urban applications remain at the descriptive and predictive stage. This is not for lack of technical methods in principle, but because the data infrastructure, standardisation depth, and operational incentives that make advanced modelling viable in leading sectors, are absent in urban contexts. The prescriptive modelling approaches, (near-)real-time sensing pipelines, and immersive and game-engine-based visualisation approaches already operational in precision agriculture or communication-focused applications represent concrete opportunities that urban biodiversity modelling can selectively draw on, adapted to the distinct data conditions, stakeholder landscapes, and planning tasks of urban contexts. UDT development cannot import these approaches wholesale, but they provide methodological reference points that inform the work reported in both Aims 2 and 3.

Second, there is a structural mismatch between what urban stakeholders need vegetation-aware digital twins to represent, including dynamic structural properties, management histories, species composition, phenological change, and what the CityGML 3.0 standard currently can encode. The CityGML 3.0 Vegetation module allows basic representation of solitary vegetation object and plant cover features but lacks parameters for structural components such as crown, trunk, roots, dynamic properties including growth trajectories or management history, and biodiversity-relevant semantics e.g. habitat type. Critically, a semantically rich, standards-compliant data model does not resolve data scarcity directly, but it creates the necessary precondition: by defining what attributes should be captured and how they should be stored, it enables systematic monitoring programmes to populate models incrementally. This ensures that data accumulated over time can feed e.g. projection models in an interoperable and reusable way. The CityGML ADE mechanism offers a standard-compliant extension pathway, and the participatory user needs processes documented provide the stakeholder grounding required to ensure that any such extension reflects genuine planning requirements rather than technical abstraction. This mismatch between user needs and semantic capacity directly informs Research Aim 2 and the development of the conceptual model for the CityGML 3.0 Vegetation ADE reported in Section 4.2.

Third, the human-facing dimensions of biodiversity-related digital twins namely, usability, and communicative effectiveness, receive insufficient systematic attention relative to technical modelling efforts, and the epistemically responsible handling of uncertainty is rarely addressed explicitly. Most implementations are oriented toward expert analysis. The needs of non-specialist urban audiences remain underserved, and the risks of miscommunication through overconfident visualisations of uncertain future states are not adequately managed. This gap motivates the VR demonstrator work in Research Aim 3, which treats communicative design not as a downstream aesthetic concern but as a substantive empirical challenge.

4.2 Conceptual model for CityGML 3.0 Vegetation ADE

CityGML 3.0 can be feasibly extended to enable interoperable, semantically explicit, and dynamic representation of urban vegetation, provided the extension is grounded in practitioner needs and validated through international stakeholder participation.

The conceptual modelling work presented in Publications II and III addresses Research Aim 2, taking the shortcomings identified in Aim 1 as its design brief: Publication II translates identified semantic deficiencies and user requirements into a conceptual model for a CityGML 3.0 Vegetation Application Domain Extension. Publication III subjects this model to international expert evaluation

and produces the refined ADE conceptual model v1.1. The resulting framework covers both individual plants and plant covers, and introduces semantic support for structural components, management history, growth dynamics, and externally referenced ecological classification systems, capabilities that go beyond what the existing CityGML 3.0 Vegetation module or other CityGML extensions currently provide in an integrated way.

4.2.1 Design requirements and inherent tensions

As established in Chapter 2 and Section 4.1, the CityGML 3.0 Vegetation module provides an insufficient semantic basis for biodiversity-relevant urban modelling. It lacks the structural, dynamic, vegetation management, and ecological attributes that planning-relevant stakeholders require. The information needed to connect e.g. field observations or projection model outputs in support of planning decisions cannot be represented, exchanged and used within digital twin workflows at scale in a sufficiently structured, standardised, and interoperable form using the existing module.

The design of the conceptual model for the Vegetation ADE goes beyond a straightforward mapping of known requirements onto an available extension mechanism. The challenge is determining how to extend CityGML 3.0 well. Four requirements, identified through the design and evaluation process, frame this challenge concretely: the Application Domain Extension must i) be formally interoperable with CityGML 3.0's conceptual model and encoding mechanisms; ii) support dynamic temporal representation of vegetation change, enabling the integration of time-series data and model outputs into digital twin update workflows; iii) be generic enough to represent diverse urban vegetation classes, from individual trees to mixed-species assemblages; and iv) be semantically rich enough to encode maintenance activities, structural and biodiversity-relevant properties without constraining local adaptations or overspecifying implementation-level detail (Publications II and III).

These requirements create inherent tensions that cannot be fully resolved through technical design decisions alone. They require principled prioritisation among competing demands. On one hand, stakeholders require fine-grained properties, e.g. trunk diameter, crown clearance, species classifications, management regimes, to support planning, analysis, and communication. On the other hand, the Application Domain Extension must remain manageable, avoid excessive complexity, and allow e.g. cities and software providers to adopt it incrementally. Furthermore, the model must address data heterogeneity and classification diversity. Vegetation species and habitats are classified using numerous, sometimes incompatible systems worldwide, and the Application Domain Extension needs to support references to these systems without hard-

coding region-specific categories. The design decisions made in developing the ADE are principled responses to these tensions (Publications II and III).

4.2.2 Conceptual model of the CityGML 3.0 Vegetation ADE

The Vegetation Domain Extension conceptual model v1.0 resolves the design tensions identified in section 4.2.1 through five structural decisions, each advancing the model's contribution beyond what any single design choice could achieve in isolation.

CityGML 3.0's extension architecture can accommodate substantial vegetation-relevant complexity without core standard modification. The ADE extends both feature types via hook mechanisms, namely *ADEOfSolitaryVegetationObject* and *ADEOfPlantCover*, introducing dedicated *SolitaryVegetationObjectProperties* and *PlantCoverProperties* data types (Publication II). For solitary vegetation objects, these hold attributes like *dateOfPlanting*, *protectionStatus*, *ownership*, and initial *speciesClassification* and *classificationReference*. For plant covers, they include among others *plantCoverSpecies*, *habitatClassification*, and *relativeAbundance*. The applied approach preserves backward compatibility through syntactic adjustments and thereby protects existing tools and datasets while enabling practical adoption without infrastructure overhauls (Publication II). It makes the Application Domain Extension adoptable in practice, as cities and software providers can integrate it without abandoning existing infrastructure.

The semantically relevant unit for solitary vegetation object modelling is not the plant as a whole but its structural components, which carry distinct and separable functional significance. The Application Domain Extension decomposes solitary vegetation objects into three explicit feature types, namely *Crown*, *Trunk*, and *Root*, each derived from *AbstractFeatureWithLifespan* to support temporal properties. *Crown* carries properties including *crownDiameter*, *crownType*, *crownDensity*, *Trunk* includes *trunkHeight*, *trunkDiameter*, *trunkType*, *Root* specifies *rootBallDiameter*, *rootBallMaximalDepth* and *rootType*. Extensible code lists standardise types like *crownType* or *trunkType* (Publication II). This decomposition structures field measurements or simulations, elevating the Application Domain Extension from mere data container to analytical substrate.

Management history is semantically constitutive of vegetation state. Urban trees and plant covers exist within active management regimes that shape their ecological condition, structural state, and ecosystem service provision. The Application Domain Extension introduces the *VegetationManagement* feature type to record interventions via *managementType* and *managementBody* for both solitary vegetation objects and plant covers as a formally structured, temporally anchored component (Publication II). No prior CityGML class accommodates this. Without it, the Application Domain Extension would represent vegetation as purely

biological objects. With it, the Application Domain Extension represents vegetation as managed urban infrastructure, what planning-relevant and biodiversity-aware decision-making requires and enables analysis of maintenance impacts on changing conditions and risks over time.

Prescribing fixed vocabularies for vegetation classification would constrain global adoption to specific regional or domain contexts. Cities routinely employ diverse local systems as available international standards often do not sufficiently capture local specificities. Therefore, the Application Domain Extension employs Uniform Resource Identifier-based referencing to link vegetation objects such as *SolitaryVegetationClassification* and *PlantCoverClassificationSystem* data types to locally applicable external systems such as habitat schemes, taxonomic databases, where fixed code lists and enumerations fall short (Publication II). This mechanism functions as a semantic bridge between urban planning data infrastructure and ecological classification systems, without imposing a vocabulary that limits broader adoption.

Dynamic temporal representation requires *Dynamizer* integration. Dedicated *SolitaryVegetationObjectGrowth* and *PlantCoverGrowth* classes inheriting from *AbstractDynamizer* are introduced in the Application Domain Extension. This enables time-series representation of measured or simulated structural attributes, including e.g. *trunkHeight*, *crownDiameter*, *healthStatus*, and *potentialHazard* alongside *growthValue* and the *observationProcedure* used, in a form compatible with digital twin update workflows, supporting the transition from static 3D models to dynamic UDTs (Publication II).

4.2.3 Stakeholder survey and Vegetation ADE CM v1.1

Vegetation representation in urban data standards cannot be achieved through technical modelling alone. It requires systematic coupling between formal semantic design and documented stakeholder validation. The multi-stage development process across Publications II and III demonstrates this directly: technical modelling confirms that CityGML 3.0's extension architecture is sufficient to accommodate the semantic complexity required for vegetation representation without modification to the core standard, whilst stakeholder validation reveals that the semantic precision and global applicability of any such extension can be substantially enhanced through participatory evaluation.

The international stakeholder validation unanimously endorsed the core data modelling structure of the ADE CM v1.0, whilst delivering evidence-based modifications that produced a substantially improved ADE CM v1.1, demonstrating both the robustness of the original design and the value of participatory validation.

The hook-based extension architecture, the decomposition of solitary vegetation objects into structural components, the *VegetationManagement* class, and the

Dynamizer integration were endorsed without reservation by 37 respondents across 19 countries, spanning research, urban planning, GIS analysis, landscape architecture, software development, and governmental roles (Publication III). This result is a cross-disciplinary and cross-geographic confirmation that the ADE's foundational design decisions are sound, and that a structurally disaggregated, management-aware, and standards-compliant approach to vegetation semantics reflects requirements across professional fields and geographies.

The targeted refinements implemented in ADE CM v1.1 are more than incremental improvements: several signal a design principle with implications beyond the attribute level. A total of 15 attributes were modified. These modifications encompassed renaming for enhanced clarity of the attribute and/or to enable a multiplicity, instead of only zero or one [0..1], of zero or more [0..*]. Additionally, 12 attributes were added for more semantic depth of the conceptual model, and one removed to avoid redundancy (Table 3, Publication III). Nine code lists were revised and one added to align closely with stakeholder survey feedback on v1.0, incorporating key modifications for better vocabulary coverage, naming conventions, and domain-specific needs. Two enumerations were updated to provide unified and domain-appropriate descriptions (Table 4, Publication III). The resulting conceptual model of the CityGML 3.0 Vegetation ADE v1.1 is presented as UML diagrams in Figures 8, 9, 10 and 11 (Publication III). These figures are displayed in full size in Publication III for improved readability.

Table 3 Adapted, added and removed properties of conceptual model for CityGML 3.0 Vegetation ADE v1.1. (Publication III).

Class	Adapted		Added to ADE v1.1	Removed for ADE v1.1
	ADE V 1.0	ADE V 1.1		
SolitaryVegetationObject Properties	dateOfPlanting: Date [0..1]	dateOfEstablishment: Date [0..1]	establishmentMeans: EstablishmentMeansValue [0..1]	age: Integer [0..1]
	ownership: OwnershipTypeValue [0..1]	ownershipType: OwnershipTypeValue [0..*]	protectionStatusReference: URI [0..1]	
	significance: significanceTypeValue [0..*]	significance: significanceValue [0..*]		
	crownType: CrownTypeValue [0..1]	crownTypeNatural: CrownTypeValue [0..1]	crownTypeTrimmed: CrownTypeValue [0..1]	
Crown	crownBaseHeight: Measure [0..1]	crownBaseHeight: Length [0..1]	leafAreaIndex: Real [0..1]	normalizedDifference VegetationIndex: Real [0..1]
	crownDiameter: Measure [0..1]	crownDiameter: Length [0..1]		
Trunk	trunkDiameter: Measure [0..1]	trunkDiameter: Length [0..1]		
	trunkHeight: Measure [0..1]	trunkHeight: Length [0..1]		
Root	rootBallDiameter: Measure [0..1]	rootSystemDiameter: Length [0..1]		
	rootBallMaximalDepth: Measure [0..1]	maxRootSystemDepth: Length [0..1]		
	observationProcedure: ObservationProcedureValue [0..1]	observationProcedure: ObservationProcedureValue [0..*]	seasonalChange: SeasonalChange [0..*]	
PlantCoverProperties	dateofPlanting: Date [0..1]	dateOfEstablishment: Date [0..1]	establishmentMeans: EstablishmentMeansValue [0..1]	
	ownership: OwnershipTypeValue [0..1]	ownershipType: OwnershipTypeValue [0..*]	protectionStatusReference: URI [0..1]	
	significance: SignificanceTypeValue [0..*]	significance: significanceValue [0..*]	leafAreaIndex: Real [0..1]	
	startHeightOfCanopy: Measure [0..1]	startHeightOfCanopy: Length [0..1]	normalizedDifference VegetationIndex: Real [0..1]	
PlantCoverGrowth	observationProcedure: ObservationProcedureValue [0..1]	observationProcedure: ObservationProcedureValue [0..*]	seasonalChange: SeasonalChange [0..*]	
Vegetation Management			managementReference: URI [0..1]	

Table 4 Unaltered, revised and added code lists and enumerations of the conceptual model for CityGML 3.0 Vegetation ADE v1.1 (Publication III).

Enumeration / Code List	Unaltered from ADE v1.0	Revised in ADE v1.1	Added to ADE v1.1
Code List	SeasonalChangeTypeValue	EcosystemServiceValue ObservationProcedure OwnershipTypeValue PotentialHazardValue SignificanceTypeValue CrownTypeValue TrunkTypeValue RootTypeValue ManagementTypeValue	EstablishmentMeansValue
Enumeration	HealthStatusValue UnitOfMeasure	SolitaryVegetationObjectGrowthTypeValue PlantCoverGrowthTypeValue	

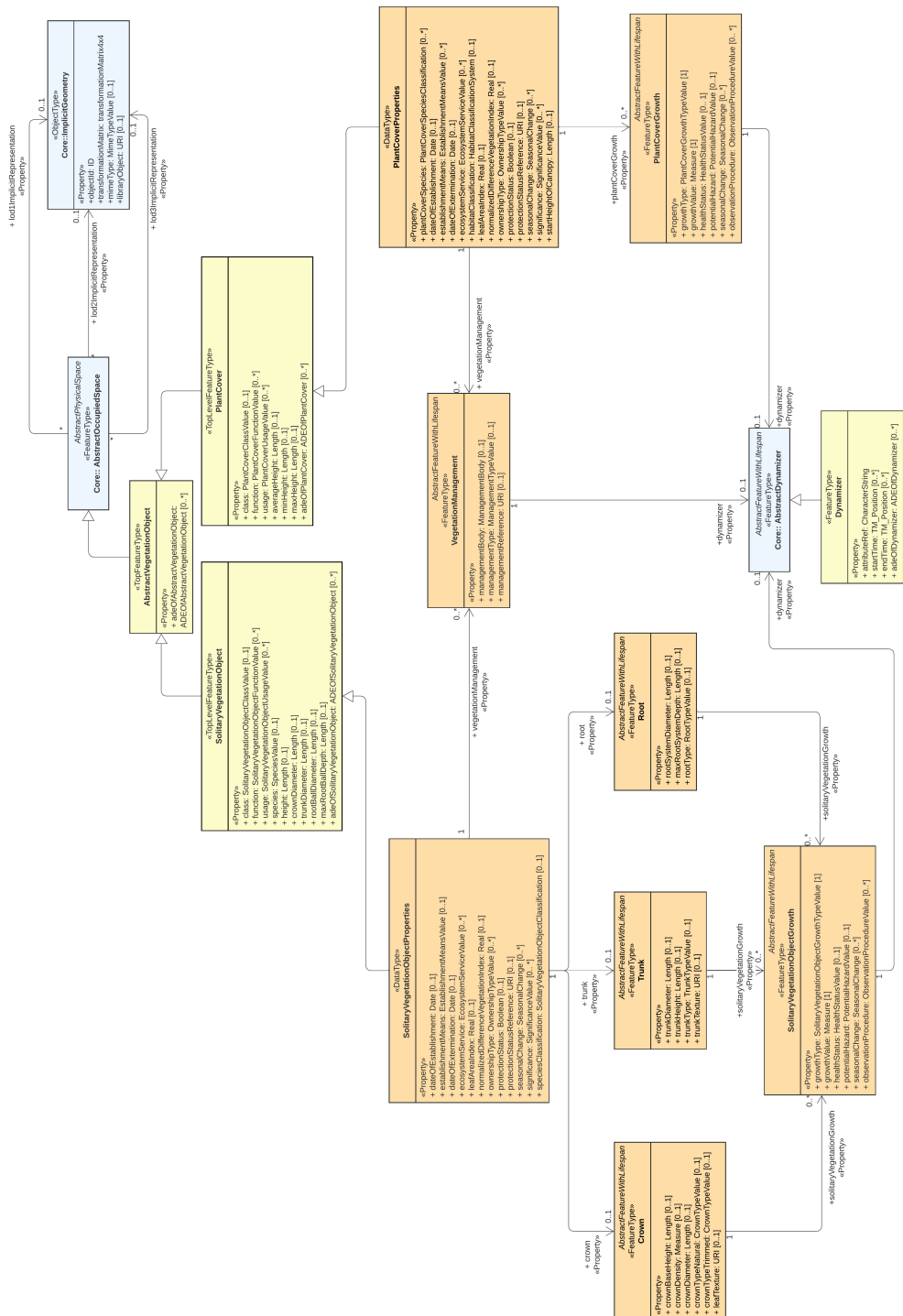


Figure 8 UML (Unified Modelling Language) diagram covering the proposed CityGML Vegetation ADE v1.1 (orange) with all relevant classes. Existing CityGML requirement classes are shown in yellow and in blue (Publication III).

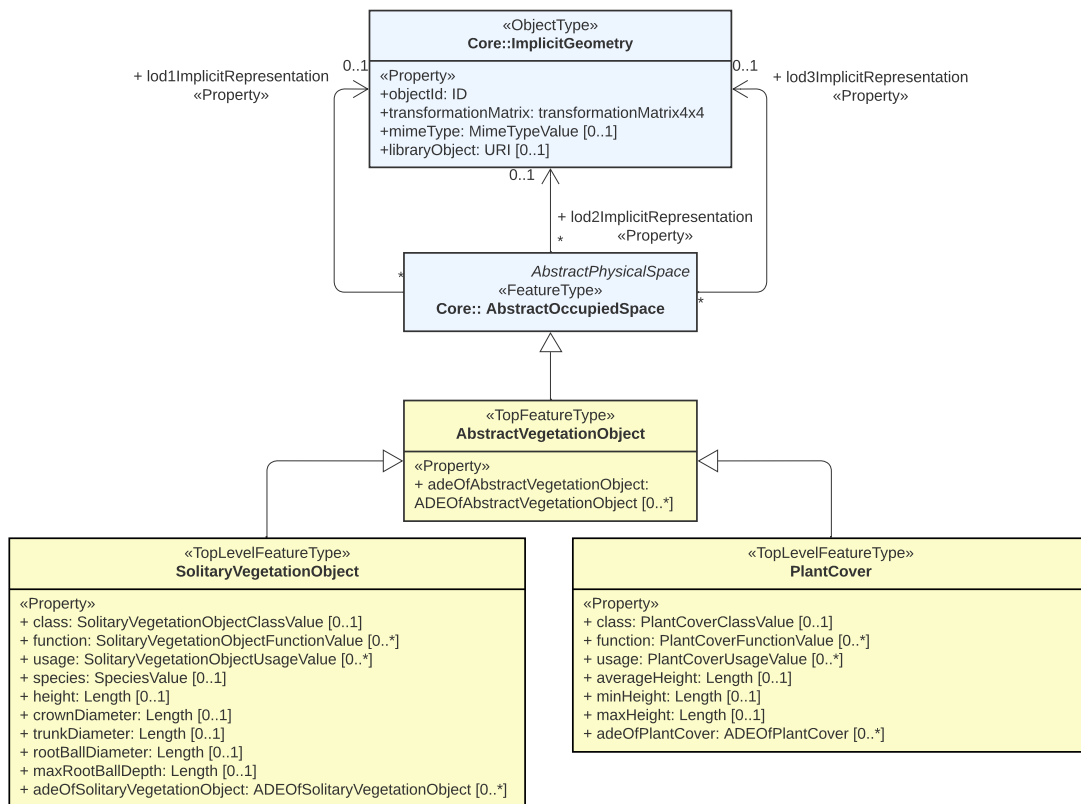


Figure 9 Existing CityGML 3.0 Vegetation module classes *SolitaryVegetationObject* and *PlantCover* (yellow) and requirement classes from CityGML sections (blue) (Publication III).

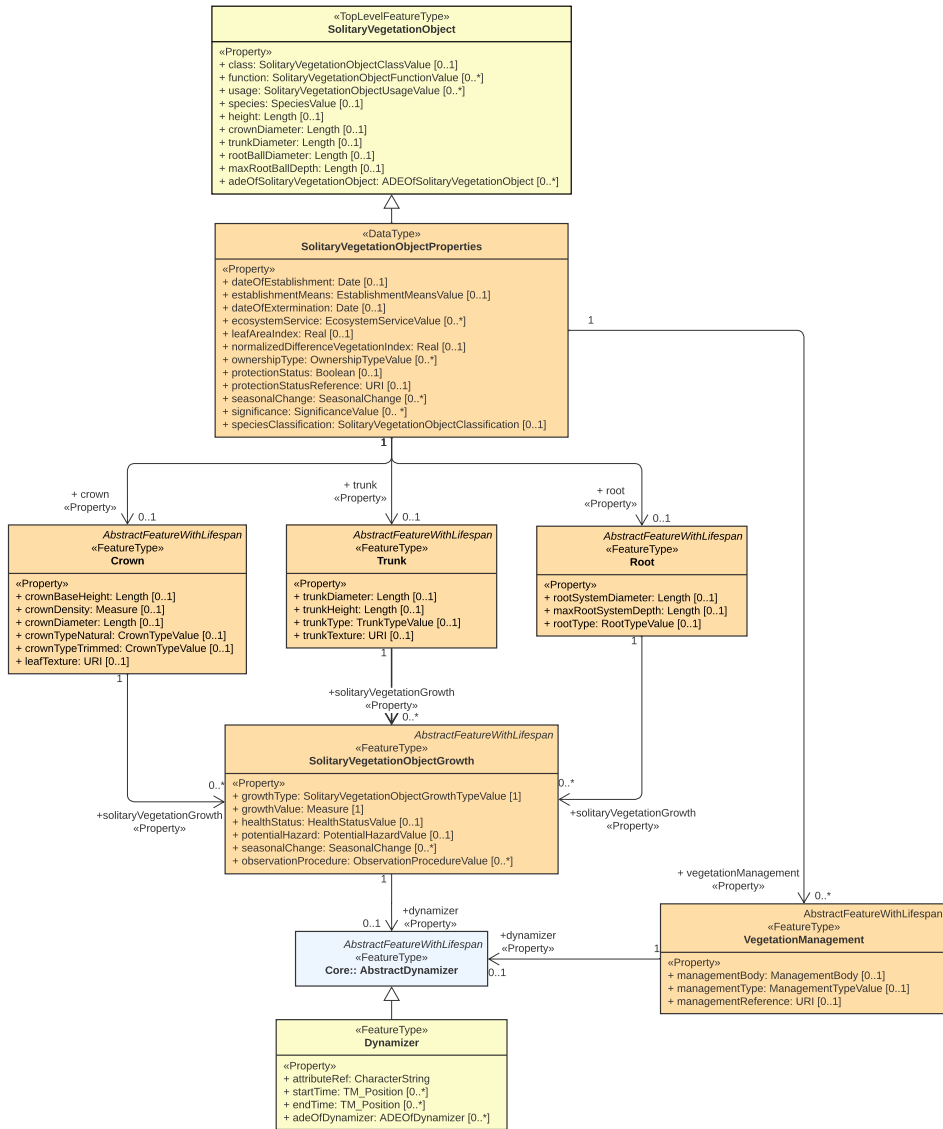


Figure 10 Excerpt from the updated UML (Unified Modelling Language) diagram of the CityGML 3.0 conceptual model for the Vegetation ADE v1.1 on solitary vegetation object (orange), illustrating the proposed extensions in Vegetation ADE v1.1: *SolitaryVegetationObjectProperties*, *Crown*, *Trunk*, *Root*, *SolitaryVegetationObjectGrowth*, and *VegetationManagement* (orange). Existing CityGML requirement classes are shown in yellow and in blue (Publication III).

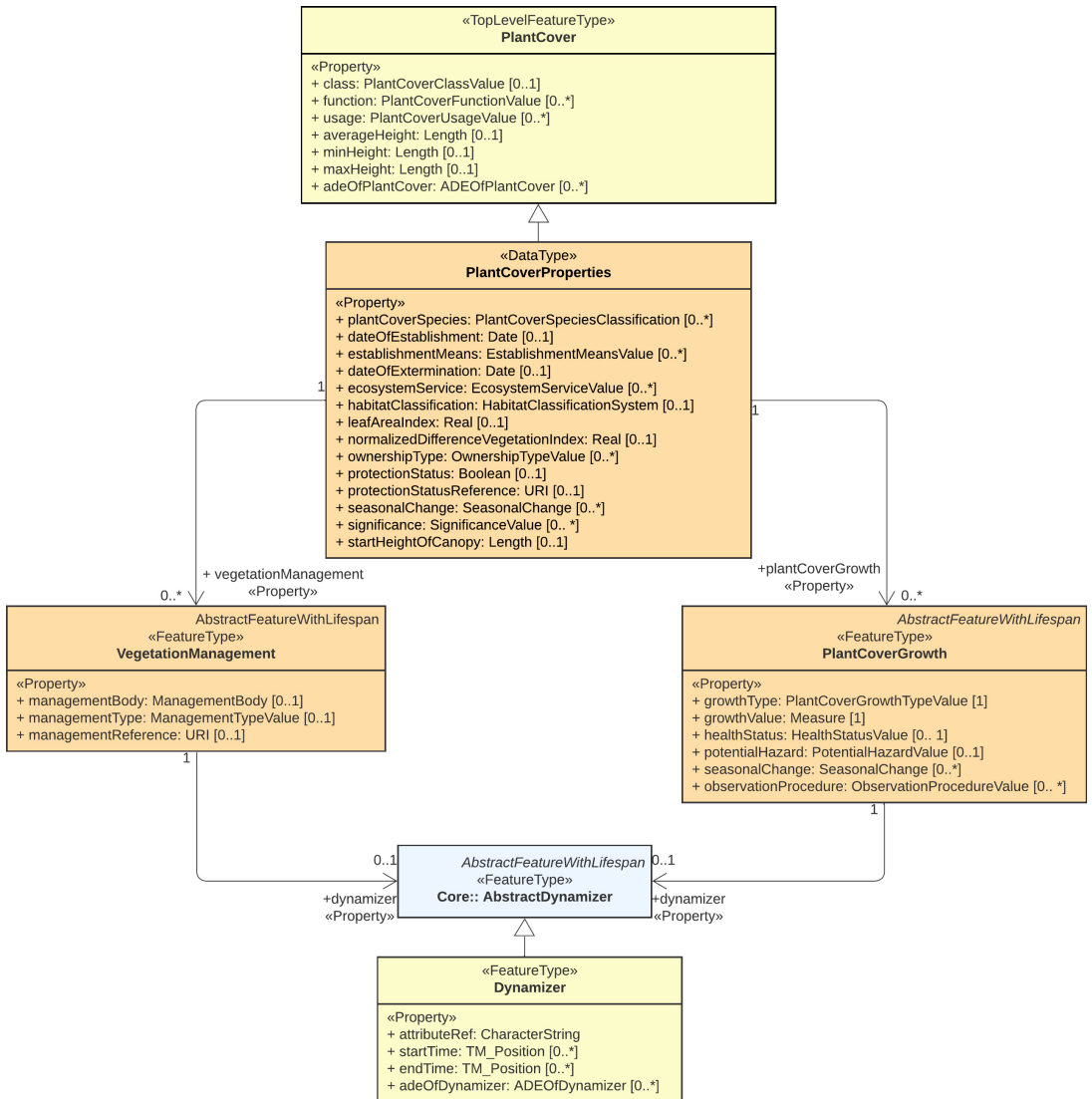


Figure 11 Excerpt from the updated UML (Unified Modelling Language) diagram of the CityGML 3.0 conceptual model for the Vegetation ADE v1.1 on plant cover (orange). Existing CityGML requirement classes are shown in yellow and in blue (Publication III).

Renaming *dateOfPlanting* to *dateOfEstablishment* and introducing the *establishmentMeans* attribute reflects the recognition that urban vegetation enters the landscape through diverse modes, including natural regeneration, seeding, and direct planting, and that a globally applicable standard must accommodate this diversity without prescribing a single mode of origin (Publication III).

The removal of the *age* attribute follows from the principle of avoiding derivable redundancy: *dateOfEstablishment* enables its approximate derivation. Retaining a separate *age* attribute would risk temporal inconsistency and impose an update burden that most urban datasets cannot reliably sustain (Publication III).

Renaming *rootBallDiameter* to *rootSystemDiameter* and *rootBallMaximalDepth* to *maxRootSystemDepth* addresses a representational inaccuracy in the ADE's parent class: the spherical root-ball abstraction does not reflect the full morphological diversity of root systems. This correction simultaneously improves the ADE's own semantic precision and identifies the *SolitaryVegetationObject* class as a candidate for future revision, representing an instance where the ADE development process exposes a limitation in the core standard rather than merely extending it (Publication III). Corresponding data types across *Crown*, *Trunk*, *Root*, and *PlantCover* were updated from *Measure* to *Length* to ensure correct unit inheritance throughout (Publication III).

Across two distinct attribute domains, the stakeholder process revealed a consistent structural pressure toward greater multiplicity. *OwnershipType* was revised from [0..1] to [0..*] for both *SolitaryVegetationObjectProperties* and *PlantCoverProperties*, reflecting the layered and overlapping ownership arrangements typical of urban trees and managed green areas. *ObservationProcedure* was equivalently broadened in both growth classes to accommodate combinations of simultaneous data collection methods, such as LiDAR and AI-based inference (Publication III). Together, these adjustments indicate that the v1.0 model underestimated the multiplicity of real-world institutional and methodological arrangements in urban vegetation management. Regional variation in stakeholder priorities revealed semantic divergences across geographic and institutional contexts. European respondents rated *protectionStatus* substantially higher than non-European respondents, reflecting differing statutory prominence of tree and habitat protection frameworks across planning systems. Non-European respondents placed greater emphasis on *seasonalChange*, reflecting phenological patterns, including rapid growth phases and wet-dry seasonal cycles, distinct from temperate European seasonality (Publication III).

The small subsample sizes mean these regional differences are indicative rather than statistically robust, but they were consistent enough in direction to inform targeted decisions in v1.1. In response, the ADE schema was revised to accommodate regional diversity without modifying the core structure. The custom

EcosystemServiceValue code list was replaced with the Millennium Ecosystem Assessment Classification, adopting an internationally recognised vocabulary to improve alignment with existing policy and assessment frameworks (Publication III). The *managementReference* attribute in the *VegetationManagement* class was introduced as a URI-typed property, enabling direct linkage to municipal forestry databases and operational management records. Protection status was refined through the introduction of *protectionStatusReference* as a URI-typed attribute in v1.1, allowing region-specific statutory classifications to be referenced externally rather than encoded prescriptively within the schema (Publication III).

The iteration process also defined the appropriate scope of this extension. Several respondents proposed the inclusion of fauna-associated properties, such as animal presence and habitat suitability for animal species, within vegetation objects. These were deliberately excluded from v1.1: fauna-vegetation linkages constitute a distinct ecological domain and are identified as a candidate for a dedicated future extension (Publication III).

4.2.4 Synthesis for Aim 2

The conceptual model for a CityGML 3.0 Vegetation ADE, refined through stakeholder evaluation from v1.0 to v1.1, constitutes the central contribution of Research Aim 2. It is a concrete, openly available, and internationally validated addition to urban data infrastructure. It supports filling a semantic gap that is constraining biodiversity-aware UDTs since the inception of CityGML's Vegetation module, and doing so without requiring modification of the core standard (Publications II and III).

Its development was directly informed by the findings of Aim 1. The structural mismatch between what stakeholders require vegetation-aware UDTs to represent was translated into semantically rich *SolitaryVegetationObjectProperties* and *PlantCoverProperties* classes, *Crown*, *Trunk*, and *Root* classes, a *VegetationManagement* class, *SolitaryVegetationObjectGrowth* and *PlantCoverGrowth* classes, and URI-referenced classification mechanisms introduced in the conceptual model.

Beyond the conceptual model itself, Research Aim 2 demonstrates that the challenges encountered in integrating vegetation semantics into UDTs are not purely technical. CityGML's Application Domain Extension mechanism provides a formally adequate extension pathway. The challenges were also semantic and organisational. The attributes required for planning-relevant and ecologically meaningful vegetation representation are not defined in the existing standard, are not collected systematically by most cities, and are not prioritised uniformly across disciplines and regions (Publications I, II, III and V) The conceptual model

addresses these barriers directly. It defines what should be captured and how, creating the necessary precondition for systematic data collection to populate the conceptual model of the Vegetation ADE incrementally, and establishing a standards-compliant substrate upon which more advanced vegetation-aware digital twin workflows can be built.

Section 4.2 has thereby established that a standards-based semantic substrate for biodiversity-relevant vegetation representation is both achievable and formally realisable within existing standards infrastructure. Semantic richness and interoperability address the data infrastructure layer but do not in themselves ensure that biodiversity information is accessible and meaningful to the diverse (non-)specialist audiences that UDTs are intended to serve.

Section 4.3 addresses this complementary challenge, examining how empirical biodiversity data can be translated into immersive representation, and what practical constraints that translation exposes about the communicative responsibilities of biodiversity-aware UDTs. Where Section 4.2 addresses what can be represented and how it should be encoded, Section 4.3 addresses how it can be experienced in a constrained VR environment.

4.3 Translating empirical biodiversity data into VR under practical constraints - design trade-offs and solutions

Translating empirical biodiversity data into an immersive VR environment surfaces a three-way negotiation between modelling fidelity, computational performance, and communicative legibility that structures representational decisions in a performance-constrained implementation. The case study work presented in Publication IV addresses Research Aim 3, applying the representation shortcomings and user needs identified in Aim 1 to a real-world implementation: a VR-based biodiversity game set at the Jaamamõisa stream intervention site in Tartu, Estonia, developed for the Meta Quest 3.

It is positioned as a design-oriented demonstrator, reporting practical workflow decisions, iterative design choices, and formative user feedback on the translation of empirical field data and planned biodiversity-enhancing interventions into an immersive biodiversity representation. This case demonstrates the feasibility and design logic of that translation under practical design and performance constraints. It complements rather than duplicates the semantic modelling work of Aim 2 by addressing the experiential register of the same challenge: where Aim 2 establishes how biodiversity data should be structured for UDT interoperability and workflows, Aim 3 tests how biodiversity data can be made perceptually and communicatively effective for human users in immersive interfaces.

4.3.1 From field inventory to VR scene: Data translation challenges

Producing a perceptually realistic VR scene from empirical biodiversity data required site-specific adaptations to both data collection and scene assembly, as standard approaches proved insufficient under the combined constraints of site complexity and performance requirements. Geographic data were transformed into Unity's internal coordinate system and assembled as a tiled 4 km² terrain of 13 tiles, with a central 1 km² tile receiving higher modelling effort while surrounding tiles provided contextual background. Orthophotos alone were insufficient for street-level viewing distance and required additional detail texture layers applied to the centre tile. This tiling structure required an explicit prioritisation of where to concentrate detail relative to where users would observe biodiversity at close range, as spatial context and rendering effort competed for the same computational budget (Publication IV).

The most substantive data-related revision concerned herbaceous vegetation. For data collection purposes, the intervention site was divided into two ecologically distinct sections: an intensively managed southern part and a more naturalistic northern flower meadow, each inventoried separately to reflect their differing vegetation composition and management regimes. Initial inventories used 1×1 metre study squares, one per section in 2023 and three per section in 2024, from which plant densities were intended to be interpolated across the site. However, the limited number of study squares relative to the spatial complexity of the site, including fine-scale topographic gradients and the presence of the stream, meant that interpolation-based plant placement did not produce realistic assemblage patterns in the virtual reality scene (Publication IV). Vegetation was therefore re-inventoried by delineating polygons of visually homogeneous areas, each associated with a species list, vegetation cover estimate, and mean herbaceous height (Publication IV). This revision aligned data units with the spatial structure visible in the scene and improved scene realism, but required additional field and interpretation effort. The revision illustrates the dependency between scene spatial resolution and data collection design as the required inventory density was determined by the virtual reality scene structure rather than by standard ecological survey conventions.

4.3.2 Representation trade-offs under performance and asset constraints

Performance constraints and asset availability imposed a consistent ceiling on representational fidelity across all modelling domains, requiring trade-offs between ecological accuracy, visual consistency, and computational feasibility.

Computational performance was the most pervasive constraint, driving representation substitutions throughout. Herbaceous plants were implemented as 2D billboards rather than 3D meshes. Maintenance-driven height variation required duplication-based workarounds that increased computational cost, and billboard densities had to be calibrated visually through Unity's painting tools, as translating ecological cover measurements directly into algorithmic placement parameters proved impractical. Herbaceous plant aggregation patterns similarly required manual authoring from site photographs, because ecological placement complexity exceeded what available algorithmic tools could implement. Terrain-change interventions required activation of an additional 1 km² tile for scenario switching, producing loading delays that constrained the before-and-after interaction design (Publication IV).

Asset availability constituted another structural constraint. The absence of a coherent library of taxonomically accurate, regionally correct plant and animal models with suitable licensing and consistent Level of Detail series meant that models from different sources varied in visual style and detail, requiring manual correction, shader enhancements, and species substitutions for both woody vegetation and fauna (Publication IV). For fauna, PlutoF observation data provided the initial candidate pool, filtered by age, frequency, and seasonality, from which city experts made a final selection based on site representativeness. However, animated models simulating natural behaviours remained largely unavailable within the performance constraints of the project (Publication IV). The available asset pool therefore constrained which species could be represented and at what visual quality, independently of the quality of the underlying empirical data.

4.3.3 Communicative design for diverse audiences

Communicating biodiversity effectively in an immersive environment required design decisions that went beyond data accuracy, as the legibility and engagement value of the demonstrator, developed as a biodiversity game, depended on how information was made accessible and interactive for users with varying levels of species literacy.

The VR-based biodiversity game was designed around a virtual walking trail guiding players between biodiversity-enhancing intervention sites, with intervention signs scripted with interactive before-and-after scenario switching to communicate intervention goals and their ecological rationale (Publication IV). Additional information signs distributed along the trail and a plant identification tool supported learning within the virtual environment, and a time-of-day system allowed exploration beyond daylight conditions (Publication IV).

The selection and presentation of fauna illustrated the communicative complexity of targeting diverse audiences. For the presentation of animal

observations, a range of methods combining visual, interactive, and audio elements were considered. Small animals such as insects and spiders were difficult to render visibly without occlusion in their ecological context. As a practical solution, e.g. a spider was placed at original size on an information panel to increase visibility. However, user testing revealed that most participants still did not notice the small animals, indicating that communicative visibility set a practical constraint on what placement alone could achieve. Site-recorded sounds were processed and integrated as ambient and positioned soundscapes (Publication IV). Formative user testing, conducted through structured interviews and questionnaires following VR sessions, informed iterative refinements to noticeability and communicative clarity across multiple design elements, including animal placement, intervention sign content, and scene composition (Publication IV).

The before-and-after intervention switching functionality exposed a specific communicative design challenge as future intervention states were modelled from expert plans and descriptive texts rather than observed post-intervention outcomes (Publication IV). Experts contributed descriptions of intervention appearance at multiple time steps, covering the state immediately after intervention and at one and two-to-five years post-intervention, alongside intervention objectives and descriptive texts used on intervention signs. As the immersive realism of the virtual reality environment risks producing stronger perceptions of certainty than the underlying evidence warrants, the gap between expert-planned and empirically observed future states required careful attention in how intervention scenarios were presented (Publication IV).

4.3.4 Synthesis for Aim 3

The Jaamamōisa VR case study shows that the negotiation between modelling fidelity, computational performance, and communicative legibility leads to deliberate representation trade-offs. These included employing billboards over detailed meshes, selective exaggeration or placement for noticeability, simplified scene composition, and that transparency about data sources and assumptions becomes essential where future intervention states are based on expert plans rather than observed outcomes. Otherwise, immersive VR risks producing misleading perceptions of certainty, echoing the need-data mismatch cautioned in Publication V, here reappearing at the level of representation rather than data modelling.

The VR work is positioned as a demonstrator and design-oriented learning exercise, rather than functioning as a quantitative performance benchmark. It documents practical workflow decisions across data preparation, modelling, asset harmonisation, intervention state switching, and multimodal elements such as

sound, and reports formative user feedback that informed iterative refinement of communication goals.

In synthesis, Aim 3 extends the doctoral thesis from *what is modelled and should be standardised* (Aims 1-2) to *how biodiversity information can be virtually experienced and communicated*. The VR case directly complements Aim 2's contribution by addressing the question the Vegetation ADE cannot answer alone: how biodiversity information, once made structurally representable through a standards-compliant semantic model, becomes perceptually and communicatively accessible to non-specialist audiences under real performance constraints.

At the same time, the VR-demonstrator stress-tests the thesis-wide findings: data bottlenecks, semantic gaps, and performance trade-offs persist across the work, underscoring that biodiversity-aware UDTs require integrated progress in data, semantics, and human-computer interfaces rather than advances in only one of these dimensions.

5 Discussion, limitations and future outlook

5.1 Biodiversity in UDTs: A field in transition

The evidence assembled in Aim 1 leads to a central interpretive conclusion: biodiversity inclusion in UDTs is a field in transition, but currently stalled at an early stage. The marginal status of biodiversity in UDTs is not a product of any single technological shortcoming, but the outcome of coupled constraints including data availability, semantic standards, and modelling capacity that mutually reinforce one another. Where one constraint is addressed in isolation, progress stalls at the next layer. This coupling effect explains why incremental improvements in e.g. sensor resolution or data collection frequency have not translated into biodiversity-aware UDT applications. Without corresponding advances in the semantic structures needed to store, exchange, and operationalise ecological data, richer input data remains stranded at the stage of raw inventory. By establishing this coupling dynamic as the operative mechanism of underrepresentation, this research advances the UDT literature beyond generic accounts of missing green infrastructure modelling toward a structurally grounded diagnosis that specifies where coordinated intervention is required.

This finding resonates with and extends a broader consensus in the field. Systematic reviews by Lei et al. (2023) and Weil et al. (2023) independently identify semantic interoperability across disparate urban data standards as among the most severe operational barriers to realising the potential of UDTs. Azadi et al. (2025) further document that despite nearly a decade of UDT development, contributions to actual planning decision-making remain modest, particularly in domains falling outside built-environment infrastructure. What this thesis adds to this picture is specificity: for biodiversity and especially urban green infrastructure, the semantic gap can be precisely located in the absence of standardised attributes, including those for structural components, temporal dynamics, species composition within heterogeneous plant covers, and management history in the prevailing data standard for urban environments. This level of diagnostic precision constitutes a contribution to geoinformatics that prior literature reviews on UDTs have not achieved, as they treat ecological representation as a peripheral concern rather than a structurally examined failure mode.

What distinguishes the urban context from more advanced digital twin domains is the combination of ecological heterogeneity, institutional complexity, and interoperability requirements that urban planning imposes. Production-oriented sectors, particularly precision agriculture, operate under conditions of controlled environments, commercial incentives, and monospecific data targets (see Purcell & Neubauer, 2023) that are structurally absent in municipal green infrastructure management. Methods from these sectors are therefore not directly transferable but require deliberate translation. UDT applications covering aspects of biodiversity remain mostly descriptive and only in a few cases predictive, lacking the bidirectional synchronisation that would situate them at higher levels of digital twin maturity (see Metcalfe et al., 2023). By mapping this domain maturity gap, this thesis contributes to ecological modelling a cross-sectoral evidence base from which knowledge transfer pathways between agriculture-oriented and urban-oriented digital twin research can be critically evaluated.

A further implication concerns planning relevance, where the findings of Aim 1 make its most direct contribution to urban planning research and practice. The user-needs research conducted in Tallinn, Estonia and Helsinki, Finland reveals that stakeholders require not only vegetation inventory data, but also forward-looking, scenario-capable representations informing decisions about e.g. tree placement, green factor compliance, ecosystem service provision, and climate adaptation. This demand sits in direct tension with the finding that suitable calibration data for growth projection models existed for only four of twenty locally relevant tree species. The identification of six user groups and their prioritised needs constitutes an empirically grounded requirements framework that bridges practitioner demand and technical specification, grounding future data collection agendas in concrete, location-specific evidence.

The gap between what planning practice requires and what data infrastructure supports is a governance-relevant constraint, not merely a technical one. Without interoperable, semantically rich vegetation data, ecological information cannot enter urban decision-making as a structured, auditable input, remaining instead a peripheral annotation. This connects to Westerlaken (2024)'s argument that biodiversity digital twins encode particular digital logics that can marginalise relational ecological understanding. The question of which aspects of biodiversity are made legible by digital tools, and for whose planning purposes, is as consequential as the question of which technical attributes are absent. Meanwhile, large-scale biodiversity digital twin initiatives such as BioDT-project (BioDT, 2024) treat urban environments as land-use categories rather than planning contexts with institution-specific data needs and governance frameworks, leaving a currently unbridged gap between large/global-scale ambitions and the granular, user-need-driven requirements of municipal green infrastructure planning that this thesis characterises from both perspectives simultaneously.

5.1.1 Limitations and future work

The claims of Aim 1 are credible within defined boundaries that qualify their scope and direct future research.

The systematic literature review (Publication I), on which the findings of Aim 1 centrally build, covers publications up to February 2023. Given the sharp increase in publications after 2019, updated reviews are necessary to assess whether the structural gaps identified here persist, particularly in fast-developing fields such as AI-driven species modelling. Future reviews should extend search strings to address fauna-specific domains more adequately, as fauna appeared in only four of the 38 included publications. This severely restricts the strength of claims about fauna modelling trajectories, and grey-literature and proprietary developments in e.g. wildlife monitoring or agricultural practices likely represent a substantial unreflected segment of current practice.

The user needs and data availability findings of Publication V are bounded to the Tallinn and Helsinki pilot context of the GreenTwins project. While the international stakeholder survey presented in Publication III confirmed the international need for a dynamic and more fine-grained semantic representation of vegetation, claims about detailed user needs, stakeholder priorities and projection model calibration data are supported only for Northern European municipal contexts with comparable governance structures and species pools. Generalisation to substantially different geographic or institutional settings requires independent research and validation.

Research on the generalisability of the findings presented in Aim 1 should include qualitative and quantitative cross-contextual research. For example a comparative case study design covering municipalities of varying demographics, size, and governance structure, combined with structured audits of data availability and standardisation levels across municipal geographic information systems and green infrastructure registers, to test whether the findings of Aim 1 hold across different urban environments. This could take the form of replicating the action-research of Publication V, comprising structured stakeholder interviews and participatory workshops with municipal green infrastructure practitioners, in cities with differing governance structures (e.g. more centralised or privatised green space management) and climatic zones and species pools (e.g. Southern, Continental European, and non-European climatic zones), to determine whether the same user groups, prioritised needs, and data-availability constraints recur or diverge outside the Northern European municipal context.

Finally, the data availability constraints documented in Aim 1 should not be read as a permanent structural ceiling. Emerging remote sensing workflows, including UAV-based LiDAR and multispectral imaging at species-level resolution, are approaching the capacity to generate the growth-trajectory data that the pilot study found absent for most locally relevant tree species. The bottleneck identified in

Aim 1 therefore reflects a specific moment in the development of urban monitoring infrastructure. Future work should focus not only on generating this data, but on establishing the monitoring protocols and data governance frameworks that ensure newly collected empirical evidence is systematically fed back into UDTs, translating the diagnostic work of Aim 1 into continuously improving urban biodiversity representations over time.

5.2 From feasibility to adoption: Semantic infrastructure and institutional preconditions for vegetation-aware UDTs

Positioning biodiversity as an operationally embedded dimension of UDTs requires, as a foundational precondition, that vegetation data be represented in a semantically explicit, interoperable, and temporally dynamic form. The findings of Aim 2, documented in section 4.2 and grounded in Publications II and III, establish that this precondition is technically achievable within the CityGML 3.0 framework. Moreover, it is also clarifying why technical achievement alone is insufficient for operational adoption. The presented thesis-level findings develop this argument, with implications for urban geoinformatics, urban planning, and biodiversity integration in UDTs.

The architecture of CityGML 3.0 is formally adequate for semantically rich vegetation extension without modification of the core standard. The hook-based Application Domain Extension mechanism supports enhanced semantic representation through *SolitaryVegetationObjectProperties* and *PlantCoverProperties*. It further enables *Crown*, *Trunk*, and *Root* structural decomposition, *Dynamizer*-integrated temporal representation via the *SolitaryVegetationObjectGrowth* and *PlantCoverGrowth* classes, management history recording through the *VegetationManagement* feature type, and URI-referenced ecological classification, all whilst preserving backward compatibility with existing datasets and software infrastructure (Publications II and III). Prior to Publications II and III, whether CityGML could support the level of ecological and planning-relevant semantic detail required for vegetation-aware UDTs applications in an international context remained open.

The Vegetation ADE CM v1.1 synthesises requirements and modelling approaches from a range of prior work. It draws on the practitioner-defined vegetation data needs established in Publication V, on a body of existing vegetation modelling research including, among others, the root system morphology framework of Guerrero Iñiguez (2017) translated into semantic attribute definitions, and on the cross-disciplinary attribute priorities generated through the international stakeholder survey detailed in section 4.2 (Publication III). The multi-source grounding distinguishes the ADE CM v1.1 from prior CityGML vegetation

extension proposals, which drew on narrower, discipline- or context-specific evidence bases. It positions the proposed conceptual model for CityGML 3.0 Vegetation ADE v1.1 as the first comprehensive vegetation extension to integrate ecological morphology, international practitioner user needs, nomenclature standards, and participatory validation within a single standards-compliant conceptual model.

The Energy ADE migration documented by Bachert et al. (2024) provides a close methodological precedent and demonstrates that the transition from conceptual model to operational encoding constitutes a subsequent development phase. The Vegetation ADE CM v1.1 occupies an equivalent position in the middle of a multi-stage trajectory. The present findings advance urban geoinformatics by providing an openly available, internationally validated, standards-compliant conceptual pathway for semantically structured urban vegetation representation within CityGML 3.0 and establish a replicable workflow for future ecological extensions.

The barriers to semantic vegetation representation in UDTs are coupled. The absence of a shared semantic definition and the absence of systematic municipal data collection mutually reinforce each other. Cities collect vegetation data extensively, but in heterogeneous, locally defined formats that cannot be integrated across platforms, institutions, or jurisdictions without a shared semantic framework (Publication V). The Vegetation ADE addresses precisely this layer. By formally defining what attributes should be collected, how they should be structured, and how they relate to existing classification systems, it provides the definitional infrastructure that makes systematic, interoperable collection possible.

Lei et al. (2023), identifying semantic data interoperability and multi-domain integration as the leading structural barriers to functional UDTs, did not identify ecological data as a current UDT priority domain. This absence confirms that the biodiversity framing of the Vegetation ADE addresses a gap the mainstream UDT research community has not yet foregrounded, and that signals a dissemination challenge that will shape adoption trajectories. The accelerating loss of urban tree cover documented globally between 2012 and 2017 (Nowak & Greenfield, 2020) underlines the urgency of this challenge. Cities require dynamic, updateable vegetation inventories precisely as urban tree covers are decreasing, because without semantically structured, temporally explicit vegetation data, the losses themselves remain invisible to the digital planning systems through which urban sustainability commitments are operationalised. Critical analysis of UDTs as predominantly human-centred epistemic systems (Argota Sánchez-Vaquerizo, 2025) provide ground for this structural mechanism: when digital twins are designed around institutional data flows and human spatial experience, ecological entities lack the governance structures required for operational embeddedness. The Vegetation ADE CM provides the definitional foundation for systematic, interoperable vegetation data collection and, once adopted, can contribute to

advancing urban planning and green infrastructure management. However, its adoption depends on parallel institutional change that the ADE, as a technical artefact, cannot itself compel.

Participatory validation is constitutive of standards-level model quality, not supplementary to it. The revisions informed by the international stakeholder survey, detailed in section 4.2, demonstrate that cross-disciplinary and cross-geographic engagement does not merely refine a pre-existing design but constitutes a distinct phase of quality assurance with direct bearing on semantic validity and practical adoptability. Zhang et al.'s (2022) CityGML vegetation extension, developed without international stakeholder engagement, retains a narrower focus on geometric parameterisation without for instance the management, establishment, or protection status dimensions that emerged as practitioner priorities in the present survey, empirically demonstrating that non-participatory design produces proposals that are not aligned with broad user needs. Pantazatou et al. (2024), independently identifying a semantic gap in the CityGML Vegetation module from a Nordic urban planning context and recommending Application Domain Extension development as the appropriate response, provide external validation of the gap diagnosis without proposing an equivalent model, thereby strengthening the case that the deficiency is real and broadly recognised whilst confirming the originality of the ADE CM v1.1 as a response to it. The deliberate exclusion of fauna-associated properties further confirms that structured stakeholder engagement defines the legitimate boundaries of what a standards-compliant extension can responsibly achieve within a single development cycle, as much as it shapes its contents. These findings advance participatory standards development methodology in geoinformatics, and the approach is directly transferable to future Application Domain Extension development in adjacent urban ecology domains, including fauna representation.

Regional divergences in stakeholder priorities confirm that non-prescriptive, linkage-based architecture is the appropriate design response for global adoption. As detailed in section 4.2, European respondents prioritised *protectionStatus* whilst non-European respondents emphasised *seasonalChange*, reflecting institutional and phenological contexts that cannot be resolved through fixed vocabularies without producing a structurally biased standard. These findings instantiate a design principle with implications beyond the Vegetation ADE. Semantic interoperability at global scale requires for certain attributes non-prescriptive, linkage-based architecture rather than imposed controlled vocabularies. This principle is not unique to the Vegetation ADE context. The national 3D city information model initiative for Sweden encountered similar tensions between institutional diversity and standards compliance, confirming the transferability of the linkage-based design response (see Ugglå et al. 2023).

5.2.1 Limitations and future outlook

The Vegetation ADE CM v1.1 is a conceptual model conformant with CityGML 3.0's General Feature Model and ISO 19109 and 19103 standards. Its semantic richness, structural completeness, and standards compliance are validated at the level of formal model design. Operational performance, encoding efficiency, and software integration lie outside the scope of the present work, as no GML or CityJSON encoding has yet been produced and no deployment into a UDT has yet been undertaken. In the CityGML ADE literature, the progression from conceptual model to operational implementation typically includes data model documentation, schema encoding, reference implementation, real-world data validation, and institutional workflow integration (see Agugiaro and Padsala 2025; Saeidian et al. 2023), each of which requires dedicated research and development effort. At the time of submission of this thesis, data collection with pilot cities and validation of the Vegetation ADE CM v1.1 conceptual model against real-world municipal vegetation data are ongoing. This constitutes the next step towards formal encoding, testing and operational deployment. This ongoing work extends beyond the scope of the publications comprising this thesis and will be reported in subsequent research. Moreover, integration with operational CityGML toolchains and submission to the Open Geospatial Consortium are future steps (Publication III).

Cross-disciplinary and cross-geographic consensus is supported across 37 respondents from 19 countries. However, municipal data managers and private sector practitioners are underrepresented relative to research and governmental roles, and the geographic distribution skews towards European contexts. The adoption readiness within specific institutional and regulatory environments therefore remains provisional, and future validation rounds with broader non-European and municipal practitioner outreach would strengthen them (Publication III).

The ADE's focus on flora reflects the current maturity of semantic vegetation modelling in UDTs, the availability of vegetation-related standards, and practitioner requirements, which are more developed than in fauna modelling. Fauna-vegetation linkages, beyond habitat classifications, were deliberately excluded from the CityGML 3.0 Vegetation ADE CM as they form a separate domain requiring dedicated treatment. A fauna-oriented extension remains an explicitly identified direction for future research, building on the structural gaps established in Aim 1 (Publications I and III). Addressing this shortcoming requires extending the diagnostic logic of Aim 1 to fauna-specific literature, data availability, and stakeholder needs, and then applying a similar cumulative modelling approach used for the Vegetation ADE CM to a dedicated fauna-oriented semantic extension in future work.

5.3 VR as an immersive interface for representing biodiversity in UDTs

Advancing biodiversity integration in UDTs demands more than semantically structured, interoperable data models. It requires that ecological information be made perceptually accessible to diverse audiences whose engagement with biodiversity determines whether urban nature is understood, valued, and supported. The findings of Aim 3, documented in section 4.3 and grounded in Publication IV, demonstrate that immersive virtual reality constitutes a viable interface for this purpose. However, translating empirical biodiversity data into a performant, communicatively legible virtual environment is structurally constrained in ways that richer data or greater computational resources alone cannot resolve. What the Jaamamõisa stream demonstrator reveals, when read against the cross-domain evidence of Aim 1, is that immersive biodiversity representation is governed by a persistent trilemma among modelling fidelity, computational performance, and communicative legibility, and that navigating it requires principled, audience-aware design judgement rather than technical optimisation alone.

This finding has traction beyond the case study. Publication I establishes that photorealistic, communication-oriented visualisations of flora and fauna remain exceptional across digital twin domains, confirming that the constraints encountered at Jaamamõisa reflect a field-wide condition. Comparable trilemma dynamics have been documented in forest and ecosystem virtual reality contexts, though in communities for which species asset libraries are comparatively well developed (Chandler et al., 2018; Holm & Schweier, 2024). Publication IV addresses the substantially less tractable case of herbaceous meadow communities, where no taxonomically accurate, age-differentiated asset series exist and where the visual inconsistencies documented in section 4.3.2 cannot be resolved through model acquisition or 3D-model construction at reasonable effort. The implication is not that herbaceous biodiversity is unrepresentable in virtual reality, but that it currently requires outlined production workflows that constrain scalability and transferability. Data-driven 3D content generation represents the most credible near-term pathway out of this constraint, though its applicability to urban meadow flora remains to be demonstrated.

The fauna dimension of the demonstrator sharpens these difficulties further. Small invertebrates placed at realistic scale remained unnoticed during formative evaluation even after prominent repositioning. Ambient soundscapes proved a more communicatively effective channel for conveying faunal presence than visual representation, consistent with Lindquist et al. (2020)'s experimental evidence that audio fidelity significantly elevates perceived biodiversity richness. This suggests that sound warrants treatment as an equally weighted modality alongside visual

representation in biodiversity VR design, particularly for species that are visually elusive at human-accessible scales but acoustically present in the environment.

A further implication concerns data collection design. Standard plot-based ecological surveys proved insufficiently resolved for scene assembly and required redesign as polygon-delineated vegetation inventories calibrated to the spatial structure of the VR environment. This extends the data gap documented in Publication V into the representational register. The granularity of biodiversity data collection should be co-determined by the visualisation environment from the outset, not adapted retrospectively. Neither Chandler et al. (2022) nor Holm and Schweier (2024) theorise this misalignment explicitly, suggesting that Publication IV addresses a genuine gap in the methodological literature.

Finally, the demonstrator's future-state scenarios were grounded in expert projections rather than observed outcomes. The perceptual realism that makes VR communicatively powerful also risks conveying unwarranted evidential certainty about futures that remain contingent, an effect compounded by the strong perceptual influence of multimodal immersive environments on ecological interpretation (see Lindquist et al. 2020). The principle established in Publication V, that simulations of e.g. vegetation change should not misrepresent their uncertainty, should therefore be actively operationalised in immersive interface design. Transparent communication of data provenance, modelling assumptions, and temporal uncertainty is a constitutive requirement of communicatively responsible VR applications. These findings together contribute an empirically grounded specification of the representational constraints the field must address alongside the infrastructure challenges Lei et al. (2023) identify as currently dominant in the UDT research agenda.

5.3.1 Limitations and outlook

The Jaamamõisa case study constitutes a single site at one season, namely summer, in a specific urban context. The design principles that the demonstrator yields are transferable as a methodological and conceptual reference rather than as context-independent solutions. Sites with substantially different vegetation structure, climatic regime, or institutional data environments may require different strategies for navigating the fidelity-performance-communication trilemma. What the case study supports is the claim that this trilemma structures representational decisions in performance-constrained biodiversity VR as a general condition. It does not support extending the specific technical choices documented in Publication IV without critical adaptation.

User evaluation remained formative throughout the development process. Structured questionnaires and iterative interviews informed design refinements but did not assess long-term learning outcomes, attitudinal change, or decision quality

in planning contexts. Future work should pursue summative, audience-comparative evaluation of communicative effectiveness with non-specialist urban stakeholders engaging with biodiversity scenario data. This would move the demonstrator register toward one capable of supporting evidence-based claims about impact.

The VR demonstrator achieved Arnstein's (1969) "informing" rung of participation by communicating biodiversity interventions to stakeholders and incorporating feedback on usability and comprehension. Higher rungs such as consultation, partnership, or delegated power (Arnstein, 1969), were deliberately excluded as they fall outside the technical demonstrator's scope. These represent valuable extensions for future socio-technical UDT research.

The demonstrator operates as a procedurally assembled environment without automated data integration. Establishing a pipeline through which e.g. standardised, semantically structured vegetation data automatically populates and dynamically updates an immersive biodiversity interface would constitute the step from demonstrator to deployable UDT-component, and represents the most substantive direction for future development.

5.4 From fragmented data to standards and immersion: A cumulative pathway for biodiversity in UDTs

The cumulative structure of this doctoral thesis constitutes a methodological contribution in its own right. By spanning diagnostic assessment, standards-level semantic modelling, and immersive visualisation within a single coherent research programme, the work demonstrates that biodiversity integration in UDTs cannot be resolved through isolated technical advances. As demonstrated across the preceding sections, progress in data modelling alone relocates rather than removes systemic bottlenecks when representational and interoperability constraints remain unaddressed. Lei et al. (2023), whose systematic review and Delphi expert survey identifies interoperability, including diverse semantic data standards, and practical value such as actionable insights for non-experts among UDTs' most severe challenges, treat ecological data as a peripheral concern rather than examining it as a fundamental source of system failure. Specifically, where Lei et al. (2023) identify these challenges, this doctoral thesis delivers the conceptual model for a CityGML Vegetation ADE v1.1 for semantic interoperability, a use case-based VR demonstrator for communicative accessibility, and a cross-domain gap analysis mapping both to practitioner requirements. The present doctoral thesis provides that structural examination for biodiversity and urban green infrastructure, across a research arc that mirrors the challenges Lei et al. (2023) establish.

The significance of this approach extends beyond its individual contributions. Whereas prior work in this context has addressed interoperability, semantic

modelling, or immersive representation as independent research problems, this doctoral thesis makes the handoff between three layers explicit: from empirically grounded user needs to standards-compliant semantic representation, to immersive ecological communication.

The Vegetation ADE CM v1.1 advances the first transition, translating diagnosed data and interoperability gaps into a standards-compliant conceptual model proposal for CityGML 3.0. Unlike prior project-specific vegetation extensions, the Vegetation ADE CM v1.1 is the first comprehensive, openly available conceptual model to extend the CityGML 3.0 Vegetation module with structural, dynamic, and management attributes. Beyond the model itself, the international participatory validation process generated empirical evidence on regional divergence in stakeholder priorities, constituting an independent contribution to standards development methodology.

Semantic modelling can structure biodiversity information, but cannot ensure it is perceptually and communicatively accessible. The VR demonstrator explores precisely this, examining what it takes to render biodiversity information meaningfully under real performance constraints. The two therefore act as complementary strands, one addressing *how biodiversity is semantically represented*, the other *how it is immersively experienced*.

The VR demonstrator embodies the second, rendering structured ecological information legible to non-specialist audiences through an immersive proof-of-concept environment. Beyond its role in this handoff, Publication IV contributes two methodological findings specific to the translation process itself. On one hand, it establishes that empirical data collection protocols should be co-designed with the spatial resolution of the target VR environment from the outset. Standard plot-based surveys proved insufficient at the Jaamamõisa site and required redesign as polygon-delineated vegetation inventories calibrated to the scene's spatial structure. This is a dependency not addressed by standard ecological survey conventions. On the other hand, it underlines that transparent communication of data provenance and temporal uncertainty is a constitutive requirement of communicatively responsible biodiversity VR. The perceptual realism of immersive environments risks conveying unwarranted evidential certainty about intervention futures grounded in expert projections rather than observed outcomes. This finding extends the simulation credibility principle cautioned in Publication V into the experiential register of immersive interfaces. For UDT research, this demonstrates that immersive interfaces can serve as a demonstrable, proof-of-concept output layer of semantic data, a role that complements rather than replaces semantic modelling. However, further development is required before such interfaces can be integrated into operational UDT workflows.

For biodiversity communication, it provides an empirically grounded workflow for translating field-inventory data into VR under real-world asset and performance constraints, applicable beyond the Jaamamõisa case. Schewenius and Wallhagen (2024) demonstrate that immersive VR enhances planners' understanding of urban green-blue infrastructure through contextual, emotionally engaging encounters with ecosystem complexity, an outcome that semantic models cannot achieve alone. By explicitly articulating these layers, this doctoral thesis offers a coherent pathway for advancing biodiversity-aware UDTs. Meaningful progress will, however, require integrated advances across data governance, semantic standardisation and implementation, and human-computer interaction that communicates ecological complexity without overstating certainty. Improvements confined to any single layer tend to relocate, rather than resolve, the bottlenecks that currently prevent biodiversity from becoming a decision-relevant component in UDTs.

This pathway carries particular significance given current sustainability obligations. The EU Biodiversity Strategy for 2030 (European Commission. Directorate General for Environment., 2021) and the Nature Restoration Regulation (European Commission. Directorate General for Environment., 2025) require municipalities to monitor, plan, and communicate urban biodiversity with increasing precision. Biodiversity-aware UDTs offer a technically grounded infrastructure for meeting these requirements, provided that semantic, representational, and institutional layers are developed in coordination. Westerlaken (2024) cautions that biodiversity digital technologies risk reinforcing reductionist data-generation logics that marginalise relational ecological understanding, positioning non-human agency as mere data substrate rather than co-constitutive urban force. The participatory standards development process (Publications II and III) and communicative VR design (Publication IV) constitute methodological responses, prioritising stakeholder validation and experiential legibility over metrics extraction.

Several questions remain deliberately open. Operational encoding of the Vegetation ADE into GML or JSON, deployment within live UDT environments, and summative evaluation of the VR demonstrator's communicative impact on planning decisions constitute the immediate next development phase. Fauna representation, identified as a structural gap and deliberately excluded from the ADE, requires a dedicated extension built on the methodological precedent this research establishes.

Beyond fauna representation in CityGML, future work on integrating fauna into UDTs should identify which fauna-related data types are relevant for specific monitoring and planning tasks, how they should be represented semantically and communicated visually or audibly, and at which level of digital twin maturity they become actionable. This includes not only species presence, but also habitat use, movement corridors, seasonal sensitivity, and the temporal patterns that shape

ecological vulnerability. At lower maturity levels, this may involve site-specific monitoring applications such as for bird (Ovaskainen et al., 2024) and bat monitoring (Hudson-Smith et al., 2021) or urban beekeeping (Johannsen et al., 2021), where the emphasis lies on observation, detection, and the identification of local habitat conditions. At higher maturity levels, the integration of dynamic models of fauna in UDTs could support biodiversity forecasting (Ovaskainen et al., 2026) and scenario analysis of planning interventions (De Koning et al., 2023; Penteadó, 2021) affecting endangered species or animals during vulnerable periods, such as breeding seasons, migration, or nesting. In this sense, a fauna-aware digital twin would need to be developed around explicit ecological and planning questions and should not be treated as a generic extension of the current model or technology. Such a use-case-driven approach would also help determine which fauna information should be represented, at which level of detail, and with which update frequency.

While this doctoral thesis establishes conceptual, methodological and empirical foundations for biodiversity integration within UDTs, Westerlaken (2024) highlights that the governance mechanisms and institutional frameworks necessary to position biodiversity as an *active stakeholder* rather than a passive visualisation layer remain a critical frontier. Publications I-V provide the methodological groundwork upon which governance-oriented research can build. A publication by the author of this thesis, currently under review, applies the Sixfold Helix Model (Brodny & Tutak, 2025) to explore operational mechanisms for institutionalising biodiversity in UDT decision-making from project inception. Future work should test such approaches through real-world case studies and cross-sectoral collaborations, translating advances in technical substrates, semantic interoperability, and communicative representation into actionable institutional arrangements that enable a shift from anthropocentric urban planning toward more-than-human urban planning paradigms.

The cumulative design established here offers a methodological template for structurally approaching the integration of other "wicked" ecological domains within UDTs, spanning systematic gap diagnosis, standards-level conceptual modelling, and demonstrative immersive representation. Urban fauna and further aspects of urban biodiversity require analogous progression: systematic gap analysis (as per Publication I), specific ADE development (following Publications II and III), performance-optimised VR interfaces (see Publication IV). Each requires bespoke diagnosis, standards intervention, and communicative demonstration, with governance frameworks maturing in parallel. This doctoral thesis thus provides not merely case studies, but a methodological meta-framework for ecological UDT integration writ large.

By demonstrating the technical and methodological feasibility of cross-methodological research for biodiversity integration in UDTs, the work opens a research trajectory at the intersection of geoinformatics, urban ecology, and digital urbanism that no single discipline can sustain alone.

6 Conclusion

UDTs remain predominantly human-centred planning tools whose treatment of biodiversity is in many cases limited to static geometries, generic objects, and post-hoc visualisation layers with negligible semantic depth. The absence of semantically explicit, temporally dynamic, and interoperable ecological representation is the central problem this doctoral thesis addressed, through three research aims spanning systematic diagnosis, standards-level semantic extension, and immersive biodiversity communication.

Dynamic modelling of flora and fauna in digital twins has reached comparative maturity in precision agriculture, yet remains structurally underdeveloped in urban digital twin contexts (RQ1.1). The barriers operate across interconnected dimensions, namely data availability, semantic standardisation, practical applicability, and realistic representation. Empirical evidence from Tallinn and Helsinki illustrates all four. Suitable growth data for locally relevant urban trees were missing for most species. The CityGML 3.0 Vegetation module lacked the structural, temporal, and management-relevant attributes practitioners require, and existing representational approaches failed to communicate ecological dynamics to diverse user groups (RQ1.2). Advancing any one of these dimensions in isolation relocates rather than resolves the bottlenecks keeping biodiversity peripheral in UDTs.

The semantic standardisation dimension is directly addressed through a comprehensive conceptual model-based extension proposal for CityGML 3.0. The Vegetation ADE proposed and refined here, incorporating structural plant components, temporal dynamics and management history via the CityGML 3.0 *Dynamizer* module. It constitutes the first comprehensive stakeholder-validated Application Domain Extension conceptual model proposal for urban vegetation semantics (RQ2.1). The survey process that produced the ADE v1.1 from ADE v1.0 established a further result: participatory validation with domain experts across international contexts is constitutive of standards-level model quality, not supplementary to it (RQ2.2). The translation of field inventory data from the Tartu Jaamamõisa intervention site into a performance-constrained virtual reality environment demonstrated that a fundamental fidelity-performance-communication trilemma shapes immersive biodiversity applications, and that

multimodal design strategies, including species-accurate assets and ambient soundscapes, can render biodiversity tangible for non-specialist audiences (RQ3).

Semantic modelling and immersive representation address the challenge of representing biodiversity in UDTs from complementary angles. The Vegetation ADE structures semantic vegetation data for interoperable use, while the VR demonstrator examines how the same data become perceptually and communicatively accessible under real performance constraints.

The empirical case studies are situated in North-Eastern European urban contexts and may not generalise to other institutional or biogeographic settings. The primary focus on flora, with fauna addressed only to a limited extent, is a further scope boundary. The Vegetation ADE is developed as a conceptual model and not yet formally encoded. Similarly, the VR demonstrator has not been deployed in an operational UDT. Governance structures needed to position biodiversity as a decision-relevant actor in UDT workflows lie beyond the scope of this doctoral thesis and represent an unresolved frontier.

These limitations point toward the most productive directions for future research: formal GML encoding, and live-environment validation of the conceptual model for ADE v1.1; the development of an analogous fauna-specific extension; and summative evaluation of immersive biodiversity communication's influence on planning targets.

The cross-sectoral systematic review of dynamic flora and fauna modelling in digital twins, the first comprehensive stakeholder-refined and -validated conceptual model for a CityGML 3.0 Vegetation ADE, and a documented methodological framework for translating empirical biodiversity data into immersive virtual reality environments are the concrete artefacts on which the field can now build.

As cities face mounting pressure to halt biodiversity loss under frameworks such as the Kunming-Montreal Global Biodiversity Framework and the EU Nature Restoration Regulation, that foundation will only grow in importance.

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Declaration

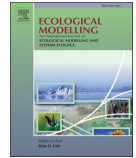
As the author of this thesis is not a native English speaker, Perplexity AI was used as a language editing tool to improve the clarity, grammar, and academic register of the text. All AI-assisted edits were subsequently reviewed and revised by the author, who takes full responsibility for the final version.

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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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ABSTRACT

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, over-exploitation 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 (Botin-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).

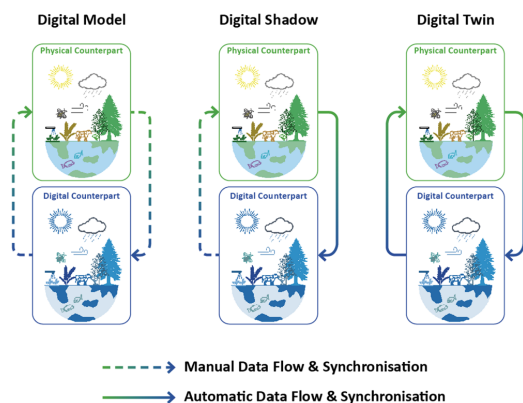


Fig. 1. Conceptual comparison of Digital Model, Digital Shadow, and Digital Twin frameworks as described by Kritzinger et al. (2018) and Botin-Sanabria et al. (2022). Digital models provide static representations of systems with manual data flow and synchronisation (left image, dashed arrows). Digital 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 (Ferre-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

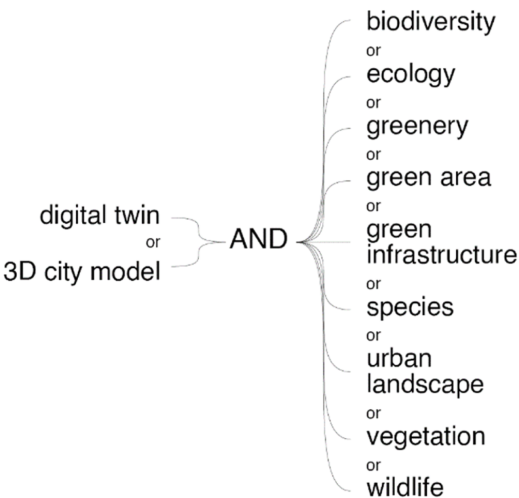


Fig. 2. Combinations of used search terms for the publication collection for the systematic literature review.

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.

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 (<http://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

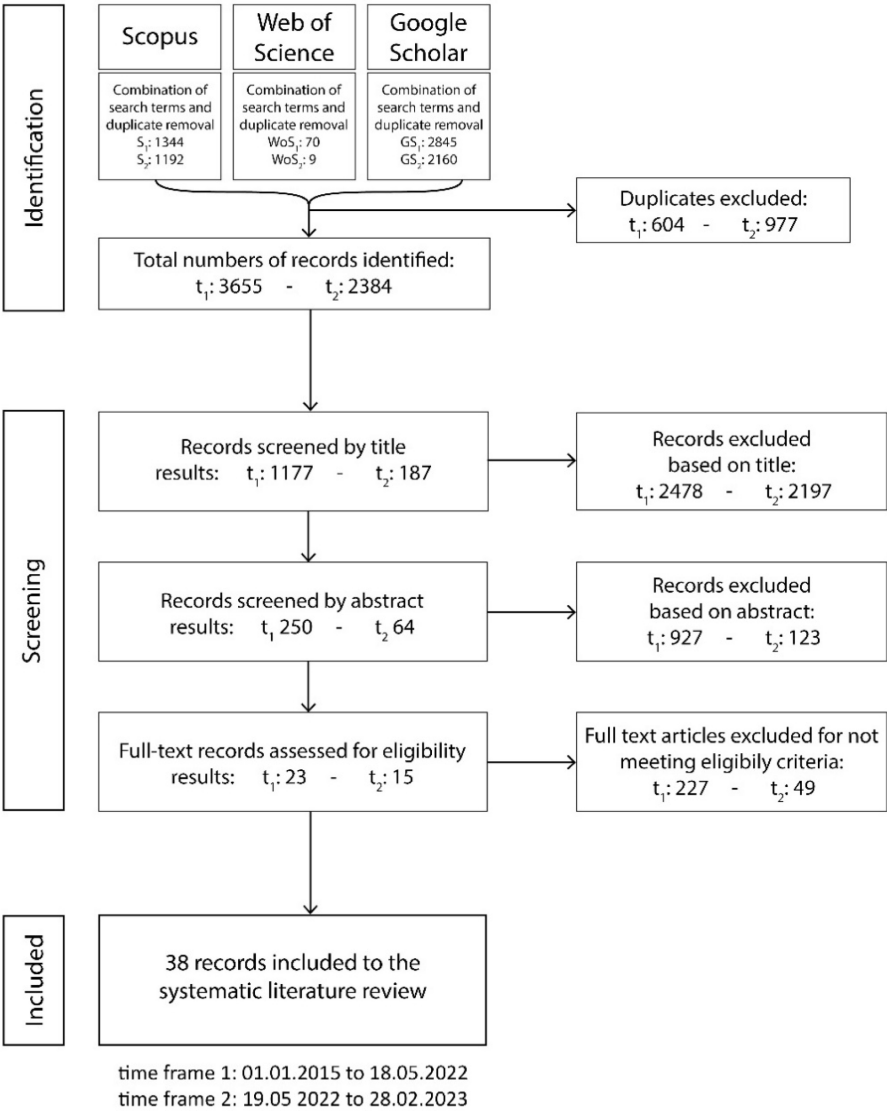


Fig. 3. PRISMA flow diagram (adapted from [Page et al. 2021](#)) illustrating the phases of the systematic literature review. It includes the numbers of publications retrieved from the Scopus (S), Web of Science (WoS) and Google Scholar (GS) databases during two data collection time frames (t_1 and t_2), 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

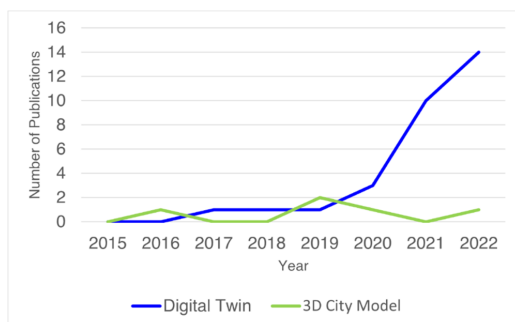


Fig. 4. The number of publications included in the literature review (y-axis) is shown by the year of publication (x-axis) and categorised by the first search term that matched each publication (line color). The year 2023 is excluded from the diagram as it was not fully covered within the literature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

(Johannsen et al., 2021), users and learners (Harrington et al., 2021), participants (Cirulis et al., 2022) and non-experts (Harrington et al., 2021).

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 (Hoferka 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,

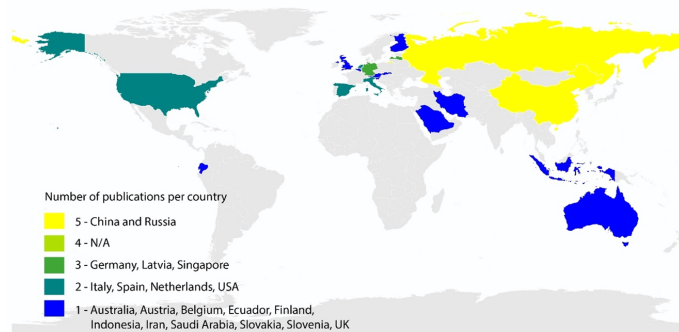


Fig. 5. The number of publications included in the literature review is displayed by country, based on first author affiliation, indicated by country colors on the world map. Countries shown in grey were not indicated as first author affiliation in any of the included publications.

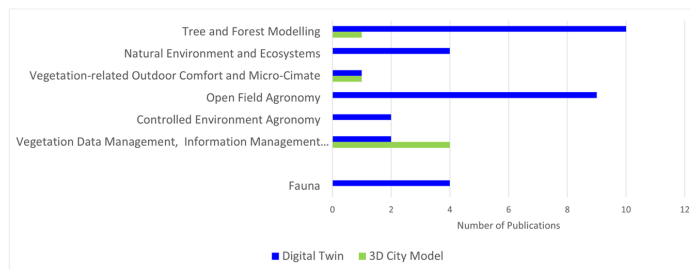


Fig. 6. Number of publications included in the literature review categorised by research focus area (y-axis) and the primary search term used ("Digital Twin" or "3D City Model," indicated by bar color). The x-axis shows the number of publications for each category.

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).

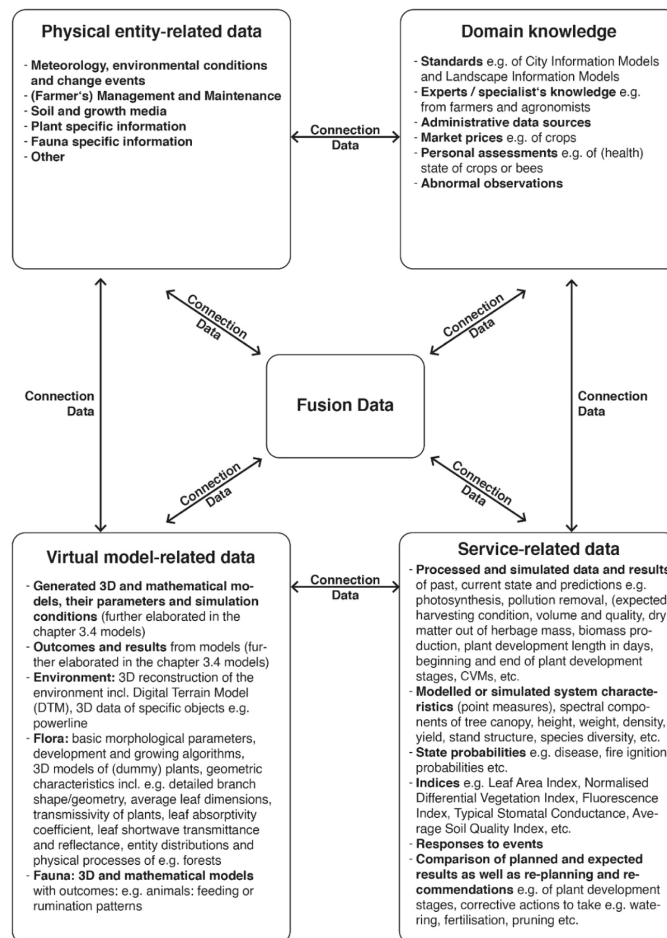


Fig. 7. Data types of flora and fauna models that appeared in the included publications, classified into the six categories of interrelated "digital twin data" types proposed by Zhang et al. (2022). A comprehensive list of the data types in this study that were classified as physical entity-related data,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

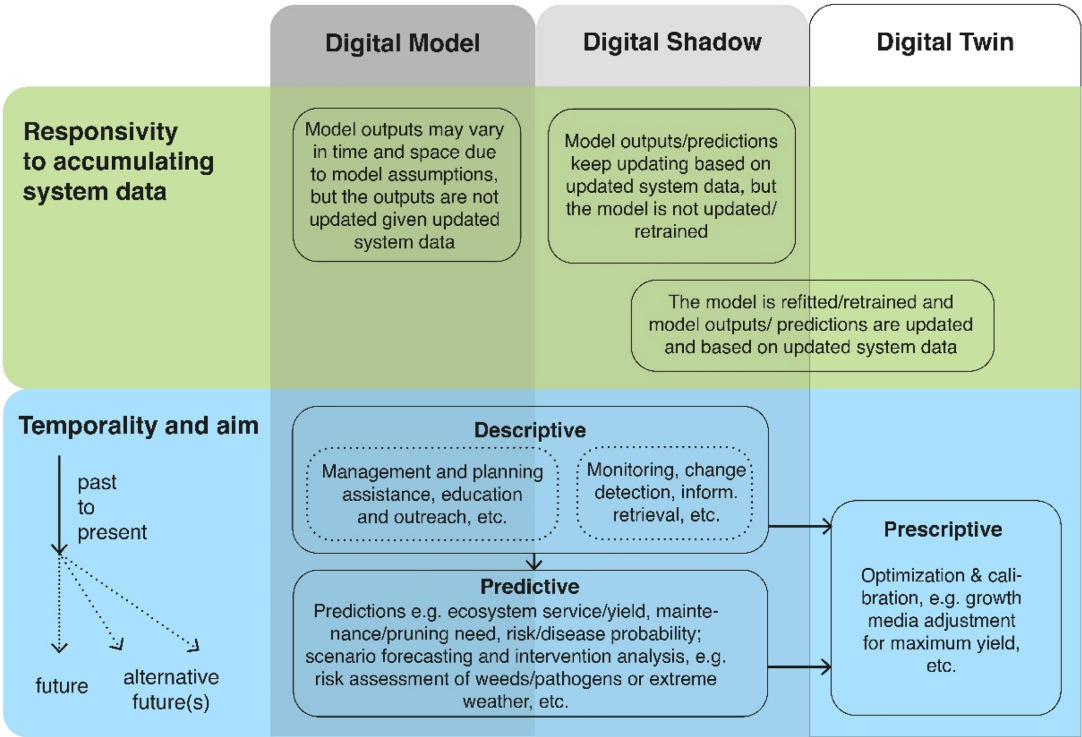


Fig. 8. Aspects of (sub-)models in the included publications, classified according to the type of data flow and synchronisation between the virtual and the physical (columns; for details of the classification, see Fig. 1), responsivity to accumulating system data (green topmost panel), model temporality (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 (Kritzing 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), interpreting 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 heterogeneous 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 requires 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 relative 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 responsiveness 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; Macias 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 attractiveness. 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 transcend 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 Mephram's Ethical Matrix for food and agriculture (Mephram 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 hand more accurately described as "digital shadows" (Botín-Sanabria et al., 2022; Kritzing 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 prototype 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 Mrosła: 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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Supplement 1:

Digital Model, Digital Shadow and Digital Twin – Background Information

1. Background

While digital twins are finding application in many different contexts, the term has become a buzzword with many divergent definitions, and is in many cases wrongly used as a synonym for a digital model or digital shadow (Kritzinger et al., 2018; Wright & Davidson, 2020).

1.1 Digital Models

Models are commonly used to represent concepts, processes, or reality. Various categorisations of models exist, and they vary greatly depending on the context and discipline. None the less, they all share a common characteristic: they provide an abstract representation of an entity - whether real or theoretical - by omitting extraneous details. (Taber & Timpone, 1996; Weisberg, 2013) The term "dynamic" is attributed to models when they respond to the alterations in system properties as they unfold over time (Ellner & Guckenheimer, 2006). Digital models, as the term indicates are computerised models. Models lack any automated data exchange between the physical and digital objects (Kritzinger et al., 2018).

In biology, ecology and environmental sciences, a wide variety of dynamic models have been developed to study flora and fauna over time. In the past decades, many of the models have been either spatially implicit, such as predator-prey models (Shiratsuru et al., 2023) or two-dimensional spatial, such as species distribution models or metapopulation models (Zurell et al., 2020) - digital models without integrated systems for data updates. Moreover, lately the development of also 3D digital models has become more prominent (Zotos et al., 2022).

1.2 Digital Shadow

Digital shadows are based on digital models and refers to a setup where an automated unidirectional data flow exists from a physical entity to its digital representation. Changes in the physical alter the digital counterpart, but not the reverse (Kritzinger et al., 2018).

1.3 Digital Twin

A common understanding, also elaborated by Kritzinger et al. (2018) and Botín-Sanabria et al. (2022), defines the key difference between a digital model, digital shadow and digital twin, that the digital twin involves fully automatic and integrated two-way data flows between a physical object and its digital counterpart. Id est that the digital counterpart can influence the physical and vice-versa. Interpretations of digital twins imply that the digital twin is a complete mirror image of the system. Therefore, it is not separate from the physical object or system but becomes the system itself. Based on this premise, logical difficulties alongside with the question whether digital twins can ever be fully achieved arise. (Batty, 2018) In contrast to the approach where digital twins are conceived as a holistic representation, digital twins can also be described as a modular system. This implies a system composed of distinct units that each model specific aspects of the physical counterpart. These components can be developed and operated independently or configured into an integrated modular system if adapted. (Rolle et al., 2021)

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Supplement 2:

Digital Twin Data

1. Digital Twin Data Categories

Zhang et al. (2022) coined the notion Digital Twin Data, referring to data tightly associated with digital twins. Herein, data is divided into the six categories:

1.1 Domain Knowledge

“Domain Knowledge” describes the domain specific knowledge such as expert experience, predefined rules, industry standards, and insights gained from data mining, used for guiding model construction and data processing. (Zhang et al. 2022)

1.2 Virtual model-related data

“Virtual model-related data” is produced by simulations and verifications of models, capturing geometric, physical, behavioural, and rule-based aspects of the virtual representations (Zhang et al. 2022).

1.3 Service-related data

“Service-related data” is generated from application and functional services, this data is derived through service construction, operation, and maintenance processes. The main outcome of the service-related data is to solve problems in the area of applications such as scheduling, prognosis and quality assurance. (Zhang et al. 2022)

1.4 Connection data

“Connection data” facilitates real-time interactions between different components of digital twins, processed to eliminate redundancy and ensure relevance and clarity in data transmission. (Zhang et al. 2022)

1.5 Fusion data

“Fusion data” also referred to as multi-source data, results from integrating physical entity-related data, virtual model-related data, service-related data, and domain knowledge, enhancing the completeness and accuracy of information.

1.6 Physical entity-related data

“Physical entity-related data” refers to information associated with tangible objects or environments. This type of data captures the real-world aspects of physical entities for analysis, monitoring, and digital replication purposes. It includes both dynamic data and static data. Static data are data which inherits static properties (Purcell, Klipic, and Neubauer 2022), such as a the species of a given tree. Dynamic Data describes changing features at a given point of time. This data is changing as e.g. the plant height (Purcell, Klipic, and Neubauer 2022) and can be metered using different methods on the real plant.

Due to the diversity and extent of it, physical-entity related data is listed in the following:

- 1.6.1 *Meteorology, environmental conditions and change events*: Records of, actual and forecasted environmental conditions and change events incl. weather/climate, air temperature, air pressure, wind speed and direction, amount of precipitation and rainfall, relative and absolute humidity, water vapour, solar radiation, sun exposure and duration, luminosity, cloud cover, CO₂ concentration, transpiration, gas exchange, mass flow, etc.
- 1.6.2 *(Farmer's) Management and Maintenance*: Ownership unit, activities such as fertilization, fungicides use, sowing (used crops, varieties etc.), treatment of diseases/parasites, water supply/irrigation conditions, used equipment, dates and frequency of interventions, sensing frequency of measurements; harvested amounts (e.g. honey, crops), resources, costs, etc.
- 1.6.3 *Soil and growth media*: Quality, profile (e.g. peat), depth, moisture, temperature, heat capacity, granulometric composition and volume density, volumetric water ratio, salinity, organic and nutrient content (e.g. nitrogen), pH level, water-log, microbiology, slope direction, etc.
- 1.6.4 *Plant specific information*: species and name, variety, location and coordinates, age, health conditions (e.g. infestation by harmful insects or fungi), development, growing stages, growth type, full development length in days, nursery production, carbon fixation type and seasonal changes, height of the state of the real plant at the moment of data collection and at maturity, density of plant canopy, tree crown size, trunk diameter at breast height etc. phenomenological parameters (of the state of the real plant), specific heat of plants, density of plant canopy, transmissivity of plants, typical stomatal conductance, average leaf dimension, leaf area index incl. monthly variation factor, leaf properties (incl. condition, density, type, leaf absorptivity coefficient), root system properties incl. depth, diameter and root zone geometry, etc.
- 1.6.5 *Fauna specific information*: Amount (e.g. of bees or livestock), inspections on fauna (e.g. bee colonies, kettle), activities, eating and drinking times, health status incl. stress level, diseases and parasites, gentleness, beehive pollen inflow, brood status, abnormal observations (e.g. bad wings), bad brood, etc.
- 1.6.6 *Other*: Cadastral data, thematic maps, "other" and not further specified data.

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Towards a Conceptual Model of CityGML 3.0 Vegetation ADE

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Abstract

The rapid growth of urban areas underscores the need for developing semantically rich 3D city models representing a variety of urban objects and integrating the results from the analysis and simulation of urban processes and environment. Adhering to standards such as CityGML, these 3D city models offer immense value in urban planning, development, and management. By encoding the spatial, functional, and thematic information in a standardized way, they provide a comprehensive digital representation of cities. This enables city authorities to evaluate the impact of proposed developments and thereby make informed decisions. CityGML-based city models facilitate the progression towards smarter, more efficient, and more sustainable cities by supporting interoperability across different systems and platforms. This fosters collaboration and data exchange among diverse stakeholders.

This paper contributes to the development of semantically rich and interoperable 3D city models by proposing a conceptual model for Application Domain Extension (ADE) of the CityGML 3.0 Vegetation module. The ADE enhances the *SolitaryVegetationObject* and *PlantCover* feature types with additional properties by leveraging the new “hook” mechanism available in CityGML 3.0. Furthermore, it considers the dynamics of vegetation in terms of growth and management through modelling of dynamic data based on the *Dynamizer* module. Additionally, new data types, code lists and enumerations appropriate to the ADE domain are defined, providing a unified description of the vegetation’s specific characteristics that are comprehensive across different platforms and disciplines. The Vegetation ADE’ conceptual model opens several avenues for future research, including development of more accurate vegetation simulations and analyses, investigation of urban heat island effect or environmental impact assessments.

1. Introduction

The digital replication of cities, in the form of 3D models and urban digital twins, is increasingly prevalent. In evaluating the progress of digitalisation across various aspects of these replicas, it is observed that advancements in green infrastructures, particularly vegetation, lag behind those of human-made objects, such as buildings. The modelling of urban vegetation presents challenges due to its dynamic nature and diverse systems. These challenges encompass the collection and management of fundamental data on vegetation, its intrinsic changes and its maintenance. It is crucial to acknowledge the widespread collection and storage of urban vegetation data globally, often conducted without adherence to standards for semantic representation and interoperability. On this note, the absence of comprehensive and systematically organized data complicates decision-making, planning, and budget allocation.

CityGML is a widely adopted open standard for modelling both the geometry and semantics of urban environments. To provide a more comprehensive depiction of urban landscapes, it enables the development of Application Domain Extensions (ADEs), thereby extending its applicability in different domains and use cases. (Kolbe, 2009) Since the ADE concept was introduced in 2007, numerous extensions have been proposed.

This study proposes a conceptual model for a Vegetation ADE of CityGML 3.0. It serves as a foundation for vegetation data modelling, overcoming the limitations of the standard in supporting routine vegetation information, management, maintenance, etc. The proposed ADE covers top-level feature types, namely *SolitaryVegetationObject* and *PlantCover*. By extending them, it aimed to enhance the semantic richness and modelling capabilities of CityGML 3.0 in capturing the complexity of urban vegetation. Thus, a more holistic representation of urban environments is achieved by

encapsulating the relationships between vegetation and the built environment. This enhancement aligns with the overarching goal of CityGML to facilitate the creation, sharing, and utilisation of semantic 3D city models.

The rest of the paper is organized as follows: Section 2 overviews the relevant related work. Section 3 outlines the methodology employed in the development of the ADE. Section 4 provides a detailed account of the ADE’s implementation. Section 5 discusses the implications and results derived from the study. Finally, Section 6 concludes the paper.

2. Related Work

2.1 CityGML Development

While the City GML standard aims to provide a universal and non-biased geographical information model, the popularity of the standard throughout the years has created the need for additional domain-specific add-ons that would be able to meet the requirements of a wide range of applications. To address those initial shortcomings without disrupting and overcomplicating the base model, the Application Domain Extension (ADE) has been introduced. The ADE concept is part of the model from the early stages of its development or, more superficially, in May 2007 with the deployment of version 0.4 of the standard. It allows for extending the existing CityGML schema and opens the opportunity for many domain and field experts to adapt and utilise CityGML in serving their own case specific scenarios, applications or projects. ADEs enable users to define additional attributes, new feature classes, and relationships.

CityGML has been developed since 2002 by the members of the Special Interest Group 3D (SIG 3D) of the Open Geospatial Consortium (Gröger et al., 2008). Since the publication of CityGML 1.0 in 2008, it has undergone several further

improvements, which have resulted in the publication of CityGML 2.0 in March 2012 (Gröger et al., 2012). Additional change requests for version 2.0 since its publication have been considered and the standard has been further developed to version 3.0. The transition from CityGML 2.0 to CityGML 3.0 in the year 2020 introduced several significant enhancements and changes aiming to reflect the increasing need for better interoperability with other relevant standards (Kutzner, et al., 2020). A revision of the existing modules *Core*, *Generics*, *Building*, and *Transportation* is performed as well as new modules *Dynamizer*, *Versioning*, *PointCloud*, and *Construction* are added. The *Vegetation* module has not been revised, which further motivates the work in this study on implementation of *Vegetation ADE*.

In CityGML 3.0, all city objects are mapped to the onto the semantic concepts of spaces and space boundaries (Kutzner et al., 2020). The spaces are further subdivided into logical spaces and physical spaces, which in turn can be occupied and unoccupied. Nearly all geometry representations are moved from the thematic modules to the *Core* module and are associated with the semantic concepts of spaces and space boundaries. Thus, the redundancies in some modules such as *Buildings* and *Tunnels* are overcome. 3D point clouds can be used to represent the geometries of physical spaces and space boundaries through the new *PointCloud* module. The dynamic variations of the objects' properties are handled by the *Dynamizer* module and bitemporal timestamps for those objects are introduced by the *Versioning* module.

The Unified Modelling Language (UML) semantic data models in the geographic information system (GIS) domain typically conform to relevant standards from the ISO 191xx series of geographic information standards. The data model of CityGML 3.0 also adheres to these established standards. Applying ISO-compliant transformation rules to CityGML 3.0 results in changes to the XML encoding, altering it from that of CityGML 2.0 and 1.0. Although the conceptual model remains the same as in CityGML 2.0, the encoding differences require converting datasets and adapting CityGML 2.0 software for compatibility with version 3.0. However, all updates in CityGML 3.0 are designed to maintain backward compatibility with versions 1.0 and 2.0, allowing for dataset transformation through syntactical adjustments only. This backward compatibility is crucial to preserve existing investments in CityGML tools, datasets, and extensions.

2.2 CityGML ADEs

An overview of the CityGML 2.0 ADE developments has been published by Biljecki et al. in 2018. The existing *Noise ADE* previously conceptualised by Gröger et al. in 2012, is further extended by Kumar et al, 2017. The enhancements cover *Transportation*, *Building*, and *City Furniture* modules. The modifications have been designed to incorporate noise data seamlessly into the CityGML framework.

The CityGML *Utility Network ADE* proposes a unified data model for depicting various supply and disposal networks, including those for electricity, freshwater, wastewater, gas, oil, district heating, and telecommunications (Kolbe et al., 2018). It supports advanced analyses and simulations by providing a cohesive perspective of 3D city models alongside supply infrastructures.

The CityGML *Indoor ADE* is specially designed for management of indoor spaces and facilities (Kim et al., 2014). It consists of two feature models: one for representing the characteristics of indoor spaces, known as the indoor space feature model, and another for depicting indoor facilities within these spaces, referred to as the indoor facility feature model.

Another study is acknowledging the rise and need for workflows and technologies for translating BIM to CityGML (Lim et al., 2020). It presents an approach that uses a combination of generic rules to extract information from both standard CityGML and ADEs. A flexible web interface is developed for visualization of the CityGML ADE-enabled models, contributing to their usability.

The number of published works on ADEs of the new version of the standard, CityGML 3.0, is limited. *Underground Land Administration ADE*, called *VicULA*, is proposed at the conceptual level (Saeidian et al., 2023). The *VicULA ADE* aims at managing subterranean data through a unified 3D model that integrates legal and physical aspects on an urban scale. It introduces semantic entities for subterranean legal domains, thereby facilitating the delineation of spatial and semantic linkages among various categories of legal spaces.

Efforts are made towards mapping the existing *Energy ADE* to CityGML 3.0 (Bachert, 2023). The *Energy ADE* version 1.0 is built upon CityGML 2.0 and extends the *Core* and *Building* modules in the context of energy domain. The changes in CityGML 3.0 directly affect the portability of the *Energy ADE*, leading to the need of its conversion from CityGML 2.0 to CityGML 3.0 (Bachert, 2024). The mapping performed employs a model driven approach and is validated on actual data transformation. Following the current developments of CityGML 3.0, the modelling of floor plans in CityGML is considered and a delineation of multiple variants of indoor LoD0 is proposed (Konde et al., 2018).

3. Methodology Overview

The methodology employed for the implementation of the ADE adapts the model-driven framework designed for CityGML ADE developments as described by Van den Brink et al. (2013). It also adheres to the guidelines for ADEs, defined in the CityGML Conceptual Model Standard by Kolbe et al. (2021). This methodology consists of the following steps.

3.1 Selection of Formal Modelling Language

A formal modelling language to represent the ADE classes should be selected. In this study, the UML is chosen for several reasons. First, according to the CityGML 3.0 standard, ADEs should be defined as a UML conceptual model in accordance with the General Feature Model and the rules for creating application schemas in UML, specified in ISO 19109:2015 and the rules and constraints for using UML to model geographic information, specified in ISO 19103:2015 (Kolbe et al., 2021). Since UML provides a visual modelling approach, the ADE conceptual model can be easily communicated with various stakeholders, such as domain experts, software developers, city authorities, etc. As a formal language, UML can unambiguously express the structure and rules of an information model and allows the automatic and direct generation of XML schema and documentation from the model.

3.2 Selection of CityGML Feature Types to be Extended

This step includes the selection of CityGML feature types to be extended and the definition of additional properties appropriate for the ADE domain. For this purpose, a subclass of the corresponding abstract data type associated with the feature type is created. The subclass is defined as data type using the stereotype «DataType». The additional application-specific attributes and associations are modelled as properties of the ADE subclass.

The extension attribute named “adeOfFeatureTypeName” and data type “ADEOfFeatureTypeName”, referred to as the “hook”, is used, where FeatureTypeName corresponds to the class name for which the new properties are defined. The “hook” mechanism enables subclassing a CityGML feature type. The properties are modelled with either simple or complex data types in accordance with the ADE domain.

3.3 Definition of new Feature Types

Defining new feature types appropriate to the application domain is a core step in the ADE implementation. Every feature type in an ADE should be derived from the CityGML root feature type *Core::AbstractFeature*. This can be done directly or indirectly or, depending on its type and properties, from a more suitable subclass thereof. The object types and data types are not required to be derived from a predefined CityGML class. The stereotype used to represent the new feature types is «FeatureType». It represents an abstraction of a real-world phenomenon, having an identity.

3.4 Relationship Definition between Feature Types

The definition of relations between CityGML and ADE feature types follows UML notations for association, aggregation and composition between classes as well as class inheritance.

3.5 Definition of Additional Content

The definition of additional content includes the specification of data types, code lists and enumerations appropriate to the ADE domain. The stereotypes used for implementation are as follows:

- «DataType», used for holding information and defining a set of properties that lack identity.
- «CodeList», used for enumeration of an open list with valid attribute values.
- «Enumeration», used for enumeration of a fixed list with valid literal values.

3.6 Definition of Geometry Representation

The definition of geometry representation for ADE feature types is optional. It is applied when the new feature type represents a real-world object with geometry. In such a case, the new feature type should be derived directly or indirectly from *Core::AbstractSpace* or *Core::AbstractSpaceBoundary*. In the current study, this step is omitted since the proposed ADE extends only semantically the CityGML Vegetation module.

3.7 Decide on LOD

The last step requires deciding on which Level of Detail (LOD) should be topologically correct. The existing CityGML 3.0 geometries are reused instead of explicitly defining them in the ADE classes themselves. Thus, a multi-geometry representation in different LODs of the ADE classes is possible.

4. Implementation

The Vegetation module of CityGML 3.0 represents vegetation objects with vegetation-specific thematic classes. Additional properties are added to the top-level feature types *SolitaryVegetationObject* and *PlantCover* via the ADE “hook” mechanism. Additionally, new feature types are defined according to the ADE domain.

4.1 SolitaryVegetationObject Properties

The *SolitaryVegetationObject* feature type represents single vegetation objects like bushes or trees. The new data type *SolitaryVegetationObjectProperties* is derived from the *ADEOfSolitaryVegetationObject* and is used to add the corresponding Vegetation ADE properties, including planting and extermination years, protection status, classification, ownership, etc. (Figure 1). Since the vegetation objects consist of three main parts, crown, trunk and root, new classes are defined and derived from *AbstractFeatureWithLifespan* to describe the specific characteristics of these parts. The *Crown* feature type represents the crown of the tree and is described with properties representing the diameter, type, density, clearance and leaf texture. The crown type and density are defined using code lists to enable extensibility. The leaf texture is supposed to be read from a URI, providing a resource which is useful for visualization purposes. The *Trunk* feature type corresponds to the trunk of the tree and is described with properties for diameter, height, type and texture. Similarly to the crown type, the trunk type is defined using a code list and the trunk texture is available from a URI. The *Root* feature type represents the roots of the tree, having properties of diameter and root ball depth.

The solitary trees have specific crown shapes, which are not affected by neighboring trees or buildings. According to the literature and urban tree catalogues, the most commonly occurring tree crown shapes are pyramidal, cylindrical (columnar), spherical (round), oval and half-ellipsoidal (baumportal.de; Franceschi, 2022; GALK, Jinasena, 2023; Liu, 2021; Summit, 1999). Other frequently appeared tree crowns are weeping, umbrella, conical, upright funnel and irregular (Othman, 2014). Based on this, the code list is defined to describe the variability of crown types includes the following items: irregular, conical, cylindrical, spherical, ellipsoidal, oval, umbrella, upright funnel and weeping. Since the code list is extensible, new items can be added for particular requirements.

Since many different patterns of trunk branching have been defined and many of them represent evolutionary adaptations to a given environment or life strategy, three general trunk types are considered. They are related to the original development of a branch or axis. If a given trunk axis is derived from a single meristem, the trunk type is called monopodial. In contrast, if a given axis has multiple branches derived from separate meristems, the trunk type is sympodial. Finally, a rare type of branching is dichotomous, in which a single meristem divides equally into branches (Jinasena et al., 2013). The trunk types are classified in 9 categories by Tarsha Kurdi et al., 2024. The trunks are classified in 3 main classes according to the number of axes – single trunk, multiple trunk and forked trunk. From vertical point of view the trunk types are classified in vertical, oblique and twisted. To avoid complexity and make the conceptual model comprehensive for a diverse group of stakeholders three main trunk types are considered – single, multiple and low-branched. This enables a practical on-site approach in measuring the trunk height when collecting data.

Since many classification systems exist for species and habitats, which are partially inconsistent with each other, the approach applied in the ADE is based on referencing of external classification systems. A new *SolitaryVegetationClassificationSystem* data type is defined, having properties about the name of the classifications system, its unique identifier represented with URI and code, and the exact classification of the object within the classifications system. Such an approach allows several classification systems to be referenced, enabling data interoperability between different databases and registers.

The *AbstractFeatureWithLifespan* is employed as the newly introduced classes, *Crown*, *Trunk*, and *Root* have time-dependent properties. Those encompass among others *crownDiameter* for the *Crown* feature type, *trunkHeight* for the *Trunk* feature type and *RootBallDiameter* for the *Root* feature type. Since the features *Crown*, *Trunk* and *Root* are not derived from the *AbstractCityObject*, they do not inherit the relation to *AbstractDynamizer*. Therefore, a new relation is modelled

through a new *SolitaryVegetationObjectGrowth* class to *AbstractDynamizer*.

4.2 SolitaryVegetationObjectGrowth Feature Type

The growth of single trees is handled by a new *SolitaryVegetationObjectGrowth* class, inheriting *AbstractDynamizer*. The growth is described with the following properties:

growthType, corresponding to the characteristic of the tree, which is measured, e.g. trunk height, crown diameter, etc.
growthValue, specifying the value of the respective characteristic.

- *acquisitionMethod*, defining how the measured value is obtained, such as estimation, measurement, simulation, calibrated simulation, etc.
- *healthStatus*, representing the health status at the time of recording the value of the characteristic.

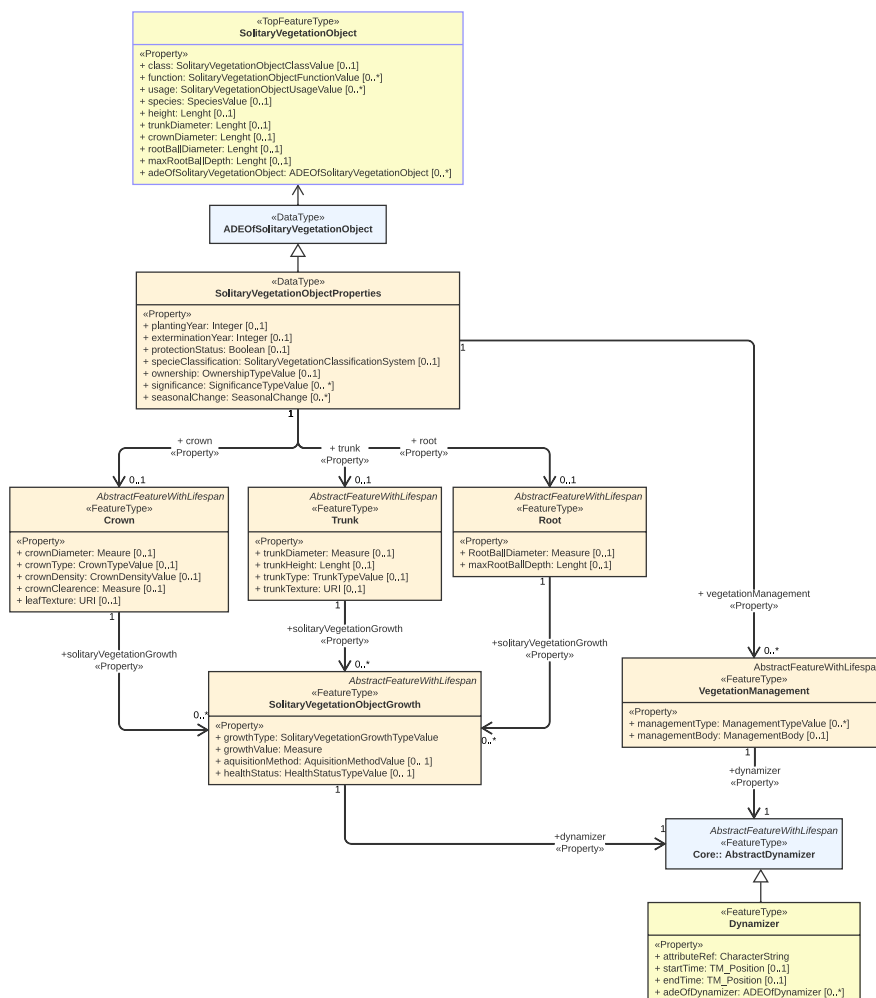


Figure 1. SolitaryVegetationObject ADE Module.

4.3 PlantCover Properties

The *PlantCover* feature type represents a space covered by vegetation. The new data type *PlantCoverProperties* is derived from the *ADEOfPlantCover*. It adds the corresponding Vegetation ADE properties, including planting year, protection status, species richness and relative abundance, ownership, etc. (Figure 2). A new *PlantCoverClassificationSystem* data type is defined, featuring properties about the name of the classifications system, its unique identifier represented with URI and code, the exact classification of the object within the classifications system, and relative abundance. In contrast to the

specieClassification property of the *SolitaryVegetationObject* feature type, where only one value is allowed, the *habitatClassification* property of the *PlantCover* feature type can have a list of values, representing the ratio of the various habitats available in the plant cover.

4.3.1 PlantCoverGrowth Feature Type

The growth of the plant cover is handled by a new *PlantCoverGrowth* class, inheriting *AbstractDynamizer*. The properties of this class are like those of the *SolitaryVegetationObjectGrowth* class.

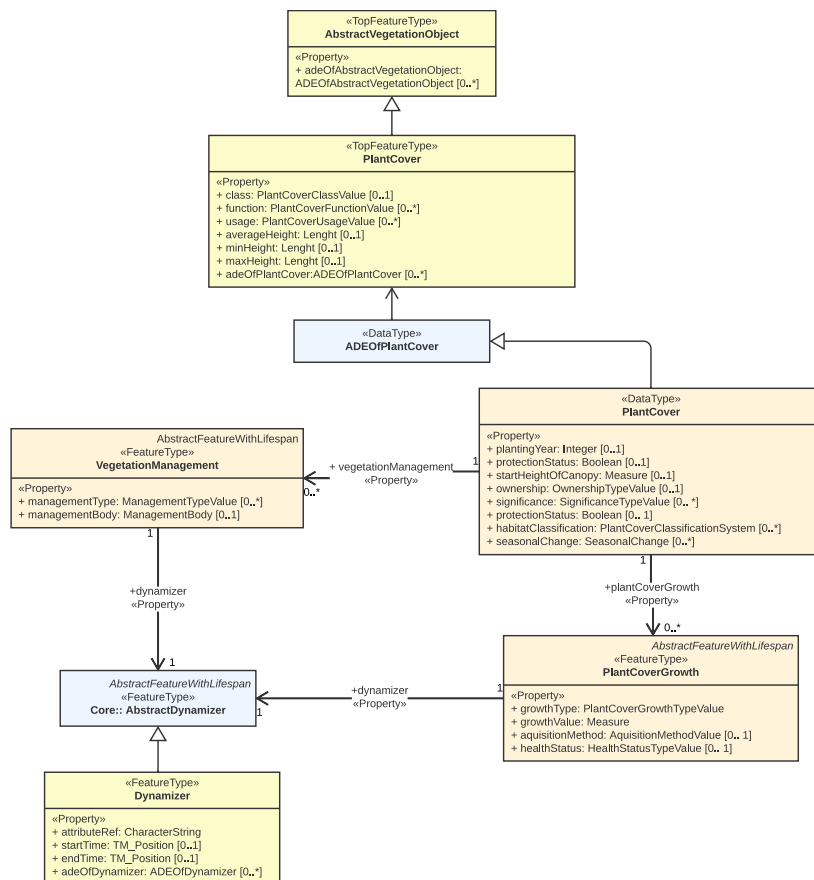


Figure 2. PlantCover ADE Module.

4.4 VegetationManagement Feature Type

The management of both solitary vegetation and plant covers are modelled by a new *VegetationManagementClass*, introducing an additional ADE property like *SolitaryVegetationObjectGrowth* and *PlantCoverGrowth*. A special *ManagementTypeValue* enumeration is defined for the management type, including values related to hazardous tree removal, tree bending, pruning, fertilisation, herbicide application, watering, etc. The management body is defined with a new *ManagementBody* data type with properties for name, type and address.

5. Discussion

Today, the modelling of vegetation data in a meaningful and comprehensive way meets many challenges which cities around the world face. Data heterogeneity and quality, integration complexity and lack of unified data models complicate the collaboration of stakeholders working in the urban vegetation domain. The CityGML standard has been conceived to overcome those challenges, yet the Vegetation module has not been revised from CityGML 2.0 to 3.0 (Kutzner, T., 2020). In consequence, the representation of vegetation in city models still lacks important properties and is less comprehensive than that of the built environment. Thereby, the accurate representation of

vegetation in 3D city models not only aims to depict the urban environment as realistically as possible, but also fosters a deeper understanding of cities through adding additional semantics. The proposed CityGML Vegetation ADE conceptual model therefore addresses this gap by extending the vegetation representation with both descriptive and dynamic characteristics. This is pivotal for simulating, managing, and analyzing urban environments in a way that handles the environment's complexity and change over time. The fact that vegetation is diverse and exhibits variegated forms and peculiarities all around the globe motivated the work on the ADE. During its implementation, especially while defining e.g. enumerations and code lists, the diversity and intricacies of vegetation posed challenges for unified representation. This issue is particularly apparent in habitat classifications, where, to date, there is no uniform global system in use that accommodates the peculiarities of locally used habitat classifications. To overcome this challenge the ADE allows reference to external classification systems based on URI, thus enabling interoperability between the systems and applications. By allowing local classifications to be introduced in the CityGML models, the flexibility of the ADE is achieved, which is a prerequisite for wide adoption.

Furthermore, different urban stakeholders have varying requirements when it comes to the representation of vegetation, which handling in the ADE could lead to increased complexity. That is why a balance between level of detail and usability is provided and therefore the broad application of ADE is encouraged. This approach opens possibilities for further improvements. Future developments of the ADE could incorporate more properties and include for instance various indices of vegetation such as the Normalized Difference Vegetation Index (NDVI), Leaf Area Index (LAI) or the Normalized Difference Water Index (NDWI). Moreover, the representation of subterranean vegetation parts could be enhanced. A more intricate depiction of underground vegetation structure, along with a comprehensive model of the subsurface environment – including potentially soil quality and biota – would broaden applications towards e.g. urban ecological models. For this purpose, a future investigation of the conceptual model for underground objects, called MUDDI (Model for Underground Data Definition and Integration) to standardize the representation of geospatial data related to the Earth's subsurface is intended.

To refine the ADE conceptual model, feedback from various stakeholders working in the urban vegetation domain, such as landscape architects, urban planners, ecologists, biologists etc., is scheduled to be collected through an online survey and expert interviews. This step aims at collecting more insights from different professionals globally to improve the representation of vegetation and to prove the ADE's applicability and usefulness.

The ADE conceptual model will be employed in the implementation of the in the City Digital Twin Pilot of Sofia, Bulgaria and Green Digital Twin of Tallinn, Estonia. Additionally, the proposed conceptual model will be applied for unified representation of the vegetation data stored in the online web-based tree mapping platform, named "OneTree". It is a citizen-science oriented GIS solution specifically designed for gathering the general information about the trees. The ADE conceptual model aligns with the specific data model behind the OneTree platform, where tree attributes are stored in a consistent manner starting with the base tree attributes like tree height, crown and trunk sizes, followed by more specific characteristics such as damages, health problems, maintenance needs and more.

A very rich knowledge base has been developed, providing for deeper species level characteristics and validation.

The Vegetation ADE contributes to the research community by opening several avenues for future research, including the development of more accurate simulations, analysis and visualizations, urban heat island effect investigation or environmental impact assessments. These directions not only promise to expand the adoption of CityGML but also offer a path towards a more integrated and holistic approach to urban modeling, reflecting the complex interdependencies of the urban ecosystems.

6. Conclusion

This paper proposes a Vegetation ADE conceptual model of the CityGML 3.0, designed to provide a more detailed and dynamic representation of vegetation. Additional properties and classes are incorporated to the existing vegetation module based on the ADE hook mechanism. The dynamic changes related to growth and management of the vegetation are addressed through the *Dynamizer* module. The ADE is defined at a conceptual level, allowing for consideration of different encoding specifications such as GML, JSON, etc. Future work includes refining the ADE by obtaining feedback from diverse stakeholders, working in different fields including urban planning, landscape engineering and architecture, ecology, and others, as well as applying the ADE to real case studies.

In summary, the proposed CityGML Vegetation ADE conceptual model marks a significant step forward in the standardized representation of urban vegetation within 3D city models and urban digital twins. While acknowledging its current limitations, we envision its evolution as an essential component of future representations of cities, aiding data interoperability and overall contributing to the data-driven development, maintenance, and management of urban landscapes.

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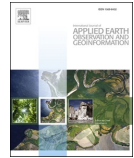
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Urban vegetation semantics in CityGML: Key stakeholder survey findings and vegetation ADE development[☆]

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ABSTRACT

Urban vegetation, providing critical ecosystem services and supporting biodiversity, is essential for sustainable and resilient cities. Yet its semantic representation in urban digital twins and 3D city models remains inadequate for advanced modeling. Open data standards facilitate interoperable urban modeling. However, the CityGML standard, despite its widespread adoption, provides limited semantic depth for vegetation in its current Vegetation module, constraining dynamic and interdisciplinary applications.

To address this, we present the international stakeholder survey evaluation alongside the updated version of the conceptual model of the CityGML 3.0 Vegetation Application Domain Extension (Vegetation ADE v1.1). The ADE enhances semantic richness by introducing extended attributes, feature types, enumerations, and code lists for both *SolitaryVegetationObject* and *PlantCover*, including structural components (crown, trunk, root) and dynamic properties via the CityGML *Dynamizer* module. Additionally, a vegetation management class is established.

Refined through feedback from an international stakeholder survey, the model reflects practical requirements from domains including urban studies, ecology, and public administration. The core data modeling structure of ADE v1.0, unanimously supported by survey participants, was retained for ADE v1.1. The new version introduces substantial improvements: 15 attributes were modified, 12 added, and one removed. Nine code lists were revised and one added. Two enumerations were updated. These enhancements ensure ADE v1.1 achieves improved semantic clarity and usability, supporting diverse applications such as vegetation monitoring and adaptive green infrastructure management. This work demonstrates a replicable methodology for participatory standard development and advances the integration of vegetation into data-driven urban digital twins and 3D city models.

1. Introduction

Urban vegetation is increasingly recognized as a key component of sustainable cities. Besides aesthetic values, urban vegetation also offers essential ecosystem services (Stroud et al., 2022) and forms a foundation for nature-based solutions to address pressing global and local challenges such as climate resilience and biodiversity loss (Lemes De Oliveira, 2025). For advanced research on and planning of urban vegetation, 3D City Models (3DCM) and Urban Digital Twins (UDTs) are being established as key technologies (Mrosła et al., 2025a). With the adoption of digital modeling tools, open standards play a vital role in fostering interoperability and integrating heterogeneous urban data.

Today, CityGML is one of the most commonly applied standards for 3DCM and UDTs (Bachert et al., 2024; Jeddoub et al., 2023). By enabling standardized representation, storage, and exchange of digital 3DCM, CityGML supports urban planning, management, and monitoring. It goes beyond capturing the geometry and visual appearance of city models by explicitly modeling object semantics, including thematic attributes, classifications, and hierarchical relationships (Kolbe, 2009). It ensures lossless data exchange, facilitates the development of reliable software solutions, and allows stakeholders from diverse backgrounds to manage complex information more effectively—ultimately enhancing overall data interoperability (Agugiaro et al., 2018). This data modeling approach is especially important since many cities collect vegetation

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data. However, this data is often fragmented, stored in diverse formats, and lacks harmonization, making integration into comprehensive urban models difficult.

The current CityGML Vegetation module provides only a basic semantic structure for vegetation, resulting in a less detailed and less functional representation of vegetated infrastructure compared to buildings and other urban features. Consequently, urban vegetation's content remains ambiguous (Zhang et al., 2022). This gap limits the potential for advanced analyses, simulations, and holistic urban planning that leverage the benefits of urban vegetation in the digital realm.

To address these shortcomings, we previously proposed a Conceptual Model (CM) for an Application Domain Extension (ADE) v1.0 of the CityGML 3.0 Vegetation module (Petrova-Antonova et al., 2024a, 2024b).

An ADE is a structured and formal extension of the CityGML CM, tailored to the needs of a specific application or domain. The ADE mechanism enables application-specific information to be integrated with the CityGML CM in a consistent and systematic manner. This approach allows CityGML to address specialized information requirements while preserving its core concepts and semantic structures. Unlike generic city objects and attributes, ADEs provide a formally defined framework that ensures application data can be validated, thereby supporting semantic interoperability. In earlier versions of CityGML, the ADE mechanism was defined exclusively at the level of XML Schema encoding. With CityGML 3.0, however, ADEs are elevated to platform-independent conceptual models that can be mapped to various target encodings (Kolbe et al., 2021; Kutzner et al., 2020).

The ADE concept has been discussed extensively in the literature, ranging from brief references to detailed accounts of implementations (Biljecki et al., 2018). One of the most advanced initiatives in this field is the Energy ADE, collaboratively developed by multiple European organizations, primarily universities (Bachert et al., 2024; Nouvel et al., 2015). The flexibility of the ADE concept was also demonstrated through Noise ADE (Konde, 2015; Kumar et al., 2017). UtilityNetworkADE facilitates the modeling of utility networks within CityGML. It extends the data model to include utilities, such as freshwater and electricity, along with details on usage, materials, operating parameters, and the population served by the network (Kutzner and Kolbe, 2016). An ADE adapted for immovable property taxation takes into account the legal and administrative aspects (Çagdaş, 2013). A few researchers have proposed extending CityGML to incorporate legal concepts from the Land Administration Domain Model (LADM) (Lemmen et al., 2015; Li et al., 2016). An ADE for grotto niches based on CityGML 3.0 was developed to standardize 3D semantic modeling of cultural heritage in Asia, enhancing data interoperability, spatial analysis and simulation (Yang et al., 2024).

The aim of developing a Vegetation ADE is to enhance the functional and semantic richness of vegetation modeling by introducing new data types, feature types, properties, code lists, and enumerations relevant to both *SolitaryVegetationObject* (SVO) and *PlantCover* (PC) feature types. Additionally, a new feature type for vegetation management was introduced. This proposed extension leverages the new mechanisms introduced in CityGML 3.0, such as the Dynamizer module for representing dynamic data (Kutzner et al., 2020), and supports references to external classification systems to ensure interoperability across platforms and disciplines (Petrova-Antonova et al., 2024a). While our previous work introduced the CM (Petrova-Antonova et al., 2024a) and technical user guide for the CityGML 3.0 Vegetation ADE v1.0 (Petrova-Antonova et al., 2024b), this study extends that work through a systematic evaluation and refinement process involving direct engagement with international stakeholders and expert communities.

Given the variability of vegetation across regions due to climate and

ecological conditions, it was essential to engage a broad, international stakeholder community. To this end, a structured online survey collected feedback from a diverse group of professionals including e.g., urban planners, ecologists, landscape architects, GIS analysts, and government authorities. This user-driven process ensured the vegetation CM addresses global requirements, accounts for regional variations, and informed the refinement of the ADE's structure, semantics, and attributes based on empirical evidence. The methodology emphasizes the democratization of standard development by fostering open participation across disciplines and geographies. Therefore, reducing the risk of regional or sector-specific biases. The resulting Vegetation ADE version 1.1 (v1.1), presented in this paper, enhances the model's robustness, interoperability, and practical applicability for use in 3DCMs, UDTs and urban green infrastructure management. It supports more reliable integration of vegetation data, e.g., derived from earth observation, into 3D city models, enabling improved environmental assessments, planning, and decision-making.

This paper presents the evaluation of the stakeholder survey, the conceptual model revisions informed by this feedback and the updated CityGML Vegetation ADE v1.1. The core data modeling structure established in ADE v1.0, unanimously supported by survey participants, has been preserved in the ADE v1.1. The enhancements implemented in the new version comprise targeted adaptations at the attribute level, including 15 modifications, 12 additions, and one removal. Furthermore, nine code lists were revised and one newly introduced. Two enumerations were updated to reflect emerging requirements and harmonize terminology. An overview of these improvements is provided in Tables 1 and 2.

The results underscore the importance of standardized, semantically rich vegetation data models for urban planning and resilience, while demonstrating a replicable methodology for participatory data model development that bridges the gap between theoretical design and operational application.

2. Background

2.1. Vegetation modeling in (3D) city models and UDTs

To date, vegetation has been depicted in 3DCMs with varying levels of detail (LoD) and accuracy, e.g., simplified geometries or symbolic representations (Dimitrov and Petrova-Antonova, 2021), procedural models ranging from L-systems to interactive modeling environments (Lintermann and Deussen, 1999; Prusinkiewicz and Lindenmayer, 1990; Wang et al., 2023) and structurally detailed representations, such as colored point clouds (Julin et al., 2018). Despite emerging methods offering integration of geometric precision with semantic richness (Ugla et al., 2023; Yazdi et al., 2024b), vegetation visualizations in 3DCMs are often used independently of semantic information. Yet, systematic semantic information can enhance the interpretability and operationalizability of vegetation data in the urban context (Argota Sánchez-Vaquerizo, 2025).

In Building Information Modeling (BIM), vegetation has been semantically represented e.g., based on the IFC standard, but plant-specific 3D models and semantic definitions are not widely adopted nor widely available in BIM authoring software (Boje et al., 2020; Gobeawan et al., 2021). Semantic attributes mostly include measured plant geometry dimensions. Meanwhile, custom definitions such as planting phase or flower color have been mentioned as ways to add more useful semantic data (Gobeawan et al., 2021; Torrejón García, 2022). City Information Models (CIMs) can incorporate more vegetation-related data (Xue et al., 2021), but there is no widely adopted CIM standard for linking trees or green areas to environmental functions or

biodiversity metrics. Another relevant input for spatially organized semantic urban vegetation modeling comes from structured urban tree registries. These include models like e.g., Shu et al. (2022)'s Tree Information Model, supporting 3D geometry in high LoD, as well as management and growth-related semantics. Further, i-Tree is designed to assess and manage urban forest resources (Nowak, 2021).

Due to the lack of standards for detailed semantic modeling of non-woody urban vegetation, their integration into 3DCMs and UDTs remains limited. In the field of ecology, species observation data are often based on standards like Darwin Core (Wieczorek et al., 2012) which may be integrated into UDTs and 3DCMs.

2.2. CityGML

CityGML is an open data model and exchange format developed by the Open Geospatial Consortium (OGC) for exchanging and coherently representing 3DCMs. CityGML supports the interoperable modeling of urban environments in different Levels of Details (LoD), enabling the integration of spatial and semantic information in a structured, standardized way. Unlike pure geometry-focused formats, CityGML incorporates semantic classes for e.g., buildings, roads, vegetation, waterbodies and allows each object to have detailed geometric, topological, and semantic properties (Kutzner et al., 2020, p. 3). Since its initial release as CityGML 1.0 in 2008 (Kolbe, 2009), the standard has undergone iterations, with CityGML 2.0 published in 2012 and the most recent CityGML 3.0 in 2021 (Kutzner et al., 2020). Each version introduced enhanced capabilities, expanded thematic modules, and improved support for dynamic and complex urban features, reinforcing CityGML's role as a key standard for interoperable 3D city modeling.

CityGML supports the extension of its core data model through ADEs, which enable the addition of custom object types, attributes, and relationships while preserving compatibility with the standard (Kutzner et al., 2020). ADEs have been widely adopted across domains such as energy, noise, utility networks, indoor features and railways (Biljecki et al., 2018).

2.3. Vegetation modeling in CityGML

Vegetation in CityGML is modeled through a dedicated Vegetation module that distinguishes between *SolitaryVegetationObject* – individual vegetation objects, such as single trees or bushes, and *PlantCover* – areas covered by vegetation, like meadows or forests (Fig. 15). Each vegetation object is represented as a feature with both geometric and semantic properties, enabling detailed descriptions such as species and height.

In recent years, several authors have proposed enhancements to the LoD framework for 3D modeling of the CityGML *SolitaryVegetationObject* class. The proposed 3D representations range from 2D representations (LoD1) and basic volumetric shapes (LoD2) to increasingly refined 3D models (LoD3 and LoD4), which reflect the main structural divisions of large plants including trunk, canopy and root depth (Gobeawan et al., 2018; Ortega-Córdova, 2018; Zhang et al., 2022). Some studies have further incorporated more detailed elements such as branches and leaves (Ambarwari et al., 2024; Zhang et al., 2022). The 3D models typically represent trunk and canopy dimensions as well as canopy shapes (Gobeawan et al., 2018; Rötzer et al., 2020; Zhang et al., 2022). The parameters are frequently derived from remote sensing and photogrammetric survey data (Gobeawan et al., 2018; Suwardhi et al., 2022; Yazdi et al., 2024b) or generated through simulations of plant allometric growth patterns (Rötzer et al., 2020; Yazdi et al., 2024a). Pantazatou et al. (2024) recommended the elaboration of a CityGML ADE for vegetation.

The authors identified potential in the utilization of semantic data encoded within CityGML in various urban planning applications

(Pantazatou et al., 2024) including e.g., the estimation of ecosystem service provision, such as air purification, recreational benefits (Ortega-Córdova, 2018), carbon sequestration and microclimate regulation (Zhang et al., 2022) and urban heat island mitigation (Ambarwari et al., 2024; Rötzer et al., 2020). However, proposed extensions to the semantic information model have been limited to plant taxonomic details e.g., age, trunk and canopy measurements, and a few ecosystem service indicators. Custom parameters have been named as a way to record e.g., soil information, nursery and plantation data (Gobeawan et al., 2018; Zhang et al., 2022).

Notably, extensions addressing attributes and LoDs for *PlantCover* objects have not been explored.

2.4. CityGML vegetation ADE proposal v1.0

To advance the holistic representation of urban environment in 3DCMs and UDTs, we previously proposed a conceptual model for a CityGML 3.0 Vegetation ADE v1.0 (Petrova-Antonova et al., 2024a, 2024b). It aims to enhance the representation, interoperability, and dynamic modeling of vegetation data within 3DCMs and UDTs, contributing to the standardization and integration of ecological information in digital urban infrastructures. The proposed ADE v1.0 extends the *SolitaryVegetationObject* and *PlantCover* feature types from the CityGML Vegetation module without modifying the core schema, using the CityGML 3.0 “hook” mechanism. Thereby, new simple and complex data types and properties, capturing both static and dynamic characteristics of urban vegetation, are introduced (Petrova-Antonova et al., 2024a).

For *SolitaryVegetationObject*, the *adeOfSolitaryVegetationObject* attribute references the new *ADEOfSolitaryVegetationObject* data type, enabling the addition of extended semantics through *SolitaryVegetationObjectProperties* (Fig. 16). To capture the main structural components of woody plants, the ADE v1.0 introduces, comparable to existing tree information models, dedicated classes for crown, trunk, and roots, each derived from *AbstractFeatureWithLifespan*. Similarly, the *PlantCover* feature type is extended using the *adeOfPlantCover* attribute and the *ADEOfPlantCover* data type (Fig. 17). *PlantCoverProperties* supports additional semantics, enhancing the ability to model complex vegetation covers (Petrova-Antonova et al., 2024a).

Dynamic aspects of vegetation, such as growth and seasonal changes, are addressed through the *Dynamizer* module introduced in CityGML 3.0 (Kutzner et al., 2020; Petrova-Antonova et al., 2024a). This module enables the integration of time-dependent data, supporting the transition from static 3D models to dynamic UDTs. By incorporating temporal vegetation data, the proposed Vegetation ADE holds potential to enhance the accuracy of spatial analyses and to strengthen decision-making for urban sustainability and resilience. To present plant cover and solitary vegetation object growth and change dynamics, the *PlantCoverGrowth* and *SolitaryVegetationObjectGrowth* classes were introduced in the ADE v1.0. Inheriting from *AbstractDynamizer*, these classes are designed to encapsulate thematic attributes related to the temporal development of the respective vegetation. A dedicated *VegetationManagement* class was introduced in the ADE v1.0 enabling the documentation of management practices for both solitary vegetation objects and plant covers (Petrova-Antonova et al., 2024a).

The Vegetation ADE also presents extensible code lists and enumerations for key attributes, such as tree crown shapes, management activities, and potential hazards. This approach ensures interoperability and adaptability across different cities and platforms. Moreover, for properties such as habitat classification, the ADE allows referencing of external classification systems via URIs to accommodate local classification systems.

The proposed Vegetation ADE thus enables detailed semantic and temporal representation of urban vegetation. Moreover, it enhances

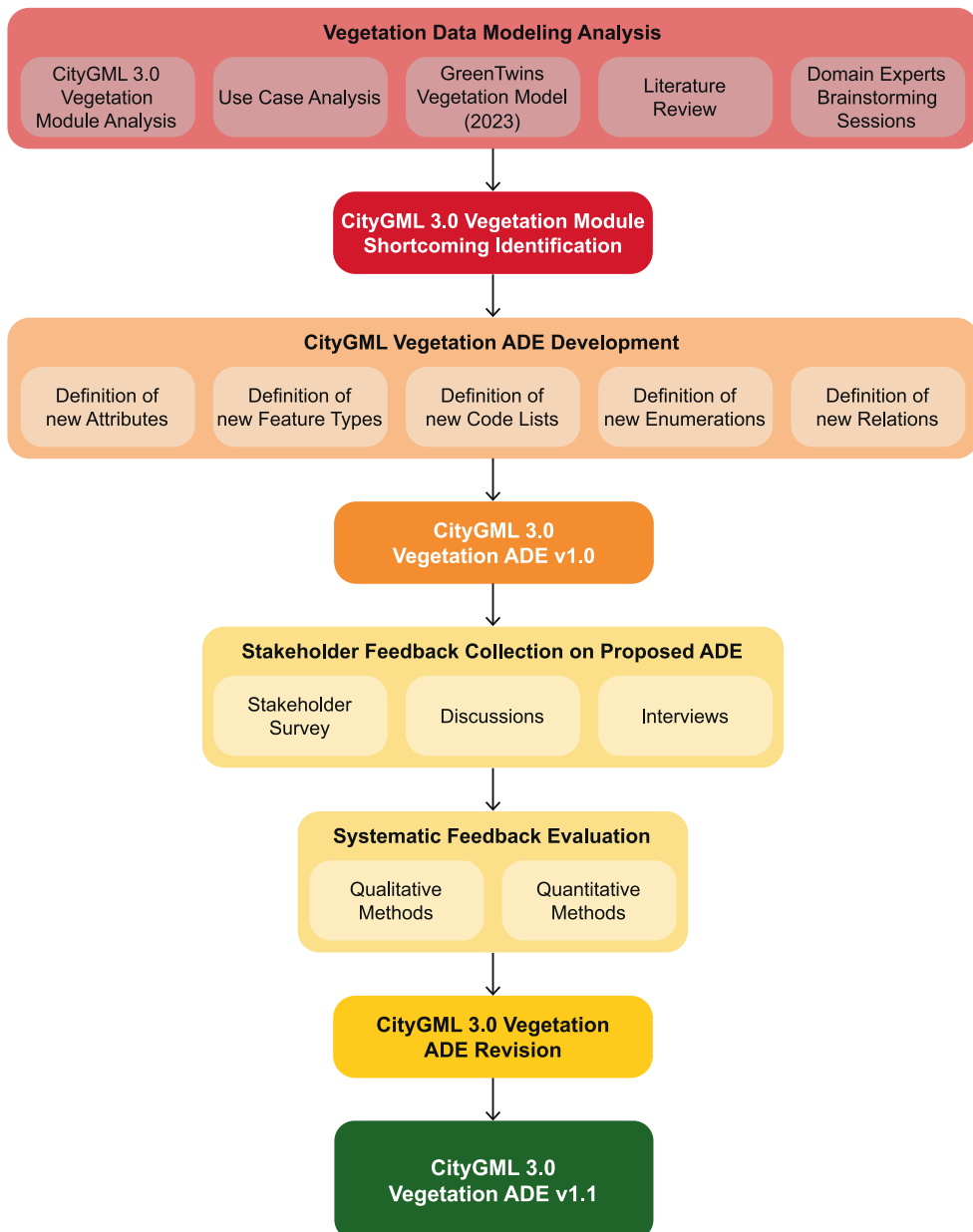


Fig. 1. Workflow of the CityGML 3.0 Vegetation ADE development from analysis and shortcoming identification (red) to development of the ADE version 1.0 (orange), to stakeholder involvement and ADE version revision (yellow) to CityGML 3.0 Vegetation ADE v1.1 release (green).

applications such as vegetation monitoring and environmental simulations.

3. Methodology

The methodology for developing the CityGML 3.0 Vegetation ADE CM (Fig. 1) is grounded in a model-driven approach for semantic data modeling, following established guidelines for CityGML ADE development (Kolbe et al., 2021; van Den Brink et al., 2013) and aligning with the ISO 191xx series of geographic information standards. Unified Modeling Language (UML) was selected as the formal modeling language to define the ADE classes, ensuring compliance with CityGML 3.0 requirements and facilitating communication with diverse stakeholders. A detailed description of the development of the CityGML 3.0 Vegetation ADE Proposal v1.0 is given in (Petrova-Antonova et al., 2024a).

3.1. Survey design and implementation

To ensure the proposed Vegetation ADE meets diverse stakeholder needs and avoids bias, we adopted a participatory approach to model validation and refinement. The aim was to assess the clarity, semantic richness, practical relevance, and integration potential and to identify gaps or additional requirements in 3DCM and UDT contexts. Therefore, a structured online survey was developed to collect stakeholder feedback.

The stakeholder survey was systematically structured to align with the components and logic of the ADE, with each section introducing concise explanations of relevant concepts, definitions, and attributes before specific questions were presented. Participation was anonymous unless respondents chose to provide contact details. All questions were optional to accommodate varying expertise levels. Stakeholders were asked to rate the relevance of each property using a 5-point Likert scale and to assess key aspects including data modeling, data types, code lists, enumerations, and the handling of dynamic data. To ensure both quantitative and qualitative insights, the survey incorporated a combination of closed and open-ended questions. For each property, open-ended questions included: (1) "Would you add, rename, or remove any [code list name/enumeration name] values? If yes, please specify;" (2) "Please share any references, standards, or other resources that could help further develop this attribute and its CodeList;" and (3) "Do you have any comments, recommendations, or thoughts on '[property name]' for the [solitary vegetation object / plant cover / vegetation management] or its code list [code list name]?" The complete survey instrument is available as Supplement S1.

To support stakeholders from varied backgrounds, a comprehensive Technical User Guide (Petrova-Antonova et al., 2024b) that explains CityGML, data modeling principles, terminology, and the proposed ADE v1.0 was published on Zenodo and referenced directly within the survey.

In addition to the online survey, participants were invited to complete the questionnaire with direct support from the research team. Semi-structured interviews and informal discussions were conducted to assist stakeholders in understanding the survey content and to ensure accurate and informed responses. This approach aimed to enhance the quality of feedback and encouraged participation from diverse backgrounds.

The survey, conducted in English and pre-tested, targeted an interdisciplinary audience. It was launched on 9 October 2024 and remained open until 15 April 2025. It was distributed internationally via professional networks, academic collaborations, and outreach to relevant associations and institutions.

3.2. Stakeholder survey evaluation and conceptual model revision

The stakeholder survey responses were comprehensively analyzed using both quantitative and qualitative methods. Quantitative data, such as Likert-scale ratings, were summarized using descriptive statistics to

identify patterns of consensus, divergence, and areas requiring further attention. Qualitative feedback was methodically coded using thematic analysis. Recurring themes, suggestions, concerns, and identified gaps were categorized to inform the refinement of the ADE. This allowed the integration of nuanced expert perspectives that may not have been captured by quantitative data alone.

The revision of the conceptual model for Vegetation ADE proposal version 1.1 was guided by two key principles: maintaining full compliance with CityGML's core framework to ensure interoperability and managing complexity by adding only stakeholder-supported and use-case essential features. This approach balances semantic richness with usability and scalability. Attributes were revised, renamed, or removed; code lists and enumerations were refined and expanded based on feedback to improve clarity, applicability, and inclusiveness across diverse contexts.

The stakeholder survey evaluation of the proposed ADE v1.0 and the resulting modifications applied to the proposed ADE v1.1 are summarized in Chapter 4 Results.

4. Stakeholder survey results and ADE v1.1 proposal release

This chapter presents the evaluation of the CityGML 3.0 Vegetation ADE v1.0 stakeholder survey and the resulting key modifications applied to the Conceptual Model, encompassing its properties, code lists, and enumerations (summarized in Tables 1 and 2) resulting in the ADE proposal v1.1. This chapter is organized to present the survey results following the CM's organization.

The comprehensive presentation of the updated ADE proposal v1.1, alongside its definitions and complete value lists and enumerations is available in Supplement S2 and Mrosła et al. (2025b).

4.1. Overview of survey respondent characteristics

The survey yielded a total of 37 submitted responses, which were included in the evaluation of the proposed CityGML 3.0 Vegetation ADE v1.0. Respondents represented a broad geographic and disciplinary spectrum, ensuring diverse perspectives in the evaluation. Survey participants reported affiliations in a total of 19 countries. When respondents indicated multiple places of work, all specified countries were included in the geographic distribution analysis (Fig. 2).

The geographic distribution shows a strong representation from European countries, particularly Germany and Bulgaria, which reflects both the project's institutional affiliations and the broader CityGML user base. The lower response rate from non-European countries could be attributed to language limitations and limited international outreach capacity. Nonetheless, the inclusion of participants from 19 countries provides a diverse, though uneven, geographic perspective on the proposed model.

Most survey respondents worked in the public research sector (19), followed by city or state institutions (11, Fig. 3). This distribution indicates strong representation from academic and governmental stakeholders in the feedback process. The predominance of respondents from public research institutions and governmental bodies (81 % combined) highlights the strong interest in standardized vegetation modeling among actors involved in planning, policy, and scientific analysis. The relatively lower representation from private sector stakeholders may indicate either limited awareness of the ADE or lower immediate relevance for e.g., commercial use cases, which should be considered in future dissemination efforts.

The most frequently represented professional fields were research and academia (22), GIS analyst (16), and urban planning/urban design (11), highlighting the technical and conceptual knowledge base among participants (Fig. 4). Several respondents also indicated experience in landscape architecture (4), software development (4), and governmental roles (4), suggesting cross-sectoral relevance of the proposed Vegetation ADE. Multiple selections were allowed. Respondents whose

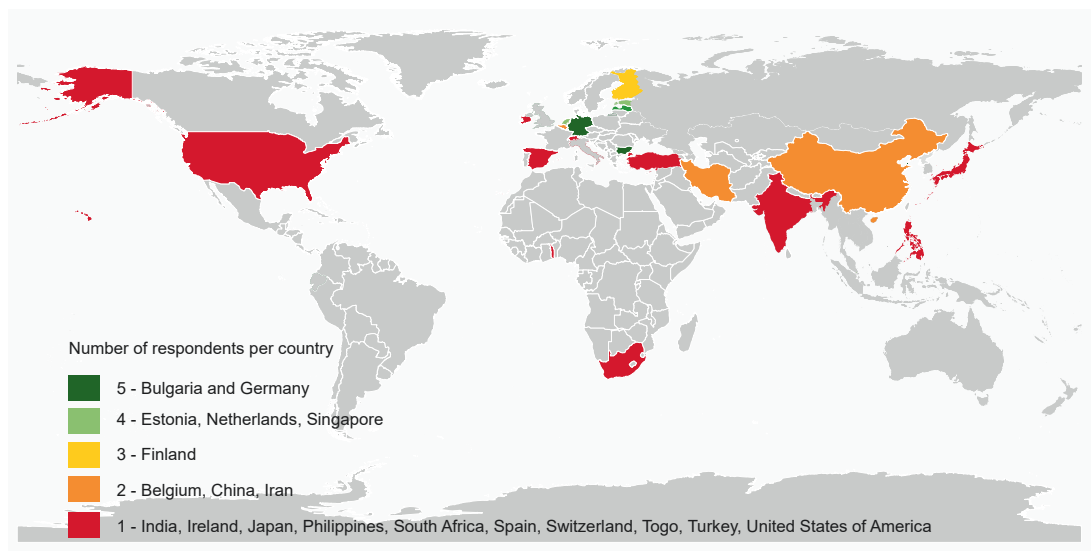


Fig. 2. Geographic distribution of survey participants by country of work. Countries are color-coded according to the number of participants.

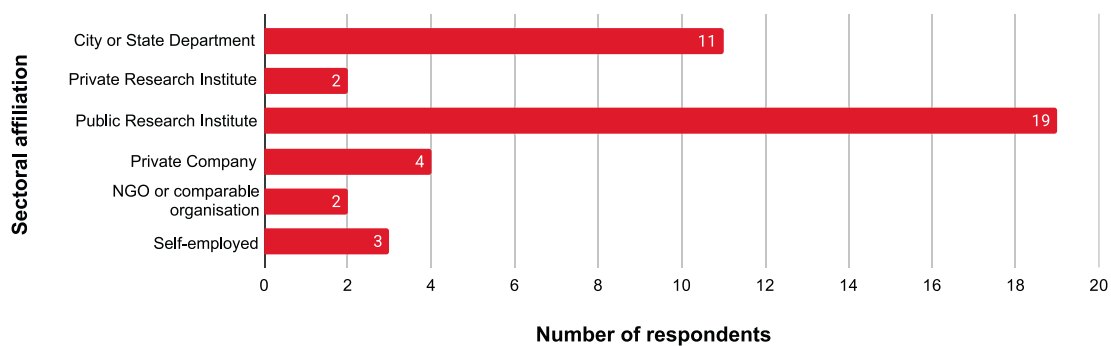


Fig. 3. Sectoral affiliation of survey respondents.

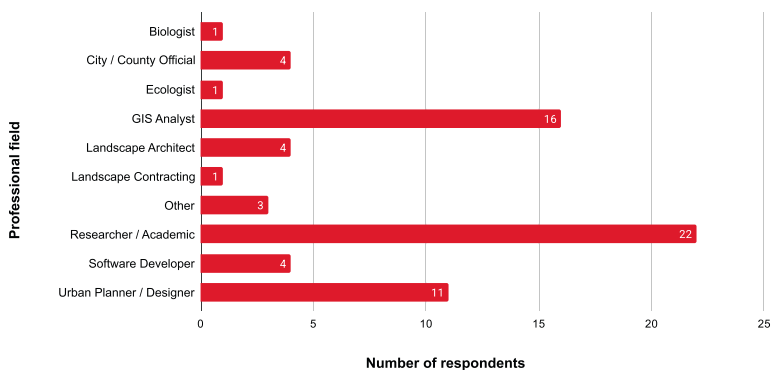


Fig. 4. Professional fields of survey respondents.

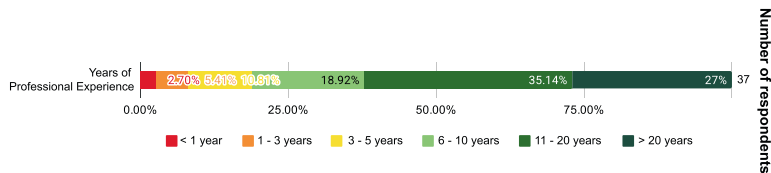


Fig. 5. Years of professional experience reported by survey respondents in their respective fields.

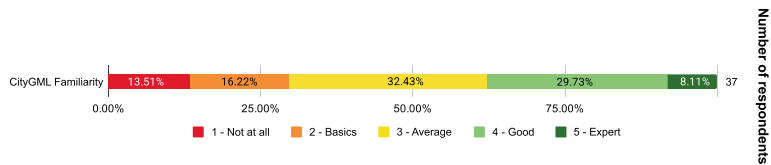


Fig. 6. Self-assessed familiarity with the CityGML standard.

specified roles were not captured by the listed categories selected 'Other' and identified themselves as manager, surveyor, and policy advisors.

The distribution of professional backgrounds reveals that the majority of participants had expertise in academia, GIS analysis, and urban planning—three key domains for implementing CityGML-based models. The presence of roles like landscape architecture, policy advisors, and software developers underlines the cross-sectoral relevance of the Vegetation ADE.

The majority of respondents have substantial professional experience: 35.1 % reported 11–20 years, and 27.0 % more than 20 years of professional experience in their respective fields (Fig. 5). Only a small proportion (2.7 %) had less than one year of experience. This indicates that the feedback was predominantly provided by seasoned professionals, likely reflecting deeper insights into the practical and technical needs of vegetation data modeling in urban contexts. The small number of early-career participants could be related to the specialized nature of CityGML and 3D city modeling, which may be less familiar to junior professionals.

4.1.1. CityGML expertise

While a majority of the respondents self-assessed their CityGML familiarity as average to good (62.26 %), only 8.11 % identified as experts

(Fig. 6). The varying expertise levels underline the challenge of balancing technical model requirements with accessibility for domain professionals who may not be deeply familiar with CityGML semantics. Participants with lower CityGML familiarity represented diverse professional backgrounds, including urban planners, landscape architects, landscape contractors, ecologists, and policy advisors focused on vegetation. Given this multidisciplinary composition, their input was highly valuable for assessing the practical applicability and interdisciplinary relevance of the proposed model, as it reflects real-world expertise with urban vegetation rather than specialized knowledge of CityGML alone. This diversity ensured comprehensive evaluation from end-users with domain-specific insights essential for effective model development.

4.2. Evaluation and refinement of solitary vegetation object

The stakeholder survey feedback showed unanimous support for the data modeling approach presented in Petrova-Antonova et al. (2024a,b), including the subdivision into structural parts crown, trunk, and roots as well as the new growth feature type. As a result, this approach was adopted unchanged in ADE proposal v1.1 (Figs. 15 and 16).

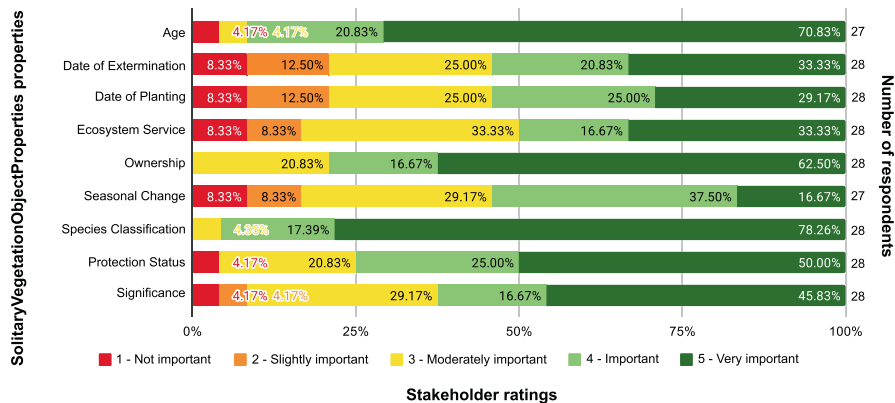


Fig. 7. Stakeholder rating of the proposed SolitaryVegetationObjectProperties properties.

4.2.1. Solitary vegetation object properties

Every attribute proposed for the *SolitaryVegetationObjectProperties* was rated as ‘important’ or ‘very important’ by at least 50 % of the respondents (Fig. 7). The ratings show strong consensus around the relevance of most proposed attributes, particularly attributes like species classification, ownership, and protection status. A regional breakdown of the responses reveals distinct priorities between European and non-European participants. For example *protectionStatus* ($n = 28$), which received 18 responses from Europe and ten from outside Europe. European respondents showed stronger support: 14 (77.8 %) rated it as ‘important’ or ‘very important’, compared to six (60 %) of non-European respondents. In contrast, *seasonalChange* ($n = 28$; 18 European, 10 non-European) displayed the opposite trend. Only 8 (44.4 %) of European respondents rated it as ‘important’ or ‘very important’, whereas 8 (80 %) of non-European respondents prioritized it. However, due to small non-European sample size ($n = 10$), these findings should be interpreted cautiously.

As suggested by the respondents, the property *dateOfPlanting* was renamed to *dateOfEstablishment* in v1.1 of the ADE proposal, to more accurately represent the various modes of vegetation establishment besides planting. Additionally, the new attribute *establishmentMeans* was introduced to define the methods of establishment, supported by the corresponding code list *EstablishmentMeansValue*. *Age* is time-varying, changing annually and therefore would require annual updates or the application of a versioning concept, which has not been considered in the ADE Proposal v1.0. Additionally, multiple respondents highlighted the lack of accurate ages for SVOs, often only being recorded in time ranges. Since an approximate *age* can be derived from *dateOfEstablishment*, the attribute was removed to avoid redundancy and promote data consistency over time.

The attribute *ownership* was renamed to *ownershipType* to more accurately convey that the property describes the category or type of ownership, rather than specifying an individual owner. This change enhances semantic clarity and ensures alignment with the intended use of the attribute. Respondents highlighted that ownership of SVOs and PCs can involve multiple parties with potentially hierarchical or overlapping responsibilities. To reflect this reality, the multiplicity of the *ownershipType* property was updated to allow zero or more [0..*] associations with the corresponding data type, replacing the previous constraint of zero or one [0..1]. Vegetation protection statuses vary widely across regions and contexts, carrying different implications, e.g., regarding permitting requirements or conservation measures. To capture this complexity beyond a simple Boolean value, the property *protectionStatusReference* was introduced in the ADE v1.1. Where available, it enables the referencing of a specific protection status via a URI, thereby supporting semantic clarity and interoperability with external

registers or databases.

Additionally, the attributes *leafAreaIndex* and *normalizedDifferenceVegetationIndex* have been added to the ADE v1.1, each as optional and of type *Real*, reflecting their relevance for a range of ecological analyses and simulation models highlighted by the respondents. The attributes *dateOfExtinction* and properties *ecosystemService*, *protectionStatus*, *seasonalChange*, *significance* and *speciesClassification* remained unchanged from v1.0 to v1.1 of the ADE proposal. As no objections were raised, the data types *Measure*, *SeasonalChange* and *SolitaryVegetationObjectClassification* have not been altered.

4.2.2. Crown

The attribute ratings indicate that *crownDiameter* (93.5 %), *crownClearance* (70.5 %), and *crownDensity* (54 %) are particularly valuable, with a majority of respondents rating them as ‘important’ or ‘very important’ (Fig. 8). These findings suggest a clear demand for modeling crown dimensions and characteristics that affect spatial configurations, environmental simulations, and urban management applications. Lower scores for *leafTexture* and *crownType* reflect their more specialized relevance with applications in representational scenarios. Since fewer than 50 % of respondents rated *crownType* and *leafTexture* as ‘not important’ or ‘slightly important’, they are retained for the ADE v1.1 to offer flexibility for projects with specific thematic or representational needs.

Based on stakeholder feedback, the attribute originally referred to as *crownClearance* has been renamed to *crownBaseHeight* to improve clarity and align with terminology commonly used in North American arboricultural and urban forestry contexts. The term *crownClearance* was considered potentially ambiguous, particularly in relation to regulatory frameworks concerning vertical clearances around e.g., power lines. The revised term more accurately reflects the intended meaning—the vertical distance from ground level to the lowest point of the tree crown—and supports clearer communication across different domains and geographic regions. The data types of *crownBaseHeight* and *crownDiameter* have been changed from *Measure* to *Length*.

In urban environments, tree crowns are frequently pruned or shaped in ways that deviate significantly from the natural growth forms typical of their species. To capture this distinction within the data model, the former *crownType* property has been particularized into *crownTypeNatural* and a new property, *crownTypeTrimmed*, was introduced. Attributes such as crown height are not explicitly included in the model, as they can be derived from existing attributes – specifically the *height* of the *SolitaryVegetationObject* and the attribute *crownBaseHeight* from the *Crown* class.

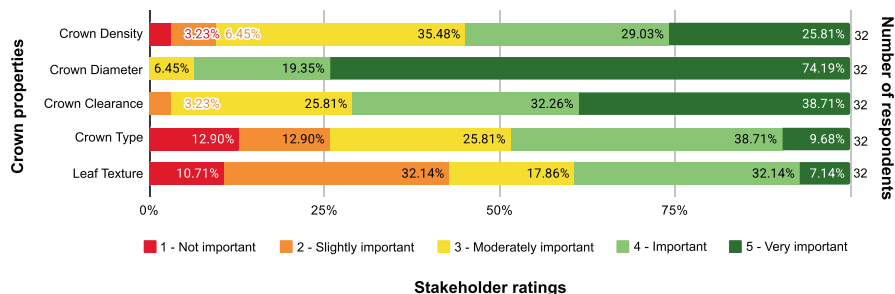


Fig. 8. Stakeholder rating of the proposed Crown properties.

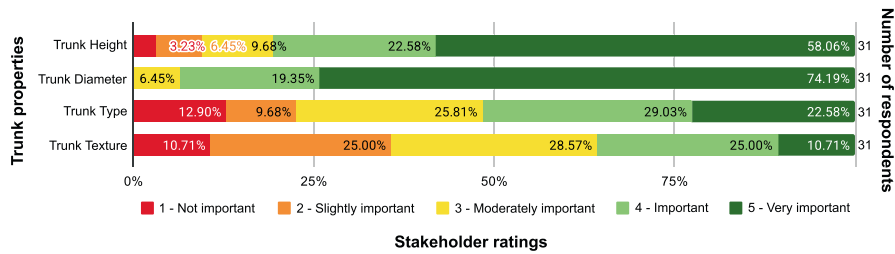


Fig. 9. Stakeholder rating of the proposed Trunk properties.

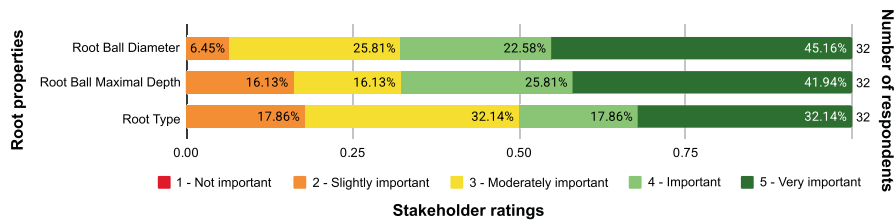


Fig. 10. Stakeholder rating of the proposed Root properties.

4.2.3. Trunk

The evaluation of the proposed *Trunk* properties underscores the high relevance of *trunkHeight* and *trunkDiameter*, with over 80 % of respondents rating them as ‘important’ or ‘very important’, followed by *trunkType* with over 50 %. In contrast, *trunkTexture* received more mixed responses, indicating lower overall priority (Fig. 9). However, it was not deemed irrelevant, suggesting its relevance in certain ecological or visualization contexts. As none of the proposed *Trunk* properties were rated as ‘not important’ or ‘slightly important’ by more than 50 % of participants, and qualitative feedback raised no significant concerns, the selection of attributes remains semantically unchanged from the initial ADE v1.0. However, as a technical refinement, the data types for *trunkHeight* and *trunkDiameter* were updated from *Measure* to *Length*.

4.2.4. Root

All proposed *Root* properties have been rated as ‘important’ and ‘very important’ by 50 % or more of respondents (Fig. 10), indicating a clear

recognition of root morphology’s significance in urban vegetation modeling. Hence, the properties were not changed.

To better reflect the diversity of root systems, which are not always spherical or ball-shaped, *rootBallDiameter* was renamed to *rootSystemDiameter* and *rootBallMaximalDepth* to *maxRootSystemDepth*. While this naming deviates from the terminology used in the CityGML Vegetation Module, where *rootBallDiameter* and *maxRootBallDepth* are still applied, it more accurately captures diverse root morphologies. This divergence introduces a temporary inconsistency, but also points to the *SolitaryVegetationObject* class, a *TopLevelFeatureType* that remained unchanged from CityGML 2.0 to 3.0 (Kutzner et al., 2020), as a candidate for future revision, in line with more nuanced vegetation modeling needs. The data types for these attributes were updated from *Measure* to *Length* to ensure proper inheritance of unit attributes.

Two respondents expressed concerns regarding the assumed symmetry of root systems when represented solely by a single diameter value, noting that such symmetry is often not present due to natural

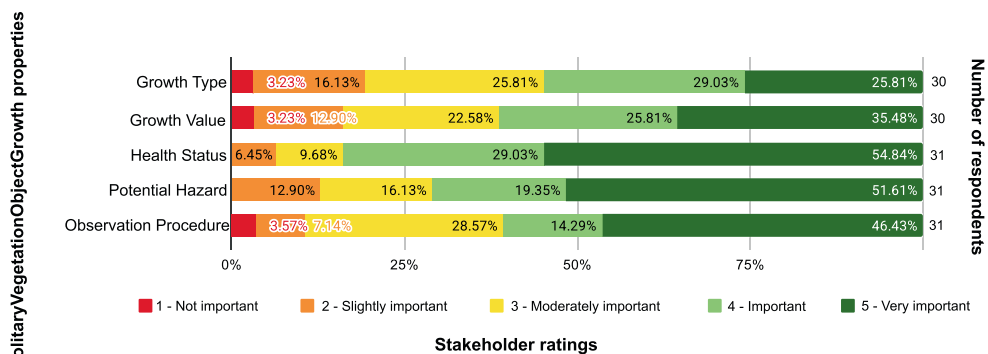


Fig. 11. Stakeholder rating of the proposed SolitaryVegetationObjectGrowth properties.

factors or underground infrastructure constraining root development. They suggested introducing additional attributes, such as width, depth, and statistical measures including minimum, mean, and maximum values, to more accurately reflect root system morphology. However, several other respondents indicated that determining parameters such as root system diameter or maximum depth is not feasible within their data collection workflows. As a result, it was concluded that incorporating these additional attributes could unnecessarily increase the complexity of the ADE without addressing a broadly recognized need. Hence, these proposed attributes were not included in the revised ADE v1.1.

4.2.5. Solitary vegetation object growth

The feature type *SolitaryVegetationObjectGrowth* was introduced in the ADE proposal v1.0 to apply the *AbstractDynamizer* Module to model dynamic growth characteristics of SVOs (Petrova-Antonova et al., 2024b). The properties included within the class *SolitaryVegetationObjectGrowth* have all been rated as ‘important’ or ‘very important’ by more than 50 % of respondents (Fig. 11). Based on this rating and the absence of explicit objections, all attributes are kept for the ADE v1.1. The uniformly high ratings across all growth attributes reflect broad recognition of the importance of capturing temporal vegetation dynamics. The strong support for properties like *healthStatus* and *potentialHazard* validates the integration of the *Dynamizer* module for time-dependent data related to conditions that pose risks to vegetation as well as human safety. Moreover, the high rating of all attributes signals the value of the model’s potential for future extensions involving sensor data, remote sensing, and AI-based monitoring systems.

For the ADE v1.1, the multiplicity of the *observationProcedure* property has been modified from zero or one [0..1] to zero or more [0..*] to allow for the representation of multiple observation procedures used in combination, such as LiDAR and AI-based methods, for determining the value of the associated property. This change enhances the model’s flexibility in supporting the representation of heterogeneous data sources and data fusion. The *seasonalChange* property was added to *SolitaryVegetationObjectGrowth* in the ADE v1.1 (Fig. 16). This allows for recording and representing observed seasonal dynamics, which can differ from the typical or reference values in *PlantCoverProperties* (Fig. 17).

4.3. Evaluation and refinement of plant cover

No amendments were suggested by the stakeholder survey participants regarding the proposed data modeling approach for plant covers. Therefore, it will be retained in v1.1. as proposed in v1.0 of the ADE proposal (Figs. 15 and 16).

4.3.1. Plant cover properties

More than 50 % of respondents rated the attributes *plantCoverSpecies*, *dateOfPlanting*, *dateOfExtermination*, *ecosystemServices*, *ownership*, *protectionStatus*, *significance*, and *startHeightOfCanopy* as ‘important’ or ‘very important’. These ratings highlight a strong consensus on the importance of core ecological and administrative descriptors. Both attributes *habitatClassificationSystem* and *seasonalChange* received lower importance ratings, as ‘important’ and ‘very important’ ratings were slightly below 50 %. This possibly reflects either limited availability of such data or lower familiarity among participants, indicating that their relevance may be more variable (Fig. 12). Since all attributes in the proposed ADE are optional, this flexible design approach accommodates the diversity of user needs identified in the survey and does not induce the need to remove any of the proposed attributes from *PlantCoverProperties* in the ADE proposal v1.1.

Consistent with the pattern observed for *SolitaryVegetationObject*, a regional breakdown of *PlantCover* responses reveals similar, although less accentuated, divergences. European respondents ($n = 20$) showed stronger support for *protectionStatus*, with 70.0 % rating it as ‘important’ or ‘very important’, compared to 50.0 % of non-European respondents ($n = 6$). For *seasonalChange*, non-European respondents attached slightly higher importance to the attribute (50.0 % rated as important or very important) than their European counterparts (42.9 %).

In alignment with the modifications made to the *SolitaryVegetationObjectProperties*, the *PlantCoverProperties* class has also been updated: the property *dateOfPlanting* has been renamed to *dateOfEstablishment* and *ownership* to *ownershipType*. Additionally, the property *establishmentMeans* has been introduced, associated with the code list *EstablishmentMeansValue* and specified with a multiplicity of zero or more [0..*]. This enables the representation of multiple establishment methods for a single plant cover, where vegetation may originate from a combination of practices such as seeding, planting, and natural regeneration. Similarly, the *ownership* property has been updated to support a

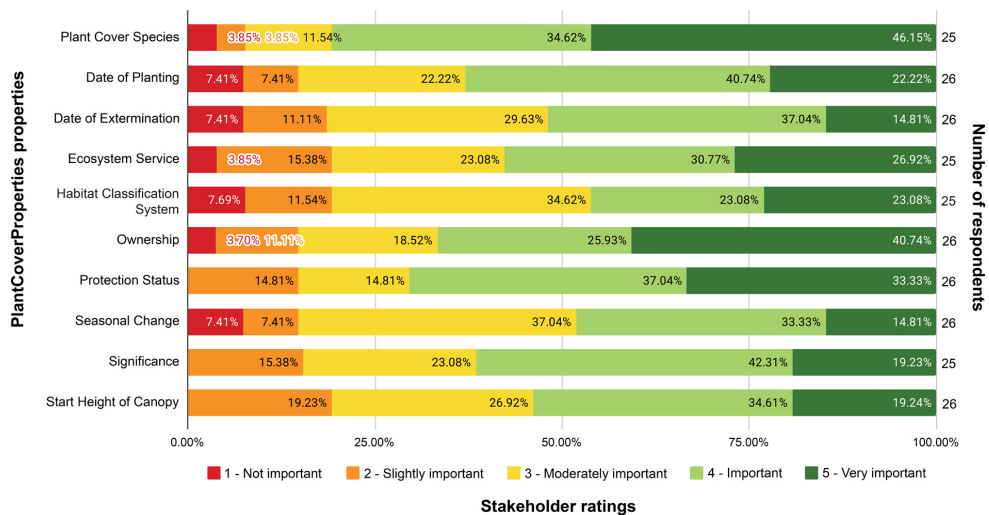


Fig. 12. Stakeholder rating of the proposed *PlantCoverProperties* properties.

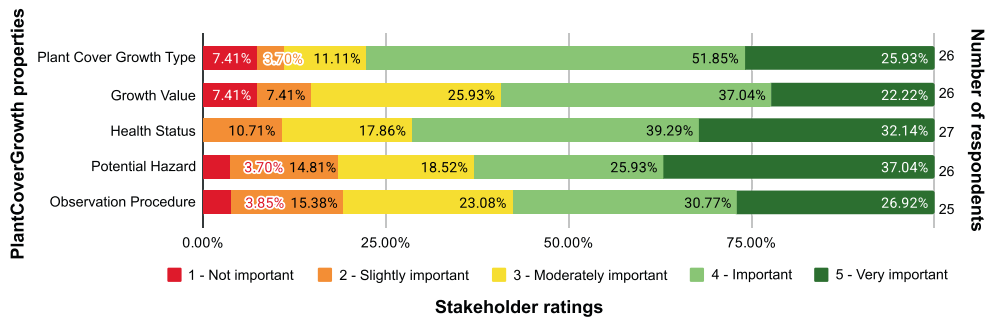


Fig. 13. Stakeholder rating of the proposed PlantCoverGrowth properties.

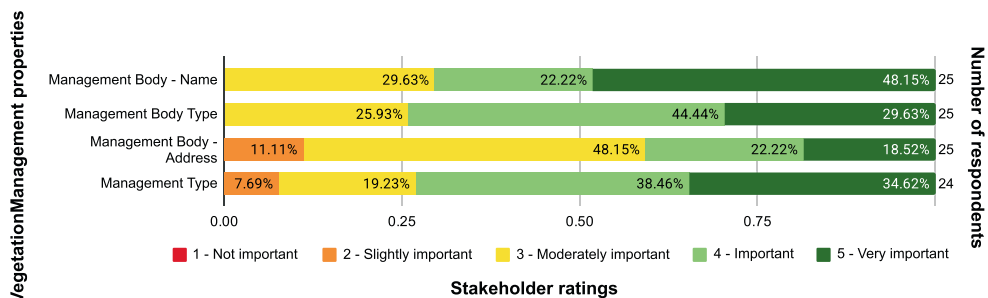


Fig. 14. Stakeholder rating of the proposed VegetationManagement properties.

multiplicity of zero or more [0..*], replacing the previous cardinality of zero or one [0..1]. Also, the new attribute *protectionStatusReference* of type URI has been introduced to enable referencing precise protection statuses associated with the plant cover.

A request was made to support multiple establishment dates for different species or individuals within a single *PlantCover*, to better represent heterogeneous or successively planted areas. However, this functionality was not included in the current ADE version, as it would require subdividing *PlantCover* or introducing a more complex data model to relate dates to specific species or groups, adding significant structural complexity. As a result, the *PlantCover* retains a single optional establishment date. Respondents did not propose specific amendments to the data types relevant for plant cover data modeling. However, to align with the technical refinements applied to *SolitaryVegetationObject*, the data type for *startHeightOfCanopy* was updated from *Measure* to *Length*. The data types *HabitatClassificationSystem*, *SeasonalChange* and *PlantCoverSpeciesType* remain unchanged.

4.3.2. Plant cover growth

All proposed plant cover growth properties were consistently rated as 'important' or very 'important' by 57 % or more of respondents (Fig. 13). This result emphasizes the attribute's relevance and the need to capture not just the structure but also the development of vegetated surfaces over time. The strong support reinforces the inclusion of dynamic elements in the ADE and suggests demand for time-series modeling of vegetation expansion, change, or degradation. Therefore, all proposed attributes are retained for the ADE v1.1.

The multiplicity for *observationProcedure* has been changed from zero or one [0..1] to zero or more [0..*]. Additionally, to align both vegetation types, SVO and PC, *seasonalChange* was added to *PlantCoverGrowth*.

4.4. Evaluation and refinement of vegetation management

The data modeling approach for vegetation management received no revision proposals from stakeholders and therefore remains as defined in ADE proposal v1.0 (Figs. 15 and 16). The properties *name*, *managementBodyType*, and *managementType* of the *VegetationManagement* class received strong approval, with 70 % or more respondents rating them as 'important' or 'very important' (Fig. 14). The high rating of these key management attributes reflects the administrative realities of urban vegetation maintenance. Only *address* was considered 'slightly important' to 'moderately important' by over 59 % of respondents, but notably, it was not rated as unimportant by any respondent. This feedback suggests that while *address* is not essential in all use cases, it could provide useful contextual detail. The rating participation rate among survey respondents for vegetation management attributes was 64 % (n = 24) or more, representing the lowest participation rate observed across all evaluated attributes. This reduced participation may reflect limited familiarity with vegetation management practices among a subset of respondents, potentially leading to abstention from rating these specific attributes. However, given that a clear majority of participants provided ratings, the collected data were considered sufficiently robust to inform evidence-based decision-making regarding vegetation management priorities. Based on these quantitative results

and the accompanying qualitative comments, all proposed attributes were retained in the ADE v1.1.

As suggested by multiple stakeholders, the attribute *managementReference* was introduced to enable the provision of more detailed resources, such as management reports from external systems like municipal records or urban forestry databases, through a URI (Figs. 15 and 16).

4.5. Enumerations

In CityGML, an enumeration is a predefined, closed list of valid values for an attribute, specified directly within the model to ensure standardized and consistent data entry (Kolbe et al., 2021). The enumerations *HealthStatusValue* and *UnitOfMeasure* remain unchanged from their definitions in v1.0 of the CM. The attributes *LeafAreaIndex* and *NormalizedDifferenceVegetationIndex* have been newly introduced in conceptual model v1.1 and are implemented as dynamic properties. They are associated with the feature types *SolitaryVegetationObjectGrowth* and *PlantCoverGrowth* respectively, and their temporal behavior is classified via the enumerations *SolitaryVegetationObjectGrowthTypeValue* and *PlantCoverGrowthTypeValue*. This allows for their time-dependent representation in accordance with CityGML best practices for modeling temporal variation.

Additionally, enumeration literals in *SolitaryVegetationObjectGrowthTypeValue* have been harmonized to ensure consistency with the naming used in the corresponding data type and feature types adapted in the ADE v1.1.

The revisions of the enumerations are presented in Table 2. The revised comprehensive lists of all enumerations, including their values and definitions, are provided in Mrosła et al. (2025b).

4.6. Code lists

In CityGML, code lists are externally referenced vocabularies that allow flexible, extensible classification (Kolbe et al., 2021).

The code lists *ObservationProcedureValue*, *OwnershipTypeValue*, *PotentialHazardValue*, *CrownTypeValue*, *TrunkTypeValue*, *RootTypeValue*, and *ManagementTypeValue* were revised for the ADE v1.1 according to the survey responses to ensure terminological consistency, broader coverage, and relevance. Additionally, the code list *SignificanceTypeValue* was renamed *SignificanceValue* to align with established naming conventions and best practices in schema design. The code list for *EcosystemServices* was replaced by the list defined by the Millennium Ecosystem Assessment (MA) (Millennium Ecosystem Assessment, 2005) of the United Nations. This classification is globally recognized and used in sub-global assessments.

Predefined code lists, such as those in Darwin Core (Wieczorek et al., 2012), encompassing establishment means of vegetation with terms like *native*, *introduced*, *cultivated*, *naturalized*, etc. are primarily designed for ecological and biodiversity contexts. These are focusing on species origin and dispersal, rather than on the practical or administrative vegetation establishments in urban environments. Therefore, the new code list *EstablishmentMeansValue* was defined to suit the urban data modeling purposes. Code list revisions are summarized in Table 2. All code lists including their definitions and values defined for the ADE proposal v1.1 are provided in Mrosła et al. (2025b) and Supplement S2.

4.7. Updated UML diagram and overview of changes

Table 1

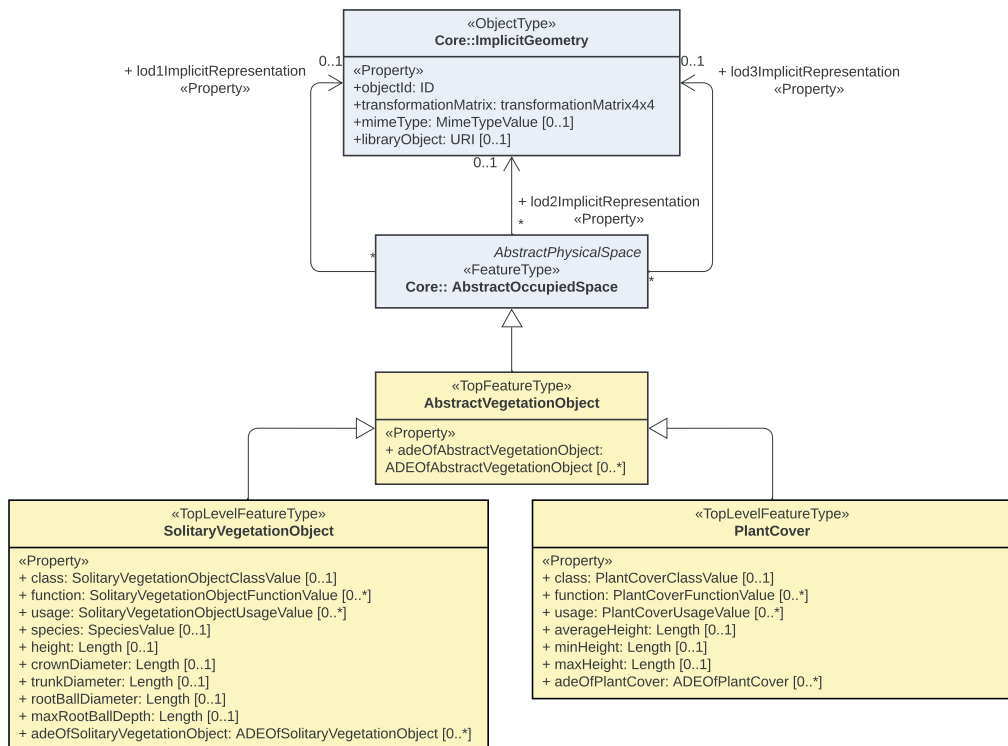
Adapted, added and removed properties of CityGML 3.0 Vegetation ADE Proposal v1.1.

Class	Adapted ADE V 1.0	ADE V 1.1	Added to ADE v1.1	Removed for ADE v1.1
SolitaryVegetationObjectProperties	dateOfPlanting: Date [0..1] ownership: OwnershipTypeValue [0..1] significance: SignificanceTypeValue [0..*]	dateOfEstablishment: Date [0..1] ownershipType: OwnershipTypeValue [0..*] significance: SignificanceValue [0..*]	establishmentMeans: EstablishmentMeansValue [0..1] protectionStatusReference: URI [0..1]	age: Integer [0..1]
Crown	crownType: CrownTypeValue [0..1] crownBaseHeight: Measure [0..1] crownDiameter: Measure [0..1]	crownTypeNatural: CrownTypeValue [0..1] crownBaseHeight: Length [0..1] crownDiameter: Length [0..1]	crownTypeTrimmed: CrownTypeValue [0..1] leafAreaIndex: Real [0..1] normalizedDifferenceVegetationIndex: Real [0..1]	
Trunk	trunkDiameter: Measure [0..1] trunkHeight: Measure [0..1]	trunkDiameter: Length [0..1] trunkHeight: Length [0..1]		
Root	rootBallDiameter: Measure [0..1] rootBallMaximalDepth: Measure [0..1]	rootSystemDiameter: Length [0..1] maxRootSystemDepth: Length [0..1]		
SolitaryVegetationObjectGrowth	observationProcedure: ObservationProcedureValue [0..1]	observationProcedure: ObservationProcedureValue [0..*]	seasonalChange: SeasonalChange [0..*]	
PlantCoverProperties	dateOfPlanting: Date [0..1] ownership: OwnershipTypeValue [0..1] significance: SignificanceTypeValue [0..*] startHeightOfCanopy: Measure [0..1]	dateOfEstablishment: Date [0..1] ownershipType: OwnershipTypeValue [0..*] significance: SignificanceValue [0..*] startHeightOfCanopy: Length [0..1]	establishmentMeans: EstablishmentMeansValue [0..1] protectionStatusReference: URI [0..1] leafAreaIndex: Real [0..1] normalizedDifferenceVegetationIndex: Real [0..1]	
PlantCoverGrowth	observationProcedure: ObservationProcedureValue [0..1]	observationProcedure: ObservationProcedureValue [0..*]	seasonalChange: SeasonalChange [0..*]	
VegetationManagement			managementReference: URI [..1]	

Table 2

Unaltered, revised and added code lists and enumerations of CityGML 3.0 Vegetation ADE Proposal v1.1.

Enumeration / Code List	Unaltered from ADE v1.0	Revised in ADE v1.1	Added to ADE v1.1
Code List	SeasonalChangeTypeValue	EcosystemServiceValue ObservationProcedure OwnershipTypeValue PotentialHazardValue SignificanceTypeValue CrownTypeValue TrunkTypeValue RootTypeValue ManagementTypeValue SolitaryVegetationObjectGrowthTypeValue PlantCoverGrowthTypeValue	EstablishmentMeansValue
Enumeration	HealthStatusValue UnitOfMeasure		

**Fig. 15.** Existing CityGML requirement classes under discussion (yellow) and requirement classes from other CityGML sections (blue).

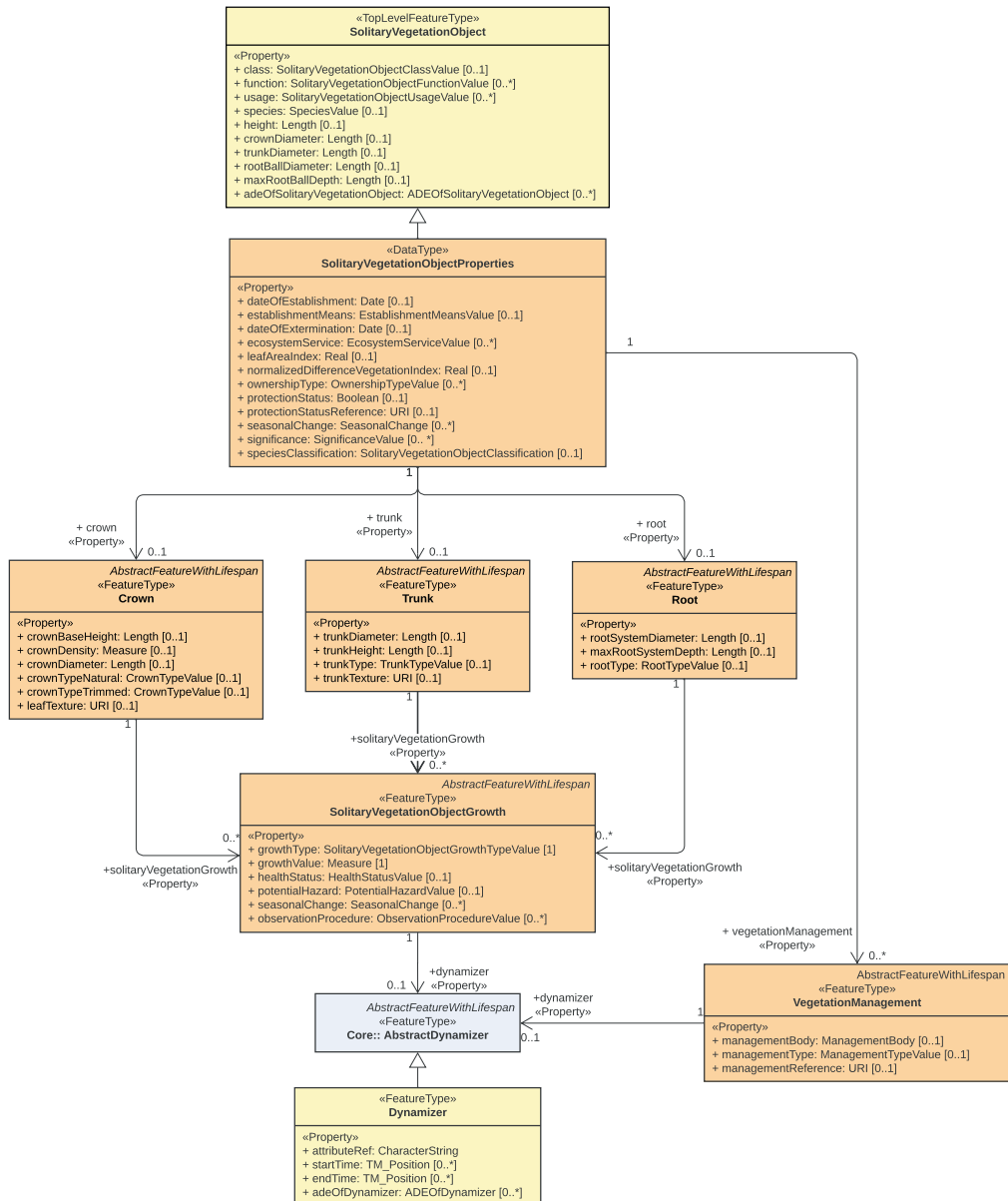


Fig. 16. Excerpt of the updated UML diagram of the CityGML 3.0 Conceptual Model for the Vegetation ADE v1.1 including the proposed extensions in Vegetation ADE v1.1 — SolitaryVegetationObjectProperties, Crown, Trunk, Root, SolitaryVegetationObjectGrowth and VegetationManagement (orange), existing CityGML requirement classes under discussion (yellow), requirement classes from other CityGML sections (blue).

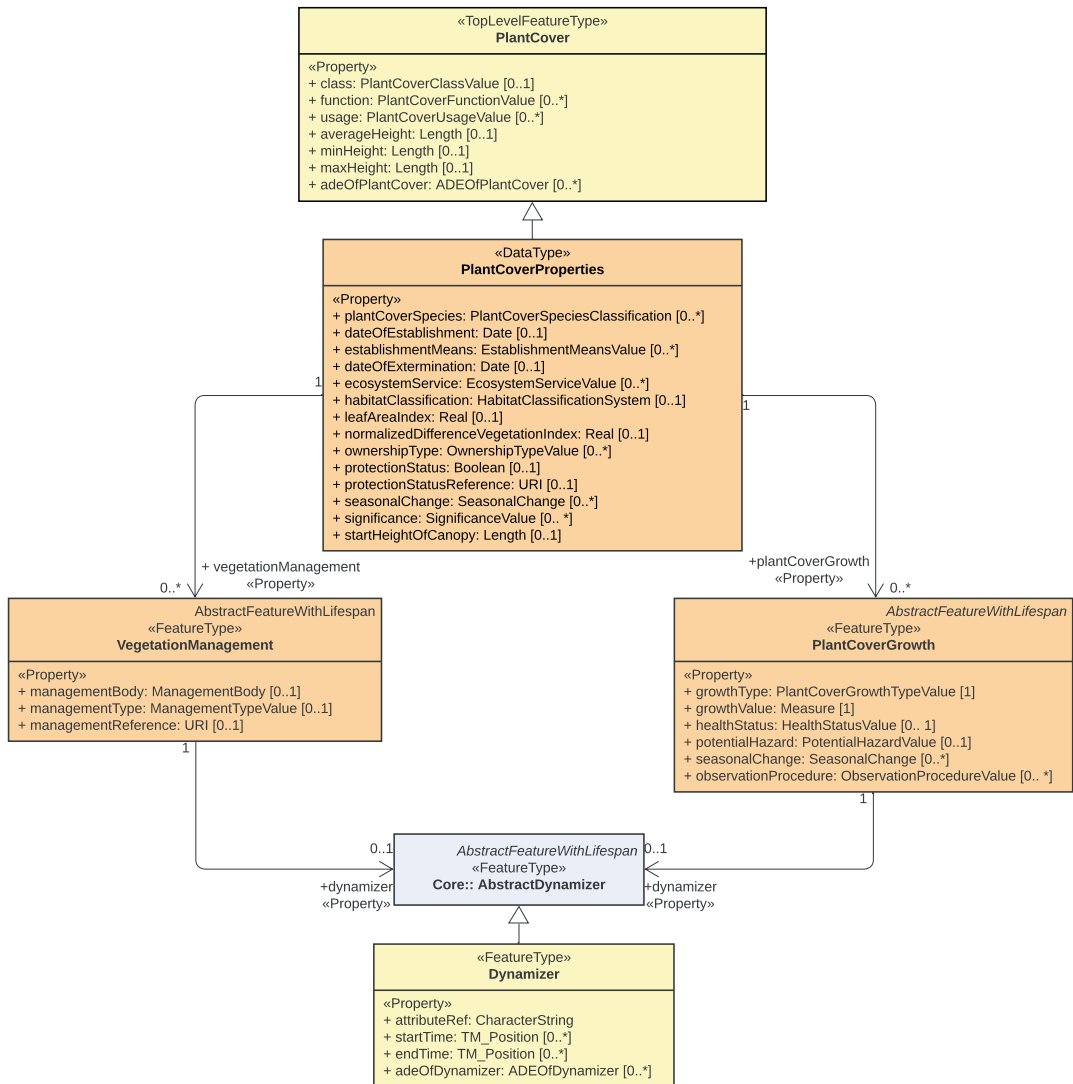


Fig. 17. Excerpt of the updated UML diagram of the CityGML 3.0 Conceptual Model for the Vegetation ADE v1.1 including the proposed extensions in Vegetation ADE v1.1 – PlantCoverProperties, PlantCoverGrowth and VegetationManagement (orange), existing CityGML requirement classes under discussion (yellow), requirement classes from other CityGML sections (blue).

5. Discussion and outlook

To date, interoperability remains a key technical barrier, with organizational, regulatory, and semantic constraints complicating the integration of heterogeneous urban datasets in UDTs (Jeddoub et al., 2023; Lei et al., 2023; Mrosła et al., 2025a). The development of the CityGML 3.0 Vegetation ADE v1.1 marks a substantial step toward resolving persistent semantic interoperability challenges in UDTs and 3DCMs related to urban vegetation.

The developed ADE v1.1 proposes a standardized semantic framework for vegetation, enabling consistent data exchange across platforms, domains, and stakeholder groups. By supporting integrated modeling of vegetation features, often derived from Earth observation, it

helps to overcome persistent fragmentation of urban vegetation datasets (Corro et al., 2025; Pantazatou et al., 2024). It integrates previous work by multiple authors across several key areas. These include e.g., the trunk, crown and root feature types proposed by Ambarwari et al. (2024), a tree growth model structure similar to the one proposed for Rhino Grasshopper by Yazdi et al. (2024b), seasonal change variables as in Ortega-Córdova (2018). Moreover, it incorporates the popular name of tree species proposed by Pantazatou et al. (2024). Additionally, it proposes novel elements such as the *VegetationManagement* class and new semantic attributes such as *ProtectionStatus* and *NormalizedDifferenceVegetationIndex* (Tables 1 and 2).

Building on this foundation, a comparison with existing urban vegetation models and software highlights key distinctions and

complementarities. While tools like i-Tree (Nowak, 2024) have been widely used for practical urban forestry applications such as tree inventories and ecosystem service valuation, the CityGML Vegetation ADE v1.1 advances beyond by offering deep semantic integration within 3DCM and UDTs. Unlike e.g., i-Tree, which primarily functions as a standalone analytical platform, the ADE supports comprehensive spatial and temporal modeling of vegetation. This includes structural components (crown, trunk, root), growth dynamics, and seasonal changes, through a standardized, interoperable and extensible framework. It also facilitates interoperability via internationally harmonized code lists and classifications, enabling advanced use cases like dynamic simulations, policy scenario analyses, and integration with sensor data. Thus, the proposed CityGML 3.0 Vegetation ADE v1.1 complements and extends existing approaches of operational tools like i-Tree. It provides a robust, interoperable semantic extension for holistic urban vegetation modeling in support of resilient and sustainable city planning.

5.1. Potential applications and use cases of ADE

The proposed ADE's semantic richness and extensibility allow for application-oriented and detailed representations of vegetation relevant to urban planning, biodiversity, and climate resilience.

For instance, detailed tree crown attributes and tree growth data enable estimation and prediction of various ecosystem services provided by urban trees, such as cooling via evapotranspiration, stormwater interception, and carbon storage/sequestration (Huang et al., 2017; Nowak and Crane, 2002) over time. These data also allow estimation of seasonal visibility, shading and perceived greenness (Ortega-Córdova, 2018). Moreover it supports proactive maintenance planning e.g., pruning to preserve sightlines to traffic signals. Furthermore, species or functional-group annotated *PlantCover* properties could inform habitat-suitability and complementarity analyses that underpin biodiversity corridors and adaptive planting strategies (Zhang et al., 2023). These capabilities have been demonstrated both in methodological work that builds 3D ecological benefit indices (Zhang et al., 2023) and 3D green-space indicators (Zhu et al., 2025).

Designed for scalability and transferability, the ADE enables harmonized vegetation data management across contexts and scales, thus responding to the need for consistent and reliable analyses in cross-jurisdictional urban assessments (González-Marín and Garrido-Cumbrera, 2025). Moreover, interdisciplinary applications in spatial planning, sustainability assessment, and environmental monitoring (Ugglá et al., 2023; Xue et al., 2021) are directly supported by the ADE v1.1.

The use of the *Dynamizer* module introduced in CityGML 3.0 (Ketzler et al., 2020) supports dynamic data and thereby enables the temporal modeling of vegetation features. This advancement supports a variety of use cases including the spatiotemporal planning of urban vegetation maintenance activities, such as pruning schedules and the monitoring of seasonal dynamics of vegetated areas (Fabritius et al., 2023). This demand is exemplified by real-world implementations like the *GreenTwins* project (Fabritius et al., 2023). Furthermore, it enhances the capacity to analyze and monitor, e.g., the Normalized Difference Vegetation Index (NDVI) (Chen et al., 2023) and vegetation fragmentation within urban landscapes (Kowe et al., 2021). This can provide critical input for evidence-based policy-making and urban environmental management.

In the future, datasets populated using the Vegetation ADE may be used to train deep learning algorithms for automatic reconstruction of urban vegetation, comparable to approaches currently being developed for buildings in this field (Wysocki et al., 2024).

5.2. Participatory design and model refinement

Enhanced through a participatory, stakeholder-driven methodology, the model integrates domain expert feedback to ensure broad usability. The stakeholder survey evaluation, combining thematic review with

quantitative analysis, confirmed the model's relevance across UDT and 3DCM communities. Participants highlighted the need for additional attributes, e.g., vegetation indices, and the importance of consistent terminology and structured code lists. Notably, no structural changes were proposed to the conceptual model of the ADE proposal v1.0 (Petrova-Antonova et al., 2024a, 2024b), validating its design for v1.1. The refinements in the ADE proposal v1.1, including enhanced properties, code lists, and enumerations (see Tables 1 and 2, Mrosła et al. (2025b)) reflect this feedback and strengthen the model's practical applicability.

Finally, the participatory standardization approach offers a replicable model for future ADEs. By aligning technical development with operational needs, our work provides a robust foundation for next-generation UDT and 3DCM applications in urban ecology, adaptation, and sustainable urban planning.

5.3. Limitations of this study and remaining challenges

The conceptual model and survey were developed in English, which may have limited participation from non-English speakers. Although the authors aimed to collect globally diverse feedback, 25 of the 37 surveys included in the evaluation were respondents based in Europe, which impacts the geographic diversity of perspectives. This geographic concentration may bias the findings towards European regulatory, ecological, and management contexts, potentially overlooking region-specific requirements, cultural perspectives, and data practices prevalent in underrepresented areas. While the ADE allows referencing external classification systems, this flexibility may also lead to inconsistencies and complicate data integration. The lack of unified global classification systems for vegetation and habitats was identified as a significant challenge.

Although the limited sample size precludes definitive statistical generalizations, the divergence in importance ratings suggest that regional contexts shape data modeling priorities. For example the strong European support for *protectionStatus* of SVOs and PCs (e.g., SVO: European respondents:77.8 % vs. 60 % non-European respondents) likely reflects the prevalence of strict regulatory frameworks, such as tree preservation regulations, in European municipal planning. Conversely, the significantly higher prioritization of *seasonalChange* of SVOs by non-European respondents (e.g., SVO: 80 % non-European respondents vs. 44.4 % European respondents) suggests that dynamic vegetation modeling may be more relevant in non-European regions. This likely reflects the need to capture distinct phenological patterns, such as wet-dry cycles or rapid growth phases, that differ from the more static or strictly seasonal models used for temperate European zones.

Based on these findings, the current model's focus may limit its immediate applicability in distinct climatic and regulatory environments. To address these limitations and enhance the robustness of the Vegetation ADE, future research will aim to broaden the survey outreach to achieve a more geographically balanced and diverse respondent base. Furthermore, future research will focus on developing semantic extensions tailored to diverse climate zones, such as tropical, arid, and boreal regions. Finally, compatibility schemes with non-European regional standard will be explored. These adaptations aim to transition the ADE into a globally applicable standard for vegetation data integration in UDTs and 3DCMs.

Additionally, survey feedback indicated concerns that the ADE's comprehensiveness and the inclusion of numerous attributes may increase complexity, potentially limiting its applicability. Simultaneously, several participants suggested additional attributes—such as the reason for extermination in the SVO properties, trunk angle, growth rate, additional specific information on root length density, maximum measures for the vegetation at maturity, e.g., of crown, trunk or root system diameter—which were not included in the current ADE proposal v1.1. The evaluation of the qualitative feedback revealed, besides a strong support of the proposed properties, also differing stakeholder opinions,

interests and needs for more specific use-case dependent vegetation modeling. These findings highlight the ongoing challenge of balancing semantic richness with practical usability in the context of a globally applicable standard. Moreover, the qualitative feedback suggested introducing more biodiversity-related properties such as e.g., presence of animal species in relation to vegetation. These considerations require further evaluation and may be relevant for a separate ADE.

5.4. Future work: Validation of the data model with use-cases

At present, the ADE has been evaluated at the conceptual level by stakeholders and experts. Future work will include broader validation through real-world deployments and integration with operational UDTs and 3DCM. A structured validation plan is being developed to test the ADE in urban scenarios, including validating the proposed ADE with distinct vegetation datasets.

To ensure the model's application value beyond European contexts, the ADE v1.1 was designed with a flexible, standard-agnostic architecture. Instead of hard-coding regional taxonomies, the model employs generic classification data types (e.g., *SolitaryVegetationObjectClassification*, *PlantCoverSpeciesClassification*, *HabitatClassificationSystem*) that utilize URI references (classificationReference). This mechanism serves as a universal compatibility scheme, allowing adopters in diverse climate zones to link vegetation objects to their specific local standards (e.g., USDA PLANTS Database, Australian Plant Census) without altering the ADE schema. Consequently, future work will prioritize the validation of this mechanism through pilot implementations in non-European regions to confirm that these URI-based references sufficiently capture local ecological nuances.

Additionally, the integration of dynamic properties, such as vegetation growth and management, will be explored using time-series data. While the CityGML Dynamizer module supports such dynamic features, practical implementation will depend on the availability of relevant data, which is currently limited in many cities. An additional goal is to submit the ADE to the Open Geospatial Consortium for consideration as part of the official standard, which would further promote its adoption and sustainability in the geospatial community.

CRedit authorship contribution statement

Laura Mrosła: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dessislava Petrova-Antonova:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Simeon Malinov:** Visualization, Methodology, Conceptualization. **Henna Fabritius:** Writing – review & editing, Writing – original draft, Funding acquisition.

Use of Generative AI

The authors used ChatGPT to improve readability and language. All content was subsequently reviewed and edited, and the authors take full responsibility for the final version.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jag.2025.105043>.

Data availability

The complete CityGML 3.0 Vegetation ADE v1.1 is available at Mrosła et al. (2025b) and as Supplement S2. The survey instrument is available as Supplement S1. Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jag.2025.105043>. Aligning with personal data protection regulations, anonymized survey data, evaluation scripts, data processing and analysis are available upon request.

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Specification Document

CityGML 3.0 Vegetation Application Domain Extension (ADE) Proposal v1.1

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This document presents the CityGML 3.0 Vegetation ADE proposal v1.1. This specification document provides detailed attribute definitions, data types, code lists, and enumerations for CityGML 3.0 Vegetation ADE v1.1, enabling standardized representation of urban vegetation in 3D city models.

The CityGML 3.0 Vegetation ADE proposal v1.0 is published in form of a Technical User Guide in Petrova-Antonova, D., Mrosła, L., Malinov, S., 2024. CityGML 3.0 Vegetation ADE Proposal. <https://doi.org/10.5281/ZENODO.13906831>

The document at hand is a non-normative resource and not an official position of the Open Geospatial Consortium (OGC).

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1 CityGML 3.0 Vegetation Module and ADE proposal v1.1: UML Diagram

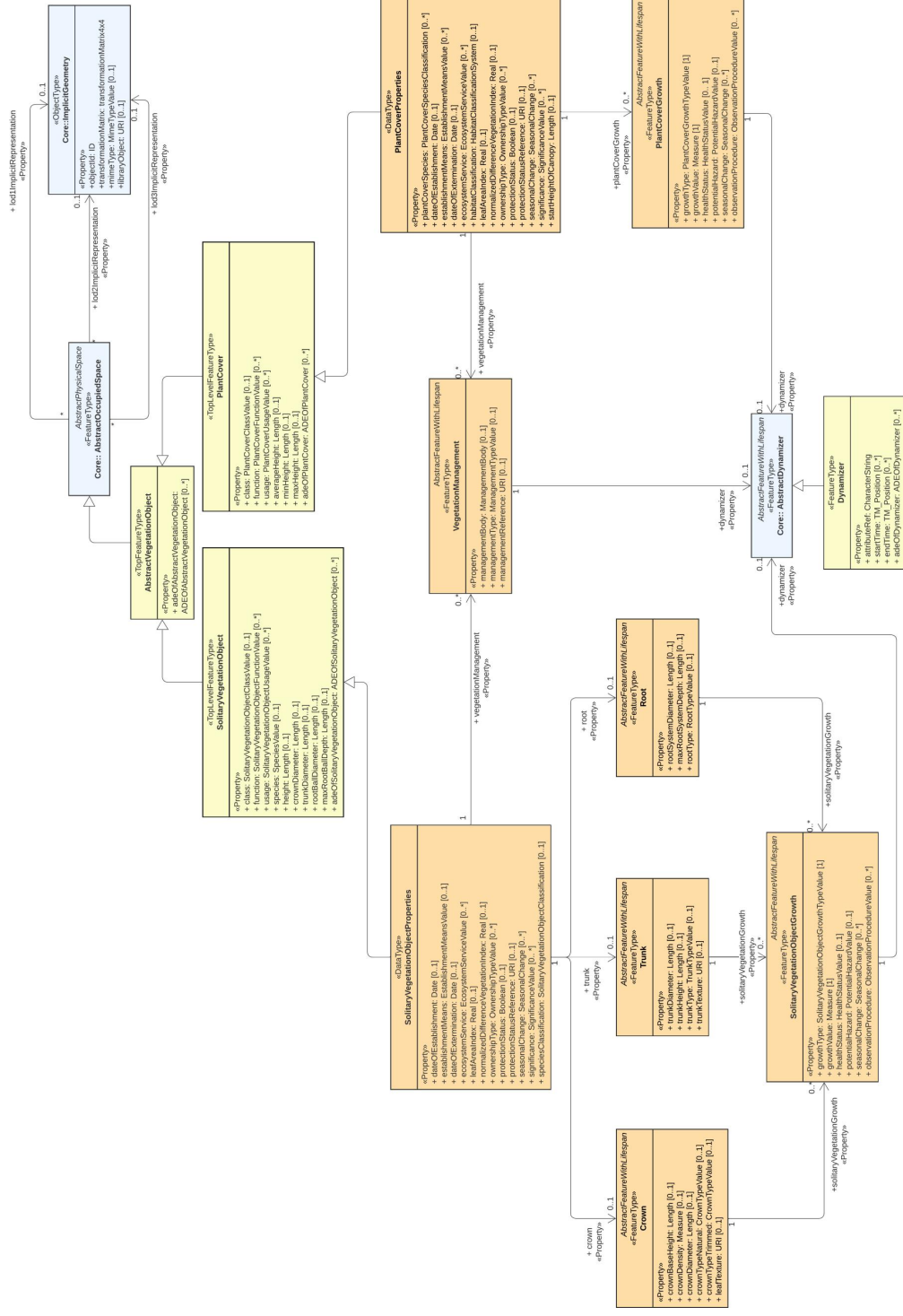


Figure 1: CityGML 3.0 Conceptual Model of the Vegetation ADE v1.1. Classes highlighted in yellow represent existing requirement classes from the CityGML Conceptual Model that are currently under discussion. Classes highlighted in blue correspond to requirement classes from different sections of the CityGML Conceptual Model. Classes highlighted in orange denote the proposed extensions introduced with the CityGML Vegetation ADE v1.1.

2 Attribute Lists of CityGML 3.0 Vegetation ADE Proposal v1.1

2.1 SolitaryVegetationObject

The ADE does not change the SolitaryVegetationObject class, it only adds further properties.

2.1.1 ADEOfSolitaryVegetationObject

The new properties of SolitaryVegetationObject are added to a new subclass of the data type ADEOfSolitaryVegetationObject with the stereotype «DataType».

NOTE: Unless otherwise specified, all attributes and role names have the stereotype «Property».

2.1.2 SolitaryVegetationObjectProperties

Table 1: Metadata of SolitaryVegetationObjectProperties (DataType)

Definition:	SolitaryVegetationObjectProperties is a data type that encapsulates additional properties of SolitaryVegetationObject through the ADEOfSolitaryVegetationObject extension mechanism.
Subclass of:	ADEOfSolitaryVegetationObject
Stereotype:	«DataType»

Table 2: Attributes of SolitaryVegetationObjectProperties (DataType)

Attribute	Value type and multiplicity	Definition
dateOfEstablishment	Date [0..1]	Specifies the date when the SolitaryVegetationObject was planted or by other means established at the current site.
establishmentMeans	EstablishmentMeansValue [0..*]	Defines by what means the SolitaryVegetationObject has been established on site.
dateOfExtermination	Date [0..1]	Specifies the date that a SolitaryVegetationObject has been cut down or removed in other ways.
ecosystemService	EcosystemServiceValue [0..*]	Specifies the ecosystem services which are especially supported.
leafAreaIndex	Real [0..1]	Leaf Area Index (LAI) provides an overall measure of canopy density. The LAI is calculated as follows: $LAI = \text{leaf area} / \text{ground area}$. LAI is widely used in modeling processes such as photosynthesis, evapotranspiration, and carbon flux.

normalizedDifferenceVegetationIndex	Real [0..1]	Specifies the Normalized Difference Vegetation Index (NDVI) of the SolitaryVegetationObject. NDVI is a spectral index calculated from near-infrared and red light reflectance. NDVI values typically range from -1 (water/non-vegetated) to +1 (dense vegetation). Positive values indicate vegetated areas; higher values generally indicate denser, healthier vegetation, though interpretation depends on vegetation type, phenological stage, and urban context. It is used as a key indicator for monitoring vegetation dynamics and health in urban environments
ownershipType	OwnershipTypeValue [0..*]	Categorizes the ownership status or entity responsible for the management and maintenance of the SolitaryVegetationObject.
protectionStatus	Boolean [0..1]	The protection status provides information about the protection status of the SolitaryVegetationObject (true or false).
protectionStatusReference	URI [0..1]	Provides a reference for the protection status of the SolitaryVegetationObject.
seasonalChange	SeasonalChange [0..*]	Defines the type of morphological visible changes that a SolitaryVegetationObject is undergoing due to seasonal transitions as well as the start and end dates.
significance	SignificanceValue [0..*]	The significance attribute refers to the importance of a given SolitaryVegetationObject relevant to the corresponding environment. SolitaryVegetationObject may be associated e.g. with historical events, figures, or timelines, such memorial trees, trees at historical landmarks, or ancient trees.
speciesClassification	SolitaryVegetationObjectClassification [0..1]	Specifies the classification of a SolitaryVegetationObject (e.g. tree or bush) at the species level, according to a referenced classification system and a popular name.

Table 3: Attributes of SolitaryVegetationObjectClassification (DataType)

Attribute	Value type and multiplicity	Definition
classificationName	CharacterString [0..*]	Specifies the name of the referenced classification system to define the SolitaryVegetationObject.
classificationReference	URI [0..1]	Provides a URI for the referenced classification system.
classificationCode	CharacterString [0..*]	Specifies the code within the referenced classification system corresponding to the SolitaryVegetationObject at a species level. It's a part of the scientific naming convention binomial nomenclature, where organisms are designated by their genus followed by their species identifier. This classification is used universally by scientists to ensure clear communication and understanding about a particular organism without ambiguity.
speciesPopularName	CharacterString [0..*]	Defines the popular name(s) of the SolitaryVegetationObject's species.

Table 4: Attributes of SeasonalChange (DataType)

Attribute	Value type and multiplicity	Definition
seasonalChangeType	SeasonalChangeTypeValue [0..1]	Defines the type of morphological visible changes that a SolitaryVegetationObject is undergoing due to seasonal transitions.
startDate	Date [0..1]	Defines the date when the seasonal change defined with SeasonalChangeTypeValue begins.
endDate	Date [0..1]	Defines the date when the seasonal change defined with SeasonalChangeTypeValue ends.

2.1.3 Crown

Table 5: Attributes of Crown (FeatureType)

Attribute	Value type and multiplicity	Definition
crownBaseHeight	Length [0..1]	Describes the vertical distance from the ground to the point where the crown of a tree begins. It is, amongst others, used to calculate crown volume together with tree height and crown diameter. The

		crown base height is also known as clearance height, stem extent, "bole extent", tree bole height, or trunk height to the first branch.
crownDensity	Measure [0..1]	Defines the quantity of stems, branches, twigs, shoots, buds, foliage, and reproductive structures within a tree's crown that obstruct light from passing through. This includes both live and dead branches as well as dead tops. It is recorded as a percentage.
crownDiameter	Length [0..1]	Defines the average diameter of the canopy of the SolitaryVegetationObject.
crownTypeNatural	CrownTypeValue [0..1]	Defines the type of tree crown, also known as "tree crown form" in its natural shape. It is a fundamental characteristic of the overall shape of the solitary vegetation object's crown, inherent to the respective species.
crownTypeTrimmed	CrownTypeValue [0..1]	Defines the trimmed type of solitary vegetation object's crown. When trees or bushes are cut in another than their natural shape, e.g. in triangles, rectangles, cylinders.
leafTexture	URI [0..1]	A link to a URI, providing a resource with the typical texture of the leaf. This facilitates the automatic visualization of the leaves.

2.1.4 Trunk

Table 6: Attributes of Trunk (FeatureType)

Attribute	Value type and multiplicity	Definition
trunkDiameter	Length [0..1]	Specifies the trunk diameter at breast height (DBH).
trunkHeight	Length [0..1]	Specifies the average trunk height.
trunkType	TrunkTypeValue [0..1]	Defines the structural configuration and branching pattern of a tree's main stem or trunk. It classifies trunks into distinct categories based on the number and arrangement of primary trunks.
trunkTexture	URI [0..1]	A link to a URI, providing a resource with the typical texture of the trunk. This facilitates the visualization of the trunk.

2.1.5 Root

Table 7: Attributes of Root (FeatureType)

Attribute	Value type and multiplicity	Definition
rootSystemDiameter	Length [0..1]	Specifies the average diameter of the root system.
rootSystemMaximalDepth	Length [0..1]	Specifies the maximal root system depth.
rootType	RootTypeValue [0..1]	Specifies the root type.

2.1.6 SolitaryVegetationObjectGrowth

Table 8: Attributes of SolitaryVegetationObjectGrowth (FeatureType)

Attribute	Value type and multiplicity	Definition
growthType	SolitaryVegetationGrowthTypeValue [0..1]	Indicates a dynamic attribute of the SolitaryVegetationObject which is monitored and measured.
growthValue	Measure [0..1]	Defines the Measure of the indicated growthType.
healthStatus	HealthStatusValue [0..1]	Represents the health status of the SolitaryVegetationObject at the time of measurement or observation.
potentialHazard	PotentialHazardValue [0..1]	Specifies potential hazards associated with the SolitaryVegetationObject.
observationProcedure	ObservationProcedureValue [0..*]	Defines the method or procedure by which the Measure is obtained. It provides insight into how a particular set of data is derived or collected.
seasonalChange	SeasonalChange [0..*]	Defines the type of morphological visible changes that a SolitaryVegetationObject is undergoing due to seasonal transitions as well as the start and end dates.

2.2 PlantCover

The ADE does not change the PlantCover class, it only adds further properties.

2.2.1 ADEOfPlantCover

The new properties of *PlantCover* are added to a new subclass of the data type *ADEOfPlantCover* with the stereotype «DataType».

NOTE: Unless otherwise specified, all attributes and role names have the stereotype «Property».

2.2.2 PlantCoverProperties

Table 9: Metadata of PlantCoverProperties (DataType)

Definition:	PlantCoverProperties is a data type that encapsulates additional properties of PlantCover through the ADEOfPlantCover extension mechanism.
Subclass of:	ADEOfPlantCover
Stereotype:	«DataType»

Table 10: Attributes of PlantCoverProperties (DataType)

Attribute	Value type and multiplicity	Definition
plantCoverSpecies	PlantCoverSpeciesClassification [0..*]	Specifies the classifications of the species present in the PlantCover which are <u>not</u> listed as a SolitaryVegetationObject, e.g. different grasses, flowers or herbs growing on the PlantCover, at the species level according to the referenced classification system, popular name, as well as the species relative abundance.
dateOfExtermination	Date [0..1]	Specifies the date that a PlantCover has been cut down, removed or died.
dateOfEstablishment	Date [0..1]	Specifies the date when the PlantCover was planted or by other means established at the current site.
establishmentMeans	EstablishmentMeansValue [0..*]	Defines by what means the PlantCover has been established on site.
ecosystemService	EcosystemServiceValue [0..*]	Specifies the ecosystem services which are especially supported.
habitatClassification	HabitatClassificationSystem [0..1]	Defines the habitat classification system, which is used for the habitat

		classification, specifying which habitat represents the PlantCover.
leafAreaIndex	Real [0..1]	Leaf Area Index (LAI) provides an overall measure of canopy density. The LAI is calculated as follows: $LAI = \text{leaf area} / \text{ground area}$. LAI is widely used in modeling processes such as photosynthesis, evapotranspiration, and carbon flux.
normalizedDifferenceVegetationIndex	Real [0..1]	Specifies the Normalized Difference Vegetation Index (NDVI) of the PlantCover. NDVI is a spectral index calculated from near-infrared and red light reflectance. NDVI values typically range from -1 (water/non-vegetated) to +1 (dense vegetation). Positive values indicate vegetated areas; higher values generally indicate denser, healthier vegetation, though interpretation depends on vegetation type, phenological stage, and urban context. It is used as a key indicator for monitoring vegetation dynamics and health in urban environments
ownershipType	OwnershipTypeValue [0..*]	Categorizes the ownership status or entity responsible for the management and maintenance of the PlantCover.
protectionStatus	Boolean [0..1]	Defines the protection status of the PlantCover (true or false).
protectionStatusReference	URI [0..1]	Provides a reference for the protection status of the PlantCover.
seasonalChange	SeasonalChange [0..*]	Defines the type of morphological visible changes that the PlantCover is undergoing due to seasonal transitions as well as the start and end dates.
significance	SignificanceValue [0..*]	Refers to the importance of a given PlantCover relevant to the corresponding environment. PlantCover may be associated with e.g. historical events, figures, or timelines such as areas which are sites of historical events, ancient habitats,

		places of memorandum or old agricultural practices.
startHeightOfCanopy	Length [0..1]	Specifies at which height the canopy of the PlantCover starts. It is especially relevant for e.g. forests.

Table 11: Attributes of PlantCoverSpeciesClassification (DataType)

Attribute	Value type and multiplicity	Definition
plantCoverClassificationName	CharacterString [0..*]	Specifies the name of the referenced plant classification system to define Plant Cover.
plantCoverClassificationReference	URI [0..1]	Provides a URI for the referenced plant cover classification system.
plantCoverClassificationCode	CharacterString [0..*]	Specifies the code within the referenced classification system corresponding to the PlantCover at a species level. It's a part of the scientific naming convention binomial nomenclature, where organisms are designated by their genus followed by their species identifier. This classification is used universally by scientists to ensure clear communication and understanding about a particular organism without ambiguity.
speciesPopularName	Character String [0..*]	Defines the popular name of the PlantCover species.
speciesTypeRelativeAbundance	Integer [0..1]	Specifies the relative abundance of the PlantCover's species. It is the proportion of individuals belonging to a specific species compared to the total number of individuals of all species in a defined community or area. It is calculated as follows: Relative Abundance (%) = (Number of individuals of one species / Total number of individuals of all species) * 100.

Table 12: Attributes of HabitatClassificationSystem (DataType)

Attribute	Value type and multiplicity	Definition
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habitatClassificationName	CharacterString [0..*]	Specifies the name of the habitat classification system referenced for the habitat classification.
habitatClassificationReference	URI [0..1]	Specifies the URI of the referenced habitat classification system.
habitatClassificationCode	CharacterString [0..*]	Specifies habitat code of the referenced habitat classification system, which corresponds to the PlantCover object.

Table 13: Attributes of SeasonalChange (DataType)

Attribute	Value type and multiplicity	Definition
seasonalChangeType	SeasonalChangeTypeValue [0..1]	A code list that enumerates the different types of seasonal changes of vegetation.
startDate	Date [0..1]	Defines the date when the seasonal change defined in SeasonalChangeTypeValue begins.
endDate	Date [0..1]	Defines the date when the seasonal change defined in SeasonalChangeTypeValue ends.

2.2.3 PlantCoverGrowth

Table 14: Attributes of PlantCoverGrowth (FeatureType)

Attribute	Value type and multiplicity	Definition
growthType	PlantCoverGrowthTypeValue [0..1]	Defines a dynamic attribute of the PlantCover object which is monitored and measured.
growthValue	Measure [0..1]	Defines the Measure for the indicated growthType.
healthStatus	HealthStatusValue [0..1]	Represents the health status of the PlantCover object at the time of measurement or observation.
potentialHazard	PotentialHazardValue [0..1]	Specifies potential hazards associated with the PlantCover Object.
observationProcedure	ObservationProcedureValue [0..*]	Defines the method or procedure by which the Measure is obtained. It provides insight

		into how a particular set of data is derived or collected.
seasonalChange	SeasonalChange [0..*]	Defines the type of morphological visible changes that a PlantCover is undergoing due to seasonal transitions as well as the start and end dates.

2.3 VegetationManagement

Table 15: Attributes of VegetationManagement (FeatureType)

Attribute	Value type and multiplicity	Definition
managementBody	ManagementBody [0..1]	Defines the management body responsible for the management of the vegetation.
managementType	ManagementTypeValue [0..*]	Defines how the vegetation is being managed and maintained.
managementReference	URI [0..*]	Provides a URI to reference the specific management type, e.g. in form of a report.

Table 16: Attributes of ManagementBody (DataType)

Attribute	Value type and multiplicity	Definition
name	CharacterString [0..*]	Provides the name of the management body e.g. company name.
managementBodyType	Character String [0..*]	Defines the type of management body responsible for the vegetation.
address	CharacterString [0..*]	Defines the address of the management body.

3 CityGML 3.0 Vegetation ADE Proposal v1.1: DataTypes

The new data types for the Vegetation ADE are represented in Figure 2.

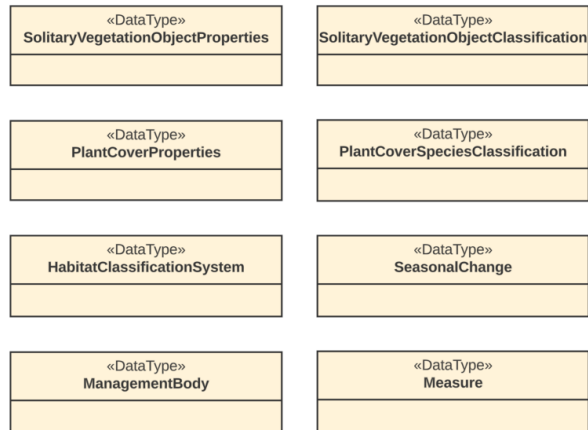


Figure 2: Data Types of the CityGML 3.0 Vegetation ADE Proposal v1.1.

4 CityGML 3.0 Vegetation ADE Proposal v1.1: CodeLists

«CodeList» enumerates the valid attribute values. In contrast to “Enumeration”, the list of values is open and, thus, not given inline in the CityGML UML Model. The allowed values can also be provided within an external code list.

The newly defined code lists for the Vegetation ADE (Figure 3) are defined in the following tables.

«CodeList» CrownTypeValue	«CodeList» EcosystemServiceValue	«CodeList» OwnershipTypeValue	«CodeList» SignificanceValue
«CodeList» TrunkTypeValue	«CodeList» EstablishmentMeansValue	«CodeList» PotentialHazardValue	«CodeList» managementTypeValue
«CodeList» RootTypeValue	«CodeList» ObservationProcedureValue	«CodeList» SeasonalChangeTypeValue	

Figure 3: Code Lists of the CityGML 3.0 Vegetation ADE Proposal v1.1.

Table 17: Metadata of EcosystemServiceValue (CodeList)

Definition:	EcosystemServiceValue is a code list that enumerates ecosystem service categories provided by SolitaryVegetationObject or PlantCover features. The classification aligns with the Millennium Ecosystem Assessment (MA; https://www.millenniumassessment.org/en), a comprehensive United Nations-coordinated assessment framework, ensuring consistency with globally recognized standards and supporting regional and local implementation.
Subclass of:	None
Stereotype	«CodeList»
Values	food biomass freshWater waterForNonDrinkingPurposes fibreAndTimber geneticResources biochemicals ornamentalResources biomassBasedEnergySources mechanicalEnergyAnimalBased airQualityRegulation waterPurificationAndWaterTreatment mediationByEcosystems

	waterRegulation moderationOfExtremeEvents erosionRegulation climateRegulation soilFormationSupportingServices pollination pestRegulation primaryProductionNutrientCyclingSupportingServices soilFormationAndComposition maintenanceOfWaterConditions maintenanceOfGeneticDiversity spiritualAndReligiousValues aestheticValues culturalDiversity spiritualOrEmblematic recreationAndEcotourism knowledgeSystemsAndEducationalValues otherCulturalOutputs
--	---

Table 18: Metadata of EstablishmentMeansValue (CodeList)

Definition:	EstablishmentMeansValue is a code list that enumerates means by which a SolitaryVegetationObject or PlantCover has been established on site.
Subclass of:	None
Stereotype	«CodeList»
Values	assistedNaturalRegeneration naturalRegeneration planted remnant seeded spontaneousColonization other

Table 19: Metadata of ObservationProcedureValue (CodeList)

Definition:	ObservationProcedureValue is a code list that enumerates the different procedures, processes, methods, algorithms or instruments, or system of these, which may be used in making an observation to measuring or otherwise determining the value of a property – to obtain data.
Subclass of:	None
Stereotype	«CodeList»
Values	AI fieldSurvey

	aerialPhotography CCTV expertEstimation externalDataBase LiDAR multispectralImaging HyperspectralImaging syntheticApertureRadar simulation otherSensor streetViewImagery volunteeredGeographicInformation unspecified
--	---

Table 20: Metadata of OwnershipTypeValue (CodeList)

Definition:	OwnershipTypeValue is a code list that enumerates ownership status or entity responsible for the governance and maintenance.
Subclass of:	None
Stereotype	«CodeList»
Values:	communityOrCollective indigenous institutional privatePublicHybrid privateResidential privateCommercial privateAgricultural publicFederal publicDistrict publicMunicipal publicState other

Table 21: Metadata of PotentialHazardValue (CodeList)

Definition:	PotentialHazardValue is a code list that enumerates the different types of potential hazards of SolitaryVegetationObject and PlantCover.
Subclass of:	None
Stereotype:	«CodeList»

Values:	allergenic diseaseVectorHabitat encroachmentOnInfrastructure fallingBranches fireHazard infected interferenceWithInfrastructure invasiveSpecies leafLitter nutrientDepletion obstructionOfVisibility poisonous punctureWounds rootIntrusion skinIrritation toxicBerries unstableVegetation waterContamination wildfire windthrow
----------------	---

Table 22: Metadata of SeasonalChangeTypeValue (CodeList)

Definition:	SeasonalChangeTypeValue is a code list that enumerates the different types of seasonal changes of vegetation.
Subclass of:	None
Stereotype:	«CodeList»
Values:	growth leafEmergence floweringPeriod fruitAndSeedDevelopment seedDispersal leafSenescence leafShedding needleDrop retentionOfFoliage dormancy

Table 23: Metadata of SignificanceValue (CodeList)

Definition:	SignificanceValue is a code list that enumerates the different types of significance.
Subclass of:	None
Stereotype:	«CodeList»

Values:	aesthetical conservational cultural dendrologicalRarity economical environmental global historical recreational religious spiritual other
----------------	--

Table 24: Metadata of CrownTypeValue (CodeList)

Definition:	CrownTypeValue is a code list that enumerates the different types of crowns of a SolitaryVegetationObject.
Subclass of:	None
Stereotype:	«CodeList»
Values:	conical cylindrical elliptical invertedOvate irregular ovate palmShaped spherical umbrellaShaped weeping

Table 25: Metadata of TrunkTypeValue (CodeList)

Definition:	TrunkTypeValue is a code list that enumerates the different types of trunks of a SolitaryVegetationObject.
Subclass of:	None
Stereotype:	«CodeList»
Values:	fallenTreeTrunk singleTrunk multipleTrunk nurseTreeTrunk snagTrunk banyanLikeTrunk

Table 26: Metadata of RootTypeValue (CodeList)

Definition:	RootTypeValue is a code list used to specify root types of the SolitaryVegetationObject.
Subclass of:	None
Stereotype:	«CodeList»
Values:	tapRoot lateralRoot heartRoot tuberousRoot rhizomeRoot sinkerRoot

Table 27: Metadata of ManagementTypeValue (CodeList)

Definition:	ManagementTypeValue is a code list that enumerates the different types of management or care activities applied to a SolitaryVegetationObject or PlantCover.
Subclass of:	None
Stereotype:	«CodeList»
Values:	adaptationOfSupportSystem additionalSupporting brushRemoval barkOrTrunkTreatment canopyManagement cleaning covering diseaseAndPestControl diseaseAndPestMonitoring fertilisation grazingManagement hazardousTreeRemoval herbicideApplication intensifiedUse invasiveSpeciesRemoval irrigationManagement recreationalManagement mowing ecologicalMowing mulching prescribedBurning pruning removingObjects speciesConservation soilAmendment

treeBending wildlifeHabitatManagement
--

5 CityGML 3.0 Vegetation ADE Proposal v1.1: Enumerations

The newly defined Enumerations for the CityGML Vegetation ADE v1.1 (Figure 4) are defined in the following tables.

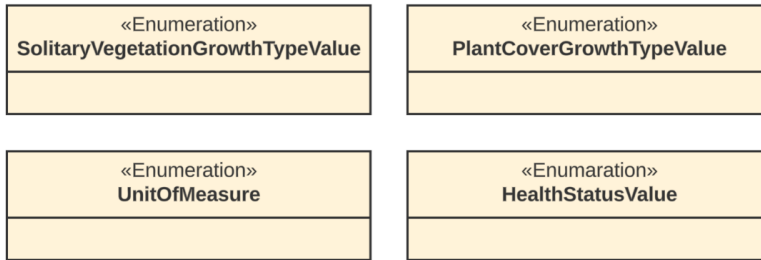


Figure 4: Enumerations of the CityGML 3.0 Vegetation ADE proposal v1.1

Table 28: Metadata of HealthStatusValue (Enumeration)

Definition:	HealthStatusValue is an enumeration that enumerates the different types of health states of vegetation. It is the same for SolitaryVegetationObject as for PlantCover.
Subclass of:	None
Stereotype:	«Enumeration»
Values:	excellent good fair poor critical dead

Table 29: Metadata of SolitaryVegetationGrowthTypeValue (Enumeration)

Definition:	SolitaryVegetationObjectGrowthTypeValue is an enumeration that encompasses the different attributes used to describe a SolitaryVegetationObject’s growth.
Subclass of:	SolitaryVegetationObjectProperties
Stereotype:	«Enumeration»
Values:	height crownBaseHeight crownDensity crownDiameter trunkDiameter trunkHeight

	rootSystemDiameter maxRootSystemDepth leafAreaIndex normalizedDifferenceVegetationIndex
--	--

Table 30: Metadata of PlantCoverGrowthTypeValue (Enumeration)

Definition:	PlantCoverGrowthTypeValue is an enumeration that includes the different attributes used to describe a PlantCover's growth.
Subclass of:	PlantCoverProperties
Stereotype:	«Enumeration»
Values:	averageHeight minHeight maxHeight startHeightOfCanopy leafAreaIndex normalizedDifferenceVegetationIndex

Table 31: Metadata of UnitOfMeasure (Enumeration)

Definition:	UnitOfMeasure is an enumeration used to specify the unit of a measure.
Subclass of:	None
Stereotype:	«Enumeration»
Values:	cm m km in ft miles percentage

Publication IV

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Empirical Data Meets Immersive Design

Lessons learned from 3D modelling a biodiversity intervention site for virtual reality

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3D models of urban biodiversity emerge as innovative tools to foster biodiversity awareness, engage stakeholders, and support adaptive urban planning. However, 3D visualisations of urban biodiversity are still rarely in a meaningful level of accuracy for communicating biodiversity values, due to challenges related to empirical data collection and species 3D modelling. We present insights gained from the 3D modelling of a biodiversity intervention site in Tartu, Estonia, for virtual reality. To attain high model fidelity, empirical data collection should be planned carefully, considering the aimed spatial resolution of model accuracy, the shortcomings of available data sources and performance limitations. Secondly, the shortage of taxonomically accurate species 3D models in correct age versions and Levels of Detail still complicate ensuring consistency across visual elements, unless modellers use methods of 3D model creation from data. The findings also underscore the importance of defining goals and target audiences for communication, to determine how to prioritise data accuracy and design elements. However, successful model implementation may foster species knowledge and support conservation, promoting pro-environmental attitudes for a more sustainable future.

Keywords: 3D Modelling, Urban Biodiversity, Virtual Reality, VR, Immersive Design, Empirical Data

INTRODUCTION

The accelerated decline in biodiversity driven by anthropogenic pressures, also known as the Holocene extinction (Turvey, 2009) takes its toll on urban biodiversity, causing far-reaching consequences such as the disruption of essential ecosystem services (Jansson, 2013). Biodiverse green spaces in cities also support recreation, physical health and mental well-being. Counteracting biodiversity loss within cities requires innovative tools to foster awareness, engage stakeholders, and support adaptive urban planning (Bulkeley, Kok and Xie, 2021). One

such tool can be highly realistic 3D models of urban biodiversity. Realistic 3D models support collecting feedback from urban stakeholders by making plans more understandable (Eilola et al, 2023). 3D models of biodiversity can enhance environmental awareness by providing immersive learning experiences through virtual reality (VR) and augmented reality (AR), fostering deeper understanding and advocacy for biodiversity (Harrington et al, 2022; Höftberger et al, 2023) and its conservation. Consequently, integrating biodiversity into urban 3D models is becoming

increasingly relevant for urban planning and stakeholder engagement.

3D visualisations of urban biodiversity are however still rarely in the level of accuracy that would be meaningful for communicating biodiversity values. In 3D city models and urban digital twins, modelling of plant individuals is often still restricted to large woody plants, such as trees, and arranged plantations, leaving e.g. spontaneous herbaceous vegetation classified as 'grass' (Feng, Liu and Gong, 2015; Fernández-Alvarado et al, 2022; Li et al, 2025). Outside of the urban realm, there has been an increase in biotic environment-related extended reality (XR) solutions on the topics of sustainability and conservation (Cosio et al, 2023), but only a few examples (e.g. Harrington, 2020; Harrington et al, 2021; Chandler et al, 2022) have 3D modelled biodiversity based on empirical data beyond woody plants.

The shortage of models of biodiversity in virtual reality is likely due to the fact that unlike 3D visualisations built for computer games (Wills, 2002), 3D models built for reality-based communication purposes need to attain high model fidelity – the truthfulness and accuracy of the data that the model is based on – to the represented site, which can be challenging for their creators. Attaining high information fidelity requires mapping biodiversity over wider spatial scales with either fieldwork, the usage of proxy measures for diversity (Vihervaara et al, 2017), or high-resolution remote sensing data (Biljecki and Ito 2021; Finizio et al, 2024) coupled with AI-based models for species identification (Wang and Gamon, 2019; Finizio et al, 2024; Gillespie, Ruffley and Exposito-Alonso, 2024). Attaining high visual and audio fidelity – the truthfulness and realism of the sensory experience conveyed by the modelled elements – (Harrington, 2023; Lindquist et al, 2020) may also be complicated e.g. by the difficulty of locating either species 3D models and audio files that match the collected empirical data and suit the computational

limitations of the modelling environment, or a method of model construction from data (e.g. Fol et al, 2024; Singh and Kaunert, 2025).

In this paper, we present insights gained from the 3D modelling of a biodiversity intervention site in Tartu, Estonia, for virtual reality. Our findings highlight key considerations for biodiversity data collection and model development that teams should consider when creating immersive representations of biodiversity-rich sites in virtual reality.

THE JAAMAMÕISA STREAM INTERVENTION SITE MODEL

Jaamamõisa stream (58°23'03.2"N 26°44'59.1"E) is a 3 km long waterway in Tartu, Southern Estonia, forming a green corridor from a nearby nature reserve towards Tartu city centre. The stream is bordered by a biodiversity-rich riverbank meadow, home to a wide variety of herbaceous plants, as well as new a construction area. The area is a target intervention site for the urbanLIFEcircles project, which aims to establish a connected network of biodiversity-rich green areas in Tartu (Võsaste, 2025). The city's intention is to extend the biodiversity-rich areas of the Jaamamõisa stream beyond the riverbank meadow via several interventions, designed to enhance ecological connectivity and habitat diversity while improving accessibility and public engagement. Additionally, the project aims at enhancing digital accessibility to biodiversity by creating virtual nature trails of the city.

As the Jaamamõisa stream intervention site is a popular recreational area for the local population, a 3D model-based immersive biodiversity game was envisioned as a tool for communicating intervention goals. The model was agreed to visualise the present and anticipated future biodiversity of the intervention site – particularly herbaceous plant diversity – alongside the planned interventions and their underlying goals and rationales. Given the focus especially on the herbaceous vegetation diversity,

it was agreed to model the site as it is in summer without seasonal variations.

Scene modelling

To present the site model in a realistic manner, QGIS was used to preprocess geographical real-world data, which was subsequently exported to Unity. As Unity does not directly support geographic coordinate systems, all data were transformed into Unity internal coordinate system with the centre of the target area at origo. Terrains with a combined size of 4 km² were created from grayscale heightmaps and textured with orthophotos. The terrain was split into 13 tiles, with a central tile of 1 km² representing the detailed target area, while surrounding background tiles measured 0,25 km² each. To enhance visual realism, detail texture layers were applied to the centre tiles, compensating for the insufficient resolution of the orthophotos at street level viewing. In addition to the terrain, a simplified city model was imported and optimised in Blender (blender.org). An imaginary walking trail was designed to guide players from one

intervention to another. Intervention signs were modelled in Blender, scripted with interactivity in Unity and equipped with an activation button, to allow players to see changes in the model before and after the intervention. Additional information signs were distributed across the trail to communicate information about biodiversity. An advanced physics-based VR interaction Unity asset was implemented for player character control.

Further, a plant identification tool (Figure 1) was also developed and implemented to support interactive learning within the virtual environment. A time-of-day system was implemented to allow the player to explore the virtual world even at night. The User interface was developed to be compatible primarily with a specific model of a VR headset (Meta Quest 3) and with standard PC monitors.

Herbaceous vegetation modelling

Herbaceous plant modelling of the Jaamamõisa stream started with the inventory of the pre-intervention herbaceous vegetation at the site

Figure 1: A plant identification tool allows game users to study different species of the biodiversity-rich meadow



during summers 2023 and 2024. Key areas of the intervention site were divided into two sections, i.e. into the intensively managed Southern part and a more Northern flower meadow. For both sections, experts compiled lists of observed herbaceous plant species, estimated relative species coverages (%) and average vegetation heights (cm) of herbaceous plants using 1x1 m² plant study squares (one square per section in 2023 and three squares per section in 2024). The intention was to interpolate plant densities between the study squares to create gradients of vegetation across the studied sections. However, due to the detailed topographic gradients and the presence of the stream at the intervention site, the visual placement of plants to the model following this method did not turn out realistic, given the observed spatial patterns of plant assemblages in the area. Therefore, site vegetation was re-inventoried, and polygons of visually distinct areas of homogeneous vegetation were delineated, each with a species list, vegetation cover (%) and average herbaceous vegetation height (cm).

Herbaceous plants were self-modelled in the project to attain an as a coherent look across the models as possible. As many of the sighted herbaceous species as possible were photographed against a grey background, resulting in 70 photographed species. Apart from very common species, plants were photographed on site, without removing them from the soil. Whereas some recent examples have used hand-created low-polygon 3D models based on photographs (Harrington et al, 2021; Chandler et al, 2022), 2D presentation was chosen for this project, due to computational limitations caused by large numbers and rather small sizes of herbaceous plant species at the site. Subsequently, plant photographs were rendered into 2D billboards with transparent backgrounds. As plants were photographed over a two-month period, some plants appear in the scene in slightly different seasonal forms.

The use of 2D billboards posed a challenge in aligning the plant cover measurements recorded by the fieldworkers with billboard placement densities in the virtual model. Plant densities applied through Unity's painting tools were calibrated to visually correspond with the empirical coverages of plants. An additional problem was caused by the different maintenance regimes across the intervention site, due to which individuals of the same species appeared as low-cut and fully-grown versions at different parts of the intervention site. Since Unity did not provide tools for plant cutting, the available options for incorporating species models with varying vegetation heights were either to duplicate the plant models and algorithmically trim them to the desired heights, or to use different texture UV maps for each height variation. However, both approaches result in additional computational cost due to model duplication.

Considering the high numbers of herbaceous plants, it is common not to model each plant individually. However, the usage of 1-3 billboards per plant species and instancing technology calls for computational methods that create variation between individuals, e.g. small height variations, rotation, tilt angle, to avoid scenes from looking repetitive. Additionally, the multiplication of only a few individual plant models can bias the outlook of a meadow from its empirical outlook, if the photographed individuals are even slightly atypical to the species in terms of their size, shape or colour. Additionally, post-process colour grading, which is typically used in games for artistic style, can affect whether the modelled herbaceous species will match their real-life counterparts.

Herbaceous plants typically appear in spatially aggregated patterns, which are determined by an array of ecological factors for different species (Lara-Romero et al, 2015; Perret et al, 2022). Correct plant aggregation patterns are important for attaining a realistic feel for a virtual natural scene (Chandler et al, 2022; Holm and Schweier,

2024). Therefore, aggregation patterns of herbaceous species required careful balancing in order to attain a realistic result even beyond the spatial scale of delineated homogeneous plant assemblages created by fieldworkers. Some game engine assets offer algorithmic tools for element distribution across space (Harrington, 2023) based on e.g. topographic or soil variables. However, in this project, plant aggregation patterns were created by hand due to the complexity of the placement rules required for a potential algorithm. Site photographs were used as reference to achieve the most realistic plant placement (Figure 2).

Woody plant modelling

While urban tree modelling from point clouds is becoming mainstream (e.g. Münzinger, Prectel and Behnisch, 2022; Chen et al, 2024), robust solutions for projecting the growth of point-cloud derived tree shapes in a species-specific manner are still lacking (Holm and Schweier, 2024). Therefore, trees of the sites were modelled using representative models of trees of same age,

without trying to model trees by individual branch structures. Tree locations, species, heights (m), canopy widths (m) and Diameter Breast Heights (DBH; cm) were derived as a shapefile from the City of Tartu. For the northernmost parts of the intervention site, where GIS data on tree locations was unavailable, drone images were used for tree placement. Matching tree models were either created algorithmically (Fabritius et al, 2023), or models were purchased from the Unity Asset Store that matched as closely as possible with the tree species and tree dimensions in the empirical data.

The lack of a coherent library of taxonomically and regionally correct plant models with suitable licenses and growth age series complicated the creation of coherent-looking sceneries. Purchasing models from different sources resulted in different paint tones and different used modelling techniques, styles (e.g. realistic vs stylised or cartoon-like) and level of detail (LoD), which could easily have created a collage-like visual appearance for the trees. Some of the visual issues were corrected by hand before model

Figure 2: Detailed topographic variations and the presence of a stream create fine-scale spatial patterns for herbaceous vegetation. The digital nature trail is equipped with information signs



placement to site, e.g. the low-polygon algorithmic trees were modified in Blender to include more roundness and detail. Algorithmic tree models were also enhanced with self-built shaders simulating shadows and wind movement for more realistic feel in a virtual reality environment. Some tree species' models were replaced by either a closely related species or a model of another species with the same general outlook due to the lack of a combination of the taxonomically correct species in the correct heights, for the prediction of tree growth into the future to represent the post intervention site.

Animal modelling

Animal observations of the site were available in the PlutoF database (Abarenkov et al, 2010), which holds both systematic observations from expert field surveys and citizen science data. For the presentation of animal observations, four methods were considered: information signs of animal observations, static and mobile animal 3D models, ambient sounds and positioned sounds. The use of animal observation data raised questions of how to filter observations based on age, frequency and time of year to choose species to include in the 3D model. Eventually, modelled animal species were selected by city experts based on representativeness to the site and model availability. Species densities were decided visually.

The use of purchased animal 3D models resulted in similar challenges as in the case of woody plants with the limited availability and licencing restrictions of taxonomically accurate digital assets. Furthermore, existing models varied in terms of level of detail, visual quality and modelling style. Further, smaller animals, such as insects and spiders, were difficult to model and visualise without being obscured from view. To address this issue, we positioned e.g. spiders in their original size on informational panels where they are more visible to users. However, during

user testing of the VR environment, most participants did not notice the small animals.

Animal 3D models with dynamic animations could further enhance 3D model realism by simulating natural behaviours such as movement and interaction with the environment. Birds in flight or insects crawling across surfaces add a layer of dynamism that static models cannot achieve. Unfortunately, to date, animated models of animals that behave in a natural way are limited. Additionally, these animations require careful optimisation to ensure smooth performance within computationally constrained environments like VR. The integration of moving animals into their virtual habitats introduced additional complexity. For instance, birds might be depicted flying between trees or insects pollinating flowers, requiring precise coordination between animal animations and plant placement. Animal reactions to human presence were considered but not modelled.

Soundscapes have emerged as a highly effective tool for enhancing the perception of animal biodiversity. Realistic audio representations of local fauna by geolocation significantly increase users' perceived biodiversity richness (Lindquist et al, 2020) and support a multimodal, multisensory immersive embodied experience (Harrington, 2023). For this project, sounds recorded at the intervention site were processed and integrated as 2D ambient sounds. An alternative approach to implementing sound would be to have individual objects, such as birds, emit 3D (positional) audio.

Intervention modelling

The planned biodiversity interventions for the site included the placement of submerged and on-the-ground dead wood, to enhance habitat diversity for aquatic and specialist species. Additionally, sections of flat banks, stones, floodplain ponds, aquatic plants and a small wetland were introduced to the stream to increase aquatic habitat diversity. The removal of

a dam in the upper course of the stream aimed at facilitating species movement and biomass flow. A bridge was added to access the flower meadow, while the introduction of bushes and trees was intended to increase overall species diversity on the site.

City experts planned biodiversity interventions in terms of their locations and described how the scene would appear before, immediately after, and at two later stages (one month or year, depending on the type of intervention, and 2-5 years) post intervention. Additionally, experts provided details on the objectives of each intervention and contributed descriptive texts to support model communication via intervention signs. The purpose of this timeline was to elicit a more detailed quantitative and qualitative understanding on the experts' assumptions regarding long-term effects of interventions on both site appearance and biodiversity. This included factors such as moss growth on dead wood, increases in e.g. insect densities within the newly established aquatic ecosystem, and tree growth throughout the years.

3D model objects needed for intervention modelling (stones, dead wood, bridge) were purchased from the Unity Asset Store. Interventions with terrain changes were particularly challenging to implement, as they required activation of an additional 1 km² centre tile to visualise the intervention scenario terrain with separately placed herbaceous vegetation, which had long loading times during intervention activation. As also some interventions, e.g. terrain changes, were not easily noticeable from the walking trail, interventions were slightly exaggerated to make them more visible to model users.

BALANCING MODEL AUTHENTICITY, PERFORMANCE AND COMMUNICATION GOALS

This study demonstrates the potential of 3D modelling and immersive VR as tools to communicate urban biodiversity, using the Jaamamõisa stream site in Tartu, Estonia, as a case study. The findings underscore the importance of defining clear goals and target audiences to balance data accuracy with design elements. For instance, audiences with varying levels of species literacy are likely to perceive a 3D model of site biodiversity differently, and appreciate different model details (Hooykaas et al, 2019). To ensure informed engagement with biodiversity data in educational and interactive contexts, it is important to consider how to communicate the sources and assumptions behind predictive and analytical models. At best, successful model implementation may foster species knowledge and support biodiversity conservation, ultimately promoting pro-environmental attitudes for a more sustainable future (Härtel et al, 2024).

To attain high model fidelity, empirical data collection should be planned considering the aimed resolution of model spatial accuracy, the shortcomings of each available data source and performance limitations. For instance, the usage of LiDAR or 360° photography would allow highest accuracy in data collection, but for performance reasons, the modelled 3D objects may still need to be converted to low-polygon 3D models, to balance visual fidelity and model performance (Chandler et al, 2022; Holm and Schweier, 2024). When modelling herbaceous vegetation, data collection should match the targeted spatial resolution and extent of the site 3D model. A meaningful spatial resolution for empirical data collection may depend on the modelled ecosystem and the typical aggregation patterns of its main flora (Perret et al, 2022). The plan for plant placement may contain hierarchical levels of data classification, e.g. the definition of visually uniform vegetation areas as polygons,

and within them, estimation of plant densities (Harrington et al, 2021) and small-scale aggregations using e.g. expert validation for visual realism and credibility (Chandler et al, 2022). The empirical data plan should also consider the changing seasons and how management measures, e.g. mowing the vegetation, would affect suitable data collection times.

The shortage of taxonomically accurate 3D representations of species, across different ages and LoDs, still complicates ensuring visual consistency in virtual environments. As the field of 3D content generation advances rapidly (e.g. Chen et al, 2024), including animal models (Li et al, 2024), creators may increasingly turn to data-driven methods for producing these assets.

TOWARDS DIGITAL TWINS OF URBAN BIODIVERSITY

By leveraging the confluence of tools, immersive technologies, methods, and domains of expertise, urban planners can foster public understanding of biodiversity interventions, promote environmental awareness, and inspire pro-conservation attitudes. Unlike static models, future urban biodiversity digital twins could act as a digital monitoring tool, automatically tracking and visualising changes and the effectiveness of interventions over time. Automated data integration e.g. via APIs ensures included models remain dynamic and relevant (Rantanen et al 2023), allowing for (real-time) updates and adaptive decision-making based on changing parameters derived from the real environment and new insights. Future development should focus on integrating Geographic Information Systems (GIS), 3D modelling, game engines, different presentation methods such as through VR and automated data updating into a unified framework. This fusion leverages e.g. GIS's semantic data capabilities and ecological modelling (Xie et al 2021), combined with game engines' realistic visual and audio rendering, to effectively communicate biodiversity aspects to

diverse audiences. In the field of architecture, such integrative systems could support nature-inclusive design processes, inform site-specific interventions, and enable early-stage evaluation of ecological impacts within planning workflows.

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Varying Data on Urban Trees Complicates Meeting User Needs for Digital Twins of Urban Green Infrastructure

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Abstract. Digital twins are becoming common in urban planning and space management. However, dynamic modelling urban green infrastructure is lagging behind this development. Using interviews, online polls and questionnaires, we identified user groups and needs for a digital model of urban green infrastructure for pilot cities in Estonia and Finland. We found that several user needs were associated with users being able to see and analyse the anticipated future development of existing and proposed vegetation. To meet these needs, digital twins require projection models that are calibrated using regionally suitable data. In our case study of urban tree growth, based on literature searches of pilot area species, the availability of suitable data was limited and varied per species. This suggests that initial projection models may need to be built on expert estimates. Suitable empirical data can later be retrieved by monitoring the focus areas of digital twins, but this requires time.

Keywords: Digital Twins, Urban Digital Twins, Green Infrastructure, User Needs, Urban Trees, Projection Model

1. Introduction

Digital Twins are developing in various fields (Qi *et al.* 2019) and becoming more common in urban planning and urban space management. Although no uniform definition of digital twins exists (Ketzler *et al.* 2020), we refer in this paper to urban digital twins (UDTs) as parts of cyber-physical-social systems, where physical entities are coupled with their digital counterparts (Tomko & Winter 2018). Urban digital twins can be defined as containers of digitised, continuously updating information of the urban environment, such as semantic data and 3D models, which can also influence the physical entity (Ketzler *et al.* 2020). Digital twins can furthermore be enhanced through applications, including simulations (Dembski *et al.* 2020). Digital twins can incorporate models of the existing, future or imaginary environments, and they can be used to simulate different scenarios by altering certain input data. Thus, a digital twin allows to study and compare different alternatives without actually touching or harming the existing environment. In urban planning, digital twins act as data collection and analysis

platforms, as well as data-driven decision support systems (White *et al.* 2021). Digital twins help urban planners with for example modelling transportation flows (Dasgupta *et al.* 2021), enhanced risk-informed decision making (Ham 2020), simulating daylight and wind conditions (Hämäläinen 2020), and modelling energy systems and climate data (Savage *et al.* 2022). Digital twins are created by multiple developers with varying interests and resources. Hence, no urban digital twin entails all the existing applications and therefore potentials than an all-encompassing digital twin could have, as the different urban digital twins are elaborated with different purposes. Even though the idea of a real, all-encompassing digital twin exists, there are discussions about if this might ever be attainable (Batty 2018).

Modelling of urban green infrastructure for urban digital twins lags behind the modelling of different aspects of for example real estate, utility and road infrastructure. Few urban digital twins exist so far that have modelled urban greenery beyond static 3D models for street trees and green terrain texture or aerial imagery for green areas (Mrosła *et al.* in prep.). The increasing use of digital twins in urban planning without an advanced model of green infrastructure causes several drawbacks from the viewpoint of planning and maintaining urban greenery. First, plans made using digital twins could entail conflicts between city infrastructure and greenery (e.g., plant roots interfering with underground infrastructure) that are only discovered in later planning phases or after construction. Second, urban planners could make planning decisions without adequate visibility to for example the interactions of urban nature or to the provided Ecosystem Services to residents (Woodruff & BenDor 2016). Third, digital twins could not be fully used in the design of urban greening, to meet Sustainable Development Goals (Bauer *et al.* 2021).

Technological capacity for the detailed modelling of urban green infrastructure is advancing in several fields. Besides fieldwork, data on urban vegetation can be collected and updated using remote sensing methods, volunteered geographic information, citizen science and sensors (Dobbs *et al.* 2017). Also, methods for modelling algorithmic 3D plants and vegetation allow realistic 3D visualisations of plant growth and individual variation (e.g., Ackerman *et al.* 2021). At the same time, digital twins are constrained by the limited run-time calculation and rendering power for large numbers of interactions and details, and the need to maintain compatibility and interoperability with urban data sources and visualisation as well as analysis tools. International standardised data models for semantic urban data, such as CityGML and CityJSON, define data object types for modelling individual plants and green areas (Labetski *et al.* 2018) and can be extended using Application Domain Extension modules (ADE; Biljecki *et al.* 2018). However, any potential expansions should be based on genuine user needs, to prevent the creation of unnecessarily complex data structures and models, which are unlikely to be adopted and utilised widely, and which would incur significant expenses for data collection.

It is likely that meeting user needs for a digital twin of urban green infrastructure require the possibility to simulate the development of urban green infrastructure into the future, either from the status quo or for specific scenarios (Dietze *et al.* 2018, Bodner *et al.* 2021). This can be attributed to the dynamic nature of green infrastructure, that is, how ecological assemblages may change in terms of their species composition, height, mass, visual outlook and ecosystem services depending on maintenance and environmental factors. CityGML already contains extensions and standard updates that

support dynamically changing objects (Open Geospatial Consortium 2012). However, to simulate vegetation changes without misleading users with a false sense of certainty about their future, projection models should be created that are based on ecological knowledge and calibrated with reliable empirical data (Kastuari *et al.* 2020).

We studied the enablers of creating a digital model for urban green infrastructure in the FinEst Centre of Smart Cities large pilot project GreenTwins. The GreenTwins pilot project (2020-2023) aimed at creating a dynamic green information model for the digital twins of pilot areas in Tallinn, Estonia, and in Helsinki, Finland (Prilenska *et al.*, submitted for CUPUM 2023). We focused on the following three questions:

- RQ1. Who are the potential user groups of a digital model of urban green infrastructure in Tallinn and in Helsinki, and what are their related user needs?
- RQ2. Are projection models necessary to meet the identified user needs, and if yes, what kind of empirical data is required to calibrate the projection models for the local vegetation of the pilot areas?
- RQ3. Does suitable empirical data exist in research literature for calibrating the projection models?

2. Methods

2.1 RQ1: User groups and user needs for a digital model of urban green infrastructure

The user groups and their needs for a digital twin of urban green infrastructure (RQ1) were identified during a user research process which was carried out as action research (see detailed description in Nummi *et al.*, 2022). During the process, data were collected using a variety of methods in interactive sessions, and the understanding of user needs was refined throughout.

The initial understanding of the user groups, their activities and needs were defined based on the first online workshops and questionnaire (May and June 2021). However, descriptions of user groups and needs were refined during the process (Table 1), as is typical for iterative action research.

Table 1. User research activities, participants and description of the applied methods.

Research activity and participants	Methods
Online workshops, polls and questionnaire - Dates: May 25th 2021 and June 17th 2021 - Participants: Professionals (land use planners, landscape architects, architects, ecologist, researchers, IT experts) and active citizens (workshop n=44, online polls n=19, questionnaire n=19)	The concept of digital vegetation was introduced to the participants, followed by a focus group discussion, where the participants' initial thoughts and perceptions on if and how digital vegetation could improve their everyday work were gathered. The perceived usefulness of the concept was asked with an online poll during the session. A questionnaire with detailed questions about the needs and expectations for digital vegetation (e.g., the expected level of detail and availability of semantic information on vegetation, or preferred simulation features) was shared with online workshop participants.
Online workshops and questionnaire - Dates: Three sessions in Oct 2021 - Participants: Citizens (active citizens, city planning activists) and professionals (experts in planning, city representatives, researchers, students, NGOs; in total n=88)	The concept of a 3D planning tool using digital vegetation was first presented and demonstrated for the audience. A city planning activist gave a commentary speech, and open discussion followed. The perceived usefulness of the concept was asked with a poll, and detailed feedback was gathered through a questionnaire.
Interviews - Dates: Sept 2022 - Participants: Professionals from city of Tallinn (transportation specialist, landscape architect, urban planners; n=5)	Viewpoints of the experts in the city planning department in Tallinn were studied to understand more in depth the prevailing practices. The covered topics were digital tools and plan data, participatory planning practices, and collaboration between experts.
Co-development of the tools - Dates: May 2021 – May 2023 - Participants: Professionals from city of Tallinn (GIS specialists, landscape architects, urban planners; n=5)	During the GreenTwins project, the employees of the city of Tallinn have participated in weekly meetings and in the development of digital vegetation. The collaborative action research process has enabled to refine our understanding of the needs of the professional users.

The gathered user data were co-analysed in online sessions. In Autumn 2021, initial user needs were formulated as user stories to describe the need and motivation behind them. Based on the user stories, detailed user requirements were written. These requirements were then prioritised jointly with GreenTwins research team (n=13) and representatives from the city of Tallinn (n=2) during online workshops. Each participant voted for three requirements they considered most important. Further details

of the user research methods to generate user insight are provided in Nummi *et al.* (2022).

2.2 RQ2: Need for projection models and data for model calibration

For each identified user need that was prioritised for our implementation, we assessed whether meeting the user need would require (1) expanding the information model of urban green infrastructure with new object types or object attributes in comparison to the CityGML standard, or (2) adding projection models for the digital twin that should be calibrated based on reliable empirical data (RQ2). For each projection model, we analysed which kind of empirical data would be needed for model calibration (Fig. 1).

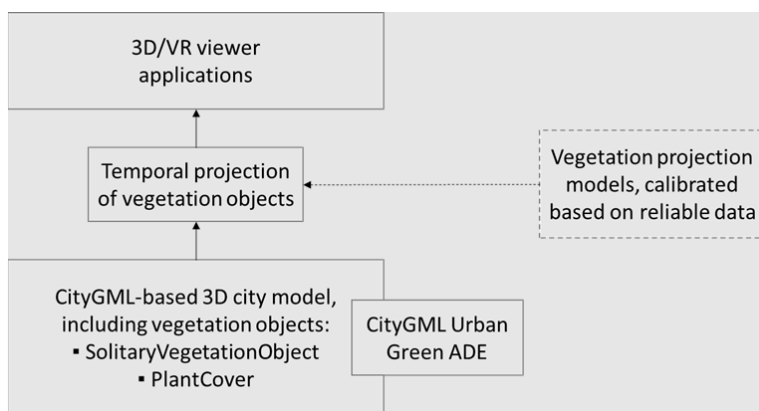


Fig. 1. Technical architecture of the digital twin of urban green infrastructure, as anticipated in the GreenTwins project. SolitaryVegetationObject and PlantCover are CityGML classes for storing vegetation data (Open Geospatial Consortium 2012).

2.3 RQ3: Data availability for model calibration for pilot area tree species

We studied data availability for creating projection models for a digital twin of urban green infrastructure (RQ3) by conducting a case study on one of the identified user needs that required a data-calibrated projection model. For the case study, we chose the user need to be able to see the anticipated future growth of urban trees in terms of their height and canopy width, depending on the tree species in question.

Inventory of pilot area tree species

To identify what species data would be needed for projecting tree growth at the GreenTwins pilot areas, we identified the tree species of the GreenTwins project's two main pilot areas. Those comprise a 0.3 km² park named Toompark in the city of Tallinn, Estonia (59.44°N and 24.75°E), and a 0.9 km² mixed-type area called Hermannin rantapuisto in Helsinki, Finland (60.2°N and 24.94°E; Fig. 2). We identified the tree species using multiple methods, including field inventories, existing city records and remote sensing methods (Yao *et al.* in review). In Tallinn, the location of the trees was

specified using point cloud information from the National Land Survey. The species of trees and, if possible, the lower taxonomic unit were determined during field visits following the city procedures for vegetation inventories. In Helsinki, the tree and green area data layers of the city's general base map were used to create the base plan. We used remote sensing data in combination with existing urban records to discriminate trees, while field research was carried out to assess accuracy and to make corrections.

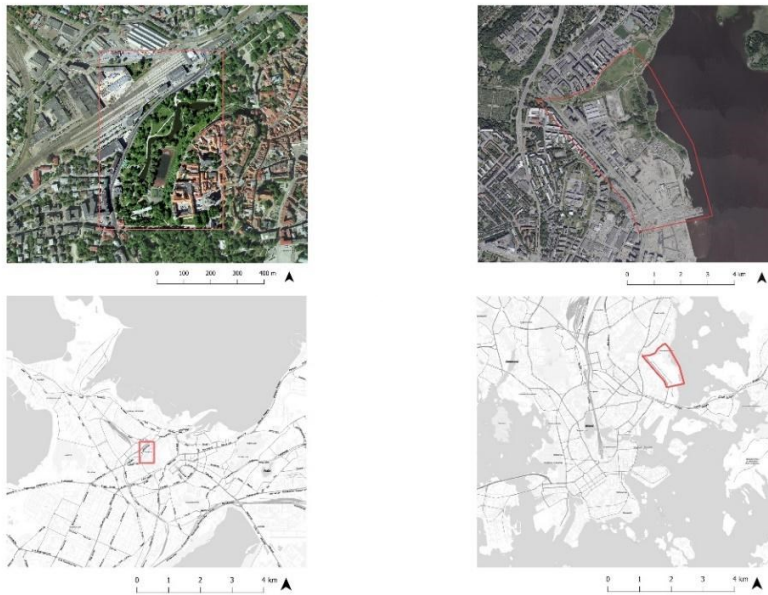


Fig. 2. Pilot areas of the GreenTwins project in Tallinn, Estonia (left) and Helsinki, Finland (right). Vegetation of main pilot areas is illustrated in the top panels.

Search for pertinent data on the pilot area tree species

To estimate data availability for projecting urban tree growth, we carried out article searches for this feature in the Scopus abstract and citation database in January 2023. For each of the GreenTwins pilot area species, we created the search terms by combining the species' scientific name in quotation marks with the feature-related search term "growth", using the Boolean operator AND (as in "'Acer platanoides' AND growth").

Trees are known to grow differently in urban areas, for example in streets and parks versus forests (Sanders *et al.* 2013, Pretzsch, *et al.* 2017). We thus further narrowed the search by including the keyword "urban", again using the Boolean operator (as in "'Acer platanoides' AND growth AND urban"). Next, we checked the country of analysis, and narrowed the list of matching articles further to those that were done either in Estonia or Finland or in their neighbouring countries (Germany, Poland, Baltic and Nordic countries, and Western parts of Russia). From the final resulting list of articles, we evaluated article relevance by reading article titles and abstracts. We included those

articles as relevant that contained data that could be useful for fitting a growth curve for tree height, tree crown diameter or trunk diameter.

3. Results

3.1 RQ1: User groups and user needs for a digital model of urban green infrastructure

We identified several user groups for the GreenTwins digital model of green infrastructure (Table 2), which had partly overlapping user needs (Table 3). Each user group was represented to some degree at the various stages of our user research. However, groups with the highest and most active representation were urban planners and landscape architects or planners. Representatives of these groups were also involved in the co-development of the project through their own work.

Table 2. Main user groups for a digital model of urban green infrastructure in Tallinn and Helsinki, as identified during user research, and their key tasks related to urban greenery.

User group	Definition and main tasks related to urban greenery in urban planning
Urban planners	In Estonia and Finland, urban planners are usually architects, landscape architects or geographers. Public-sector planners create plans, coordinate planning projects and organise public participation in planning projects. Planners in the private sector design, visualise, and produce studies and analyses for plans. In the master planning level, planners ensure the adequacy and ecological sustainability of green spaces, green networks and corridors. In detailed planning, green areas are designated e.g., for recreational use, and the amount and quality of greenery is defined by local building regulations and city master plans (e.g., Green Factor in Tallinn). Individual trees or rows of trees can also be assigned on street areas.
Landscape architects or planners	Landscape architects work in private and public sector in different landscape and urban planning roles. In the city organisation, landscape architects analyse the existing landscape and vegetation, assess landscape and ecological impacts of plans, and do inventories of natural values (e.g., valuable trees or landscape areas) in planning areas.
Real-estate developers	Real estate developers develop large housing estates and business campuses either for sale or for rent. Making a detailed plan is often a part of their development package. They are often ready to invest in urban greenery, as a high-quality environment raises the selling price of developments. The increasing demands from cities towards vegetation quality (e.g., through Green Factor) is likely to affect the developers in the future, and will increase the need for vegetation planning tools.
Transportation engineers,	Transport engineers can work in a wide range of roles on transport planning solutions. Street designers often define locations of street trees. They must ensure that vegetation does not impede traffic safety

street designers	(e.g., clear view areas). They need information about e.g., the underground infrastructure, as it limits the placement of trees in street areas.
GIS specialists and city model experts	GIS specialists and city model experts are IT specialists or geographers working with spatial data. They work with city green elements, as green elements are part of the urban space. They often encounter issues of needing to constantly update city greenery data, or receive data requests related to the lack of data on greenery.
City gardeners	City gardeners are working for the landscape or park division in the cities. In Tallinn, city gardeners maintain plants (incl. summer flowers and perennials) on city-owned areas and monitor the quality of the public green environment. They also consult private construction projects that involve the cutting of valuable trees.
Active citizens and citizen activists	Active citizens take a role in improving their own living environment or neighbourhood. They may also promote a personally important topic or local issue. They follow urban planning, give their opinions in different stages of the planning process, and make initiatives and alternative plans to the city planning. These suggestions may relate to urban greenery.
Urban ecologists or conservation biologists	Urban ecologists plan how to maintaining diverse urban nature, ecological processes, a connected network of green areas, and sustainable coexistence of urban wildlife with urban residents. Conservation biologists plan ways to support the viability of threatened populations or species. Urban ecologists and conservation biologists collect data on urban nature, seek for data collected by others for their analyses, communicate the values of urban nature to urban residents, and give feedback on the ecological or species impacts of urban development plans.

Table 3. Identified and prioritised user needs for a digital model of green infrastructure, the necessary information model extensions to the CityGML data, and the needed projection model and model calibration data.

User need and user groups associated with the need	Required information model extension, projection model and parameterisation data
Need to see how the outlook of lawns would change if their maintenance intensity was reduced to support more biodiversity-rich green areas (city gardener, landscape planner, urban planner)	Extend the PlantCover object vegetation types (CityGML 2016) to contain lawns. Project the change of the species composition of a PlantCover object over projected years, given their vegetation type and Maintenance class (a new parameter). Calibrate the model for lawns. (*)
Need to see how a tree grows in order to understand how and when it will provide shade/shelter (urban planner, landscape planner, citizen activist)	Extend the species list for SolitaryVegetationObjects (CityGML 2016) to contain GreenTwins pilot area species. Project the change of Height, trunkDiameter and crownDiameter of SolitaryVegetationObjects over projected years depending on their species.
Need to model the growth of the tree root system and fit to narrow underground street spaces (urban planner, landscape planner, citizen activist)	Add parameters for root system diameter and depth for SolitaryVegetationObjects. Project the change of SolitaryVegetationObject root system diameter and depth over projected years, given plant species and available data on soil availability. (*)
Need to see how the planned vegetation changes over seasons (flowering, falling of the leaves, autumn colours; landscape architect / planner)	(no projection model needed)
Need to understand the effects of environmental factors, such as weather, climatic conditions, and soil type, on tree growth (landscape architect / planner, urban planner, citizen activist)	Add local environmental parameters (not planned yet). Extend the projections of plant aboveground and underground system measures of trees to account for the defined environmental parameters (not planned yet).
Need for up-to-date information about green infrastructure (all user groups)	(no projection model needed)

(*) In the future, the model should be extended to account for local site conditions.

3.2 RQ2: Need for projection models and data for model calibration

Four out of six of the identified and prioritised user needs were linked to users being able to see and analyse the likely future development of planned and existing vegetation. This meant that meeting such user needs would require projection models and model parameterisation data (Table 3). These user needs were mainly related to urban planning and thus linked to the requirements of urban planners and landscape architects or planners. However, the needs of urban planners and landscape architects are somewhat different: Our findings suggest that urban planners, who do not have landscape expertise, do not themselves identify plant species in the plans. Nevertheless, they are interested in how the plant species selected for a more detailed green space plan by landscape architects perform in the planning area, and how they for example contribute to the urban microclimate by providing shelter and shade in the street space.

3.3 RQ3: Data availability for model calibration for pilot area tree species

Our case study on data availability for meeting the user needs for a digital twin of urban green infrastructure showed there was very limited suitable data available for calibrating projection models for urban tree growth in research literature, and that the amount and of available suitable data varied per species. Numbers of overall matches per tree species varied from 52 (*S. intermedia*) to 31,253 (*Prunus spp.*; a group of several commercially important species). However, the number of matches including the search term ‘urban’ reduced the number of matches per species to the maximum of 21 matching articles. Relevant data for growth model calibration was found for four of the 20 pilot area tree species among the articles considered geographically or climatically suitable (Fig. 3).

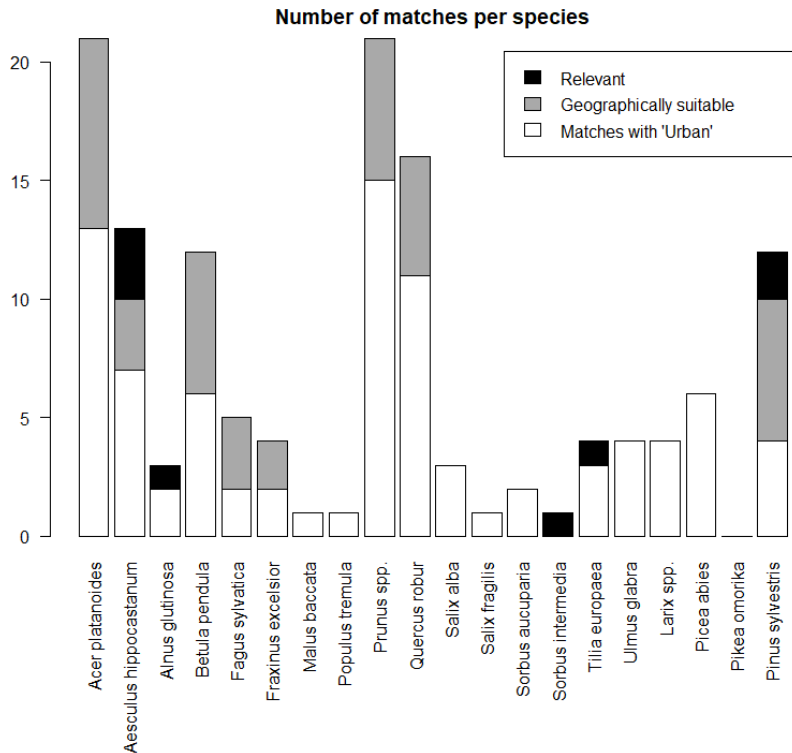


Fig. 3. Number of article matches in the Scopus database in a literature search on tree growth, sorted by tree species in the GreenTwins pilot area, and by article relevance. Relevant articles (black) are shown separately from those that also contained the keyword 'urban', but were either geographically not suitable (white) or geographically suitable but not relevant (grey).

4. Discussion

Our study results suggest that there are multiple user groups in cities that could benefit from a digital model of urban green infrastructure, and that many of their user needs are linked to being able to project the development of planned and existing vegetation into the future. Also, our case study showed that the available data on urban vegetation in research literature is not uniform enough nor of adequate quality to provide a solid basis for creating such models for digital twins.

By restricting our searches to only articles that mention 'urban' in the title, keywords or abstract, we may have excluded some relevant articles that use other equivalent terminology to indicate focus on urban trees, or articles that address growth in tree species that would grow quite similarly in their typical locations at urban areas than they growth elsewhere. However, the conducted study provides valuable insights into the limited scope of articles that address urban tree growth specifically, as well as the

scarcity of available publications containing data that could be used to develop similar model calibrations across different tree species.

Given the current circumstances, the most feasible avenue for creating the climate-appropriate evidence base for vegetation models lies in collecting expert estimates. Local professionals working with urban green areas and urban ecology typically possess expertise on vegetation that is relevant to the regional weather and climate, and also on the local soil conditions and urban green area maintenance histories. If this expertise is carefully elicited (McBride & Burgman 2012), it may give the best available basis for retrieving uniform data to function as the basis of calibrating vegetation projection models for local use.

In the longer run, as cities have designed and prepared urban digital twins including digital models of urban green infrastructure, it will also become possible to base algorithmic vegetation projections on constant model calibration based on accumulating data from the digital twin target area itself. The modelling approach can be chosen so that it easily allows constant model calibration and improvement based on accumulated data (Bodner *et al.* 2021), for example by using self-learning models (Pukkala *et al.* 2021). This solution requires regular monitoring systems that can track and measure changes in urban vegetation over time, to ensure the correctness and most real representation of the modelled vegetation. Additionally, locally collected data can also provide the best possibility for predicting variations of for example growth rates due to variations in environmental conditions.

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