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NINA Report

Accounting for amenities and regulating ecosystem services of urban trees

Testing a combined field protocol for VAT19 and i-Tree Eco valuation methods

Alexandre Nollet
David N. Barton
Zofie Cimburova
Anders Often

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CONTACT DETAILS

NINA head office
P.O.Box 5685 Torgarden
NO-7485 Trondheim
Norway
P: +47 73 80 14 00

NINA Oslo
Sognsveien 68
0855 Oslo
Norway
P: +47 73 80 14 00

NINA Tromsø
P.O.Box 6606 Langnes
NO-9296 Tromsø
Norway
P: +47 77 75 04 00

NINA Lillehammer
Vormstuguvegen 40
NO-2624 Lillehammer
Norway
P: +47 73 80 14 00

NINA Bergen:
Thormøhlens gate 55
NO-5006 Bergen.
Norway
P: +47 73 80 14 00

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Abstract

Nollet, A., Barton, D.N., Cimburova, Z. & Often, A. 2021. Accounting for amenities and regulating ecosystem services of urban trees. Testing a combined field protocol for VAT19 and i-Tree Eco valuation methods. NINA Report 1948. Norwegian Institute for Nature Research.

Monetary valuation of the ecosystem services provided by urban trees can contribute to general awareness-raising about the importance of trees, cost-benefit analysis of tree investments, prioritization of management measures and damage compensation calculations. This report provides support for the standardization of tree valuation methods in Norway. Until 2019, Norwegian tree assessors typically used the Danish Verdsetting af Trær (VAT03) method, which accounts for several aspects of amenities and recreational ecosystem services. Updated in 2019, the VAT19 guidelines have extended their scope to consider the valuation of regulating ecosystem services through expert assessment. In this sense, the implementation of an integrated protocol which contains both amenities and regulating ecosystem services could serve the valuation of urban trees and help to determine the places where a planted tree is the most valuable. However, in the VAT19 field methodology, there is no explicit link to the i-Tree Eco model, which is the dominant way to assess regulating ecosystem services. Furthermore, the current VAT19 method does not make use of available geospatial data which can be used to model tree variables (e.g. tree crown dimensions).

The aim of this study is therefore to develop, test and document a cost-effective and sufficiently accurate field protocol for the assessment of variables that can be then used in the VAT19 and i-Tree Eco valuation methods. We call this combined field protocol the *VAT19-i-Tree field protocol*. To ensure its cost-effectiveness, we assessed each field variable in terms of its contribution to the tree compensation value and the ease of recording it in a field survey, to retain only a limited number of key field variables. In addition, we assess which field variables could potentially be modelled using geospatial analyses. We then test the combined field protocol by conducting a field survey on a sample of trees in Oslo and by demonstrating the calculation of compensation value for trees within this sample. Finally, we use a Bayesian belief network to assess uncertainty within subjective expert assessments. Future research should address limitations of the resulting VAT19-i-Tree field protocol related to tree visibility assessment and valuation of extraordinary old trees.

The data preparation, collection, analysis and report writing were done over 6 months (February 2020 – July 2020) in Oslo as part of a M.Sc. of the first author, supervised by co-authors and an experienced arborist at the Oslo City Agency for Urban Environment. Within the Urban Ecosystem Accounting project, this study contributes to the testing of accounting valuation methodologies for urban trees. The study provides a number of practical tools in the appendix including: a detailed user manual for the VAT19-i-Tree field protocol, an Excel-based example of calculating tree compensation value, an open-source QField application to calculate individual VAT19 scores and tree compensation values on the fly using an Android device, and a calculator to estimate tree age based on a review of circumference-age statistics.

Alexandre Nollet, AgroParisTech, 14 rue Girardet, 54000 Nancy, France.
Email: alexandre.nollet@protonmail.com

David N. Barton, Zofie Cimburova, Anders Often. Norwegian Institute for Nature Research (NINA), Sognsveien 68, 0855 Oslo, Norway. Email: david.barton@nina.no, zofie.cimburova@nina.no, anders.often@nina.no

Résumé

Nollet, A., Barton, D.N., Cimburova., Z., Often, A. Comptabilité des aménités et services de régulation des arbres urbains. Test d'un protocole combinant les méthodes de valuation économiques VAT19 et i-Tree Eco. 2020. Rapport du NINA 1948. Institut Norvégien pour la Recherche sur la Nature (NINA).

L'évaluation monétaire des services écosystémiques fournis par les arbres urbains peut contribuer à la sensibilisation générale quant à l'importance des arbres, à l'analyse coûts-avantages des investissements les concernant, à la priorisation des mesures de gestion arboricoles, et aux calculs de compensation des dommages infligés à ces derniers. Ce rapport soutient la normalisation des méthodes d'évaluation des arbres en Norvège. Jusqu'en 2019, les évaluateurs d'arbres norvégiens ont généralement utilisé la méthode danoise Verdsetting af Træer (VAT03), qui prend en compte plusieurs aspects des aménités et des services écosystémiques récréatifs. Mises à jour en 2019, les lignes directrices de la méthode VAT19 ont élargi leur champ d'application pour envisager la valorisation des services écosystémiques de régulation par le biais de jugements d'experts sur le terrain. En ce sens, la mise en œuvre d'un protocole intégré prenant en compte à la fois les aménités et les services écosystémiques de régulation pourrait servir à la valorisation des arbres urbains, et aider à déterminer les endroits où un arbre planté est le plus précieux. Cependant, il n'y a dans la méthodologie de terrain VAT19 aucun lien explicite avec le modèle i-Tree Eco, devenu le moyen dominant pour donner une valeur aux services écosystémiques de régulation. De plus, la méthode VAT19 actuelle ne se sert pas des données dendrométriques obtenues par télédétection (telles que les dimensions des houppiers).

L'objectif de cette étude est donc de développer, tester et documenter un protocole de terrain rentable et suffisamment précis pour récolter des variables de terrain pouvant ensuite être utilisées dans les méthodes d'évaluation VAT19 et i-Tree Eco. Nous appelons ce protocole de terrain combiné *le protocole de terrain VAT19-i-Tree*. Pour en garantir la rentabilité, nous évaluons chaque variable de terrain en fonction de sa contribution à la valeur de compensation des arbres et de la facilité avec laquelle elle peut être enregistrée sur le terrain. Ainsi, nous ne conservons qu'un nombre limité de variables clés. En outre, nous évaluons quelles variables de terrain pourraient être modélisées au travers d'analyses géospatiales. Nous testons ensuite le protocole de terrain combiné en effectuant un relevé sur un échantillon d'arbres à Oslo et en démontrant le calcul de la valeur de compensation des arbres dans cet échantillon. Enfin, nous utilisons un réseau bayésien pour évaluer l'incertitude inhérente aux évaluations subjectives. De futurs travaux de recherches devraient aborder les limites du protocole de terrain VAT19-i-Tree pour mieux traiter la visibilité des arbres, et la situation particulière des très vieux individus.

La préparation des données, leur collecte, leur analyse et la rédaction du rapport se sont déroulées sur 6 mois (février 2020 - juillet 2020) à Oslo dans le cadre d'un stage de fin de master du premier auteur, supervisé par les co-auteurs et un arboriste expérimenté de l'Agence de l'Environnement en Oslo. Dans le cadre du projet Urban Ecosystem Accounting, cette étude contribue à tester les méthodologies de valorisation comptable des arbres urbains. L'étude propose un certain nombre d'outils pratiques en annexe, y compris le mode d'emploi détaillé du protocole de terrain VAT19-i-Tree, l'exemple du calcul d'une valeur de compensation avec le logiciel Excel, une interface pour récolter les données sur le terrain et calculer en temps réel les valeurs de compensation individuelles (grâce à l'application open-source QField, sur Android), et un calculateur permettant d'estimer l'âge d'un arbre au travers des corrélations entre circonférence, espèce et âge.

Alexandre Nollet. AgroParisTech, 14 rue Girardet, 54000 Nancy, France. Courriel : alexandre.nollet@protonmail.com

David N. Barton, Zofie Cimburova, Anders Often. Institut Norvégien de Recherche sur la Nature. (NINA), Sognsveien 68, 0855 Oslo, Norvège. Courriel : david.barton@nina.no, zofie.cimburova@nina.no, anders.often@nina.no

Sammendrag

Nollet, A., Barton, D.N., Cimburova, Z. & Often, A. 2020. Kvantifisering av opplevelsestjenester og regulerende tjenester fra bytrær for naturregnskap. Testing av en kombinert feltmetode for verdsettingsmetodene VAT19 og i-Tree Eco. NINA Rapport 1948. Norsk Institutt for Naturforskning

Økonomisk verdsetting av naturgoder fra bytrær kan bidra bl.a. til bevisstgjøring om betydningen av bynatur, nytte-kostnadsanalyser av investeringer i treplanting, prioritering av tiltak og drift, og ikke minst beregning av erstatningsverdi. Denne rapporten har som mål å bidra til standardisering av verdsettingsmetoder for trær i Norge. Før 2019 har arborister i Norge som beregnet erstatningsverdi, ofte brukt den danske metoden Verdsetting af Træer (VAT03). Metoden tok høyde for en erstatningskostnad justert for treets kvaliteter, inkludert størrelse, alder, helse og en rekke opplevelses-relaterte naturgoder knyttet til treets plassering (‘amenities’ på engelsk). Med en oppdatering i 2019 (VAT19) ble den danske veiledningen utvidet til også å ta med vurdering av regulerende og støttende økosystemtjenester. Integreringen av regulerende og støttende økosystemtjenester gjør potensielt at VAT-metoden får et større bruksområde, for eksempel i prioritering av hvor det er mest verdifullt å plante nye trær.

VAT er basert på en standardisering av ekspertkunnskapen til erfarne arborister. Likevel er det i feltmetoden til VAT19 ingen eksplisitt vurdering av fysiske egenskaper ved treet som predikerer regulerende økosystemtjenester, for eksempel slik det er i i-Tree Eco modellen. i-Tree Eco er den dominerende modellen internasjonalt for verdsetting av regulerende økosystemtjenester fra bytrær. Videre anvender ikke VAT19-metoden tilgjengelige geodata om fysiske egenskaper ved bytrær som predikerer regulerende økosystemtjenester (f.eks. trekronestørrelse).

Målsettingen med arbeidet rapportert her, er å utvikle, teste og dokumentere en kostnadseffektiv og tilstrekkelig nøyaktig feltprotokoll for variabler som kan brukes i VAT19 og i-Tree Eco som metoder for verdsetting av trær. Vi benevner dette *VAT19-i-Tree feltprotokol.* For å forsikre oss om at den er kostnadseffektiv i bruk, vurderte vi alle variablene i forhold til hvor mye de (i) forklarer treets erstatningsverdi og (ii) ressursbruk ved registrering i felt. Fra en lengre liste identifiserte vi et redusert antall variabler som kunne brukes med letthet i felt. I tillegg vurderte vi hvilke variabler som kan måles med geodata. Vi testet deretter feltprotokollen på et utvalg trær i Oslo, med beregning av VAT19-verdier. Til slutt brukte vi bayesiansk statistisk analyse for å vurdere usikkerheten i de subjektive feltvurderingene. Vi påpeker til slutt behov for fremtidig forskning på beregning av treets synlighet og metoder for å håndtere usedvanlig gamle bytrær.

Metode, datainnsamling, analyse og rapportering var gjennomført i løpet av 6 måneder i Oslo som en del av et M.Sc. arbeid (februar–juli 2020). Feltarbeidet og analyser ble utført av førsteforfatter med veiledning fra medforfatterne og en erfaren arborist i Bymiljøetaten. Arbeidet bidrar til URBAN EEA prosjektets testing av naturregnskapsmetoder for bytrær. Studien har utviklet en rekke verktøy (jf. vedlegg), inkludert en detaljert brukermanual for VAT19-Tree feltprotokollen, Excel regneark-eksempel for beregning av erstatningsverdi, en åpen kildekode for QField-applikasjon for å registrere VAT19-data og beregne erstatningsverdi i felt, og en kalkulator for å beregne treets alder basert på internasjonal statistikk på forholdet omkrets-alder.

Alexandre Nollet. AgroParisTech, 14 rue Girardet, 54000 Nancy, France.
Email: alexandre.nollet@protonmail.com

David N. Barton, Zofie Cimburova, Anders Often. Norwegian Institute for Nature Research (NINA), Sognsveien 68, 0855 Oslo, Norway. Email: david.barton@nina.no, zofie.cimburova@nina.no, anders.often@nina.no

Contents

Foreword

This report is based on experiences with the VAT19 and i-Tree Eco field protocols during a 6-month internship of Alexandre Nollet at NINA Oslo. The internship was guided by Zofie Cimburova and David N. Barton at NINA.

The report provides a revised version of a field assessment form for urban trees, initially developed and tested in Oslo by two students in 2015 (Friederike Stockmann and Anna Lisa Berger) and updated by Laura Lauwers in 2017. The work of Laura Lauwers was the basis for the field survey and the Bayesian belief network model of VAT19 discussed in this report. Help from Zander Venter (NINA) and Bruno Ferry (AgroParisTech) concerning R and statistics is thankfully acknowledged.

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January 2021, David N. Barton

1 Introduction

In collaboration with Statistics Norway and the Oslo School of Architecture and Design, the Norwegian Institute for Nature Research (NINA) has conducted the mapping of green structures and vegetation diversity in the Oslo metropolitan area and tested ecosystem accounting methods (Barton 2017). NINA researchers involved in the Urban EEA project have tested the i-Tree Eco model developed by the United States Department of Agriculture Forest Service (USFS) (Cimburova and Barton 2020) and the Danish Værdisætning af træer (VAT) protocol developed by Randrup et al. (2018) for the valuation of urban trees in the accounting of municipal ecosystems.

Oslo is a city with twice as much tree canopy as roof area (Hanssen et al. 2019) and monetary valuation could be relevant to argue for tree conservation in the face of urban densification. In 2019, the Oslo City Council set the goal of planting 100 000 trees by 2030, or around 10 000 per year, in association with private landowners in the urban built zone.

1.1 Tree ecosystem services and amenities

Urban trees provide a large range of ecosystem services: temperature regulation, removal of air pollutants, emission of volatile organic compounds, reduction of ozone concentrations, reduction of heating costs through energy conservation, avoided stormwater runoff, noise reduction, wildlife habitats and enhanced biodiversity, phytoremediation, carbon sequestration, enhanced quality of urban life and privacy (Nowak and Dwyer 2007; Roy et al. 2012).

These services can be classified (Millennium Ecosystem Assessment 2005) between the “provisioning” services (food, water, timber, fibre), “cultural” services (recreational, amenities and spiritual benefits), “supporting” services (soil formation, photosynthesis and nutrient cycling) and “regulating” services (the ones affecting climate, floods, diseases, wastes and water quality). Through these ecosystem services, urban trees positively affect physical and mental human health (Beyer et al. 2014; Ulmer et al. 2016) and provide city inhabitants with numerous socio-economic benefits (Roy et al. 2012), including amenity contributions to property value. Within the cultural services, amenities refer to any aspect of the tree that is appreciable and agreeable to residents, including access opportunities to local recreation (Havinga et al. 2020). Within urban ecosystem contexts, cultural and regulating services were found to be especially important (Gomez-Baggethun and Barton 2013).

1.2 The valuation of ecosystem services

This wide spectrum of tree benefits explains the numerous studies conducted on the value of trees in urban and suburban settings (Thompson et al., 1999). Assigning a monetary value to ecosystem services from trees in urban areas fulfils awareness-raising, accounting, priority-setting, policy instrument design and damage compensation purposes (Gomez-Baggethun and Barton 2013). Thus, we argue that valuation methods such as VAT and i-Tree Eco could help to raise awareness about the monetary benefits of Oslo City Council’s plan to plant 100 000 trees by 2030, as well as guiding the cost-benefit analysis of planting locations, justifying the allocation of funding for additional tree maintenance entailed by the project, and be a tool to assess damage compensation due to injury or loss of trees planted by the project (and elsewhere).

While this study focuses on monetary valuation methods, both monetary and non-monetary valuation methods complement one another in addressing these purposes (Harrison et al. 2018).

1.3 Tree valuation in Norway/Oslo

There is currently no standard for the valuation of city trees in Norway. A series of methods that directly or indirectly map and value urban trees using both biophysical and monetary methods have been conducted in Oslo (Agency for Planning and Building Services 2018a, 2018b; Barton et al. 2015; Hanssen et al. 2019; Lauwers et al. 2017). Oslo Municipality's Agency for Urban Environment has adopted the VAT method (now VAT19) developed in Denmark by Randrup et al. (2003) to estimate the monetary value of trees damaged or killed on municipal land (Lauwers et al. 2017). This method accounts for the tree health and a wide range of amenities, but lacks explicit definitions of field variables to be observed. On the other hand, the widely used i-Tree Eco model was used in Oslo by Cimburova and Barton (2020) to estimate the regulating ecosystem services of municipal trees for accounting purposes but showed its limitations in assessing amenities.

1.4 Aims of the study

Considering that tree valuation methods would be more cost-effective by better identifying amenities (VAT19) and regulating ecosystem services (i-Tree Eco), the main objective of this study was to develop, test and document a combined field protocol for the assessment of field variables that can be then used in the VAT19 and i-Tree Eco valuation methods. We call this combined field protocol the *VAT19-i-Tree field protocol*.

With the cost-effectiveness as an objective, simply appending the VAT19 and i-Tree Eco field protocols without further considerations would result in excessively time-consuming field assessments. The first sub-objective of this study was therefore to reduce the length of the combined protocol by assessing each field variable in terms of its contribution to the damage compensation value and its ease of recording in a field survey. Thus, each field variable could either be retained or excluded from the final VAT19-i-Tree field protocol. We aimed at striking a balance between a time-efficient and sufficiently accurate field protocol, with statistical validation of expert assessment to increase the credibility of the method in determining compensation values.

In order to assess the ease of recording each field variable, as well as to test the final VAT19-i-Tree field protocol, the second sub-objective of this study was to conduct a field survey on a sample of trees in Oslo and to demonstrate a calculation of compensation values for the trees within this sample.

The recent development in the use of geospatial data showed that some field variables (such as tree height and canopy area) can be modelled using geospatial analysis with comparable accuracy to manual field surveys (Cimburova and Barton 2020). The third sub-objective of this study was therefore to assess which field variables could potentially be modelled using geospatial analyses.

The VAT19 method is an expert assessment methodology with inherent uncertainty due to differences across subjective expert judgements. Bayesian belief networks are well suited to integrate qualitative and quantitative observations from different sources (observations, model predictions, subjective expert assessment) (Barton et al. 2012; Bertone et al. 2016). The final objective of this study was thus to conduct a value of information analysis in a Bayesian belief network, which can help to (i) identify and graphically illustrate which data sources contribute the most to the monetary outcome of any variable of interest and (ii) assess variance in subjective expert assessment.

Developing such a combined field protocol, that considers both amenities (VAT19) and regulating ecosystem services (i-Tree Eco), has the potential to provide a considerable contribution to the current policy and planning. Specifically, in 2020, Standards Norway established an expert committee to turn the VAT19 protocol into a tree valuation standard in Norway[1]. We hope that the integrated field assessment methodology developed in this study will support the ongoing work of Standards Norway in developing a national standard for valuing trees.

[1] https://www.standard.no/nyheter/nyhetsarkiv/bygg-anlegg-og-eiendom/2020/vil-du-utvikle-norsk-standard-for-trars-okonomiske-verdi/

2 Methods

2.1 Background

2.1.1 i-Tree Eco

The i-Tree Eco model has been widely used for the assessment of urban trees in small inventories and regional projects, notably in the United States, Canada, Australia, Mexico and Europe ("i-Tree Eco v6.0" n.d.). Developed by the USFS, this software suite can assess a range of regulating ecosystem services provided by urban trees, along with analyses for a given context (Bassett 2015). The i-Tree Eco model merges field variables about trees (species, dimensions and close environment) with local hourly weather data, pollution data and ecosystem benefit prices to produce summary reports, giving municipalities and institutions an estimate of ecosystem services provided by individually assessed trees, along with the associated monetary values. In this study, we collected field variables necessary to estimate the removal of atmospheric pollution, the avoided stormwater runoff, the carbon sequestration and building energy savings. As our purpose was to give a monetary value to the ecosystem services, we did not record variables that estimate services not monetized in i-Tree Eco, like the production of oxygen and volatile compounds emissions (Nowak 2019).

2.1.2 VAT19

The VAT protocol was developed to give tree appraisers in Denmark a tool to estimate a monetary value for urban trees (Randrup et al. 2003). While not an official standard, it has become a convention for the calculation of the value of trees as a basis for municipal fines and compensation values for damage to trees in Denmark and Norway (Lauwers et al. 2017). Henceforth we use the term 'compensation value' for the output of the VAT method, although the estimate can be used for different purposes.

The VAT compensation values are based on the tree replacement/establishment costs, adjusted to the health state of the lost tree and the ecosystem services associated, with a definite focus on amenities. The first version of the VAT protocol (VAT03) was further updated in 2019 by Randrup et al. (2018) to account for both amenities and the importance of regulating ecosystem services, resulting in the VAT19 protocol.

In this study, we use the revised equations of the VAT19 method. The protocol is divided into three main categories:

1. General information about
   - **1.1.** tree characteristics,
   - **1.2.** tree dimensions,
   - **1.3.** tree location.
2. Health factor divided into three scores
   - **2.1.** roots,
   - **2.2.** stem,
   - **2.3.** crown,
3. Location factor divided into five scores
   - **3.1.** ecological adaptation,
   - **3.2.** conservation value,
   - **3.3.** architecture,
   - **3.4.** aesthetics,
   - **3.5.** visibility.

Once all the supporting field variables have been assessed, the validator can use them to assign a value ranging from 0 to 5 to each criterion. The Health and Location factors are then automatically calculated and integrated into the VAT19 equation (which has the same variables as the VAT03 equation), giving the final compensation value.

According to Lauwers et al. (2017), the VAT03 equations are as follows:

Tree compensation value = *B* x *H* x *L* x *A*

where *B* is a Base value, *H* is a tree Health factor, *L* is a tree Location factor and *A* is a tree Age factor.

1. **The Base value (*B*)**

The Base value is calculated using the following equation:

$$B = E + ((S_d - S_n) \times (\frac{Pn}{Sn}))$$

where *E* is the establishment cost of a new tree (NOK), S_d is the stem circumference of the assessed tree (cm), S_n is the stem circumference of the new tree (cm) and P_n is the price of the new tree (NOK).

A new tree here refers to a tree of the same species as the assessed one, with stem circumference at 1 meter above ground of 18-20 cm (standardized tree nursery size). The establishment cost *E* includes the removal of the damaged tree, the replacement of the substrate and rooting medium, the purchase of a new tree, its planting, the aeration and watering systems, the re-establishment of surface materials and the tree guarantee for 5 years. For the valuation examples in this study, we estimated the establishment cost *E* to be 25 000 NOK, the stem circumference S_n of a new tree to be 18 cm and the price P_n of a new tree to be 5 000 NOK. The planting costs are an estimate for the Oslo area and the same as in Lauwers et al. (2017). A recommendation for standardisation is that tree planting cost statistics are compiled regularly for the price to be indexed by a competent authority and serve as a standard for a region with a common market (the same nurseries and suppliers). This will also be cost-saving for tree assessors.

2. **The Health factor (*H*)**

The Health factor is calculated using the following equation:

$$H = \frac{r + s + Mb + mb + t}{25}$$

where *r* is the Root score (0-5), *s* is the Stem score (0-5), *Mb* is the Major branches scores (0-5), *mb* is the Minor branches score (0-5) and *t* is the Twigs/leaves/buds score (0-5). The sum of the five scores is divided by 25, which results in a normalized value for the Health factor between 0 and 1.

However, we simplified this equation by reducing the number of field variables recorded in the field survey. We merged the *Mb* and *s* scores into a new *s* value – the Stem/main branches score (0-5) and the *mb* and *t* scores into a new *c* value – the Crown score (0-5).

The equation used in this study is thus:

$$H = \frac{r + s + c}{15}$$

where *r* is the Root score (0–5), *s* is the new Stem/main branches score (0–5) and *c* is the new Crown score (0-5). The sum of the three scores is divided by 15, which results in a normalized value for the Health factor between 0 and 1.

3. The Location factor (*L*)

The Location factor is calculated using the following equation:

$$L = \frac{ad + co + ar + ae + v}{12.5}$$

where *ad* is the Ecological adaptation score (0-5), *co* is the Conservation value score (0-5), *ar* is the Architecture score (0-5), *ae* is the Aesthetics score (0-5) and *v* is the Visibility score (0–5). The sum of the five scores is divided by 12.5, which results in a normalized value for the Location factor between 0 and 2 [2]. In the original VAT03 protocol, Randrup did not justify why the method assigns a twice higher weight to the Location factor (*L*) than to the Health factor (*H*). The equation parameters were designed to produce outputs within a range of values deemed as reasonable incentives in cases of damaged trees in the Danish context (Randrup 2005).

4. The Age factor (*A*)

The Age factor is calculated using the following equation:

$$A = \sqrt{\frac{(Ae - Aa) \times 2}{Ae}}$$

where *Ae* is the life expectancy of the tree (years) and *Aa* is the actual age of the tree (years). The Age factor decreases as the tree grows towards its expected lifetime. The VAT19 method uses standard life expectancies values for all the trees belonging to a given species across a whole city. Examples of life expectancies for individual tree species for the study area in Oslo is provided in **Appendix 1**. For trees older than their life expectancy, we chose to assign an arbitrary Age factor of 0.05 since we could not work with negative values. The approach for such "old trees" needs further clarification in the VAT19 method (**Box 1**).

An example of tree compensation value computation using the equations presented here is provided in **Appendix 2**.

In VAT03 (Randrup et al.2003), each factor is scored by an expert based on field assessment. However, there was little guidance on the supporting field variables that can be used determine the respective scores. Lauwers et al. (2017) proposed that expert assessment scores for each VAT03 factor should be supported by documented field observations. Thus, they proposed an updated protocol with a list of supporting variables to be recorded in the field survey ("field variables"). The VAT19 guidance (Randrup et al., 2018) refers to Lauwers et a. (2017) as one of several basis for the update, but does not propose any modifications to field protocol. In this report we extend the proposal by Lauwers et al. (2017) to better cover habitat services and regulating services represented by i-Tree Eco variables. The individual field variables are described in section 3.1.

[2] Correction: In the final version of VAT19 (Randrup et al. 2018), the Location factor is normalized by dividing the sum of score by 10, resulting in a Location score of [0, 2.5].

***Box 1** Further guidance needed for valuing old trees.*

There will always be the possibility of finding trees that exceed the mean/median maximum age in a set of tree populations. Recommended expected tree ages in the VAT19 guidelines are specified for park-like growing conditions, but are still lower than those used by Lauwers et al. (2017), which were based on recommendations by Oslo Municipality Agency for Urban Environment. Recommended standards for age of trees under Norwegian urban conditions, therefore need to be developed. This could include a definition of (i) likely maximum age (e.g. 95th percentile of the population) of urban trees, (ii) in different types of urban growing environments (Jutras et al. 2010), (iii) in different climates and (iv) assuming optimal tree maintenance through the tree's life.

VAT19 recommends that the valuation method not be applied to value protected status trees, which are usually of exceptional age. However, exceptional age and/or protected status does imply that the tree does not have cultural amenity or regulating services which cannot be valued as part of urban tree accounting. It only suggests that VAT19 should not be interpreted as covering habitat and conservation values of particularly old trees.

2.2 Workflow

To address the main objective of the study, i.e. to develop, test and document a combined VAT19-i-Tree field protocol, we proceeded in five consecutive steps. First, we combined the field variables from both the i-Tree Eco and VAT19 field protocols. Second, to assess the ease of recording each field variable, the variables from the combined protocol were recorded in a field survey. Third, we used geospatial analysis to post-process some of the variables recorded in the field survey and to assess variables that can easier be modelled using geospatial analysis. Fourth, we conducted a statistical analysis to determine for each field variable its contribution to the respective score, as well as to detect redundant field variables. In the fifth step, we implemented the retained field variables into a Bayesian belief network to analyse the strength of their relation and to handle uncertainty within a dataset composed of quantitative and qualitative variables. Finally, based on thorough discussions with tree experts, field considerations and statistical analyses, we retained a limited number of field variables that were (i) objectively recordable in the field survey or possible to model using geospatial analysis, (ii) simple to record in a rapid field survey and (iii) highly correlated with VAT19 scoring based on expert assessment.

The methodology workflow is illustrated in **Figure 1** and the individual steps are described in detail in the following sections.

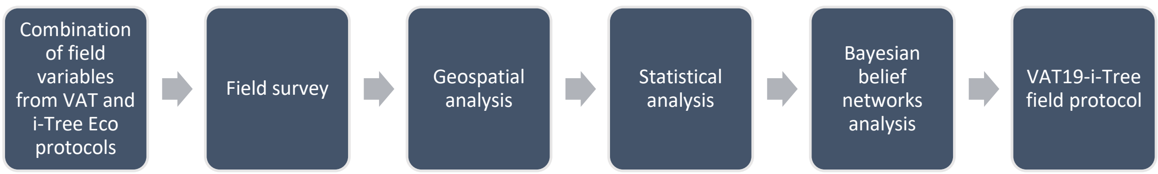

***Figure 1** Methodology workflow*

2.3 Combination of field variables from VAT19 and i-Tree Eco protocols

Lauwers et al. (2017) tested a total of 103 field observation variables to support expert judgement in VAT03. We combined a selection of supporting field variables from the VAT03 protocol as outlined by Lauwers et al. (2017) with i-Tree Eco field variables as specified in *i-Tree Eco Field Guide v6.0* (2019). In addition, we added a set of new supporting field variables, selected based on discussions with tree experts – Anders Often, NINA, and Tørres Rasmussen, Agency for Urban Environment, Oslo Municipality.

Combining the VAT19 and i-Tree Eco protocols resulted in 92 field variables (51 variables from VAT19, 26 variables from i-Tree Eco, 23 added variables; note that some of VAT19 and i-Tree Eco variables are redundant). A comprehensive overview of all field variables that were considered for the VAT19-i-Tree field protocol is presented in **Table 2**.

2.4 The field survey

To support the creation of the VAT19-i-Tree protocol, a field survey with the 92 variables mentioned above was carried out on a sample of urban trees drawn from the total tree population in the study area. The recorded variables are marked as recorded in the field survey in **Table 2**.

2.5 Study area

The field survey was carried out in the study area of Oslo's built zone (147 km²) of which 47 % was covered by vegetation in 2017 (Agency for Planning and Building Services 2018a).

There are different estimates of the total number of trees within this area. Using the 2011 LiDAR-based tree top identification from the Agency for Planning and Building Services, Barton et al. (2015) estimated the number of individual city trees to be at least 700 000 within the built zone. LiDAR (abbreviation for Light Detection and Ranging) is a remote sensing method based on measuring distances using laser light, which can provide a cost-effective and accurate detection and delineation of individual trees. A more recent estimation of individual trees within the built-up zone of Oslo using LiDAR data is approximately 390 000 – 393 000 individual canopies taller than 2.5 meters (Hanssen et al. 2019). In addition, by analysing the LiDAR-detected canopies, it is possible to estimate several tree variables, used e.g. in the i-Tree Eco model. These are the 3D crown structure, crown area, crown volume and tree height (Hanssen et al. 2019).

In this study, we used the Hanssen et al. (2019) dataset of individual trees to select a tree sample to be included in the survey.

2.5.1 Sampling method

From the complete dataset of the LiDAR-detected tree population (Hanssen et al. 2019), individual trees were sampled from manually delineated sampling locations, which were stratified across 11 urban form types. Within the sampling locations, individual trees that were analysed as being visible from public spaces were selected randomly with equal distribution from public trees and private publicly accessible trees. Publicly visible trees were sampled because (i) these trees were mostly accessible for field survey and (ii) the VAT method was originally intended to assess public amenity values, although it has since been used in practice also for private trees. The sampling was carried out using ESRI ArcMap 10.6 (ESRI 2018).

The sampling was conducted twice in order to optimally use the time available for the field survey (5 weeks). A first sample of 105 trees was selected at the beginning of the field survey. After the first sample was surveyed, a second sample of 84 trees was selected, based on remaining field survey time and the expected time taken to survey one tree. In total, we selected a sample of 189 trees to test the VAT19-i-Tree field protocol. The sample is considered representative of "publicly visible" trees in Oslo's built zone, but not of trees that are only privately visible.

An overview of urban form types, sampling locations and numbers of sampled trees is provided in **Table 1**. A map of the spatial distribution of urban form types and sampled trees in the study area is provided in **Appendix 3**.

Table 1 *Urban form types, sampling locations and numbers of sampled trees*

Urban form type	**Sample 1**			**Sample 2**		
	Area	Public trees	Private trees	Area	Public trees	Private trees
Low-rise low-density	Solvang kolonihager	5	5	Lindøya	4	4
Low-rise medium-density Small house area	Steinerud	5	5	Simensbråten	4	4
Low-rise medium-density	Vinderen	5	5	Nordstrand	4	4
Low-rise high-density Residential	Kampen, Vålerenga	5	5	Kampen, Vålerenga	4	4
Low-rise high-density Industrial/commercial	Alnabru, Furuset	5	5	Østre Aker	4	4
Mid-rise low-density	Haugerud, Tveita	5	5	Lambertseter	4	4
Mid-rise medium-density	Finnmarkgata, Ila	5	5	Oppsal	4	4
Mid-rise high-density	Frogner	5	5	Kvadraturen, Majorstuen	4	4
High-rise low-density	Haugerud, Tveita	5	5	Årvoll	4	4
High-rise medium-density	*Not present*	-	-	*Not present*	-	-
High-rise high-density	Vika, Regjeringskvartalet, Oslo S, Barcode	5	5	Vika, Regjeringskvartalet, Oslo S, Barcode	4	4
Open areas	Slottsparken, Østre Aker gravlund	5	0	Bygdøy	4	0
Total		**105**			**84**	

2.5.2 The QField application

The survey was carried out using a field protocol through the interactive QField application[3] loaded on a tablet, which enabled a fast recording of the tree variables in the field survey, as well as a mean to export and post-process the collected data.

Developed by the OpenGIS team, the QField application (Android, iOS) is an open-source GIS (geospatial information system) application allowing researchers to collect field data with a GIS-built interface tailored to each project. The application can display several layers of data and take pictures with the device camera. Each tree was represented as a point (stem location), accompanied by a set of attributes corresponding to field variables. Supporting map layers included crown geometry, location of other trees, background orthophoto and topographical maps. **Appendix 4** illustrates the usage of the application to carry out the field survey.

We also included the VAT19 formulas into the application to calculate individual VAT19 scores and tree compensation values on the fly. Furthermore, a dynamic VAT19-i-Tree Excel spreadsheet was made for users unfamiliar with GIS. This spreadsheet is available for download at GitHub[4].

2.5.3 The tree age calculator

As different species can have different growth rates (Rozas 2003), the visual estimation of a tree's age needed for the survey can be difficult. We have therefore developed an automatic tree age calculator using the R "Shiny" package, which estimates tree ages from stem circumference at breast height, tree species and existing growth factor tables (**Appendix 1**). The script displays a user-friendly interface with a copyright-free picture. The calculator has also been implemented into a dynamic VAT19-i-Tree Excel spreadsheet.

The R script for the tree age calculator is available for download at GitHub[5].

2.5.4 The field survey

The field survey was conducted between May 25th and June 30th 2020.

The recording of i-Tree Eco field variables was conducted following the procedures outlined in the i-Tree Eco Field Guide (*i-Tree Eco Field Guide v6.0* 2019). The VAT19 field variables were recorded following the rules defined in **Appendix 4**. A hypsometer (Nikon Forestry Pro) was used in the measurement of tree heights and a diameter tape was used to measure stem circumferences at breast height.

The tree sample was drawn from a LiDAR-detected tree population (Hanssen et al. 2019). LiDAR detection of tree crowns is prone to a range of errors. The following rules were therefore followed when surveying individual trees:

- If the sampled tree did not exist in the field (due to misclassification of trees with tall poles or buildings, or because the tree had been removed recently), the assessment could not be done and this was noted in the field survey protocol.

[3] https://qfield.org/
[4] https://github.com/NINAnor/VAT19-i-Tree-field-protocol/raw/main/VAT19-i-Tree%20Spreadsheet.xlsx
[5] https://github.com/NINAnor/VAT19-i-Tree-field-protocol/raw/main/%5BR%20script%5D%20Tree%20age%20calculator.zip

- If the sampled tree was not accessible but was visible, field variables which could be assessed from a distance were recorded.
- If the sampled tree was neither accessible nor visible, the assessment could not be done and this was noted in the field survey protocol.
- If the sampled tree comprised several trees (i.e. several trees were detected as one tree), this was noted in the field survey protocol. The tree closest to the stem point of the detected tree was surveyed. The additional trees were recorded as supplementary trees together with their position and basic dimension variables.
- If the crown geometry of the detected tree varied significantly from the actual crown geometry, this was noted in the field survey protocol for further corrections in GIS.

In addition, the following rules were applied when recording individual tree field variables:

- Trees were identified to the species level where possible and to the genus level at a minimum.
- There were no height/diameter/species requirement for a tree/shrub to be assessed as long as a plant was standing at the designated location.
- Trees driven to grow in coppice were fully assessed except for the stem variables.
- Trees that had been pruned to extremely unnatural growth forms were compared to ideal natural forms when some field variables required it.

In total, 143 trees were recorded in the field survey. None of the recorded trees were previously identified in the municipal tree inventory database provided by the Oslo municipality Agency for Urban Environment.

The precise surveying guidelines are described in the VAT19-i-Tree tutorial in **Appendix 4**.

2.6 Geospatial analysis

The recorded data were downloaded as a spatial dataset (i.e., tree point with associated attributes) from the QField application into a computer, where they were further processed.

2.6.1 Crown dimensions calculation and adjustment using GIS

Crown diameters were not recorded in the field survey, but modelled from the dataset of LiDAR-detected trees. If the sampled tree comprised several trees or if the crown geometry of a LiDAR-detected tree varied significantly from the actual crown geometry, the crown geometry in the spatial dataset was adjusted accordingly and the stored crown diameter was recomputed.

2.6.2 Modelling additional tree variables using GIS

As shown in Cimburova and Barton (2020), some tree field variables can be effectively modelled using available geospatial data. Therefore, we used ESRI ArcMap 10.6 (ESRI 2018) for geospatial analysis to model the following tree variables: latitude, longitude, crown light exposure, public and private visibility values, distance and direction to three nearest buildings and a land-use value corresponding to the i-Tree Eco classification.

A map of the spatial distribution of values of tree public and private visibility is provided in **Appendix 5**.

2.7 Statistical analysis

To determine which field variables were significant regarding their respective score, as well as to detect redundant field variables and thus shorten the VAT19-i-Tree protocol, we conducted statistical analyses.

Since we wanted to include i-Tree Eco variables in the VAT field protocol, we tested the correlations between the i-Tree Eco variables we had selected (genera, tree height and canopy size) and the VAT19 calculated value and sub-scores. We also performed correlation tests between individual field variables and their respective associated VAT19 scores (Roots, Stem/main branches, Crown, Ecological adaptation, Conservation value, Architecture, Aesthetics and Visibility score) (**Appendix 6**). Since the recorded data did not follow the normal distribution, we used the non-parametric Spearman's and Kruskal-Wallis tests to assess the correlations. The resulting correlation and statistical significance were then used to decide on retaining/excluding the given variable from the VAT19-i-Tree protocol, together with the ease of recording it in the field survey or the possibility to model it using GIS (**Table 2**).

The statistical analysis was conducted using R, from the R Project for Statistical Computing (R Core Team 2018).

2.8 Bayesian belief network analysis

A Bayesian belief network (BBN) represents a structure of correlations in a causal network and works well with uncertainty and missing data. Barton et al. (2015) used the VAT03 method with a BBN to handle uncertainties in the large variation of tree sizes, qualities and locations across the city of Oslo to estimate the total compensation value of the municipal trees.

In this study, the Hugin Expert® software (Madsen et al. 2003) allowed us to build a BBN in which the different VAT19 factors - and especially the subjective expert assessments - could be handled with probabilities rather than definitive values. Each VAT19 score was implemented into the BBN and linked to nodes leading to the final compensation value. Some tree field variables (age distribution, age expectations, heights and circumferences at breast height) were also linked to the model. The resulting network (illustrated in **Figure 2**) is based on the VAT19 equations, supported by the field variables. Most of the nodes are VAT19 field variables (amenities), but some are shared between i-Tree Eco and VAT19. The field variables conditioning the factors (green nodes) in the VAT19 method and the compensation value are all linked by conditional probability tables within the network. The causal directions between the field variables were based on choices made within the Hugin Software: all chosen field variables were manually linked to their score. Then, the machine learning assistant detected the most likely correlations, based on its analysis of the data, and we had to agree or disagree with these potential connections. Therefore, some field variables are linked to the respective score and to another field variable – such as "Compaction over root extent" and "Limitation of roots formation". Some connections were manually indicated, as "Tree age" to "Tree > 170-year-old". The i-Tree Eco field variables likely to find their place in this model during further research are the crown diameter, crown height and pollution zone, as their importance was demonstrated by Cimburova and Barton (2020). The BBN network developed in this study is available for download at Hugin[6].

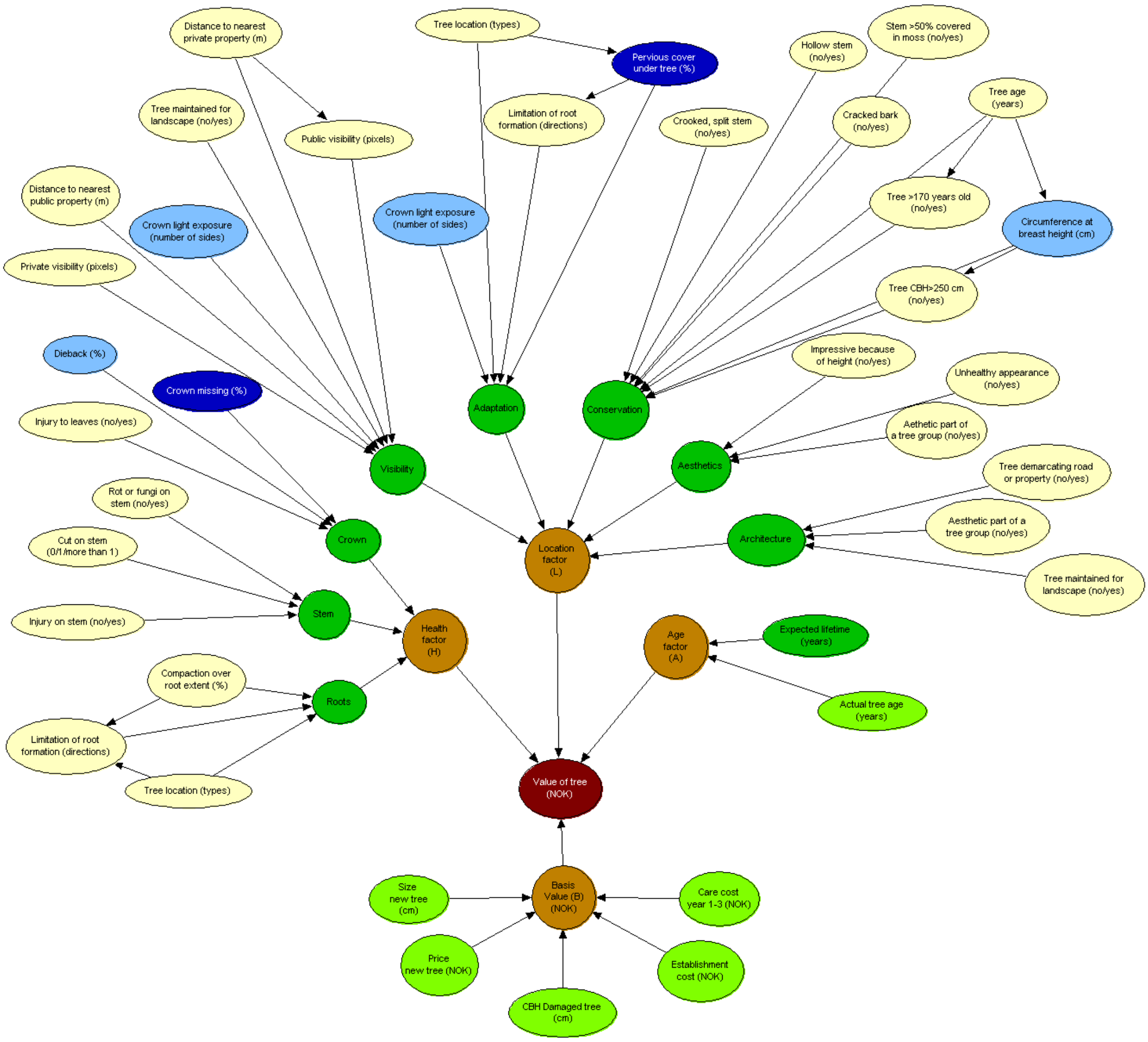

Figure 2 *Bayesian belief network with the variables retained in the VAT19-i-Tree field protocol. The colour code is as follows: Light yellow: VAT19 field variables, light blue: VAT19/i-Tree Eco field variables, blue: i-Tree Eco field variables, light green: exact observations, green: VAT19 scores, brown: VAT19 factors, dark red: compensation value. To inspect variables names use screen zoom. To inspect the data see also http://demo.hugin.com/example/VAT19*

[6] http://demo.hugin.com/example/VAT19

3 Results

3.1 The VAT19-i-Tree field protocol

Combining the VAT19 and i-Tree Eco protocols resulted in 92 field variables: 51 of the variables tested by Lauwers et al. (2017) for the VAT03 field protocol, 26 variables from the i-Tree Eco protocol, as well as an additional 23 variables suggested by the authors for consideration in this particular study. We noted that some of VAT19 and i-Tree Eco variables were redundant. Eventually, for the VAT19-i-Tree field protocol, we selected 35 field variables out of the 92 tested during the fieldwork. 18 variables were excluded because they could be modelled by geospatial analysis (13) or calculated automatically from other variables (5). 39 variables were excluded because their correlation to a given score was low or insignificant, because they were redundant with other variables or because their recording in the field survey was assessed as difficult.

Table 2 summarises all the 92 field variables obtained by combining the VAT and i-Tree Eco protocols, their documented origin, the means of assessing the variable (recorded in the field survey, modelled in GIS or calculated automatically from other variables), as well as the information on whether each variable was retained or excluded from the final VAT19-i-Tree field protocol. Immediately following **Table 2** we summarise the results of the statistical analysis of the correlation between VAT19 scores and individual field variables and the results of the field survey. The correlation analysis was the basis for a shortlist of variables selected for inclusion in the field protocol.

Detailed results of the correlation test for individual field variables and scores are provided in **Appendix 6**. The field variables retained in the VAT19-i-Tree protocol are described in detail in **Appendix 4**. The field variables excluded from the VAT19-i-Tree protocol are described in detail in **Appendix 7**, together with the reason for exclusion.

***Table 2** Field variables obtained by combining the VAT19 and i-Tree Eco protocols, their origin, means of assessment and information on whether each variable was retained or excluded from the final VAT19-i-Tree field protocol.*

Name of the field variable	Origin	Assessment	Retained
1. TREE CHARACTERISTICS			
1.1 Age and species			
Validator name	Lauwers *et al.*, i-Tree Eco	Field survey	YES
Date	Lauwers *et al.*, i-Tree Eco	Field survey	YES
Tree ID	Lauwers *et al.*, i-Tree Eco	GIS-modelled	YES
Species	Lauwers *et al.*, i-Tree Eco	Field survey	YES
Species code	i-Tree Eco	Automatic	YES
Other species (if not in the list)	Lauwers *et al.*	Field survey	YES
Minimum age estimation	Lauwers *et al.*	Field survey	YES
Maximum age estimation	Lauwers *et al.*	Field survey	YES
Calculated age	Our addition	Automatic	YES
Life expectancy	Lauwers *et al.*	Automatic	YES
1.2 Dimensions			
Circumference at breast height (CBH)	Lauwers *et al.*, i-Tree Eco	Field survey	YES
CBH estimation distance	Lauwers *et al.*, i-Tree Eco	Field survey	YES
Height	Lauwers *et al.*, i-Tree Eco	Field survey	YES
Height to live top	i-Tree Eco	Field survey	YES
Height to crown base	i-Tree Eco	Field survey	YES
Crown diameter North-South	i-Tree Eco	GIS-modelled	YES
Crown diameter East-West	i-Tree Eco	GIS-modelled	YES
Crown missing	i-Tree Eco	Field survey	YES
Dead tree	i-Tree Eco	Field survey	NO
1.3 Location			
Street tree	i-Tree Eco	Field survey	YES
Land-use type	i-Tree Eco	GIS-modelled	YES
Latitude	i-Tree Eco	GIS-modelled	YES
Longitude	i-Tree Eco	GIS-modelled	YES
Seedling type	Our addition	Field survey	NO
Slope	Lauwers *et al.*	Field survey	NO
Stem on property type	i-Tree Eco	Field survey	YES
Access limitation	Our addition	Field survey	YES
Stem location	Our addition	Field survey	YES
Roots in structure limiting growth	Our addition	Field survey	NO
Stem protection	Our addition	Field survey	YES
Distance to the 3 nearest buildings	i-Tree Eco	GIS-modelled	YES
Direction of the 3 nearest buildings	i-Tree Eco	GIS-modelled	YES

Table 3 (cont.)

Name of the field variable	Origin	Assessment	Retained
2. HEALTH FACTOR			
2.1 Root score			
Root excavation	Lauwers *et al*.	Field survey	NO
Root exposure	Lauwers *et al*.	Field survey	NO
Soil bulge	Lauwers *et al*.	Field survey	NO
Rot on root	Lauwers *et al*.	Field survey	NO
Girdling root	Lauwers *et al*.	Field survey	NO
Insects on root	Lauwers *et al*.	Field survey	NO
Injury on root	Lauwers *et al*.	Field survey	NO
Cut on root	Lauwers *et al*.	Field survey	NO
Scar on root	Lauwers *et al*.	Field survey	NO
Compaction (load, pavement, trampling zones) over root extent	Lauwers *et al*.	Field survey	YES
Limitation of root formation	Lauwers *et al*.	Field survey	YES
Compacted soil	Lauwers *et al*.	Field survey	NO
Saturated soil	Lauwers *et al*.	Field survey	NO
2.2 Stem/main branches score			
Rot or fungi on stem/main branches	Lauwers *et al*.	Field survey	YES
Hollow stem	Lauwers *et al*.	Field survey	NO
Injury on stem/main branches	Lauwers *et al*.	Field survey	YES
Parasite on stem/main branches	Lauwers *et al*.	Field survey	NO
Epicormics	Lauwers *et al*.	Field survey	NO
Crack on stem/main branches	Lauwers *et al*.	Field survey	NO
Sloping position of stem	Lauwers *et al*.	Field survey	NO
Fork	Lauwers *et al*.	Field survey	NO
If fork, number of stems	Lauwers *et al*.	Field survey	NO
If fork, height of division	Lauwers *et al*.	Field survey	NO
Resin flow on stem	Lauwers *et al*.	Field survey	NO
Scar on stem/main branches	Lauwers *et al*.	Field survey	NO
Dead stem/missing bark	Lauwers *et al*.	Field survey	NO
Missing terminal shoot	Lauwers *et al*.	Field survey	NO
Cut on stem/main branches	Our addition	Field survey	YES
2.3 Crown score			
Dieback	Lauwers *et al*., i-Tree Eco	Field survey	YES
Injury to leaves/twigs/buds	Lauwers *et al*.	Field survey	YES
Parasite on leaves/twigs/buds	Lauwers *et al*.	Field survey	NO

Table 4 (cont.)

Name of the field variable	Origin	Assessment	Retained
	3. LOCATION FACTOR		
	3.1 Ecological adaptation score		
Proximity to road: potential de-icing salt stress	Lauwers *et al.*	Field survey	NO
Trampling	Lauwers *et al.*	Field survey	NO
Crown light exposure	i-Tree Eco	GIS-modelled	YES
Shrubs under tree	i-Tree Eco	Field survey	NO
Pervious cover under tree	i-Tree Eco	Field survey	YES
Impervious cover under tree	i-Tree Eco	Field survey	YES
Site clearing	Lauwers *et al.*	Field survey	NO
Changed hydrology	Lauwers *et al.*	Field survey	NO
	3.2 Support of habitat and conservation value score		
CBH > 250 cm	Our addition	Automatic	YES
Tree > 170-year-old	Our addition	Automatic	YES
Cracked bark: > 3 cm deep at breast height	Our addition	Field survey	YES
Crooked, split stem, surface for substrate accumulation	Our addition	Field survey	YES
Hollows, cracks, nests, nesting holes, bird boxes	Our addition	Field survey	YES
Stem covered > 50 % by moss/lichen	Our addition	Field survey	YES
	3.3 Architecture score		
Tree demarcating road/property	Lauwers *et al.*	Field survey	YES
Tree blocking road visibility	Lauwers *et al.*	Field survey	NO
Tree screening residence	Our addition	Field survey	NO
Tree blocking view from residence	Our addition	Field survey	NO
Branch distance to closest building	Our addition	Field survey	NO
Tree maintained for landscape architecture	Lauwers *et al.*	Field survey	YES
	3.4 Aesthetics score		
Impressive height	Lauwers *et al.*	Field survey	YES
Impressive growth form	Lauwers *et al.*	Field survey	NO
Unhealthy appearance	Our addition	Field survey	YES
Unnatural growth from due to pruning	Our addition	Field survey	NO
Tree part of an aesthetic group of trees	Our addition	Field survey	YES
	3.5 Visibility score		
Distance to nearest public property	Our addition	GIS-modelled	YES
Distance to nearest private property	Our addition	GIS-modelled	YES
Public visibility	Our addition	GIS-modelled	YES
Private visibility	Our addition	GIS-modelled	YES

The results of statistical analysis of the correlation between VAT19 scores and individual field variables are summarized below in the following manner: *"✓ Name of the field variable selected for inclusion in the field protocol: correlation coefficient*** (number of significant correlations to other field variables within the score)*". The correlation analysis was the basis for a shortlist of variables selected for inclusion in the field protocol.

Root score selected variables:
- ✓ Limitation of root formation (number of directions): -0.77*** (3)
- ✓ Compaction (load, pavement, trampling zones) over root extent: 0.74*** (3)
- ✓ Stem location (road, parking, pavement, unpaved): 0.55*** (3)

These field variables are relatively easy to record in the field survey. They are significantly highly correlated to the Root score and can be recorded from a distance, even if the roots are hidden by tall grass or fences. Despite being highly correlated to the Root score (see **Figure 48**), we did not retain the "Impervious cover under tree" variable because it is redundant with "Compaction over root extent".

Stem/main branches score selected variables:
- ✓ Cut on stem/main branches: -0.63*** (6)
- ✓ Injury on stem/main branches: -0.55*** (2)
- ✓ Rot/fungi on stem/main branches: -0.43*** (3)

These field variables are representative of usual traumas for city trees to the stem and main branches. They are relatively fast to record if the validator can take a close look all around the tree. The correlation coefficients with other variables are relatively high, indicating that these variables are relevant in covering several aspects of the stem/main branches health.

Crown score selected variables:
- ✓ Dieback: -0.87*** (1)
- ✓ Injury to leaves/twigs/buds: -0.4*** (2)
- ✓ Crown missing: -0.25*** (0)

These field variables cover a wide range of phenomena affecting the crown health of urban trees: dieback, parasites, light competition.

Ecological adaptation score selected variables:
- ✓ Pervious cover under tree: 0.59*** (3)
- ✓ Limitation of root formation: -0.57*** (5)
- ✓ Stem location: 0.56*** (4)
- ✓ Crown light exposure: -0.39*** (0)

The selected field variables indicate that the Ecological adaptation score is heavily dependent on the properties of the plantation site. The selected field variables assess in priority the freedom of the tree to expend its roots. A tree limited neither in nutrient supply nor in sunlight is likely to have a good Ecological adaptation score. The variable "impervious cover under tree", deductible from the variable "pervious cover under tree" (since they are always opposite) could further be useful to ground truth GIS modelling of permeability under tree crown.

Conservation value score selected variables:
- ✓ Crooked, split stem, surface for substrate accumulation: 0.68*** (8)
- ✓ Hollows, cracks, nests, nesting holes, bird boxes: 0.67*** (4)
- ✓ Circumference at breast height/CBH: 0.64*** (9)
- ✓ Calculated age: 0.57*** (9)
- ✓ Cracked bark: > 3 cm deep at breast height: 0.55*** (3)
- ✓ Tree > 170-year-old: 0.35*** (6)
- ✓ CBH > 250 cm: 0.32*** (5)

- ✓ Stem > 50 % covered by moss/lichen: 0.33*** (0)

Represented by mild-strong but numerous correlations, these field variables offer a satisfying overview of the ecosystem services provided by the tree. Crooked stem and cracked bark can be recorded in seconds, but assessing the hollowness of a tree is difficult even at close range. Age is estimated from the circumference at breast height but differs widely among species: these two values are linked but can provide different information.

Architecture score selected variables:
- ✓ Tree maintained for landscape architecture: 0.76*** (2)
- ✓ Tree demarcating road/property: 0.56*** (2)
- ✓ Tree part of an aesthetic group of trees: 0.54*** (1)

Determining whether a tree is contributing to the landscape architecture can take some time observing the nearby environment and constructions, but is worth considering the high correlation of this field variable with the Architecture score.

Aesthetics score selected variables:
- ✓ Unhealthy appearance: - 0.41*** (2)
- ✓ Impressive height: 0.39*** (4)
- ✓ Tree part of an aesthetic group of trees: 0.3*** (1)

These three field variables provide an overview of the tree size, environment, and shape. However subjective, all of these field variables are relatively easy to record.

Visibility score selected variables:
- ✓ Distance to nearest public property: - 0.02 (0)
- ✓ Distance to nearest private property: - 0.04* (0)
- ✓ Public visibility: - 0.17*** (1)
- ✓ Private visibility: - 0.34 (0)

VAT19 tree visibility scoring on the ground is prone to interpretation and potentially widely different among validators. We retained some variables relating to private/public visibility and distance to property boundaries that were not statistically significant in order to recognise that our sample of assessment trees does not represent trees on private land. The public/private visibility ratio can vary significantly depending on the location (**Appendix 5**). The low correlations here are also due to the comparison of subjective field judgements of Visibility score in VAT19 compared to a modelled visible pixel indicator. Further work is needed on variables modelled in GIS that are better proxies for human-perceived visibility. This work is ongoing at NINA. Modelling tree visibility in GIS and making the map available to the assessor in the field survey would avoid this bias.

3.2 The field survey

In the field survey, we tested the recording of 74 field variables, i.e., all variables that could not be modelled by geospatial analysis or calculated from other variables. These variables are marked as recorded in field survey in **Table 2**. The assessment time per tree was 30 minutes on average, depending on the visibility conditions for the assessment of hidden tree variables. The assessment time per tree using the final VAT19-i-Tree field protocol, which contains only 35 field variables, is estimated to be as low as 12 minutes for an experienced assessor.

Not all field variables could be recorded for all assessed trees. **Figure 3** illustrates the proportion of trees that were assessed in the field survey to those that were assessed partially (only some field variables were recorded) or not assessed at all, stratified by the various reasons for why they were not assessed. The initial tree sample contained 189 trees. In total, 107 trees could be assessed completely (illustrated in green). 35 trees were partially assessed, since some parts of them could not be seen or accessed (illustrated in blue); the 3 trees that had been driven to grow in coppice had no assessment of the stem and thus were identified as partly assessed. 46 trees were not assessed at all, either because they could not be reached or because they did not exist (illustrated in red).

Assuming we use the crown dimensions of the trees that could not be reached, we could run correlation analyses on 164 trees (all the trees minus those misclassified in the LiDAR dataset and the removed ones). In this dataset, 107 trees (65 %) have all the field variables recorded.

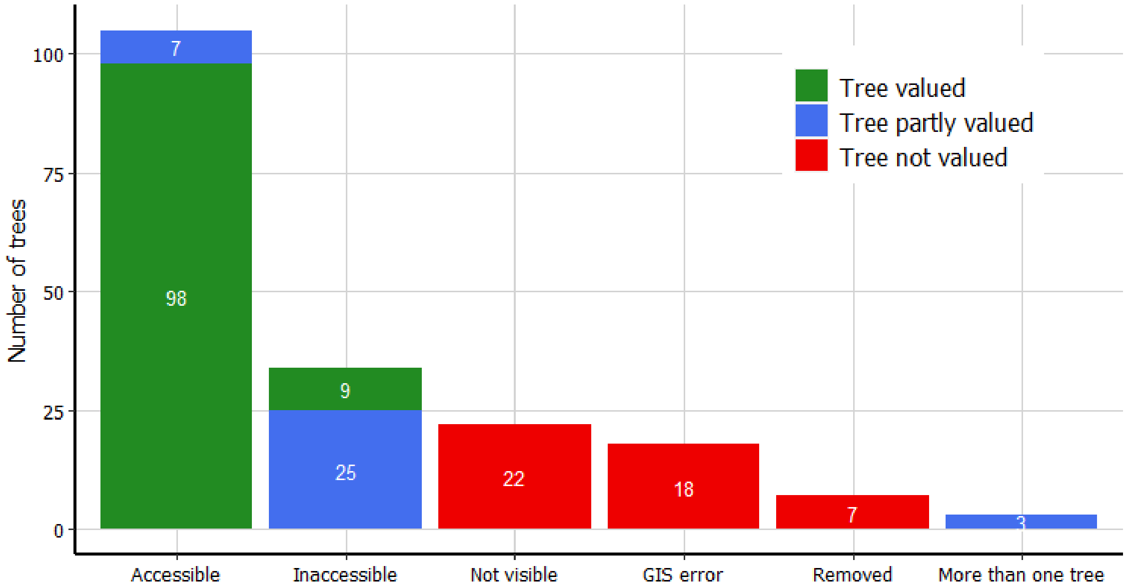

Figure 3 *Proportion of trees assessed in the field survey to those assessed partially or not assessed at all, stratified by the various reasons for why they were not assessed*

In total, 26 genera were assessed in the field survey. **Figure 4** shows that the seven most frequently assessed genera were *Betula*, *Pinus*, *Acer* and *Tilia*, followed by *Prunus*, *Ulmus* and *Aesculus*.

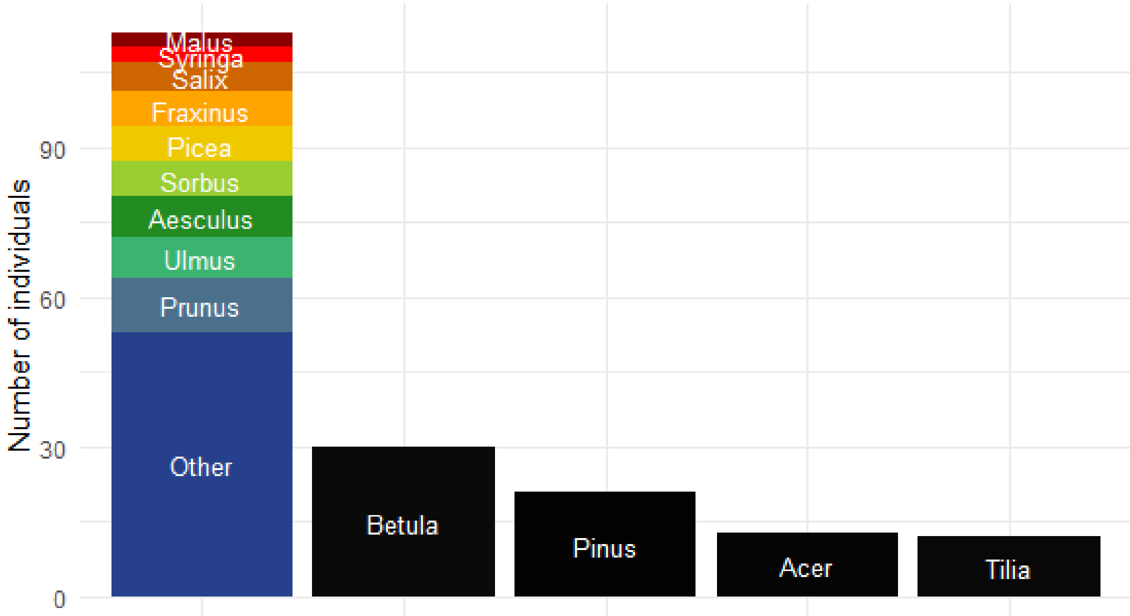

Figure 4 *Tree genera assessed in the field*

3.3 VAT19 tree compensation value

To demonstrate a concrete application of this study, we calculated the compensation values for our sample of trees according to the VAT19 equations[7]. Regardless of the genera, the mean compensation value per tree (estimated using the VAT19 protocol) is 55 000 NOK. Within the seven most represented tree genera (other genera have too few individuals recorded to be relevant in general analyses), the *Tilia* genus showed the highest mean compensation value (84 139 NOK) and the *Aesculus* genus showed the lowest mean compensation value (7 514 NOK). The very low compensation values for the *Aesculus* genus is explained by the old age of the surveyed trees relative to their computed expected age (**Table 3**).

Species	Number of trees	DBH (cm)	Height (m)	Crown width (m)	Age (years)	Expected lifespan (years)	Value (NOK)
Betula	30	39.4 (16.4)	16.6 (5.9)	11.4 (3.4)	78 (32)	120	41,979
Pinus	22	37 (11.4)	14.4 (4.2)	10.6 (2.4)	52 (16)	184	63,710
Acer	13	40.3 (17.8)	12.5 (4.4)	13.1 (4.5)	71 (32)	200	54,712
Tilia	12	39.2 (16.9)	12.9 (5)	11.2 (3.7)	50 (19)	300	84,139
Prunus	11	26.9 (11.3)	7.2 (2.2)	9.7 (2.5)	53 (22)	100	35,089
Ulmus	8	78.5 (35)	14.7 (6)	14.9 (3.5)	123 (55)	200	40,555
Aesculus	8	64 (17.4)	17.6 (4.6)	16.5 (4.7)	202 (55)	150	7,514

DBH, height, crown width and age are average values, with the standard deviation between brackets.

Table 3 *Mean compensation values (VAT19) for the seven main genera*

As shown in **Appendix 6**, circumference at breast height, tree height and crown width are correlated between themselves and with other tree characteristics. However, **Table 3** shows that DBH, height and crown width are not sufficient to explain variations in mean compensation value between genera. This is because the VAT19 method accounts for tree-specific local conditions in addition to the tree's structural characteristics (e.g. actual relative to expected age).

The tree with the highest compensation value assessed in the survey was a pedunculate oak (*Quercus robur*) in Sognsveien street (**Figure 5**), with an estimated compensation value of 244 000 NOK. Despite an estimated old age of 261 years, the relatively high age expectancy for this species does not impact the Age factor in a way that would drastically diminish its compensation value. In addition, the Location factor and Health factor have excellent scores: the tree is high, impressive and visible from far away. There is no direct competition to the crown and the roots are mostly free to expand. The stem and leaves seem to be free from parasites despite the old age. The extended stem surface (horizontal substrate accumulation), the extension of the branches (birds), the cracking of the stem and roots (arthropods) and the tree species itself (relatively rare in Oslo) led to a perfect score for conservation value.

[7] i-Tree Eco values of regulating ecosystem services were not calculated for this report as explained in section 4.3.

***Figure 5** The tree with the highest compensation value was a pedunculate oak, estimated to be worth 244 000 NOK*

In the case of the Aesculus individuals in the sample the low VAT19 values due to the role of the age factor for trees in the last ¼ of their expected life. The tree with the lowest compensation value assessed in the survey was a common horse chestnut (*Aesculus hippocastanum*) in Bygdøy allé (**Figure 6**), with an estimated compensation value of 2 880 NOK. The Age factor for this tree significantly diminished its compensation value, since the tree was estimated to be older (circumference-age calculator: 217 years old) than its standardized life expectancy (150 years). In this report we used a nominal age factor of 0.05 for cases where actual age exceeds standardized expected age (in this case leading to a value of 2880 NOK). In the VAT19 methods, a zero/negative age factor would result in a compensation value of zero. Problems with the effects of the age factor for high age trees was discussed in **Box 1** above and further in the Discussion section.

The Health factor is very low because the tree stem is injured (injuries and dead bark) and the crown suffers from considerable levels of dieback, in addition to visible parasites on leaves. The roots are limited to expand in all four directions by pavement and road, and only a small area around the stem is not covered by pavement. The Location factor is average since the crown is under heavy competition and shaped to let pass buses and trucks, which lowers the Ecological adaptation and Aesthetics score. The Visibility and Architecture scores are quite good since the tree belongs to an avenue and is relatively easy for people to see from public spaces.

The example here shows some counter-intuitive effects of the age factor, given that the tree evidently has visibility and architectural value in a public place. Also, despite apparent constraints on growing conditions, the tree has an age that exceeds standardized or mean life expectancy for a population. This is addressed further in the Discussion section.

An example of the usage of the VAT19-i-Tree field protocol for assessment of an imaginary tree is provided in **Appendix 2**.

Figure 6 The tree with the lowest compensation value was a common horse chestnut, estimated to be worth 2 880 NOK.

3.4 Value of information analysis in Bayesian belief network

Figure 7 shows a graphical representation of the BBN representation of the VAT19 method with all the retained field variables. Compared to the overview in **Figure 2**, this network shows the relationships between variables with the highest mutual information, similar to a correlation factor in classical statistics. The graph gives a visual overview indicating that the Base value is the most important one in determining the VAT19 tree compensation value, followed by the Age factor. Current tree age and circumference at breast height of the damaged tree are the two most important field variables.

Figure 8 shows results of the Value of information analysis in which the individual variables are ranked by order of importance in explaining the tree compensation value. This confirms the visual picture in **Figure 7**, and demonstrates the importance of care costs, expected age and prices of a new tree. Furthermore, the Location factor is more important than the Health factor in determining tree compensation value. The relative importance of the different VAT19 factors can, of course, also be observed directly by looking at the weighting in the VAT19 formula.

The other take away message from **Figure 8** is that each field variable makes two orders of magnitude less difference to the tree compensation value than e.g., the circumference at breast height of the damaged tree (H=0.35). This means that if the field survey cost is more important than documenting accuracy, the field variables for tree Health factor and Location factor can be further reduced. Furthermore, the network shows that the impact of amenity services – visibility, aesthetics and architecture – through the Location factor is orders of magnitude lower than the structural characteristics of the tree. Unless corrected this will lead to a mismatch between accounting values using VAT19 (which supposedly addresses regulating services), and monetary values calculated by i-Tree Eco. This suggests that the value of ecosystem services may be better reflected by removing regulating service criteria from the VAT19 Location factor and adding i-Tree Eco-calculated monetary values to a revised VAT19 calculation.

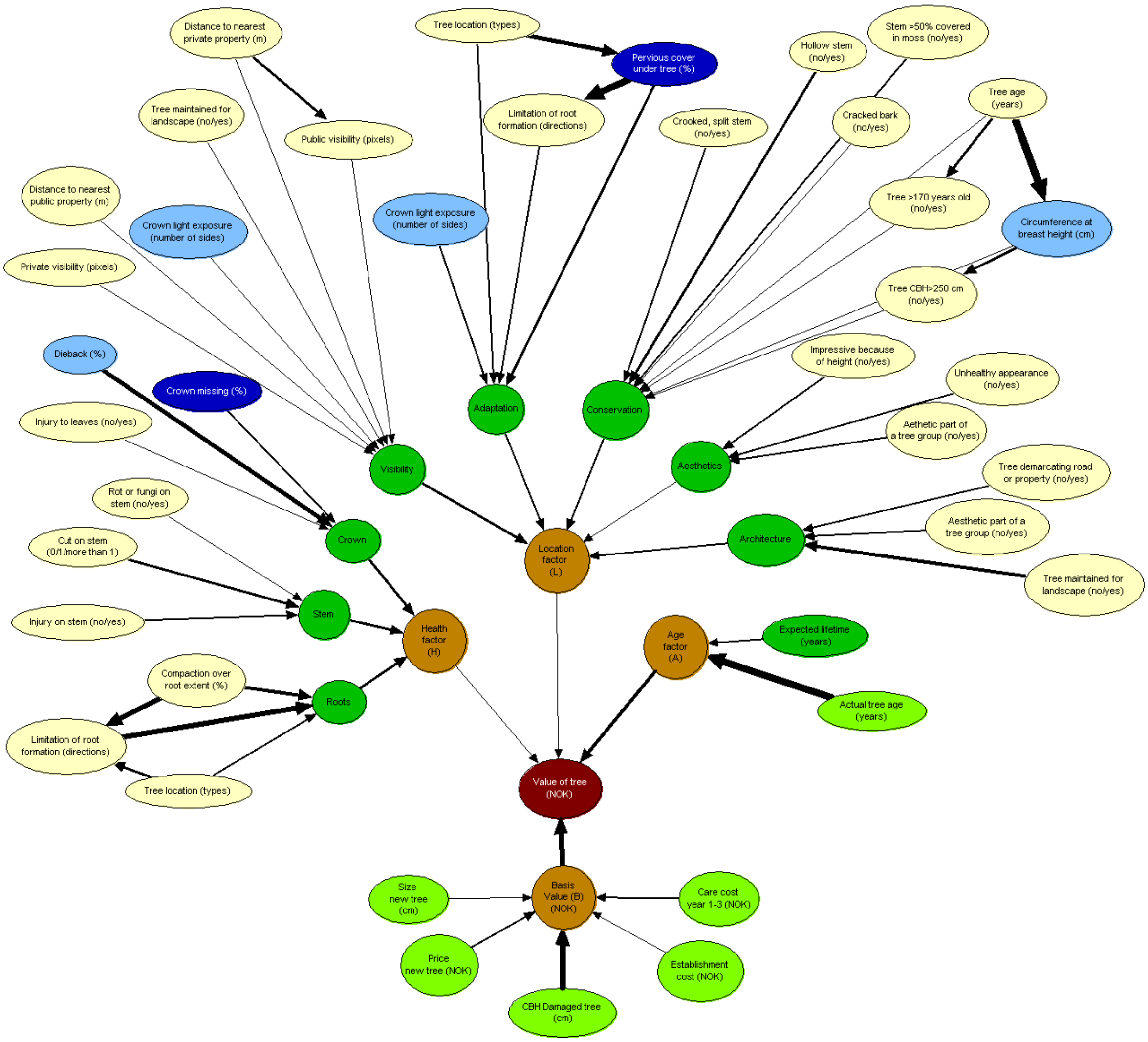

Figure 7 *Visualization of the variable relationships with the highest mutual information. Widths of edges between nodes visualise the relative strength of mutual information. The colour code is as follows: Light yellow: VAT19 field variables, light blue: VAT19/i-Tree Eco field variables, blue: i-Tree Eco field variables, light green: exact observations, green: VAT19 scores, brown: VAT19 factors, dark red: compensation value.*

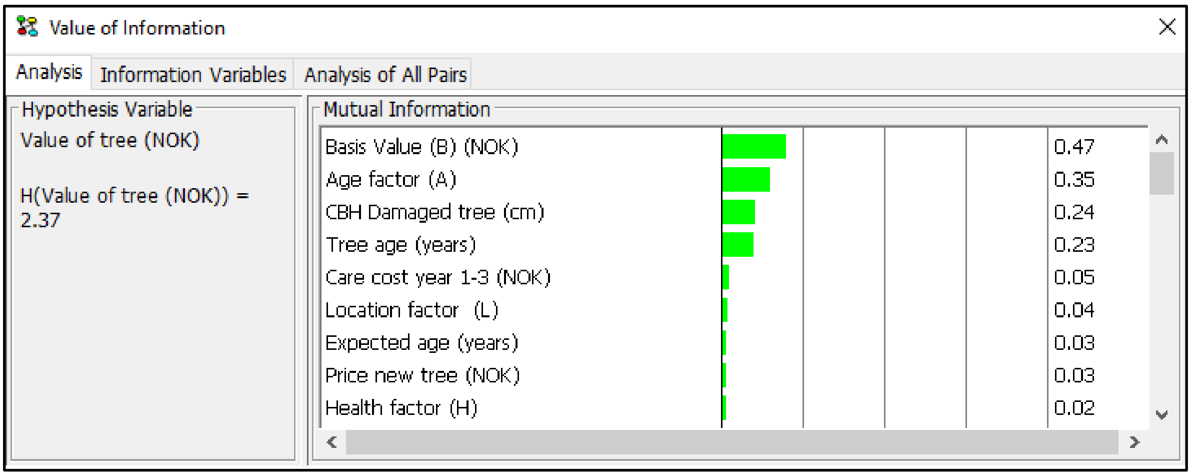

Figure 8 *Ranking of the variables by order of influence on the calculated compensation value of tree (NOK). Variables with a H index < 0.01 are not shown.*

Figure 9 zooms into the central part of the network, which focuses on the VAT19 variables (in dark green). The node windows have been "opened", showing the distributions of values for the tree population considered in this study. The node windows show the probability distribution (in green), the expected value and variance. By selecting the observed values (red bars), we can see how data affect the tree compensation value (brown monitor). Observing tree size, cost and age (red values in node windows) leaves a range of variation in the "value of tree (NOK)", which depends on the expert assessment of the VAT19 factors. While each field variable makes a very small contribution to determining the tree compensation value (**Figure 8**), together they reduce the variance (uncertainty) of the subjective expert assessment concerning the scores (dark green) for the Health factor and the Location factor.

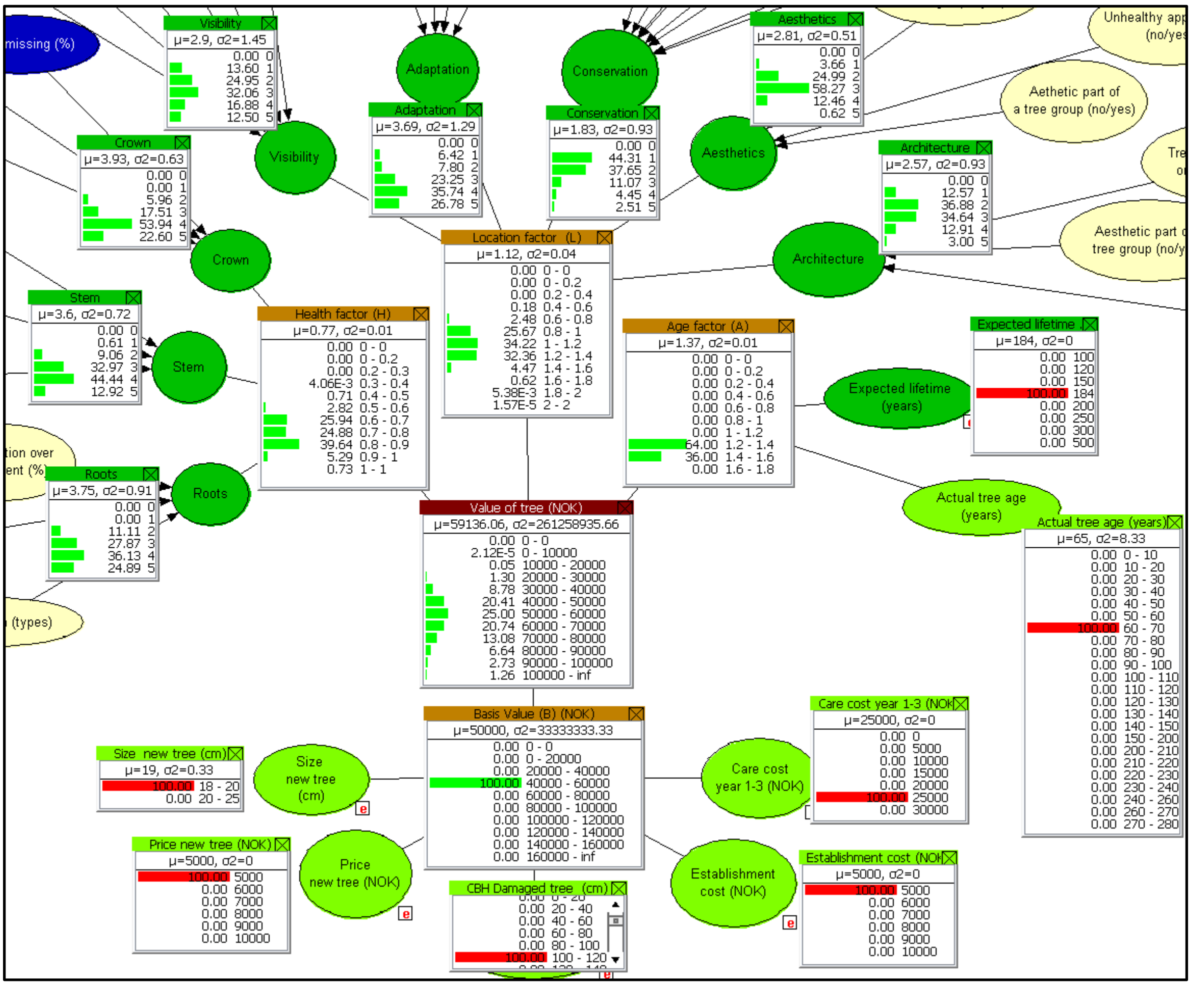

Figure 9 Diagnosing uncertainty in VAT19 using Bayesian belief network. See further explanation in the text.

4 Discussion

We developed, tested and documented a combined cost-effective field protocol called VAT19-i-Tree. We have built upon the work of Lauwers et al. (2017) and the USFS ("i-Tree Eco v6.0," n.d.), and the resulting protocol is thus a combination of the VAT19 protocol (assessing amenities) and the i-Tree Eco model (assessing regulating ecosystem services). As a result, where the i-Tree Eco model is needed for accounting purposes and the VAT19 to calculate compensation values, the VAT19-i-Tree field protocol provides field variables allowing to calculate compensation values, as well as field variables that can be processed through i-Tree Eco to value regulating ecosystem services.

We further assessed each field variable in terms of its relevance for the individual VAT19 scores, redundancy with other variables, ease of recording in a field survey, and tendency to subjective interpretations. Calculating these values with a Bayesian belief network allowed us to conduct a Value of information analysis for the field variables and thus to determine the importance of each variable in the tree compensation value. In consequence, the VAT19-i-Tree field protocol is expected to be robust and more time-efficient than the VAT03 protocol proposed by Lauwers et al. (2017). Instead of their total 103 field variables tested, the validator of the VAT19-i-Tree field protocol needs to record only 35 variables in the field survey.

Used together with geospatial methods for modelling some field variables, the VAT19-i-Tree field protocol could become a tool for conducting tree inventories in support of ecosystem accounting at a city level. The documented field variables may provide additional support for individual cases where tree compensation value needs further justification, such as fines or legal proceedings (Lauwers et al. 2017). Compensation value may also be a relevant decision support tool when deciding upon removal, replacement and protection of larger numbers of urban trees.

In this study, we have also demonstrated the feasibility of including i-Tree Eco variables in the VAT field protocol (i) without increasing field costs and (ii) because i-Tree Eco variables make it possible to estimate the value of regulating ecosystem services which can be added to the VAT19 calculated value.

4.1 Assessment cost considerations

The assessment of field variables implies some field costs. These costs are easier to justify when decisions are made about many trees rather than single trees. Therefore, the cost of assessing a tree should be added to the compensation value in the case of fines and fees. There should however be some consideration of "limit" cases, where the assessment costs are similar or greater than the expected compensation value of a single tree. In those cases, some simplified field assessment with minimal field observations (perhaps only using geospatial methods) could be deemed enough to settle a compensation value. Based on time use experiences from the simplified field methodology, travel time costs to the site of the tree are expected to be the main assessment cost in most cases. Assessment time at publicly accessible locations was as little as 12-15 minutes recording variables onsite for publicly accessible trees. Travel time cost is therefore a relevant assessment cost threshold if evaluated using in-house experts on municipal land (e.g. a municipality using their own arborists). Access costs are higher for private trees due to the need to obtain permission from property owners. In case consultants need to be hired, the consulting cost per tree can be compared to expected compensation values in this report to make a decision on whether to apply a simplified assessment using only GIS variables. When the VAT19-i-Tree protocol is used as evidence in legal proceedings an on-site inspection will likely be necessary. In that case, legally required on-site assessment costs could be added to the tree compensation value.

4.2 Limitations of the VAT19-i-Tree field protocol

The assessment of tree health, age, expected age and ecosystem services relies on subjective expert judgement of experienced/certified tree assessors. A lack of field documentation of tree characteristics and lacking database of cases to use as precedents can lead to undocumented differences between assessors in choices made in the scoring of the different field variables.

The protocol developed for this report aims to provide a better documentation basis for expert judgement and aims at covering a wide range of urban tree contexts. However, the sampling criteria used for this report provide limited representation of the population of urban trees. Trees visible only on private properties were not included in the sample due to expected access difficulties in the field. Trees on private property visible and accessible from public space were included in sampling.

We also found the VAT approach hard to implement for certain tree management practices. The following cases proved difficult to score for the health state of branches and trunk respectively: (i) trees that are heavily pruned, such as municipality managed *Tilia* or private trees pruned to form an aesthetic shape very different from the natural state and (ii) trees driven to grow in a coppice.

4.3 Use of geospatial analysis for modelling field variables

In this study, we have shown that a significant proportion of field variables from the VAT19-i-Tree protocol can be modelled using geospatial analysis. In future assessments, i-Tree Eco modelling of regulating ecosystem services might be able to process data mainly obtained through geospatial analysis, with cost-effective ground-truthing (Hanssen et al. 2019). For example, the municipal tree database in Oslo, set up to manage private tree maintenance contracts, contains 29 928 geolocated trees in streets and parks. This database is poor relative to the needs of i-Tree Eco (Cimburova and Barton, 2020) and tree assessments more generally (Sjöman et al. 2012). However, it provides partial records of tree species and DBH, which can be combined with geospatial data for modelling purposes. Cimburova and Barton (2020) demonstrated how geospatial methods and machine learning can replace field data normally used to run the i-Tree Eco model. The combination of rapid ground survey and geospatial analysis is a promising alternative to longer and costly traditional field surveys. Indeed, the physical tree dimensions can largely be recorded by remote sensing for large-scale projects that do not rely on individual-level accuracy.

Nevertheless, current LiDAR based tree canopy segmentation of a tree population (Hanssen et al. 2019), from which the surveyed sample was drawn, still did not accurately represent trees observed in the field. Thirteen percent (13%) of the trees in the tree sample selected using LiDAR data were not found in the field visit, either due to misclassifications or because the trees were removed after the LiDAR was recorded. In addition, many LiDAR-detected trees consisted of several trees. In average, for each LiDAR-detected tree in the survey, 0.76 supplementary trees were identified. This corresponds to the difference between tree counts found in the studies of Barton et al. (2015) and Hanssen et al. (2019).

4.4 Regulating ecosystem services

The trees assessed in the field survey had their compensation values calculated according to the VAT19 method. Cimburova and Barton (2020) illustrated how machine learning methods in a Bayesian belief network make it possible to extrapolate the results of i-Tree Eco in an “emulation model” to evaluate all municipal trees based on only inventoried trees.

Due to the need to run the i-Tree Eco model through the USFS, it was not possible to produce the i-Tree Eco model of all public trees in Oslo for this study. A weakness of i-Tree Eco is that its current set up assumes single average air pollution levels for the city's airshed. To compute i-Tree Eco for three different pollution zones in Oslo in separate model runs, it would have been necessary to submit our data to the USFS within the time frame of this study since we required them to process the data. However, because of the special conditions of Covid-19 limitations during the period of the internship, USFS did not have available manpower to assist with this request. While this step is fast under normal circumstances, it still represents an additional assessment requirement for municipalities. Covid-19 made evident possible delays in depending on an external USFS assistance to generate i-Tree Eco results. The i-Tree Eco input data collected for this study and the model integration with VAT is a topic for future research.

While the VAT19- i-Tree field protocol records relevant variables to run i-Tree Eco, a municipality is still left with the challenge of formatting data on the desktop application, submitting a model run to the i-Tree server and generating a report. i-Tree Eco was demonstrated by Cimburova and Barton (2020) for Oslo municipality's tree inventory using research funding. I-Tree Eco requires specialist knowledge. Smaller municipalities will likely not have access to expertise or funds to run the model on their own. Future research is needed on easier ways of implementing i-Tree Eco in other cities or methods for extrapolating findings from similar cities. This is also referred to as "value transfer" and can be carried out using e.g. Bayesian belief networks to adjust for some local conditions, while quantifying confidence in transferred estimates. A field-ready method will require incorporating the valuation results from i-Tree Eco either as (i) simplified look-up tables with a few site variables or (ii) from an online database/digital map tool where i-Tree Eco values are associated with each tree in a city.

The three most important site-specific variables to adjust for using a look-up table approach are tree canopy area, air pollution levels and DBH (Cimburova and Barton 2020). Tree canopy area is a proxy for leaf area, which is a driver for most of the regulating ecosystem services of a tree. DBH is a proxy for tree biomass and carbon storage. Air pollution mitigation represents the larger part of the monetary value of regulating ecosystem services of trees in Oslo (93.5 % according to Cimburova and Barton (2020)). While the average air pollution improvement due to trees has been found to be relatively low in urban environments (< 1 % according to Nowak et al. (2006)), even such a minimal improvement at the scale of a city can represent hundred to thousands of metric tons of mitigated air pollutants per year, to which large populations would have been potentially exposed. If results are extrapolated from one city to another, adjusting for differences in air pollution levels between cities will therefore be important. In time, look-up table values can be replaced by city specific i-Tree Eco modelling.

4.5 Visibility concerns

The correlation tests showed no significant correlation between tree dimensions (height, crown diameter) and field variables related to the visibility score, which was modelled by geospatial analysis (distance to nearest public/private property, public/private visibility). This indicates that in our sample, high and large trees were not significantly more visible from public spaces. The lack of correlation between tree dimensions and a GIS-based visibility score appears counter-intuitive relative to the assumptions in the VAT19 visibility criteria. An initial explanation is that visibility scores were determined by surrounding structures to such an extent as to make correlation with height and canopy size insignificant. Further testing is needed. We would expect the visibility score to be more strongly correlated in less densely built urban environments.

Several considerations should be taken into account when assessing the correlation between tree dimensions and field variables related to the visibility score. The surveyed tree sample was drawn from publicly visible trees (not only trees on public grounds). In consequence, the tree sample does not cover the variability of visibility across a private/public gradient. Further sampling from private trees would be needed to represent a full private/public visibility gradient.

For actual field implementation, we conclude that the current visibility score in VAT19 requires a definition clear enough to enable GIS modelling using viewshed analysis, and to allow for subjective-based assessment on the ground. Better proxies to compute tree visibility could be explored in further research projects, for example via calculating a vertical angle to connect the height of a tree to the total green area visible from the ground. This modelling work may in turn help in standardising the subjective field-based assessment.

4.6 Unexpectedly old trees

On average, in the surveyed tree sample, the Age factor increased the product of *B* x *H* x *L* by 25 %. However, in the field survey, there were some examples where the calculated age using our model was greater than expected age as defined by Lauwers et al. (2017). In these cases, the Age factor in the spreadsheet model is negative or returns an error. We call these "unexpectedly old trees" for the purposes of a discussion about VAT19. The VAT19-i-Tree protocol showed limitations to properly assess unexpectedly old trees.

The highest mean compensation values of the *Tilia* genus were expected since this is the most recently planted genus and thus the one having potentially the youngest individuals to assess. Indeed, *Tilia x Vulgaris 'Pallida'* accounted for 70 % of the newly planted street trees in Oslo according to a 2002 review (Pauleit et al. 2002). In VAT tree compensation value starts to fall in the last 1/3 of the expected life. We found that the very low compensation values for the *Aesculus* genus could be explained by the estimated age of the surveyed trees being close to the calculated expected age. In our modelling for this study, we replaced a negative Age factor by an arbitrarily small value of 0.05 simply to avoid a computation error. This mathematically decreases the value calculated by the other factors in VAT19 (B x H x L) by 95 %. In the *Aesculus hippocastanum* valuation example mentioned above, we found that the tree would be worth 57 600 NOK without the Age factor adjustment, compared to the estimated compensation value of 2 880 NOK. This tree had health issues and suffered from a poor Ecological adaptation score, but being tall and part of a green avenue, it would have had a much higher compensation value due to its good Architecture and Visibility scores. The value reduction for these unexpectedly old trees indeed seems arbitrary and should be subject to further improvement in the practice of VAT.

The age calculator gave us a value based on average growth factors, to compare with a single life expectancy value in a look-up table for all the individuals belonging to the *Aesculus hippocastanum* species. The variance in local growing conditions and tree management makes this choice problematic at times. This demonstrates the difficulties of applying fixed values to the assessment of a wide range of actual conditions. Calculations based on look-up tables are expected to give decent-enough approximations most of the time, but should be updated to different city planting contexts and climates (given the climate gradient in Norway) by competent local authorities.

In the end, the handling of unexpectedly old trees may be a challenge for future standardisation work, which would need further definition and resolution. There are two possible issues:

(i) actual tree age in our tree calculator may be overestimated for some types of trees, e.g., in very favourable growing conditions,
(ii) the expected age estimate may be too conservative in this context.

In such special cases, the solution would be to retrieve a core sample from the tree to determine the actual age. There may still be an issue that needs resolution if the core sample actual age is higher than the tabulated expected age. The VAT19 guidance suggests that the method should not be used for protected status trees. However, there is no provision for trees that are older than expected age, but not currently protected. This is a further reason for a closer discussion of the Age factor in further standardisation work of VAT19.

5 Conclusions

In this study, we propose a time-efficient field protocol, called VAT19-i-Tree, and its associated measurement and diagnostic tools to contribute to the elaboration of a Norwegian standard for the evaluation of urban trees.

The developed VAT19-i-Tree field protocol does not remove the subjectivity inherent to the assessment made by tree experts. It still contains some limitations and results in uncertainty for some special cases. However, we argue that the protocol tested in this report will contribute to integrate the valuation of trees to systematic inventorying of urban trees.

The BBN tool helps to document the variance in subjective expert assessment involved in the VAT19 method. It could facilitate an integration of the VAT19 and i-Tree Eco valuation methods.

Combined with geospatial analysis to model key field variables for both valuation methods, BBN could also be used to extrapolate values from a sample of trees to the larger population in a city. Initially, it could also be used to generate look-up tables that can extrapolate i-Tree Eco results to other cities until a bespoke model can be run.

This research has addressed individual urban trees. Since biodiversity and ecosystem services tend to increase with contiguous tree cover, further research could focus on a compensation method at the level of stands and urban woodlands.

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Appendix 1: Growth factor and life expectancies

This appendix provides an overview of growth factors and life expectancies for individual tree species present in the study area in Oslo. See **Table 4** below.

The life expectancies are used to estimate the Age factor in the VAT19 equation. We used data from the Oslo municipality's Agency for Urban Environment (Lauwers et al. 2017) and personal suggestions made by Anders Often, NINA. These life expectancy numbers are for urban conditions based on expert opinion, rather than statistical documentation.

To estimate tree age VAT19 (Randrup et al. 2018) propose a rule of thumb of a circumference growth factor of 2.5 cm/yr at breast height under good growing conditions. This should be adjusted for expert knowledge of site conditions. Extending this approach, we used growth factors to estimate tree actual ages based on observation of stem circumferences and growth factor statistics retrieved online. We retrieved data from the Minnesota Project Learning Tree[8] which is based on a method from the International Society of Arboriculture. We The growth rates likely represent growing conditions of forests in Minnesota, US. However, the source material does not document the growing condition assumptions behind the data in **Table 4**. In fact, as we were in the final write up of this report we found other online sources that document different growth rates for urban trees[9]. A study of growing conditions in different urban ecological zones of Montreal (Jutras et al. 2010) showed that species average DBH to be smaller in commercial zones than in residential zones. Common significant abiotic factors explaining growth rates across several species included overall presence/absence of metal grating, urban zone, surface geomorphological deposit type, presence/absence of aerial and underground obstacles, irradiation, street width, distance from tree to curb, tree pit soil volume, and penetration resistance. Significant soil nutrient types varied between species.

This implies that the calculations in our simple tree age calculator with no site information are associated with a substantial level of uncertainty for living trees in the urban environment of Oslo. For example, underestimation of growth factors will overestimate tree age based on observed circumference in the field, leading to possible underestimation of tree value. Growth factors in Table 4 should be considered as guestimates, highlighting the need for standardisation of age estimation methods specific for conditions in urban areas in Norway. Standardisation work should include a hierarchy of recommended methods based on the situation (i.e. historical documentation of planting age where available; tree coring, look up tables based on growth condition studies for tree species in Norwegian urban).

[8] https://files.dnr.state.mn.us/education_safety/education/plt/activity_sheets/growthfactorworksheet.pdf

[9] Morton Arboretum, Illinois
https://www.mortonarb.org/files/Find%20the%20Age%20of%20a%20Tree%20-%20middle%20school.pdf

Table 4 *Circumference growth factors used to estimate current age and estimated life expectancies of tree species present within the study area*

Species	Circumference growth factor (cm/yr)	Expected maximum age (years)
Abies	1.856	184
Abies concolor	2.953	184
Acer negundo	1.181	200
Acer nigrum	1.969	200
Acer platanoides	1.772	200
Acer rubrum	1.772	200
Acer saccharinum	1.181	200
Acer saccharum	2.165	200
Aesculus	2.559	150
Aesculus flava	1.969	150
Aesculus hippocastanum	3.150	150
Alnus	1.575	100
Betula	1.772	120
Betula nigra	1.378	120
Betula papyrifera	1.969	120
Betula pendula	1.969	120
Carya ovata	2.953	184
Cercis canadensis	2.756	184
Cornus	2.756	184
Fagus	1.969	200
Fagus grandifolia	2.362	200
Fagus sylvatica	1.575	200
Fraxinus	1.575	300
Fraxinus pennsylvanica	1.575	300
Gleditsia triacanthos	1.181	184
Gymnocladus dioicus	1.181	184
Juglans nigra	1.772	184
Larix	1.575	250
Liquidambar styraciflua	1.575	184
Liriodendro tulipifera	1.181	184
Picea	1.870	184
Picea abies	1.969	184
Picea pungens	1.772	184
Pinus	1.821	184
Pinus nigra	1.772	184
Pinus resinosa	2.165	184
Pinus silvestris	1.378	184

Table 4 (cont.)

Species	Circumference growth factor (cm/yr)	Life expectancy (years)
Pinus strobus	1.969	184
Platanus occidentalis	1.575	184
Populus	0.787	100
Populus tremuloides	0.787	100
Prunus	1.969	100
Prunus serotina	1.969	100
Pseudotsuga menziesii	1.969	100
Quercus	1.640	500
Quercus alba	1.969	500
Quercus coccinea	1.575	500
Quercus imbricaria	2.362	500
Quercus palustris	1.181	500
Quercus rubra	1.575	500
Quercus shumardii	1.181	500
Salix	0.787	100
Salix nigra	0.787	100
Tilia	1.181	300
Tilia americana	1.181	300
Tilia cordata	1.181	300
Ulmus	1.575	200
Ulmus americana	1.575	200
Other	1.575	184

Appendix 2: Calculating tree compensation value with VAT19 – an example

The purpose of this appendix is to show how the tree compensation value is calculated with the VAT19 protocol and equations, using an imaginary tree as an example.

In addition, the appendix demonstrates that the dynamic VAT19-i-Tree Excel spreadsheet developed in this study is working with the VAT19 equations and leads to identical results.

The parameters of the imaginary tree are the following:

***Table 5** Parameters of the imaginary tree used in the example*

Variable name	Variable symbol	Value
Tree species	-	*Acer platanoides*
Stem circumference (cm)	S_d	90
Root score	*r*	4
Stem/main branches score	*s*	4
Crown score	*c*	5
Ecological adaptation score	*ad*	4
Support of habitat and conservation value score	*co*	3
Architecture score	*ar*	4
Aesthetics score	*ae*	4
Visibility score	*v*	4
Calculated age (years)	*Aa*	51

In addition, the following variables are constant for all trees:

***Table 6** Constants used in the example*

Variable name	Variable symbol	Value
Establishment cost of a new tree (NOK)	*E*	25000
Stem circumference of a new tree (cm)	S_n	18
Price of a new tree (NOK)	P_n	5 000
Life expectancy of the tree (years)	*Ae*	200

The calculation of the tree compensation value follows the equations presented in section 2.1.2:

- Base value (*B*):

$$B = E + ((S_d - S_n) \times (\frac{\mathrm{Pn}}{\mathrm{Sn}}))$$

$$B = 25\,000 + ((90 - 18) \times (\frac{5\,000}{18})) = 25\,000 + 20\,000 = \mathbf{45\,000\ NOK}$$

- Health factor (*H*):

$$H = \frac{r + s + c}{25}$$

$$H = \frac{4 + 4 + 5}{15} = \frac{13}{15} \approx \mathbf{0.87}$$

- Location factor (*L*):

$$L = \frac{ad + co + ar + ae + v}{12.5}$$

$$L = \frac{4 + 3 + 4 + 4 + 4}{12.5} = \frac{19}{12.5} = \mathbf{1.52}$$

- Age factor (*A*):

$$A = \sqrt{\frac{(Ae - Aa) \times 2}{Ae}}$$

$$A = \sqrt{\frac{(200 - 51) \times 2}{200}} = \sqrt{\frac{298}{200}} \approx \mathbf{1.22}$$

- Compensation value: *B* x *H* x *L* x *A*

$$\text{Compensation value} = 45\,000 \times \frac{13}{15} \times \frac{19}{12.5} \times \sqrt{\frac{298}{200}} = \mathbf{72\,360.46\ NOK}$$

Inserting the same values into the dynamic VAT19-i-Tree Excel spreadsheet results in an identical compensation value (**Figure 11**, **Figure 12**).

VAT19-i-Tree field form	Greyed cells are for variables better off estimated with GIS methods.				
Validator name:	Alexandre Nollet				
Date:	17/08/2020				
TREE CHARACTERISTICS					
Age and species		**Location**			
Tree ID:	313	Street tree (no/yes)	No		
Species	Acer platanoides	Land use type (list of LU types)	R (Residential)		
Species code	ACPL	Latitude (degrees)	59.86		
Other species (if not in the list). Using the i-Tree Eco pdf file in the GitHub folder, you can find the species code.		Longitude (degrees)	10.78		
Life expectancy (years)	200	Stem on property type (public/private)	Public		
Minimum age estimation (years)		Access limitation (no/yes)	Yes		
Maximum age estimation (years)		Stem location (road, parking, pavement, unpaved)	Unpaved		
Calculated age (years; need CBH)	51	Stem protection (no/yes)	No		
Dimensions		Distance to the nearest 3 buildings (m)	5	12	16
Circumference at breast height/CBH (cm)	90	Direction of the nearest 3 buildings (degrees)	272	245	122
CBH estimation distance (m; 0 if at tree)	2				
Height (m)	15				
Height to live top (m)	15				
Height to crown base (m)	4				
Crown diameter North-South (m)	18				
Crown diameter East-West (m)	20				
Crown missing (%)	10				

***Figure 5** The dynamic VAT19-i-Tree Excel spreadsheet*

HEALTH FACTOR			
Roots		**Stem & Main Branches**	
Stem location (road, parking, pavement, unpaved)	Unpaved	Injury on stem/main branches (no/yes)	No
Compaction (load, pavement, trampling zones) over root extent (%)	10	Rot/fungi on stem/main branches (no/yes)	No
Limitation of root formation (number of directions)	1	Cut on stem /main branches (0, 1, >1)	>1
SCORE	**4**	**SCORE**	**4**

Minor branches, twigs and leaves					
Crown missing (%)	10	Dieback (%)	0	Injuries to leaves /twigs/buds (no/yes)	No
SCORE	**5**				

HEALTH SCORE	**0.866666667**

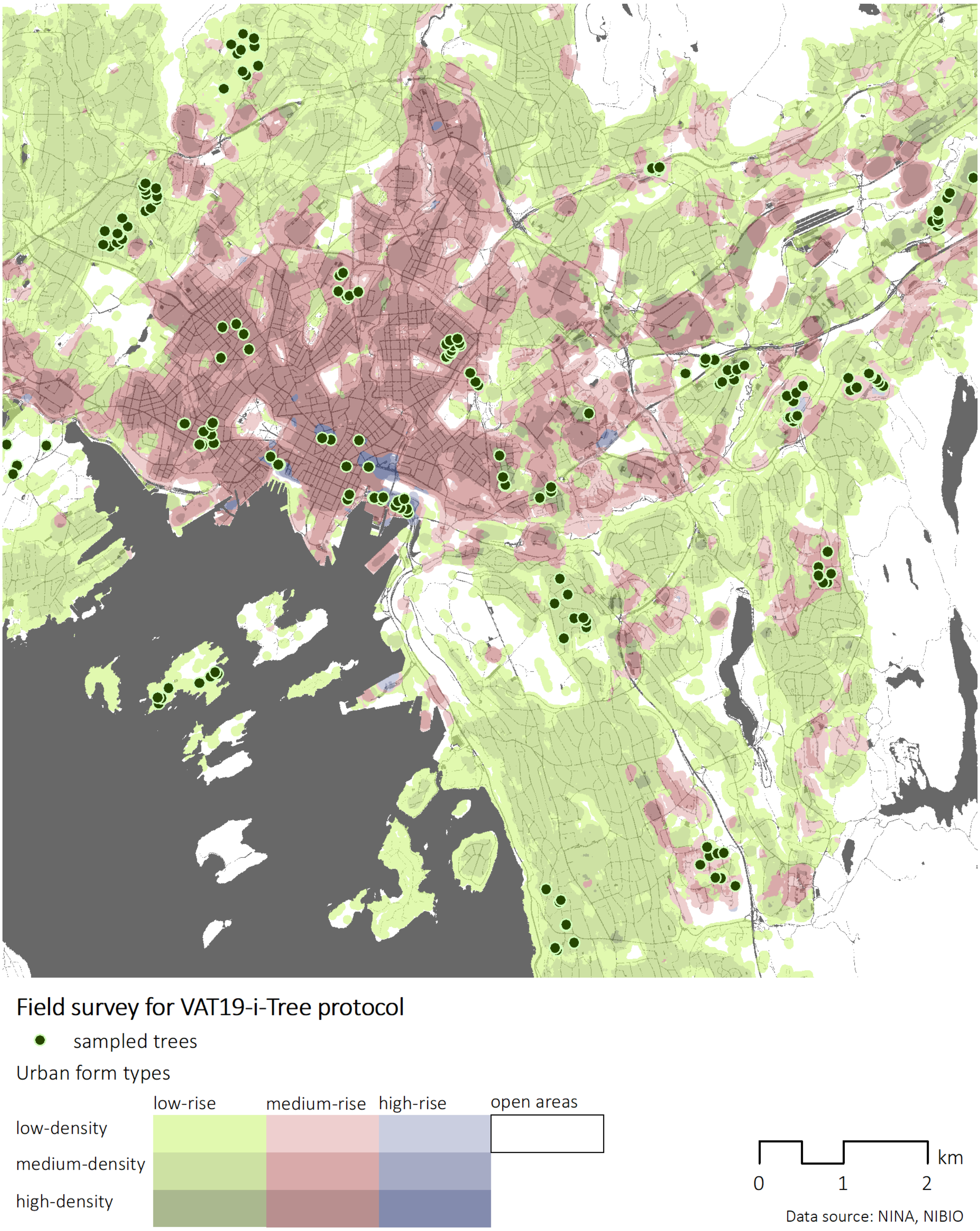
LOCATION FACTOR			
Ecological adaptation		**Architecture**	
Pervious cover under tree (%):	90	Tree demarcating road/property (no/yes)	Yes
Limitation of root formation (number of directions):	1	Tree maintained for landscape architecture (no/yes)	Yes
Stem location (road, parking, pavement, unpaved)	Unpaved	Tree part of an aesthetic group of trees (no/yes)	No
Crown light exposure (number of sides)	4		
SCORE	**4**	**SCORE**	**4**
Supporting habitat and conservation value		**Aesthetics**	
Circumference at breast height/CBH (cm)	90	Impressive height (no/yes)	Yes
		Unhealthy appearance (no/yes)	No
CBH > 250 cm (no/yes)	No	Tree part of an aesthetic group of trees (no/yes)	No
Calculated age (years)	51	**SCORE**	**4**
Tree > 170-year-old (no/yes)	No	**Visibility**	
Cracked bark: >3cm deep at breast height (no/yes)	No	Private visibility (pixels)	221
Crooked,split stem, surface for substrate accumulation (no/yes)	No	Distance to nearest private property (m)	100
Hollow, cracks, nests, nesting holes, bird boxes (no/yes)	Yes	Distance to nearest public property (m)	0
Stem >50% covered bt moss/lichen (no/yes)	Yes	Public visibility (pixels) (GIS derived)	890
SCORE	**3**	**SCORE**	**4**
LOCATION SCORE		**1.52**	

Tree value (NOK)	**72 360.46**

***Figure 6** The dynamic VAT19-i-Tree Excel spreadsheet (continuation)*

Appendix 3: Distribution of urban form types and sampled trees

This appendix provides a map of the spatial distribution of urban form types and sampled trees in the study area.



Appendix 4: VAT19-i-Tree field survey tutorial

The QField app

Launch the QField app and open your project from the main menu (**Figure 13**). Then, locate the tree to be assessed in the map view (**Figure 13**) and open the protocol (**Figure 14**). Once you filled in the validator name, you may observe inconsistencies between your map and the reality for further GIS corrections. Some inconsistencies can lead to the end of the assessment of that tree (e.g., tree removed, wrong LiDAR detection) or to fewer tree variables recordable (e.g., root health cannot be recorded when the lower part of the stem is hidden behind a fence).

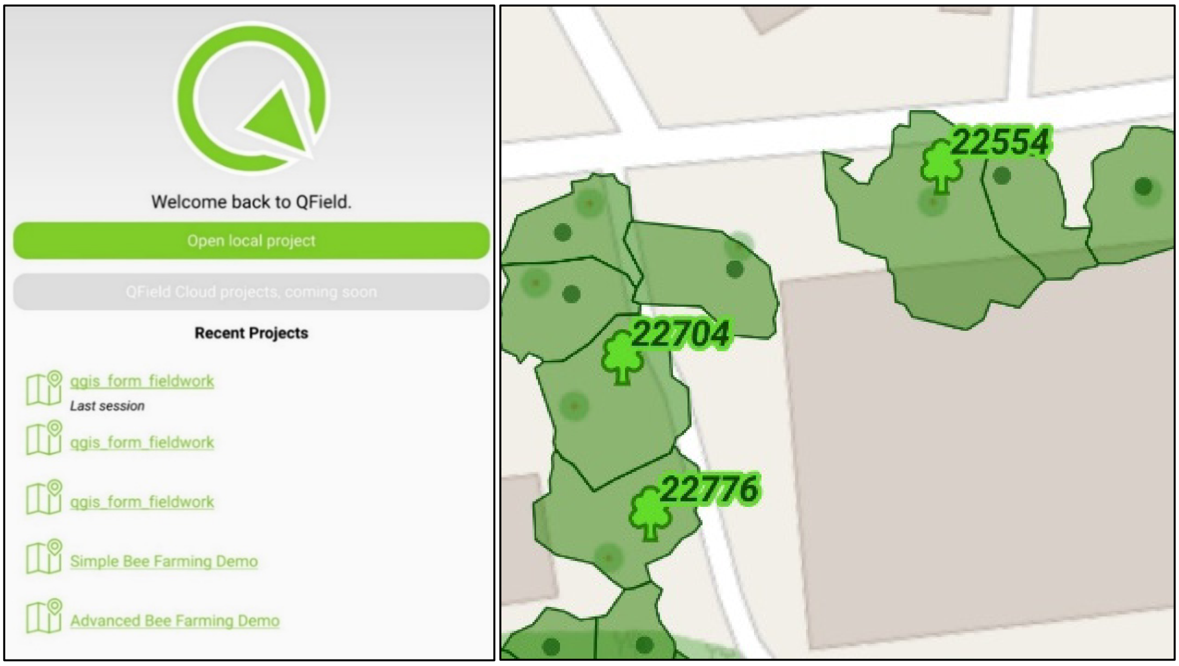


Figure 7 *Main menu of the QField application and a map view within it*

Figure 8 *The VAT19-i-Tree field protocol in the QField application*

The field values

Follow the protocol to record individual field variables. If some parts of the tree cannot be assessed, it is possible to leave the fields empty. However, note that some field variables can be estimated from a distance with acceptable accuracy.

In the following guide, the recording of individual tree variables is explained. Only field variables that cannot be modelled in GIS are presented. For further details on the recording of i-Tree Eco field variables, the reader is referred to the i-Tree Eco Field Guide (*i-Tree Eco Field Guide v6.0*, 2019).

If not stated otherwise, all photos in this section were obtained during the field survey.

1. General information

1.1 Tree characteristics

Validator name: The name of the validator assessing the tree.

Date: The time and date of tree assessment.

Tree ID: Unique ID of each tree. This depends on the project you are working on and can be determined in advance.

Photos of tree: Try to take one picture of the whole tree and close shots that could be used later to ask the opinion of a tree expert if you are unsure (age, injury, etc.)

Species: The species defines the price of a tree purchased in a nursery: this is crucial when discussing the replacement of a damaged/killed tree (Randrup, 2005). If you are unsure and do not have a guide on you, the free Pl@ntNet application[10] (Android, iOS) works well with a decent picture of the tree leaves, bark or flowers. If uncertainty remains, you can input only the genus.

Species code: Necessary to run the i-Tree data processing, this value is automatically filled-in for the most common species in the dynamic VAT19-i-Tree Excel spreadsheet. You can also use the official i-Tree documentation[9] to find the code for many species.

Other species: If you found a species that is not yet included in the form database, you can insert it there, with the associated i-Tree code. A list of species and species codes used in i-Tree Eco is available for download at GitHub[11].

Minimum/maximum age estimation (years): You can either guess an age based on your expertise, or use the NINA calculator developed in this study, which will give you an expected average tree age based on the circumference at breast height and species growth factors (**Figure 15**).

Calculated age (years): Calculated automatically in the dynamic VAT19-i-Tree Excel spreadsheet, this variable considers the growth factor of the species and the circumference at breast

[10] https://identify.plantnet.org/
[9] https://www.i-Treetools.org/documents/20/EcoSpeciesList_24Nov2014.pdf
[11] https://github.com/NINAnor/VAT19-i-Tree-field-protocol/raw/main/i-Tree%20Eco%20species%20list%20%2B%20codes.pdf

height. This can give you an idea of the age but does not replace the minimum/maximum age estimation from a tree expert.

Life expectancy (years): Life expectancy estimates are automatically calculated in the dynamic VAT19-i-Tree Excel spreadsheet for the most common species (**Appendix 1**). This is the life expectancy of a tree in an urban context, thus lower than the life expectancy in a forest. The default value is 184.

***Figure 9** The tree age calculator. Picture by suju on Pixabay.com*

1.2 Tree dimensions

Circumference at breast height (CBH) (cm): You can measure CBH with a CBH/DBH tape (DBH is the diameter at breast height). The different cases of CBH/DBH measurement are illustrated in **Figure 16**.

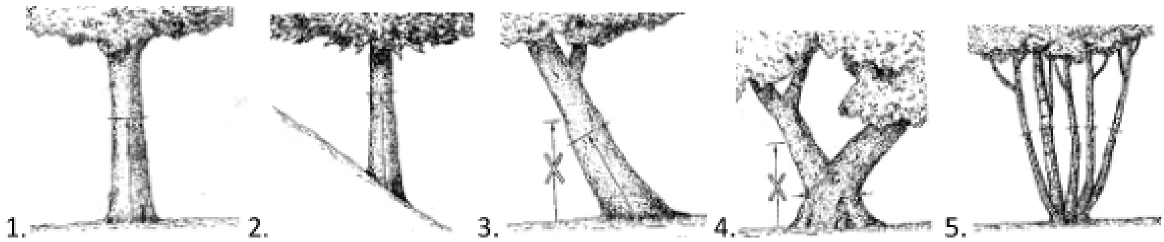


***Figure 10** Illustration of stem circumference measurements for different cases* (Randrup et al., 2003). *1. CBH measured at 1 meter above the ground, 2.CBH measured at 1 meter above the ground, measured from the middle of the stem, 3. CBH measured at 1 meter up along the stem, not at the actual 1m height, 4. CBH measured below the division point, 5. CBH measured at 1-meter height for each stem, total CBH being the sum of all stems.*

Figure 11 *Coppiced or may stemmed growth forms. Do not record the CBH, as there are too many stems. If many coppiced trees at the same place are forming a crown together, you should record the crown health and location variables as you would do for a lone tree.*

CBH estimation distance (m; 0 if at tree): To record for inaccessible trees only. This variable is not part of the modelling. When you cannot measure a CBH and have to make a guess, write the estimated distance between the tree and you. The closest is the best (**Appendix 9**). This value is 0 if you can measure the CBH at the tree.

Height (m): You can either use a hypsometer or a Vertex device to measure tree height. GIS data can also be used to estimate tree height.

Height to live top (m): This means the highest alive point on the tree. Height to live top is equal to tree height if the tree does not suffer from top dieback.

Height to crown base (m): This means the height between the ground and the first leaves belonging to the crown (not the epicormics). This value is 0 if the crown (even just a part of it) reaches the ground.

Crown missing (%): This represents the crown volume not occupied by branches and leaves (pruning, dieback, defoliation, uneven crown, sparse leaves). You should consider the natural crown shape for the tree species and compare the actual tree crown to the tree silhouette of a healthy tree in excellent condition. You can find a longer description of this variable on page 31 of the i-Tree Eco Field Guide (*i-Tree Eco Field Guide v6.0*, 2019) (**Figure 18**).

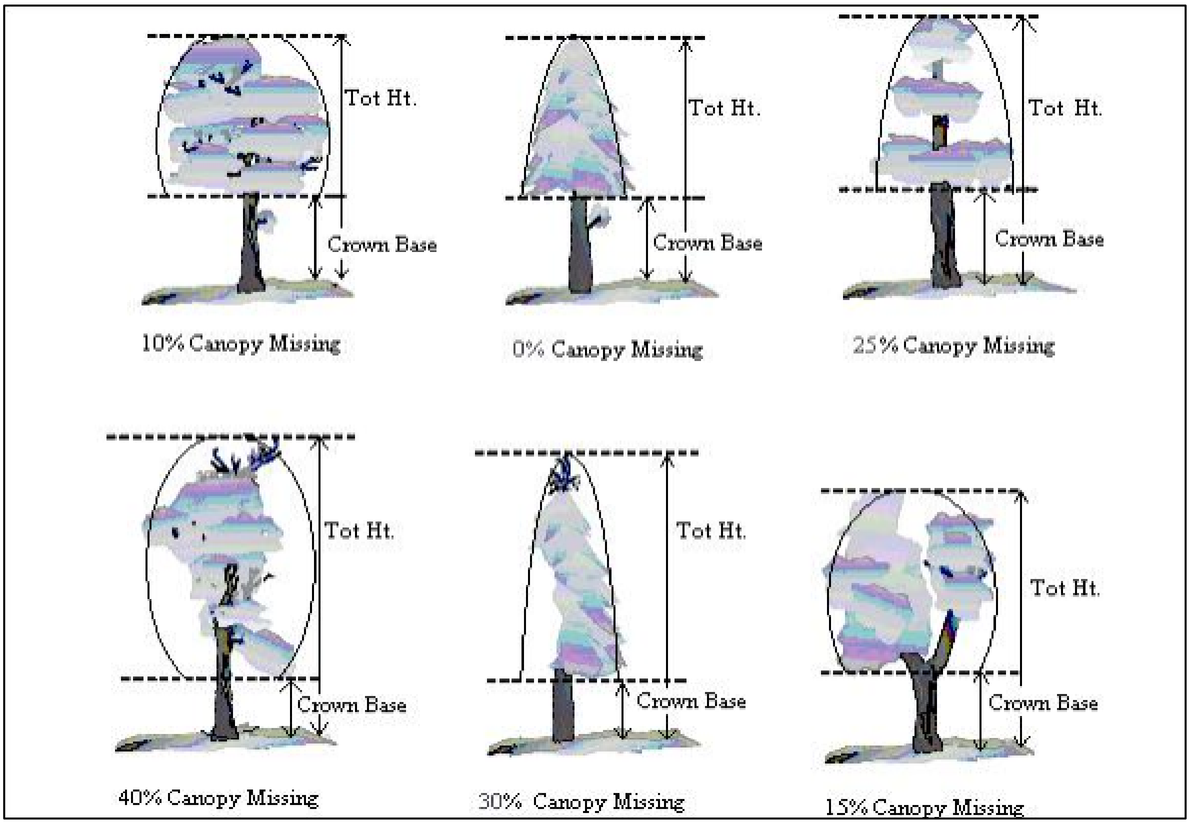


Figure 12 *How to estimate the percentage of crown missing* (*i-Tree Eco Field Guide v6.0*, 2019)

Figure 13 *Examples of heavily pruned trees. For heavily pruned trees, try to imagine the winter crown size to estimate the missing crown. For trees shaped as an arch, a square or to let a bus pass, compare with the growth form you think the tree would have in natural conditions.*

1.3 Tree location

Street tree (no/yes): Is the tree located in a street/avenue?

Figure 14 *Examples of street trees*

Stem on property type (public/private): Regardless of the crown, try to estimate if the tree stem is planted on public or private property. This variable can serve accounting and legal purposes. Modelled with GIS and verified on the ground, it could allow to clearly identify the ownership of a tree.

Access limitation (no/yes): Is there any obstacle preventing you from approaching the tree and making close 360° assessments of it? Easy to record, this variable will guide future users towards the more accessible trees.

Figure 15 *Examples of access limitation*

Stem location (road, parking, pavement, unpaved): What is the land cover of the immediate surroundings of the stem? You can leave this field empty if it is not possible to record this variable due to bad visibility.

Figure 16 *Examples of stems located on unpaved grounds and pavement*

Figure 17 *Example of a stem located near a road. Picture by [pilostic] on [Pixabay.com]*

Stem protection (no/yes): Is there any metal grid, wooden fence, rubber band on the stem to protect it from injuries? This can indicate supplementary costs to tree plantation.

Figure 18 *Examples of stem protection*

2. Health factor

2.1 Roots

Compaction (load, pavement, trampling zones) over root extent (%): This covers load, trampling zones and pavement over root extent when considering that roots cover the same surface as the crown.

Figure 19 *Examples of compaction over the root extent. The roots are limited in four directions: there are 100 % and > 90 % of compaction over the root extent, respectively. Picture 1 ("Tree v concrete") by Ruben Schade on www.flickr.com (CC BY-SA)*

Limitation of root formation (number of directions): Try to visualize the crown surface area on the ground. If the root formation (virtually equal to the ground projection of the crown surface) is limited, in how many directions? Limitations can be pavement, a wall, a hole, etc. We agreed that roots were not limited by other roots (competition).

Figure 20 *Examples of limitation of root formation*

2.2 Stem/main branches

Rot/fungi on stem/main branches (no/yes): Is there any rot or fungi, regardless of size, on the stem and/or main branches? This often results after an injury, damage or cut.

Figure 21 *Example of rot/fungi on a stem. Fungi or rot can often grow on open cuts.*

Figure 22 *Examples of lichen colouration. Be careful, lichen can look like rot or fungi but is not.*

Figure 23 *Examples of rot/fungi on main branches. Although quite rare, mushrooms should weight in the Stem/main branches score.*

Injury on stem/main branches (no/yes): Is there any injury, regardless of its size? To be recorded, an injury must be recent enough not to be counted as a scar.

Figure 24 *Examples of injury on stem/main branches. Injuries need to be recorded regardless of their size. Picture 2 by pisauikan on Pixabay.com*

Figure 25 *Examples of scars. Scars can have very different shapes and are not to be taken into account in the Stem/main branches score. Sometimes, old wounds are turned into a huge vein-like scar: this is a sign of vitality.*

Figure 26 *Included bark is also a sign of vitality, not an injury nor a scar.*

Cut on stem/main branches (no/yes): Is there any cut, regardless of its size, on the stem and/or main branches? To be recorded, an injury must be recent enough not to be a scar.

Figure 27 *Examples of cuts on stem/main branches.*

Figure 28 *Examples of cuts on stem/main branches. Most of the higher stem of this tree and all of its branches have been cut down and cuts left unsealed. Although not dead, this tree will likely get a very low Stem/main branches score.*

2.3 Crown

Dieback (%): Regarding the whole crown, record the percentage of dead branches and leaves. This includes competition between close trees and between the different tree levels (also lower branches dieback).

Figure 29 *Examples of dieback*

Figure 30 *Example of dieback*

Injury to leaves/twigs/buds (no/yes): Are there any injuries on the leaves, twigs or buds? This includes parasite damage and heavy gall cases.

Figure 31 *Example of a gall case. Some Tilia cordata leaves are impacted by the lime nail gall caused by a mite (Eriophyes tiliae). It should be counted as "Injury to leaves", but the effect on tree health is barely existent. However, a possible extreme case could lower the Aesthetics score. Picture ("Galls on a linden leaf") by stanzilla on Wikimedia Commons (CC BY-SA).*

Figure 32 *Examples of injury to leaves. Denser patches of leaves are the result of a parasite. They lower the Crown score but elevate the Conservation value score (since the parasite itself is one more species).*

3. Location factor

3.1 Ecological adaptation

Pervious cover under tree (%): How much of the projection of the crown surface on the ground is pervious? This includes grass, dirt, pebbles, shrubs, and other trees.

Figure 33 *Examples of pervious cover under a tree. Pebbles over dirt as considered as pervious ground.*

3.2 Supporting habitat and conservation value

CBH > 250 cm (no/yes): Automatically calculated in the dynamic VAT19-i-Tree Excel spreadsheet when CBH is recorded.

Tree > 170-year-old (no/yes): Automatically calculated in the dynamic VAT19-i-Tree Excel spreadsheet when the age is recorded.

Cracked bark: > 3 cm deep at breast height (no/yes): Is the bark more than 3 cm deep at breast height? This would indicate a lot of substrate for arthropods and lichen species.

Figure 34 *Examples of cracked bark*

Crooked, split stem, surface for substrate accumulation (no/yes): Is there any surface on the tree that is large or horizontal enough for a significant amount of substrate to accumulate on?

Hollows, cracks, nests, nesting holes, bird boxes (no/yes): Is there any hollowness of the stem to attest the presence of birds, bats or arthropods living on the tree? Do you see any birdboxes or nests?

Figure 35 *Examples of hollowness on stem. Picture 2 by Inklined on Pixabay.com*

Figure 36 *Examples of hollowness on a stem. Spider nests in little cracks are relevant for this variable if they are found more than once on the tree or if their size is significant.*

Stem > 50 % covered by moss/lichen (no/yes): Is the stem (from the base to the highest point) covered by 50 % or more in moss and/or lichen?

Figure 37 *Examples of stem covered in moss*

3.3 Architecture

Tree demarcating road/property (no/yes): Is the tree demarcating any road or property?

Figure 38 *Examples of trees demarcating road or property*

Tree maintained for landscape architecture (no/yes): Is the tree maintained for landscape architecture? Would its removal take away some of the consistency of the place? Pruned *Tilia* trees have a high value in this regard.

Figure 39 *Examples of trees maintained for landscape architecture*

Figure 40 *Examples of trees maintained for landscape architecture. Picture 2 by MabelAmber on Pixabay.com*

3.4 Aesthetics

Impressive because of height (no/yes): Does the tree look genuinely impressive because of its height? Is it taller than the average?

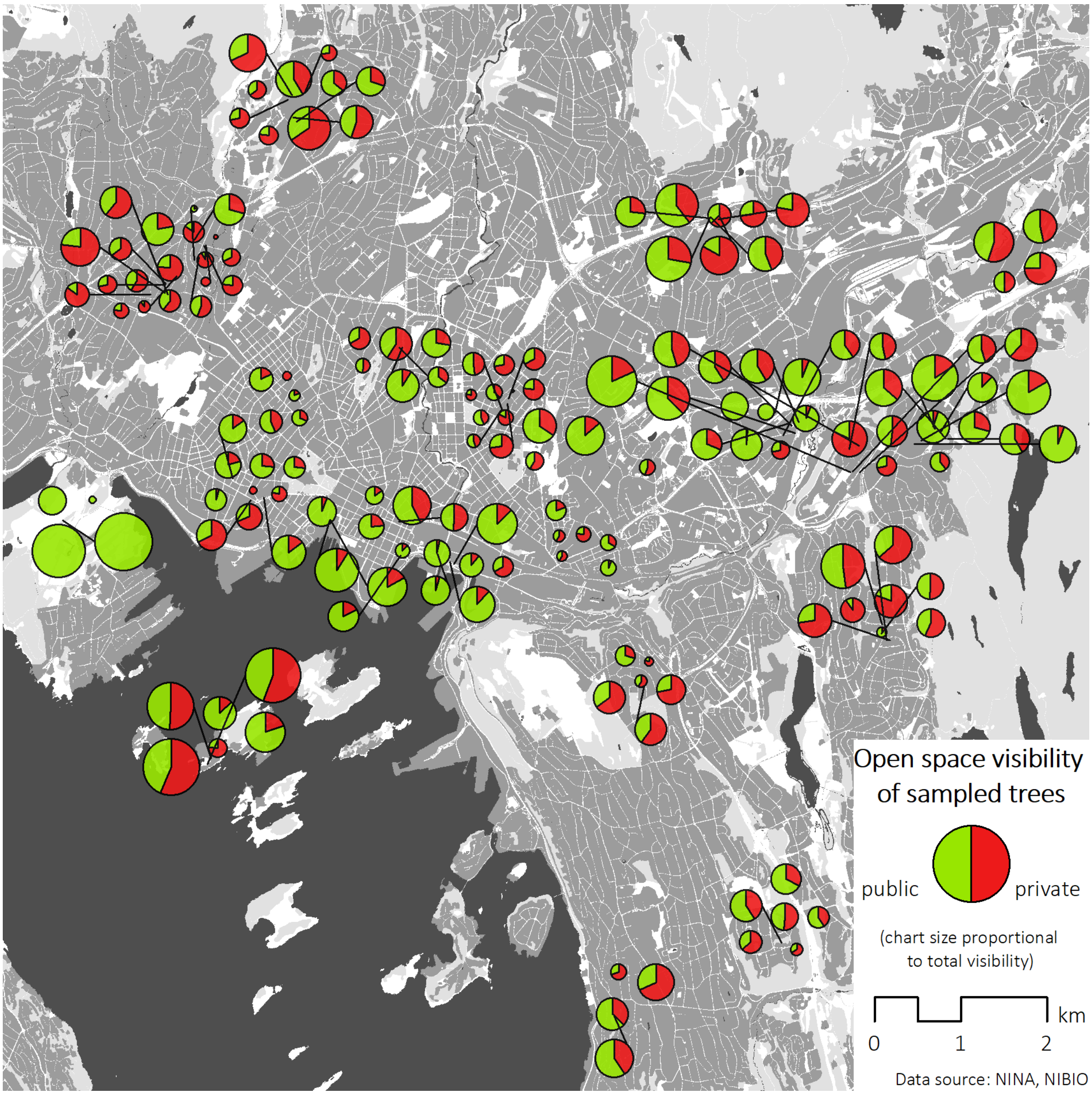
Unhealthy appearance (no/yes): Can a passer-by determine that the tree health is not optimal? This includes dieback, diseases, parasites, drought and physical damage.

Tree part of an aesthetic group of trees (no/yes): Is the tree part of an aesthetic tree group/formation?

Figure 41 *Examples of a tree being part of an aesthetic tree group/formation*

Appendix 5: Distribution of tree public and private visibility

This appendix provides a map of the spatial distribution of the values of tree public and private visibility.



Appendix 6: Correlation tests between field variables and scores

In this appendix, the results of the correlation tests between individual field variables and scores are provided.

The correlations of field variables recorded on ratio, interval and ordinal scale were assessed using a non-parametric Spearman's test. Each correlation test was conducted on a limited variable set to avoid discovering correlations between knowingly unrelated field variables. The correlation coefficient returned by Spearman's test varies between -1 to 1, where 1 indicates a perfect positive correlation, -1 a perfect negative correlation and 0 no correlation of the variables.

The correlations of the only two categorical variables recorded on a nominal scale (Genus and Seedling type) were assessed using a Kruskal-Wallis test since the data do not follow the assumptions (normality and variance homoscedasticity) necessary to run analyses of variance, normally used to assess the correlation of variables recorded on a nominal scale. To analyse the correlation of genus, we retained the seven most represented genera, which resulted in 104 observations shared between *Betula*, *Pinus*, *Acer*, *Tilia*, *Prunus*, *Ulmus* and *Aesculus*. Assessing the correlations of remaining genera is not meaningful as these genera are represented by too few observations, sometimes only one. If the Kruskal-Wallis test showed no independence between the two assessed variables, we then calculated their correlation relationship using the eta^2 value. Ranging from 0 to 1, the eta^2 value shows the amount of variation explained by the predictor variable in the total variation of the outcome variable (Adams and Conway, 2014). We considered eta^2 values as weak when below 0.04, moderate between 0.04 and 0.16, and strong above 0.16 (Corroyer, 2013). We retained Genus (important for inventory purposes and correlated to the Root, Stem/main branches, Conservation value, Architecture and Aesthetics scores) and left out Seedling type (correlated only to Root and Architecture scores, and sometimes difficult to estimate).

The following notation is used to report the significance of the correlation: p-value < 0.001: ***, p-value < 0.01: **, p-value < 0.05: *. Only the most significant correlations (p-value < 0.001) are visualised in the figures below and retained for our merged protocol.

The following R (R Core Team, 2018) packages were used to conduct the statistical analysis:

- **BioStatR** (Bertrand & Maumy-Bertrand, 2019),
- **Hmisc** (Harrell et al., 2020),
- **formattable** (Ren & Russell, 2016),
- **corrplot** (Wei & Simko, 2017).

1. Health Factor

1.1 Root score

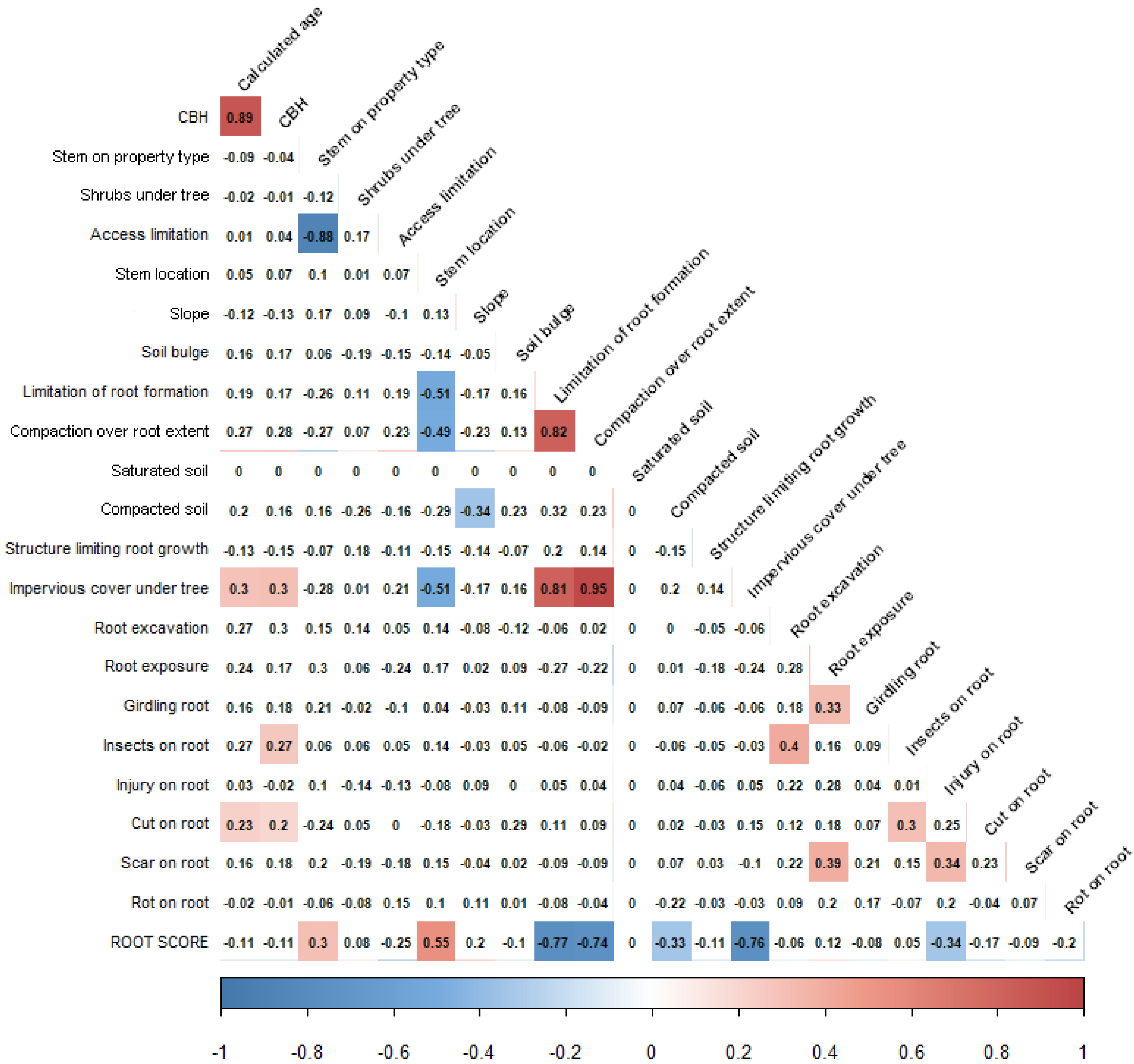


***Figure 42** Correlation of the recorded field variables to the Root score*

Kruskal-Wallis and eta² tests results:

Root score to Genus (7 genera): We could reject the hypothesis that the variables were independent (p-value = 0.017*), and their correlation was strong (eta² = 0.22).

Root score to Seedling type (Self-seeded, planted): We could reject the hypothesis that the two variables were independent (p-value < 0.001***), and their correlation was strong (eta² = 0.21).

1.2 Stem/main branches score

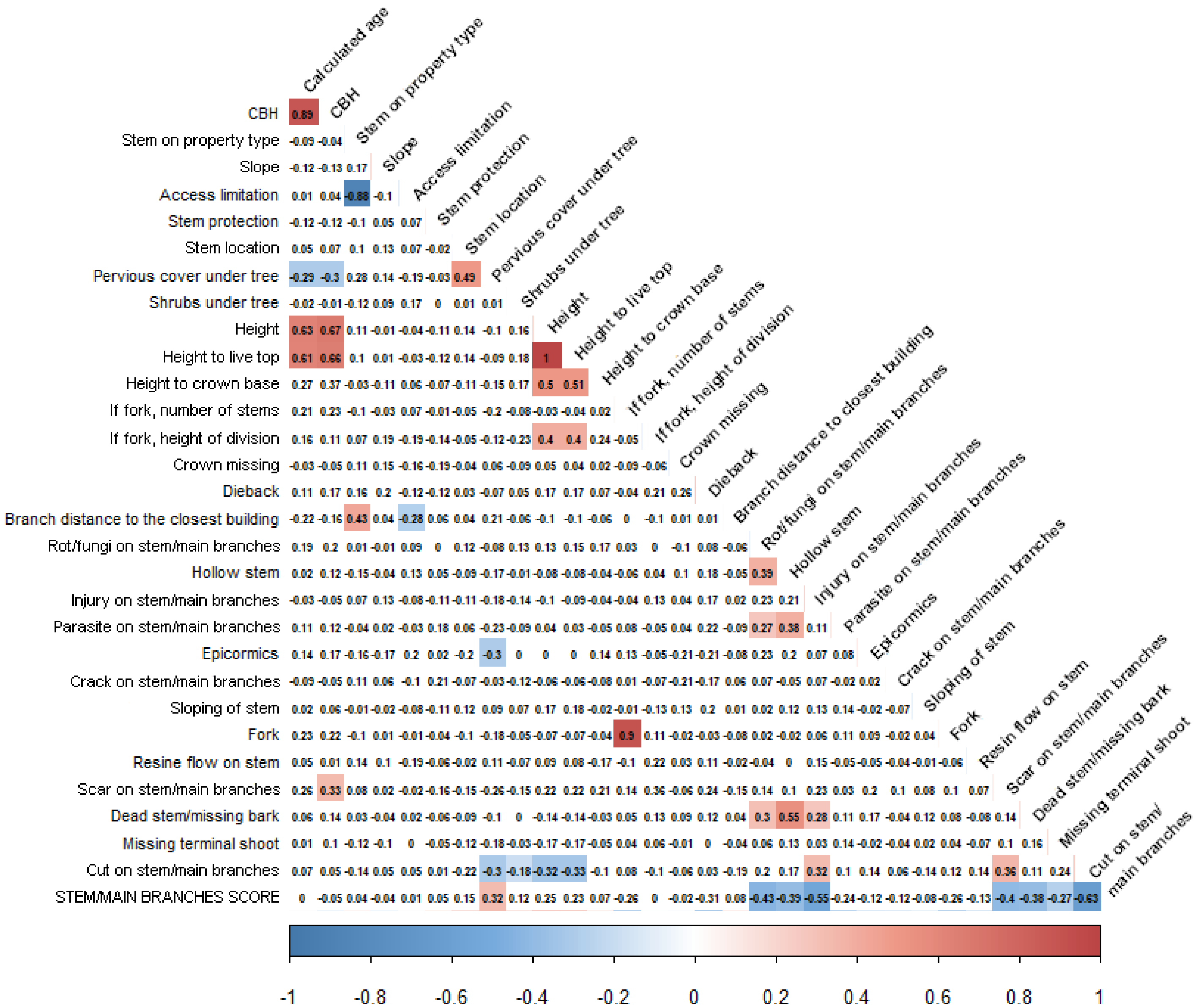


Figure 43 *Correlation of the recorded field variables to the Stem/main branches score*

Kruskal-Wallis and eta² tests results:

Stem/main branches score to Genus (7 genera): We could barely reject the hypothesis that the two variables were independent (p-value = 0.049*), and their correlation was moderate (eta² = 0.15).

Stem/main branches score to Seedling type (Self-seeded, planted): We could barely reject the hypothesis that the two variables were independent (p-value = 0.04*) but their correlation was weak (eta² = 0.036).

1.3 Crown score

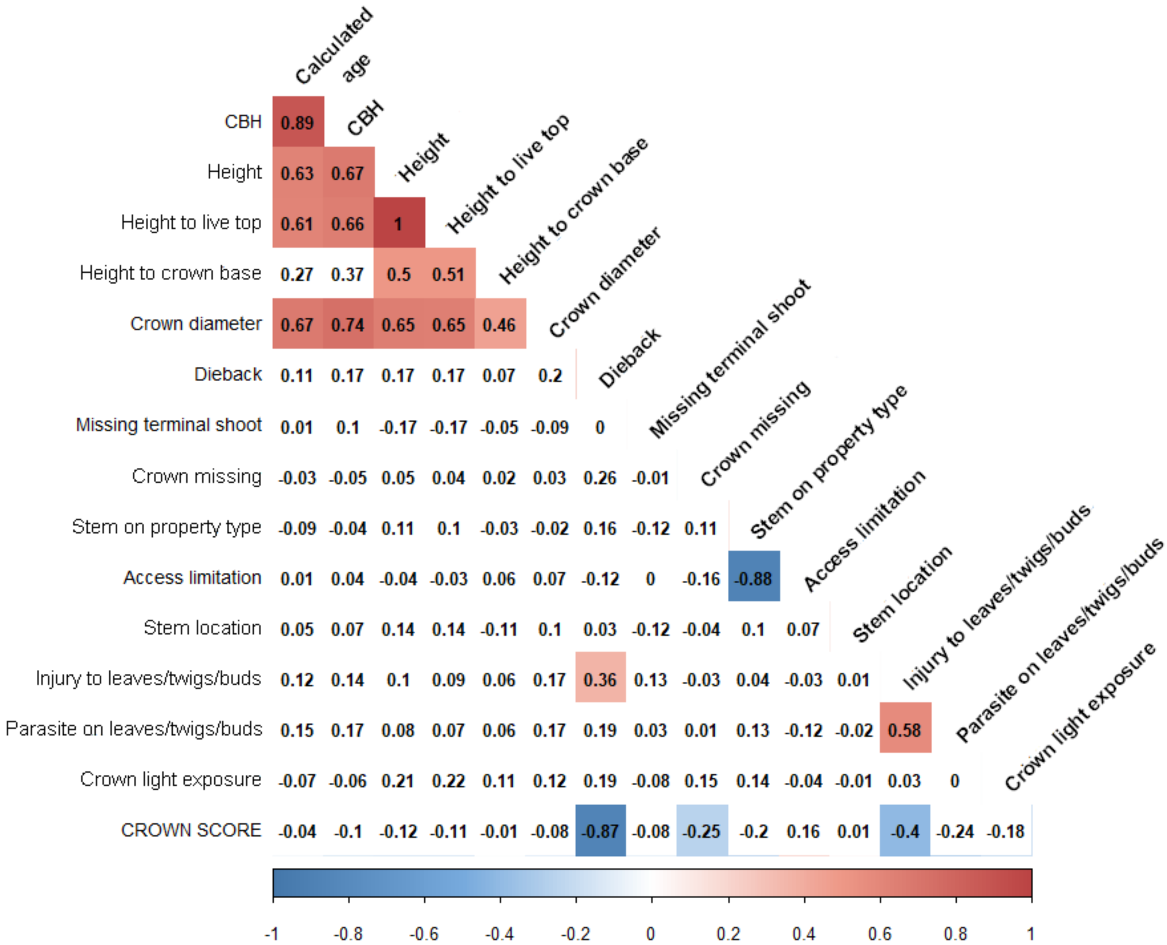


***Figure 44** Correlation of the recorded field variables to the Crown score*

Kruskal-Wallis and eta² tests results:

Crown score to Genus (7 genera): We could reject the hypothesis that the two variables were independent (p-value = 0.004**), and their correlation was strong (eta² = 0.2).

Crown score to Seedling type (Self-seeded, planted): We could not reject the hypothesis that the two variables were independent (p-value = 0.67).

2. Location factor

2.1 Ecological adaptation score

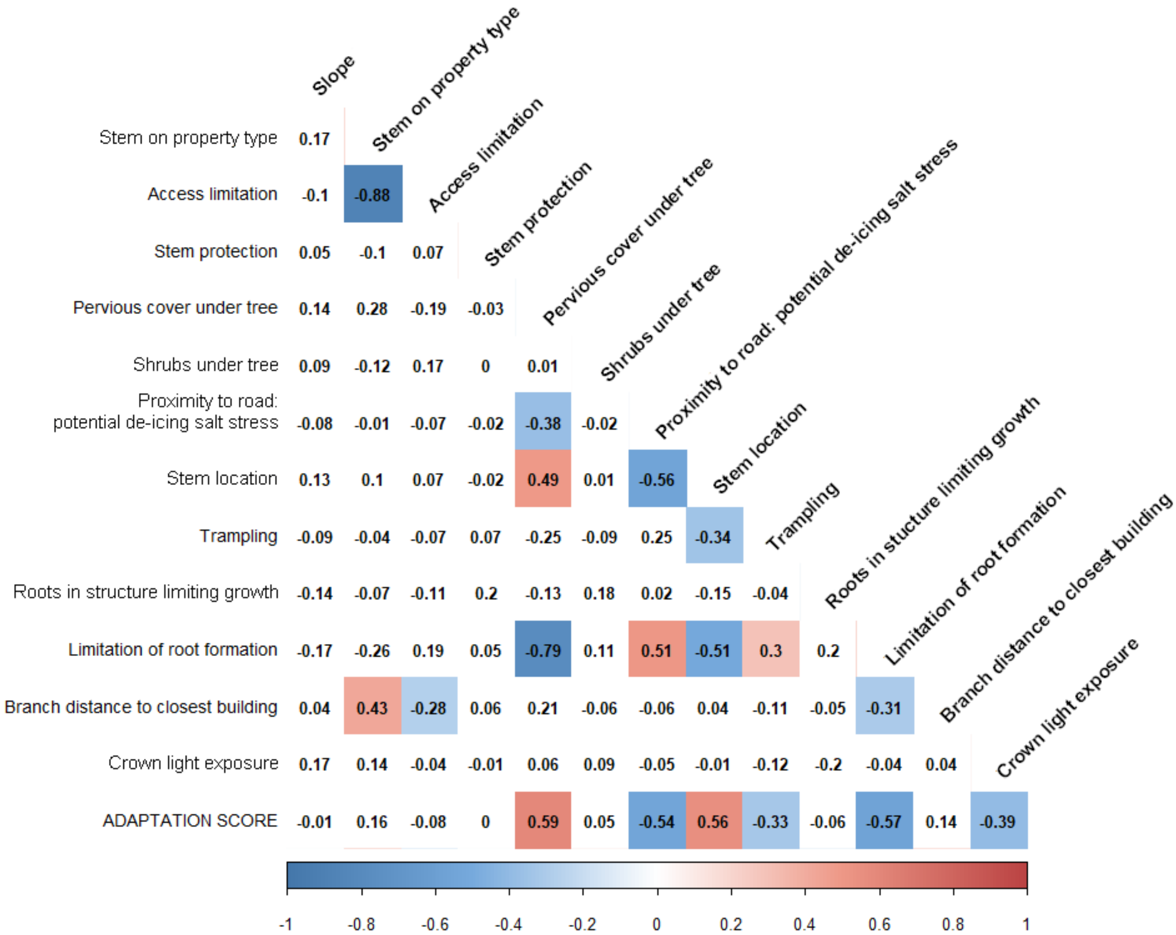


Figure 45 *Correlation of the recorded field variables to the Ecological adaptation score*

Kruskal-Wallis and eta² tests results:

Ecological adaptation score to Genus (7 genera): We could not reject the hypothesis that the two variables were independent (p-value = 0.07).

Ecological adaptation score to Seedling type (Self-seeded, planted): We could not reject the hypothesis that the two variables were independent (p-value = 0.46).

2.2 Support for habitat and conservation value score

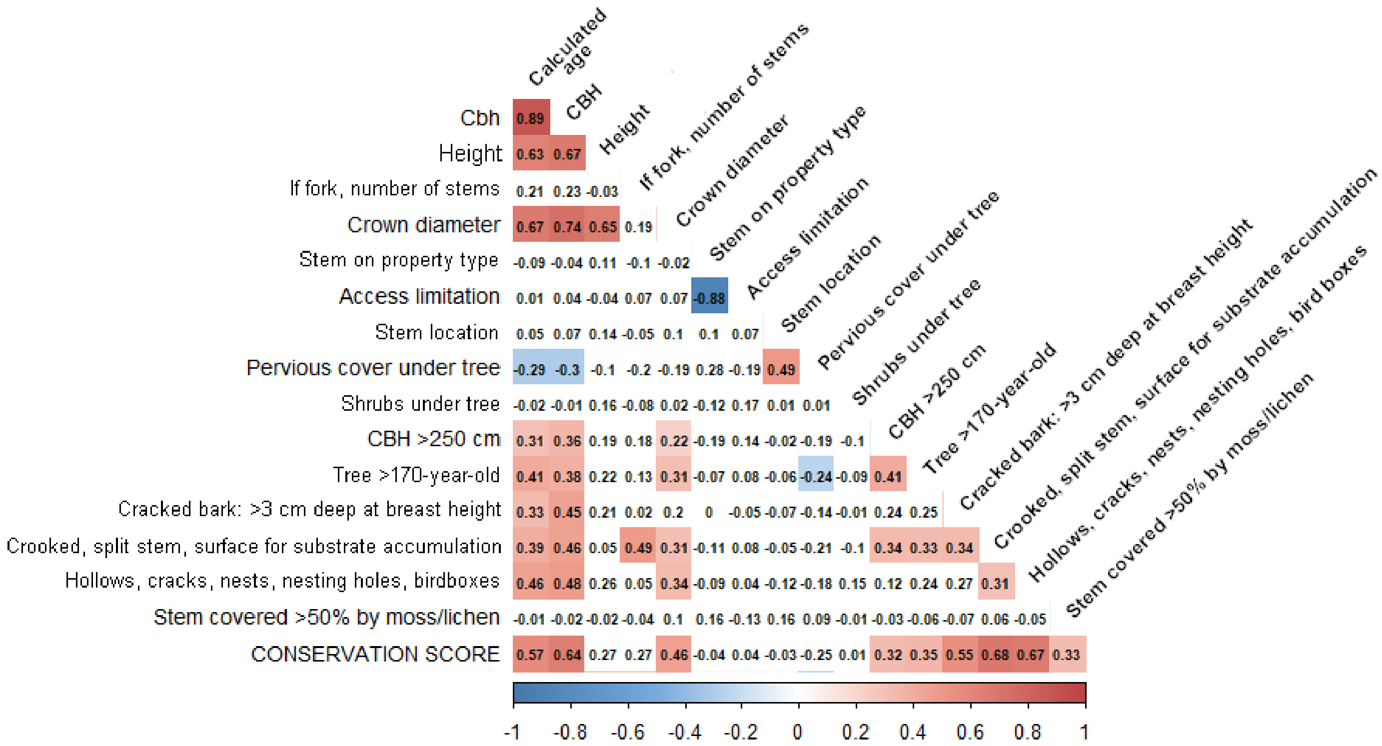


Figure 46 *Correlation of the recorded field variables to the Conservation value score*

Kruskal-Wallis and eta² tests results:

Conservation value score to Genus (7 genera): We could reject the hypothesis that the two variables were independent (p-value = 0.011*), and their correlation was strong (eta² = 0.19).

Conservation value score to Seedling type (Self-seeded, planted): We could not reject the hypothesis that the two variables were independent (p-value = 0.29).

2.3 Architecture score

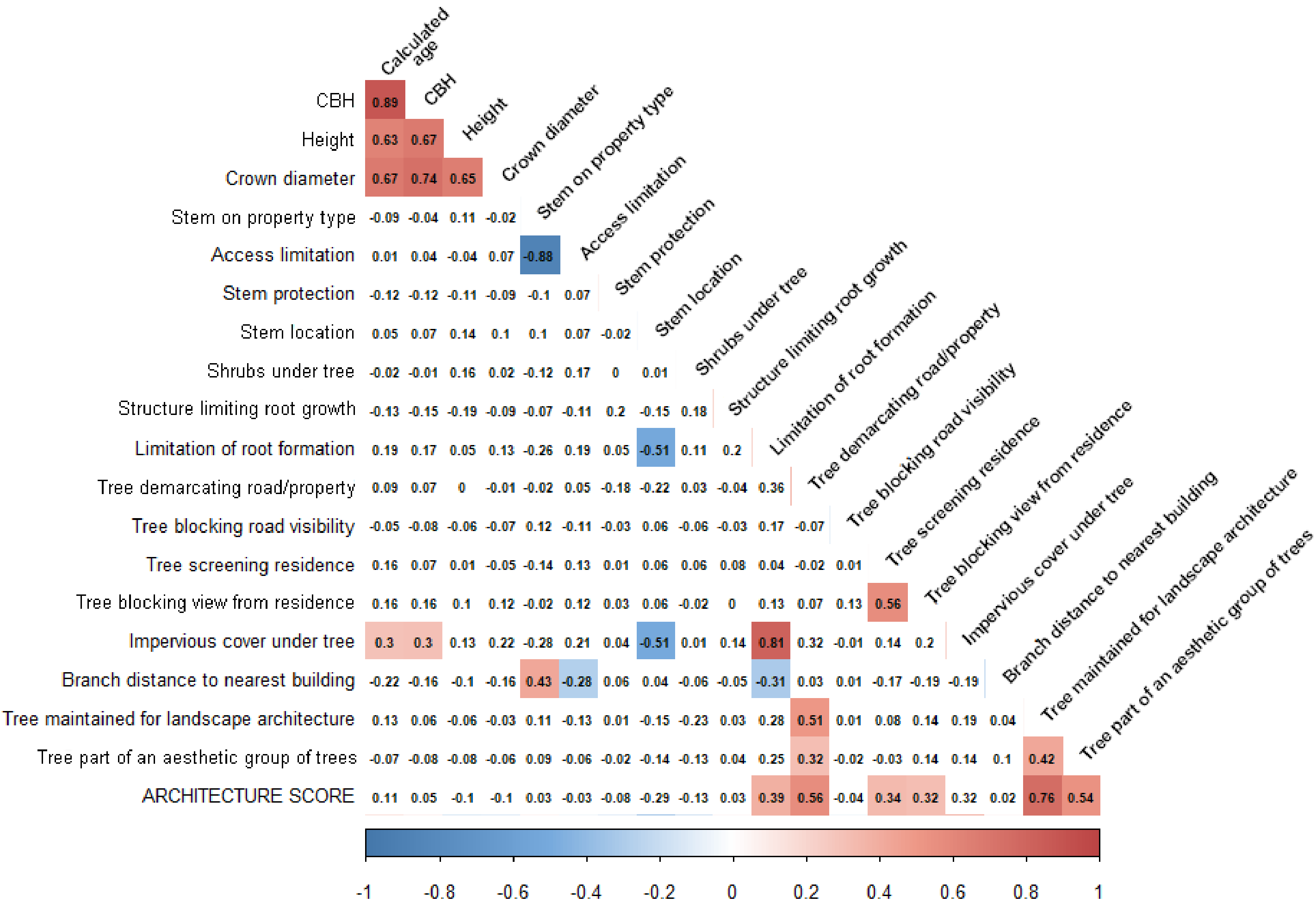


Figure 47 *Correlation of the recorded field variables to the Architecture score*

Kruskal-Wallis and eta² tests results:

Architecture score to Genus (7 genera): We could reject the hypothesis that the two variables were independent (p-value = 0.0011**), and their correlation was strong (eta² = 0.22).

Architecture score to Seedling type (Self-seeded, planted): We could not reject the hypothesis that the two variables were independent (p-value < 0.001***), and their correlation was strong (eta² = 0.37).

2.4 Aesthetics score

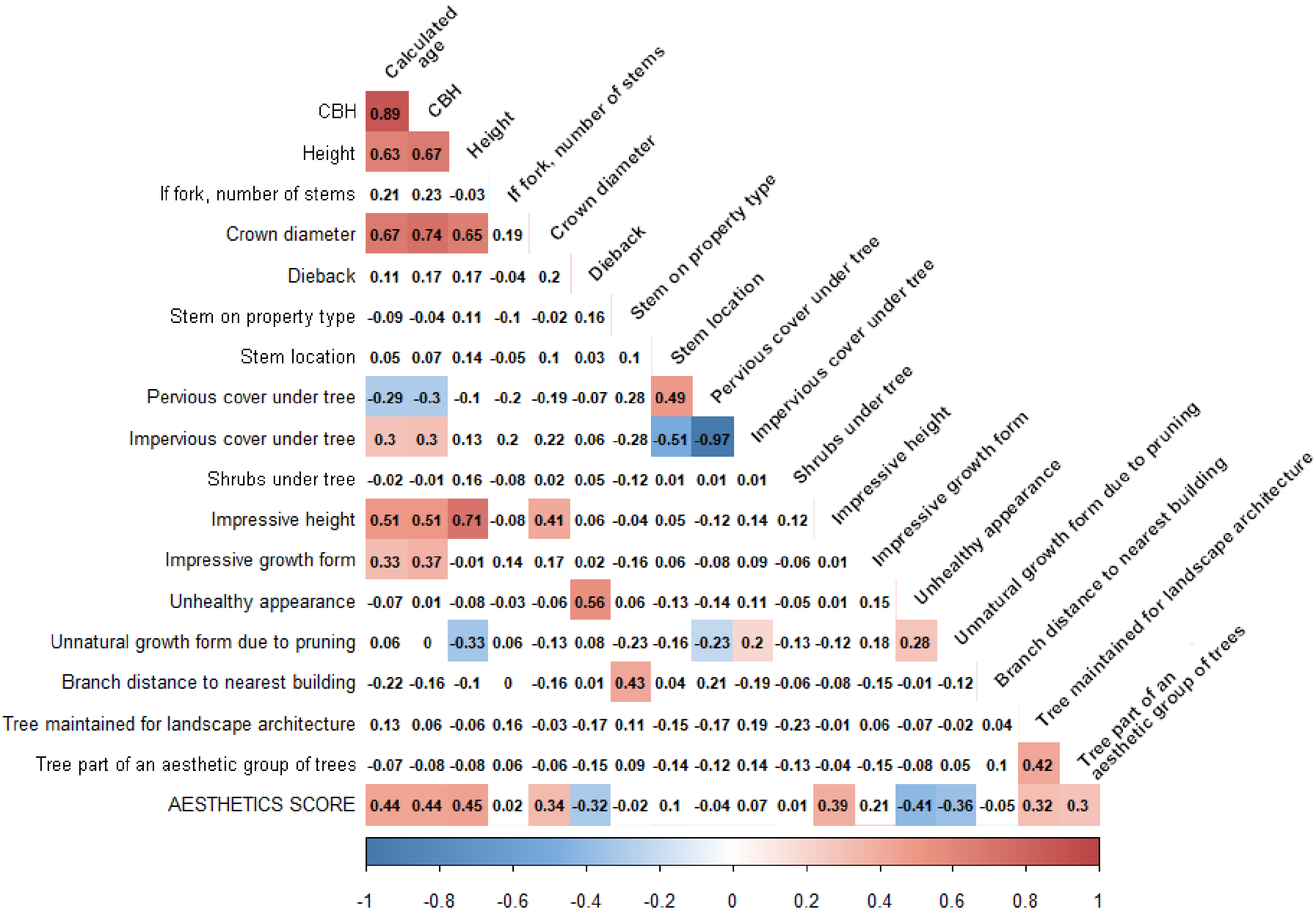


Figure 48 *Correlation of the recorded field variables to the Aesthetics score*

Kruskal-Wallis and eta² tests results:

Aesthetics score to Genus (7 genera): We could reject the hypothesis that the two variables were independent (p-value = 0.0013**), and their correlation was strong (eta² = 0.22).

Aesthetics score to Seedling type (Self-seeded, planted): We could not reject the hypothesis that the two variables were independent (p-value = 0.4).

2.5 Visibility score

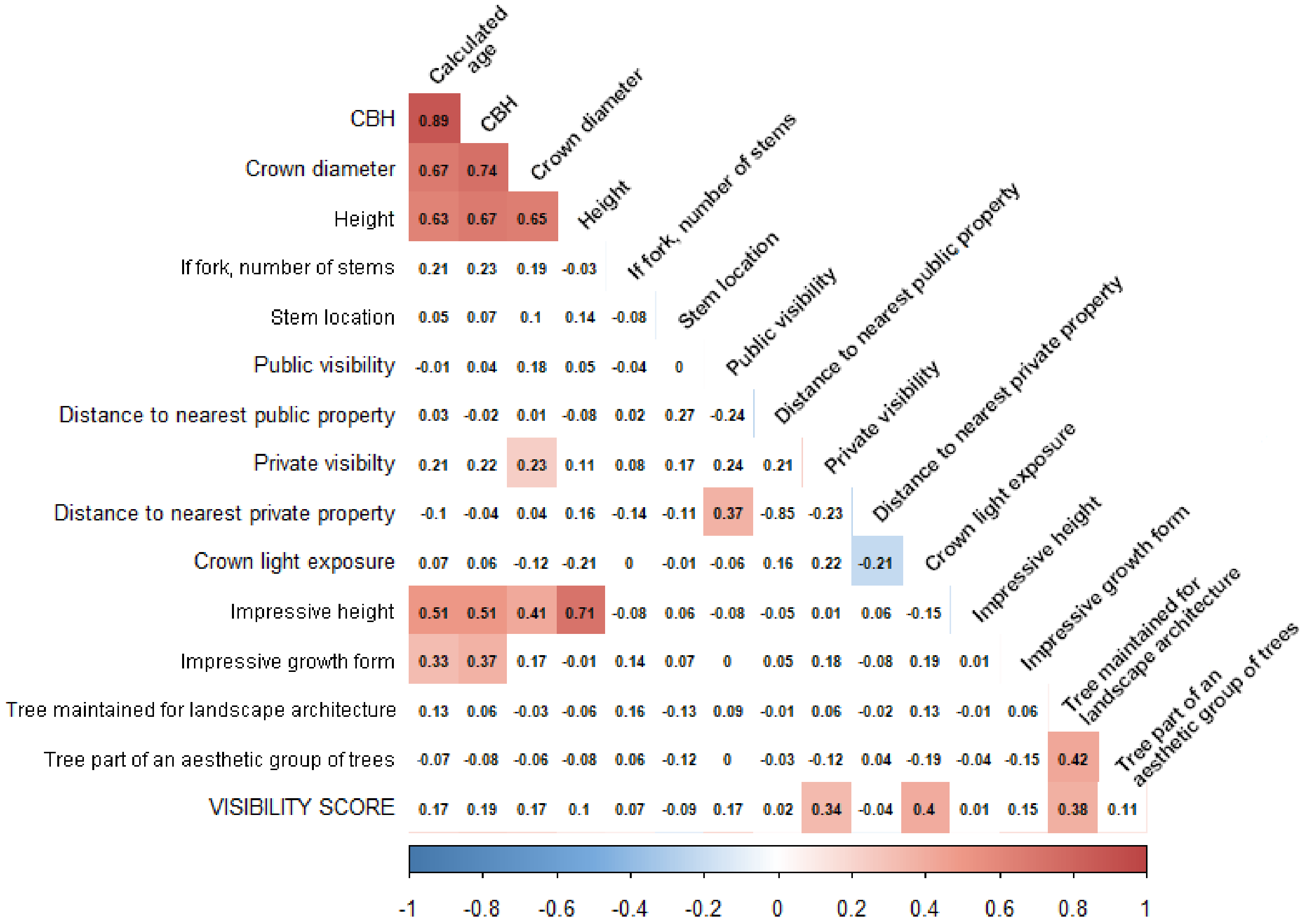


Figure 49 *Correlation of the recorded and GIS-modelled field variables to the Visibility score*

Kruskal-Wallis and eta² tests results:

Visibility score to Genus (7 genera): We could not reject the hypothesis that the two variables were independent (p-value = 0.77).

Visibility score to Seedling type (Self-seeded, planted): We could reject the hypothesis that the two variables were independent (p-value = 0.002**), but their correlation was moderate (eta² = 0.09).

Appendix 7: Field variables excluded from the VAT19-i-Tree field protocol

Table 7 summarises the variables that were recorded in the field survey but excluded from the final VAT19-i-Tee protocol. For each variable, the reason why it was excluded is provided. Following reasons were used: the need for excellent visibility, not significant, redundant, time-consuming to record or too prone to subjectivity and too rare.

Table 7 *Field variables recorded in the field survey but excluded from the VAT19-i-Tree field protocol. Abbreviations: NE: Need excellent visibility; NS: Not significant; R: Redundant; T: Time-consuming, or too prone to subjectivity; TR: Too rare*

Variable	NE	NS	R	T	TR	Note
Dead tree					✓	*This situation is very unlikely for a city tree (removed if dead). None of the trees assessed during the field survey was dead.*
Seedling type		✓		✓		*Most of the time, trees growing in parks, streets and gardens are planted. However, sometimes the validator stumbles upon a tree that may have been self-seeded but was kept and taken care of like a planted tree.*
Slope		✓		✓		*The slope is sometimes difficult to determine at the ground level.*
Roots in structure limiting growth			✓			*Redundant with “Compaction over root extent”.*
Root excavation	✓	✓			✓	
Root exposure	✓	✓				
Soil bulge		✓			✓	
Rot on root	✓	✓				
Girdling root	✓	✓				
Insects on root	✓	✓			✓	*Insects living on roots can be obvious or barely noticeable, as well as moving during different hours of the day.*
Injury on root	✓					
Cut on root	✓	✓				
Scar on root	✓	✓				*Scars are indicating neither bad nor good health, but a past trauma, which the tree was healthy enough to overcome.*
Compacted soil				✓		
Saturated soil					✓	
Hollow stem	✓				✓	
Parasite on stem/main branches		✓			✓	
Epicormics		✓			✓	*Not always a health concern, more present in some species than others.*
Crack on stem/main branches		✓			✓	
Sloping position of stem		✓			✓	*Unless extreme cases, not a big health concern.*

***Table 7 (cont.)** Field variables recorded in the field survey but excluded from the VAT19-i-Tree field protocol (continuation). Abbreviations: NE: Need excellent visibility; NS: Not significant; R: Redundant; T: Time-consuming, or too prone to subjectivity; TR: Too rare*

Variable	NE	NS	R	T	TR	Note
Fork		✓				
If fork, number of stems		✓				*Not always an indication of structural weakness if the tree is well balanced. Time-consuming to record when the tree has been driven to grow in a coppice.*
If fork, height of division		✓		✓		*Recording another height is a time-consuming process*
Resin flow on stem	✓		✓		✓	*Redundant with "Injury to stem/main branches"*
Scar on stem/main branches						*Scars are indicating neither bad nor good health, but a past trauma, which the tree was healthy enough to overcome.*
Dead stem/missing bark			✓		✓	*Redundant with "Rot/fungi" and "Injury on stem/main branches".*
Missing terminal shoot					✓	*Very rare since city trees are normally managed to avoid such injury.*
Parasite on leaves/twigs/buds			✓		✓	*Redundant with "Dieback" and "Injury to leaves/twigs/buds".*
Proximity to road; potential de-icing salt stress				✓		*Besides the soil parameters, de-icing salt is the main challenge for tree life in urban areas of Norway* (Pauleit et al., 2002)*. However, this variable relied on a guess since the assessments were made on warm sunny days.*
Trampling	✓			✓		
Shrubs under tree			✓	✓		*Redundant with "Pervious cover under tree".*
Site clearing		✓			✓	
Changed hydrology		✓			✓	
Tree blocking road visibility		✓		✓	✓	*Unlikely for a city tree (such case would quickly get taken care of).*
Tree screening residence				✓		*Time-consuming and potentially too subjective interpretation for different users.*
Tree blocking view from residence				✓		*Time-consuming and potentially too subjective interpretation for different users. This is however a major indicator of a disservice by the tree. Because of this importance, this variable could be calculated in further research using GIS modelling of viewsheds.*
Branch distance to closest building	✓	✓		✓		*Instead of recording in the field survey, this variable will now be modelled in GIS according to the i-Tree Eco Field Guide.*
Impressive growth form		✓	✓			*Growth form is open to many subjective interpretations.*
Unnatural growth form due to pruning				✓		*Pruning can be done to various extents, and validators can have a different threshold in mind for what is considered an unnatural growth form.*

Appendix 8: Most common tree species used in paved areas in Norway

Table 8 *The most common tree species used in paved areas in Norway in 2000 (*Pauleit et al. (2002)*, personal communication)*

Tree species	**% of planted street trees**
Tilia x europaea L.	40 – 70
Acer platanoides L.	7 – 10
Aesculus hippocastanum L.	5 – 10
Sorbus spp	4 – 15
Betula pendula Roth and *B. pubescens* Ehrh.	3 – 50
Populus spp	1 – 50

Appendix 9: Accuracy of estimating circumference at breast height from distance

Some trees had to be assessed from a distance (publicly visible trees on private land or physically inaccessible stem location). Therefore, we tested how the accuracy of stem circumference distant estimation varies with increasing distance from a tree. **Figure 56** shows that the further the validator was from the tree, the bigger was his error margin for the stem circumference estimation.

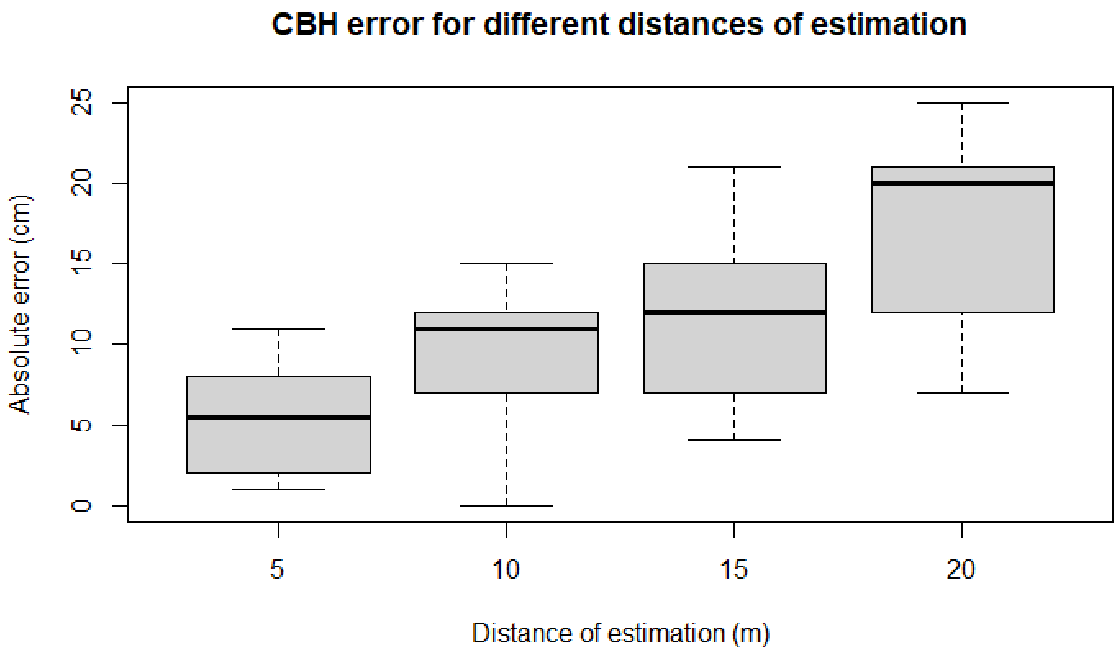


Figure 50 *Error of estimation of circumference at breast height with increasing distance from the tree*

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Norwegian Institute for Nature Research
NINA head office
Postal address: P.O. Box 5685 Sluppen, NO-7485 Trondheim, NORWAY
Visiting address: Høgskoleringen 9, 7034 Trondheim
Phone: +47 73 80 14 00
E-mail: firmapost@nina.no
Organization Number: 9500 37 687
http://www.nina.no

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