Value ‘generalisation’ in ecosystem accounting - using Bayesian networks to infer the asset value of regulating services for urban trees in Oslo

David N. Barton ‡

‡ NINA - Norwegian Institute for Nature Research, Oslo, Norway

Corresponding author: David N. Barton (david.barton@nina.no)

Academic editor: Soile Oinonen

Abstract

In this paper, we demonstrate value generalisation from a sample of ecosystem assets – municipally managed trees - to all tree assets within an urban ecosystem accounting area. A Bayesian network model is used to machine-learn non-parametric correlation patterns between biophysical site condition variables and output variables of an ecosystem service model – here iTree Eco for modelling the regulating services of urban forests. The paper also demonstrates the use of spatial Bayesian network modelling to quantify the reliability of value generalisation for accounting purposes. Value generalisation entails inferring ecosystem service values for all locations in an ecosystem accounting area, where the accounting practitioner has less information about the asset and its context, than in an available sample of managed sites within the accounting area. The modelling is carried out as a “proof-of-principle” of potential value generalisation and uncertainty analysis methods for ecosystem accounting. It does not cover all regulating ecosystem services of urban forests, nor cultural services. While noting that wide confidence intervals for generalised values pose challenges for using monetary accounts for the accounting purpose of change detection, we find that tree-specific asset valuation is possible in an urban accounting setting. Our findings serve the purpose of raising awareness about asset values of urban green infrastructure, to bring them more on a par with grey infrastructure in urban planning. We also argue that the reliability of the asset value of individual trees is also good enough to be used for non-accounting purposes, such as municipal tree damage assessments.

Keywords

Ecosystem accounting, SEEA EA, value transfer, urban ecosystem accounts, Bayesian belief network, BBN, uncertainty, monetary valuation, ecosystem services

Introduction

The SEEA EA (United Nations 2021) defines a research and development agenda aimed at making monetary ecosystem service accounts part of the UN ecosystem accounting standard in the near future. This paper is of general relevance for the research agenda call for “methods to accounting for specific ecosystem types in [..] urban areas” and “ecosystem accounts in monetary terms”. It is specifically relevant for the research agenda on “application of value transfer techniques for accounting purposes; articulation of data quality assessment frameworks, tools and process, especially concerning spatial data; articulation of relationships between ecosystem condition variables, ecosystem characteristics and processes and measures of ecosystem services" (p.332). The paper also contributes an example of “approach to the measurement of future flows and prices of ecosystem services as input to the calculation of net present values for ecosystem assets".

Asset valuation is a an estabilished aspect of the economic analysis of renewable and non-renewable resources (e.g. Neher (1990)) and more generally the management of nature as an asset (Dasgupta 2021) . Ecosystem asset accounts sit at the top of the hierarchy of ecosystem accounts in the SEEA EA (United Nations 2021). Nevertheless, examples of ecosystem asset accounts are relatively rare in the ecosystem accounting literature. They require a suite of information from core accounts including physical extent and condition accounts, physical and monetary ecosystem supply-use in order to calculate asset values (NCAVES and MAIA 2022). The most extensive examples in terms of ecosystem service coverage of ecosystem asset accounts at national level to date are for the Netherlands (Hein et al. 2020) and UK (ONS 2021). Both countries use assumptions of no future asset degradation, constant ecosystem service flows, constant prices and a 100 year ecosystem asset life. The Netherlands uses a discount rate for calculating net present values of 2-3% depending on the ecosystem service type, while the UK uses a graduated discount rate starting at 3.5% (first 30 years) falling to 2.5% after 75 years.

Our study focuses on the value of regulating services from trees – for which the iTree Eco model is a well-established model estimating annual flows of regulating ecosystem services (Nowak 2020). To our knowledge, no studies using iTree Eco for valuation of ecosystem service flows have estimated the asset value of trees. The Capital Asset Valuation for Amenity Trees (CAVAT) (Doick et al. 2018) computes an asset value for urban trees, but based on a multi-criteria scoring method rather than calculation of discounted value of ecosystem service flows as recommended by SEEA EA. Accurate assessment of asset values requires a more detailed knowledge of tree species life expectancies as a function of tree condition and the condition/stressors of particular urban environments (Esperon-Rodriguez 2022). A continuing methodological challenge for ecosystem accounting is to make ecosystem service models sensitive to ecosystem condition (Czucz et al. 2018).

EU experimental ecosystem accounts (Vysna et al. 2021) have yet to assess asset values highlighting ‘the (currently) laborious production of these accounts, as well as the uncertainty surrounding the physical and monetary estimates of ecosystem services (and even more so ecosystem assets), remain an obstacle for the mainstreaming of ecosystem accounts into other policy areas' (p.47). Hein et al. (2020) point out that the accuracy of ecosystem service models varies considerably between different ecosystem services, with uncertainty associated with variations in data quantity and quality available to represent the spatial variation of ecosystem services, as well as lacking standardisation of the choice of valuation method.

Urban ecosystem accounts are recognised as one of four key thematic accounts in the SEEA EA (United Nations 2021, chapter 13.6). For urban ecosystems, a particular integrated approach to physical ecosystem extent-condition accounting is proposed which acknowledges the need for high spatial resolution accounts and for a focus on managed assets (trees, green roofs, ponds, streams), in addition to units of land-cover more familiar to national ecosystem accounting applications.

A challenge for ecosystem accounting is assessing the uncertainty in value estimates generated from using ecosystem service valuation from a few study sites to policy analysis or accounting at other sites, referred to as 'benefit transfer' (Johnston et al. 2021), 'value transfer' (United Nations 2021, Grammatikopoulou et al. 2023) or 'value generalisation' (NCAVES and MAIA 2022). This paper uses 'value generalisation' which refers specifically to generalising estimates from a spatially explicit sample of sites to all ecosystem locations within an accounting area. It demonstrates a 'high spatial resolution' approach appropriate for an urban accounting planning setting, that considers variation in key spatial contextual factors conditioning a tree's delivery of regulating services. It demonstrates the use of spatially-explicit Bayesian networks to account for spatial variation and uncertainty in the generalisation of location-specific tree characteristics (Gret-Regamey et al. 2013a, Gret-Regamey et al. 2013b, Madsen et al. 2013).Gret-Regamey et al. 2013a

Material and methods

The approach is built around the iTree Eco for estimating the value of regulating service of individual trees and the Hugin QGIS plugin application to infer asset values to the whole urban planning area, while accounting for spatial variation in the condition of the trees' location. Fig. 1 provides a graphical overview of the chain of data and model integration used in this study. The work builds on identification of tree crown polygons and tree height for all trees in Oslo's built zone for 2011-2014-2017, using Lidar data and digital terrain maps (Hanssen et al. 2021).

The condition of tree assets was determined, based on tree canopy cover and height (Fig. 2), where taller and older trees with large canopies are expected to have higher potential to supply regulating ecosystem services due to their greater biomass and Leaf Area Index. Combining tree crown segmentation data, municipal tree inventories and urban building and land-use datasets (Cimburova and Barton 2020) demonstrated a GIS method for augmenting the data available on tree dimensions and condition available in municipal tree inventories. Using an augmented sample of 16189 municipally-owned trees, the authors ran the i-Tree Eco model (Nowak 2020) to determine four regulating ecosystem services. Building on Cimburova and Barton (2020), we estimated asset value per tree, based on the annual monetary value of ES indicators as calculated by i-Tree Eco, current tree age estimates and tree life expectancy, based on simple allometric equations (Lauwers et al. 2017). SEEA EA recommends that social discount rates should be applied in the valuation of ecosystem services that contribute to collective benefits, that is, benefits received by groups of people or society in general (United Nations 2021). We used a 1.4 % discount rate recommended by Stern (2007) for investment in climate change mitigation measures. The asset value was calculated as the present value of the discounted flow of annual monetary value of the ecosystem service for the expected lifetime of the tree. Cimburova and Barton (2020) assume that air pollution levels are constant at current levels for the tree life expectancy. If air pollution from the main pollutant particulate matter were to decline, this would mean an overestimate of discounted future air pollution mitigation services and, hence, the estimated asset value. This illustrates how development of clean technologies that lead to changes in relative prices of ecosystem services is one of the challenges of ecosystem asset valuation.

The regulating ecosystem service values of an average tree computed using i-Tree Eco by Cimburova and Barton (2020) was about 220 NOK/year (2014 prices, 0.1695 USD/NOK). By far the greatest monetary value of regulating services (about 200 NOK/year) was due to air pollution reduction by trees (PM, NOX, SO_2). The mean asset value per tree for removed air pollution, avoidance of stormwater run-off, sequestered carbon and building energy savings is approximately 12,400 NOK/tree. Accounting prices are constants in the iTree Eco model. The paper focuses on using spatial Bayesian networks to account for uncertainty due to spatial variation in tree assets. The accounting prices, including ecosystem service values and discount rate used here, do not vary spatially and are also fixed constants in the Bayesian network (BN). Admittedly, accounting prices are also uncertain for methodological reasons other than spatial variation, but this uncertainty is not the focus of the present paper.

A Bayesian network (Kjaerulff and Madsen 2007) was configured using machine-learning on a selection of input variables of the iTree Eco model and the estimates of asset values (Fig. 3). The Bayesian network is in effect emulating the joint probability distribution structure between input and output variables of the iTree Eco model. The Bayesian network predicts probability distributions of the asset value of regulating services given uncertainty about the input data. The tree (canopy height, diameter at breast height, crown area) and ecosystem condition (air pollution) variables most strongly predicting ecosystem services in the sample of municipally managed trees were retained for the Bayesian network model (Cimburova and Barton 2020). While air pollution directly determines the regulating service of air pollution removal, machine-learning also revealed an indirect effect through a dominance of Tilia species and tree crown area, height and stem width being smaller in the highest compared to the lowest air pollution areas. As would be typical of value transfer situations in ecosystem accounting, we are generalising a model estimated with ground-truthed data (e.g. DBH - diameter of the trunk at breast height) from a sample of the tree assets, to all trees in the accounting area where, for example, DBH is not observed using remote sensing Lidar data. The node "DBH measurement" shows the distribution of trees across the different types of data availability and is used to assess differences in asset value depending on the measurement approach. This inference approach using Bayesian networks has been applied previously to uncertainty quantification in ecosystem service assessments (Gret-Regamey et al. 2013a, Gret-Regamey et al. 2013b).

The Bayesian network model is then used to infer tree specific regulating services for all 406000 tree canopy polygons identified by Hanssen et al. (2021) in the accounting area of the city's built zone. A tree crown polygon may represent more than one tree trunk – other studies have estimated the number of individual tree trunks in Oslo to be larger, based on tree top identification (Barton et al. 2015). However, for the purpose of estimating regulating ecosystem services, it is the amount of canopy cover - as a proxy for leaf area index - that is the key condition variable. Each canopy polygon is treated as a single asset in the BN emulation model because the number of trunks under the canopy is unobserved. This means that estimates of carbon storage are inferred by the BN from the canopy size, adding uncertainty to the inferred asset values, relative to trees with ground-truthed stem diameters. We refer to this inference using the BN as spatial "value generalisation". Value generalisation is carried out using Hugin Expert software (Madsen et al. 2013) implemented in a QGIS plugin. The QGIS plugin runs the BN for every individual tree crown polygon in the accounting area. Results are presented as aggregate present (asset) values. Estimates of individual ecosystem services can also be generated if needed for particular policy applications. The BN model also enables results to be presented as aggregate asset values of each tree with confidence limits.

Fig. 3 shows the Bayesian network summarising the correlation patterns between tree condition and air pollution as input variables to iTree Eco and the asset value per tree and per canopy unit area. This is an intermediate result of the value generalisation methodology. The causal structure of the network is a result of guided machine-learning. For example, we specified that the model should allow for pollution zone determining tree characteristics, to allow for limiting growth of individual trees in locations with high air pollution. Cimburova and Barton (2020) also specified the model to assess possible bias in remote sensing versus ground-truth determination of unobserved DBH using the "DBN measurement" node.

As mentioned, Hugin QGIS plugin applies the model to every accounting unit – in our case a tree canopy polygon. In a general ecosystem accounting context, the inference would be done for each basic spatial units of an ecosystem as pixels or polygons in an accounting area.

The Hugin Expert QGIS plugin outputs different statistical parameters calculated on the non-parametric distribution computed for the spatial accounting unit, such as mean, median, st.dev. and 10-90% confidence limits. Reporting of aggregate asset values for the city serve the purpose of awareness-raising about the natural capital value. We discuss a possible accounting table presentation of monetary asset value of urban trees incorporating uncertainty about asset values due to value generalisation. To demonstrate an application of ecosystem accounting to urban policy and planning, we also assessed the change in tree asset values for a particular regulation plan area experiencing sub-urban infill.

Results

Total asset value of urban trees for awareness raising

First, we report on the aggregate asset values of tree canopy for the city's built zone. Fig. 4 illustrates the mapped results of the asset value inference from the sample of municipal trees to all public and private trees. The shaded background shows pollution zones in central Oslo, defined by limits for daily, winter and annual means of NO_2 and PM10 (Cimburova and Barton 2020). We can observe from the spatial pattern of tree valuation points that air pollution is the ecosystem condition which most determines the asset value due to the high value of air pollution removal by urban trees. The model also adjusts for three other tree characteristics: tree canopy size, diameter at breast height and tree height and the urban morphology of each tree location. Within each air pollution zone, the speckled pattern indicates variation in tree canopy height and size, as well as variation in land-use and tree canopy light exposure due to adjacent canopy and buildings.

Fig. 5 shows the expected value for every tree in the accounting area using the Bayesian network to infer tree value, based on remote sensing observable tree characteristics. The city-wide map scale shows even more clearly that regulating services vary spatially according to tree location relative to air pollution zones. The distribution of tree asset values is highly skewed towards lower values because the population of small young trees is much larger than large old trees. Using the probability distribution predicted [5% percentile, median, 95% percentile] asset value of regulating services per tree is estimated to be 3,414, 12,005, 25,912 NOK/tree, respectively, calculated as an average of the percentile predictions across all trees. We account for the skewed distribution by aggregating the individual model predictions for every one of the 406,000 trees in the built zone. Following this approach, the estimated aggregate asset value in 2014 is 5.42 billion NOK.

Applying the asset account to policy assessment

Ecosystem accounts can help inform planners on the impact of recent urbanisation on trees. We use the change in the tree asset account to demonstrate assessment of urban tree conservation within an urban regulation planning area, particularly in suburban infill of gardens. Oslo's Small House Regulation Plan (SHRP) covers an area of about 3000 ha and 28,000 properties, composed mainly of detached housing with gardens. The SHRP requires, inter alia, a minimum 65% of a property's area to be free from terrain modification and permits for felling large trees with Circumference at Breast Height > 90 cm. Fig. 6 shows that there was a small net loss in tree canopy extent for this regulation planning area between 2011 and 2017 of 70 decares (-70 000 m^2 or about -1% of total canopy cover; derived from modelling of available Lidar data (Hanssen et al. 2021).

This estimated change is less than the Lidar classification and tree segmentation model estimation error (Hanssen et al. 2019, Hanssen et al. 2021). The aggregate net change in canopy cover for the Small House Regulation area cannot be considered significant over the 6 years for which the tree account is compiled. There is some difference in the pattern of gains and losses 2011-2014 and 2014-2017, which may also be due to between-period differences in the resolution and classification of the Lidar data point cloud (Hanssen et al. 2021). However, over whole period a significant change pattern in tree height was observed which is relevant for assessment of the regulation plan. Net gains between 2011-2017 were observed in trees < 15 m height, while net losses were observed for established trees > 15 m. This suggests that building permits and tree felling permits, in particular, have not been effective in addressing the loss of established, older trees in the Small House Regulation Plan area.

The loss of larger trees and increase in smaller trees and in the regulation plan area raises an urban planning question relevant for ecosystem accounting. Is the change in height distribution (condition) of urban trees significant for the supply of ecosystem services and more specifically regulating services? As regulating services of trees are primarily determined by a tree's leaf area index – proxied by crown volume as a function of crown area and height – it is expected that the large increase in small tree planting may have compensated for the loss of tall trees – at the aggregate level of the regulation plan.

Starting from the physical extent-condition account (Fig. 6), we estimated the change in asset values predicted by the BN emulation of the iTree Eco model (which represents the assessment of the expected value of air pollution removal, avoidance of stormwater run-off treatment, carbon sequestration, building energy savings costs). Fig. 7 shows the monetary ecosystem asset account for trees in the Small House Regulation Plan area.

The asset accounts reflect the height class distribution of gains and losses observed in the extent-condition account. Overall, the loss of ecosystem service asset value in the smaller number of larger trees is compensated by the large increase in the canopy area of small trees. The net loss in asset value of about NOK 21 million (approximately -2% over the period) is not significant relative to the combined uncertainty in the tree segmentation modelling (Hanssen et al. 2021) and the uncertainty in asset values inferred by the Bayesian network. From an aggregate view of the regulation plan area, there is no significant loss in the regulating services provided to the population.

The Lidar-based mapping of tree canopy underpinning the asset accounts allows for identification of the spatial distribution of the gains and losses for the services. While there is no net aggregate loss in regulating services, Fig. 8 reveals that these losses and gains are unevenly distributed across the planning area. Broadly speaking, suburban areas closer to the city centre on the north-west side are more likely to experience a net loss in local tree assets, whereas the pattern for the south-eastern part of the city is more mixed. Net loss or net gain varies by neighbourhood. Considering that the air pollution reduction, stormwater regulation and energy savings provide benefits at the neighbourhood or property scale, the asset accounting tables hide an unequal distribution of the impacts of tree canopy change.

Discussion

In this section, we first discuss some sources of uncertainty in the asset accounts for urban trees. In light of this uncertainty, we then discuss policy applications of the tree asset accounts.

Temporal changes in ecosystem service supply due to future changes in urban ecosystem condition. Regulating ecosystem service supply is expected to change over time with the value of stormwater regulation services increasing as climate change brings more frequent and more intense rainfall episodes. Recent work has suggested that the full cost savings to stormwater treatment considering also future climate change projections may be roughly 5 times higher than considered by Cimburova and Barton (2020) looking only at present costs. In the opposite direction, air pollution in the built zone could be expected to fall in the next decade with increased use of electric vehicles and continued improvements in wood burning stoves. Exchange values for different ecosystem services are not fixed either. The social accounting cost of carbon in Norway will increase as authorities increase the national carbon tax to 2000 NOK/tonne towards 2030.

Sensitivity of asset value to Tree management assumptions. Ecosystem asset values depend on assumptions about sustainability of management practices and asset life (NCAVES and MAIA 2022). In the present study, individual tree asset values were calculated, based on the discounting of future flows of benefits from trees in their present sizes, using estimates of expected lifetimes for tree species under urban conditions in Oslo (Cimburova and Barton 2020). This underestimates the local asset value of individual trees that have not reached their climax growth phase. Our estimates also assume that, at locations where trees reach the end of their expected life, there is no replacement planting. This potentially underestimates the potential asset value of the tree planting location, rather than the tree itself. At the level of the whole accounting area of Oslo's built zone and for total asset value of trees, our calculations are likely to be underestimates, but the extent of underestimation depends on assumptions about management at each tree location. If new planting sites are pruned to limit tree size below its natural growth potential and if locations with dead trees are not replanted, our total asset value estimates are more reliable. On the other hand, underestimation in this paper would be at its maximum if all tree plantings were, in future, allowed to grow to the limit of their genetic and location potential and if all future dead trees were replaced with new plantings. SEEA EA recommends that estimates of asset life be based on patterns of ecosystem use that have occurred in the recent past, rather than on the utilisation of general assumptions regarding future sustainability or intended or optimal management practices (United Nations 2021, para. 10.72). Given the recent recognition of tree conservation and planting in Oslo's municipal plans, past management may not be a good predictor of future asset condition and life. Further modelling work should evaluate the potential variation in urban tree asset values given different plausible management assumptions.

Aggregation errors. A common practice in unit-value transfers is to transfer a summary statistic of central tendency, such as the mean or median (Johnston et al. 2021). The wide range of assets values per unit tree crown area in our study demonstrates a possible aggregation error from a sample to a whole population of trees when non-normally distributed in tree height (ecosystem condition). With skewed distribution towards many smaller trees with low value assets, using a mean to scale/generalise to the population will overestimate the total asset value. Summing the individual model predictions for every one of the 406,000 trees in the built zone, the estimated aggregate asset value in 2014 is 5.42 billion NOK, as compared to 7.31 billion NOK (2014) if we simply multiply a mean NOK/m^2 per height class by the canopy area per height class.

Generalisation/value transfer errors. Other uncertainties are present in the asset value generalisation using the BN QGIS model. The asset value all trees was inferred using only observed canopy area and tree height, proxies for the condition indicators which predict regulating services more directly (tree species, total leaf area, stem diameter). The Bayesian network emulates all the variance incorporated in the i-Tree Eco model due to variance of tree characteristics in the input data, as well as variance in the model simulation. Inspecting Fig. 7, it can be seen that the range of asset values per unit tree crown area varies by an order of magnitude, potentially 'drowning out' the percentage change in canopy cover during the accounting period. Even the tallest trees have asset values per m^2 in the lowest percentiles. This variance in predicted unit area asset values is perhaps surprising considering that we are generalising values from a sample of trees within the same city. We used the Bayesian network (Fig. 9) to explore some of the potentially large generalisation errors and their broader relevance for spatial value generalisation in ecosystem accounting.

We use the Bayesian network to diagnose the characteristics of the lowest m^2 asset value class relative to the whole sample used to estimate the iTree Eco model of municipal trees. The lowest asset value per canopy area class (0-50 NOK/m^2, upper right hand distribution) corresponds to the largest crown area, diameter and height classes of trees (distributions in the centre of the figure above) and the lower air pollution zone. The *Tilia* tree genus is less likely to have low asset values relative to other tree species because they tend to have smaller crown area than other species in Oslo. Different tree species have different leaf area indices, meaning differences in effectiveness per unit canopy area. Lidar data on all tree canopies in the city do not observe tree species, thus introducing uncertainty relative to a traditional iTree Eco modelling approach which is based on ground-based sampling (Cimburova and Barton 2020).

Spatially correlated urban condition variables. We generated our prediction model on roughly 16,000 municipally managed trees, of a total of roughly 30,000, as compared to 406,000 identified canopies in the built zone as a whole. Asset value per m^2 of canopy are lowest for large canopies; the largest canopies are located in the lowest air pollution zones (Fig. 9), as these correspond to the urban morphologies with less dense buildings (space for canopy) and transport density (higher air pollution). Since air pollution mitigation is equivalent to 94% of the asset value of regulating services in our iTree simulation, also the largest trees exhibit the lowest unit area values, increasing the variance of predictions. Furthermore, municipal trees are street trees and park trees located mainly in the city centre and/or along main roads. They are actively managed so pruned tree crown sizes will be different from unmanaged trees and/or trees on private land. Tree crown areas tend to be smaller in the highest pollution zones in dense road infrastructure than in other parts of the city, potentially due to pruning and higher tree mortality due to stressors (compaction, limited infiltration area, growing space, air pollution, salt) and species choice (Tilia ssp is more frequent).

Relevance of asset accounts for urban policy and planning. There are a number of potential uses of tree asset valuation. Policy uptake depends, inter alia, on sufficient accuracy of the value generalisation for the particular policy purpose (Grammatikopoulou et al. 2023).

We finish with some examples of purposes of urban tree asset valuation illustrating a broadly increasing order of accuracy requirements (Fig. 10):

· **Awareness raising**. The total asset value of regulating services from urban trees of 5.4 billion NOK is a 'big number' in absolute terms, raising awareness about the value of trees as green infrastructure providing municipal utilities, similarly to other municipal utilities infrastructure value.

· **Change assessment**. The physical extent-condition and monetary asset accounts provide time-series indicators of tree stocks and the value of benefits. The tables provide a summary tracking of the 'sustainability' of urban intensification in Oslo over time. Accounting statistics can be extracted for planning areas of particular interest. If uncertainty is accounted for, it is also possible to assess whether observed changes during the accounting period are statistically significant and, if so, whether they are also politically important. The spatial resolution of ecosystem accounts also means that change assessment can reported for different sectors, such as private land and publicly managed municipal land and in relation to spatial distribution of different cultural, social and economic demographics (see, for example, Venter et al. (2023)) .

· **Priority-setting**. Tree asset valuation highlights the value of trees to developers, urban planners, landowners and the public. This potentially makes the economic case for their preservation and for investment in additional tree planting throughout the city. Nevertheless, the monetary values of green infrastructure, such as trees, cannot compete with urban development values in dense urban areas where trees compete for space with building stock. How do tree asset values compare to other property assets values? The asset value of all property in Norway is regularly computed (Eiendom Norge 2021) – in 2019, it was 1650 billion NOK for the building stock in Oslo. Adjusted to 2019 prices, the asset value of regulating services from all trees was approximately 7 billion NOK or the equivalent 0.42% of the asset value of all buildings.

· **Instrument design.** Where urban density allows for nature-based solutions, the tree asset valuation focused on regulating services only makes the case that new urban developments can compensate for the loss of large established tree canopy with planting new trees, provided that compensation is in terms of canopy volume, rather than ‘a tree-for-tree’. It must be noted, however, that tall trees provide cultural services in terms of green views of sites which cannot be compensated on a m^2 canopy-basis by small trees. Tall trees are also older and are likely to provide more habitat niches for a variety of species. However, assessment of ecosystem services of trees has, to date, had limited influence on design of Oslo’s Blue-Green Factor instrument (Stange et al. 2022).

Physical extent-condition accounts revealed a relative loss of large trees in Oslo’s Small House Regulation Plan area. It showed to be lacking effectiveness of the current permitting requirements for felling large trees, at least relative to an objective of halting the loss of existing tree canopy in suburban areas. Mapping of canopy loss areas may, in future, contribute to both strengthening of conservation incentives and targeting of tree planting in ‘net canopy loss’ neighbourhoods. Reporting ecosystem accounts in terms of change maps will contribute to policy design that considers ‘environmental justice’ of the spatial distributional impacts on different urban populations (Venter et al. 2023).

· **Damage compensation**. Finally, the highest accuracy may be required of ecosystem asset valuation as a basis for damage compensation, especially if used in legal cases. Tree asset valuation by Cimburova and Barton (2020) has been used to argue for the inclusion of damage compensation for regulating services in a Norwegian Standard for the Valuation of Trees (VAT), extending the VAT system used in Denmark (Randrup et al. 2019). Tree asset accounting at the aggregate city level, as demonstrated in this paper, potentially provides additional economic arguments to municipal managers for the importance of implementing tree damage compensation practice more consistently across the city.

Conclusions

In this paper, we have demonstrate an ecosystem asset valuation approach using a combination of existing ground-truthed and high resolution remotely-sensed data appropriate for an urban ecosystem accounting setting. We used urban trees as a ‘proof-of-principle’ in an urban ecosystem setting requiring high accuracy to be relevant for planning and policy. The paper demonstrates how machine-learning and Bayesian inference can be used to generalise ecosystem service asset values to an accounting area. The integrated approach avoids time and costs associated with extensive additional surveying and inventorying of urban trees while keeping track of uncertainty. Considering uncertainty, the paper discussed different policy and planning applications in Oslo. The rapid low-cost estimation of regulating services from urban trees and associated asset-based ecosystem accounting may be relevant for other cities. The case study from Oslo also provides an example of so-called `value generalizstion` from a sample of ecosystem assets to all ecosystem assets of the accounting area.

Conflicts of interest

References

- Barton DN, Stange E, Blumentrath S, Vågnes Traaholt N (2015) Economic valuation of ecosystem services for policy. A pilot study on green infrastructure in Oslo. NINA Report 1114. 77 pp. URL: http://hdl.handle.net/11250/2397509
- Barton DN (2016) Monetary valuation of urban ecosystem services - operationalization or tragedy of well-intentioned valuation? / Sergi Nuss-Girona. In: Nuss-Girona S, Castaner M (Eds) An illustrated example Ecosystem services: concepts, methodologies and instruments for research and applied use. Documenta Universitaria
- Cimburova Z, Barton D (2020) The potential of geospatial analysis and Bayesian networks to enable i-Tree Eco assessment of existing tree inventories. Urban Forestry & Urban Greening 55 https://doi.org/10.1016/j.ufug.2020.126801
- Czucz B, Arany I, Potschin-Young M, Bereczki K, Kertesz M, Kiss M, Aszalos R, Haines-Young R (2018) Where concepts meet the real world: A systematic review of ecosystem service indicators and their classification using CICES. Ecosystem Services 29: 145-157. https://doi.org/10.1016/j.ecoser.2017.11.018
- Dasgupta P (2021) The economics of biodiversity: the Dasgupta review: full report . HM Treasury , London.
- Doick K, Neilan C, Jones G, Allison A, McDermott I, Tipping A, Haw R (2018) CAVAT (Capital Asset Value for Amenity Trees): valuing amenity trees as public assets. Arboricultural Journal 40 (2): 67-91. https://doi.org/10.1080/03071375.2018.1454077
- Eiendom Norge (2021) Verdien av den norske boligmassen. https://eiendomnorge.no/aktuelt/blogg/verdien-av-den-norske-boligmassen-1. Accessed on: 2021-12-03.
- Esperon-Rodriguez Mea (2022) Assessing climate risk to support urban forests in a changing climate. Plants People Planet1-13. https://doi.org/10.1002/ppp3.10240
- Grammatikopoulou I, Badura T, Johnston RJ, Barton DN, Ferrini S, Schaafsma M, La Notte A (2023) Value transfer in ecosystem accounting applications. Journal of Environmental Management 326: 116784. https://doi.org/10.1016/j.jenvman.2022.116784
- Gret-Regamey A, Brunner SH, Altwegg J, Bebi P (2013a) Facing uncertainty in ecosystem services-based resource management. Journal of Environmental Management 127 https://doi.org/10.1016/j.jenvman.2012.07.028
- Gret-Regamey A, Brunner SH, Altwegg J, Christen M, Bebi P (2013b) Integrating Expert Knowledge into Mapping Ecosystem Services Trade-offs for Sustainable Forest Management. Ecology and Society 18 (3). https://doi.org/10.5751/Es-05800-180334
- Hanssen F, Barton DN, Nowell MS, Cimburova Z (2019) Mapping urban tree canopy cover using airborne laser scanning – applications to urban ecosystem accounting for Oslo. NINA Report 1677. Norwegian Institute for Nature Research.
- Hanssen F, Barton DN, Venter ZS, Cimburova Z (2021) Utilizing LIDAR data to map tree canopy for urban ecosystem extent and condition accounts in Oslo. Ecological Indicators https://doi.org/10.1016/j.ecolind.2021.108007

- Hein L, Remme R, Schenau S, Bogaart P, Lof M, Horlings E (2020) Ecosystem accounting in the Netherlands. Ecosystem Services 44 https://doi.org/10.1016/j.ecoser.2020.101118
- Johnston RJ, Boyle KJ, Loureiro ML, Navrud S, Rolfe J (2021) Guidance to Enhance the Validity and Credibility of Environmental Benefit Transfers. Environ Resource Econ https://doi.org/10.1007/s10640-021-00574-w
- Kjaerulff UB, Madsen AL (2007) Bayesian networks and influence diagrams: a guide to construction and analysis. Springer
- Lauwers L, Barton DN, Blumentrath S, Nowell MS (2017) Accounting for urban trees. Updating the VAT03 Compensation Value Model. NINA Report 1453.
- Madsen AL, Karlsen M, Barker GC, Garcia AB, Hoorfar J, Jensen F (2013) A Software Package for Web Deployment of Probabilistic Graphical Models.
- NCAVES, MAIA (2022) Monetary valuation of ecosystem services and ecosystem assets for ecosystem accounting: Interim Version 1st edition. . United Nations Department of Economic and Social Affairs, Statistics Division, New York.. URL: https://seea.un.org/content/monetary-valuation-ecosystem-services-and-assets-ecosystem-accounting
- Neher PA (1990) Natural Resource Economics. Cambridge University Press
- Nowak D (2020) Understanding i-Tree: Summary of programs and methods. U.S. Department of Agriculture, Forest Service, Northern Research Station. DOI: 10.2737/NRS-GTR-200. https://doi.org/10.2737/NRS-GTR-200
- ONS (2021) UK natural capital accounts methodology guide: 2021. Office of National Statistics. November 12. URL: https://www.ons.gov.uk/economy/environmentalaccounts/methodologies/uknaturalcapitalaccountsmethodologyguide2021
- Randrup TB, Bühler O, Holgersen S (2019) Værdisætning af træer. Forlaget Grønt Miljø
- Stange E, Barton D, Andersson E, Haase D (2022) Comparing the implicit valuation of ecosystem services from nature-based solutions in performance-based green area indicators across three European cities. Landscape and Urban Planning 219 https://doi.org/10.1016/j.landurbplan.2021.104310
- Stern N (2007) The Economics of Climate Change: The Stern Review. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9780511817434
- United Nations (2021) System of Environmental-Economic Accounting—Ecosystem Accounting (SEEA EA). White Cover. Available at: https://seea.un.org/ecosystem-accounting. URL: https://unstats.un.org/unsd/statcom/52nd-session/documents/BG-3f-SEEA-EA_Final_draft-E.pdf
- Venter ZS, Figari H, Krange O, Gundersen V (2023) Environmental justice in a very green city: Spatial inequality in exposure to urban nature, air pollution and heat in Oslo, Norway. Science of The Total Environment 858: 160193. https://doi.org/10.1016/j.scitotenv.2022.160193
- Vysna V, Maes J, Petersen JE, La Notte A, Vallecillo S, Aizpurua N, Ivits E, Teller A, (2021) Accounting for ecosystems and their services in the European Union (INCA). Final report from phase II of the INCA project aiming to develop a pilot for an integrated system of ecosystem accounts for the EU. Statistical report. Publications office of the European Union, Luxembourg, 2021. URL: https://ec.europa.eu/eurostat/documents/7870049/12943935/KS-FT-20-002-EN-N.pdf/de44610d-79e5-010a-5675-14fc4d8527d9?t=1624528835061

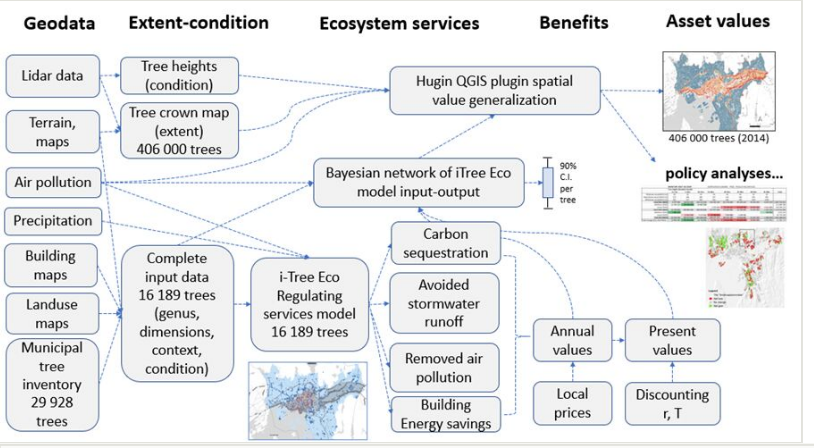

Figure 1.

Modelling chain for compiling asset accounts of the regulating ecosystem services from trees in Oslo’s built zone, including carbon sequestration, avoidance of stormwater run-off, removal of air pollution and building energy savings.

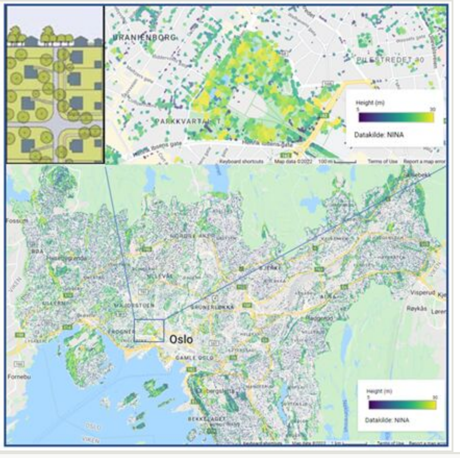

Figure 2.

The tree asset extent-condition account considers tree canopy area and canopy height. Source: adapted from https://nina.earthengine.app/view/urban-nature-atlas and https://transect.org/.

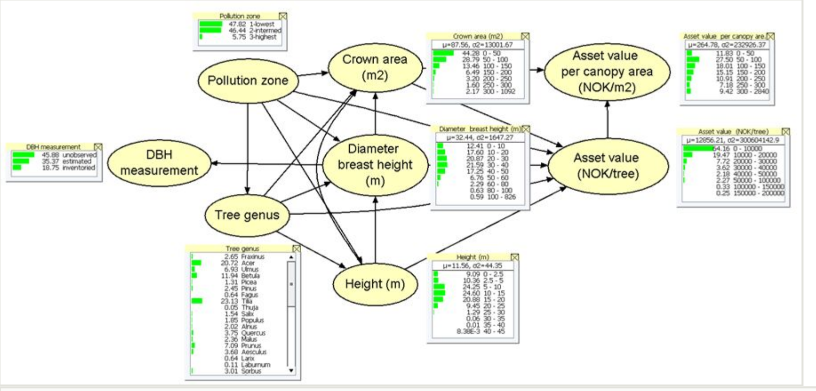

Figure 3.

Machine-learned Bayesian belief network for generalising i-Tree Eco calculated tree asset values for regulating services from municipal trees to all city trees. The graphical user interface displays the nodes, causal links and the non-parametric discrete distributions of each node. Source: BBN model used for value transfer is available as a Hugin Expert file in Suppl. material 1. Model nodes are documented in Cimburova and Barton (2020) supplementary material https://ars.els-cdn.com/content/image/1-s2.0-S161886672030618X-mmc2.docx.

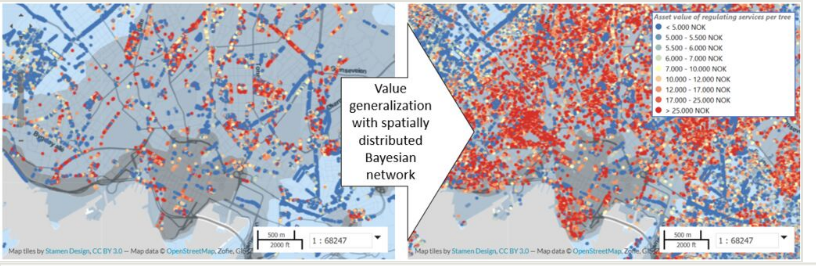

Figure 4.

Value generalisation from a modelled sample of trees managed by the municipality (left panel) to tree assets both on public and private land in the Oslo accounting area (right panel) using the spatially distributed Bayesian network in Figure 3. Map data: http://urban.nina.no/maps/396/view.

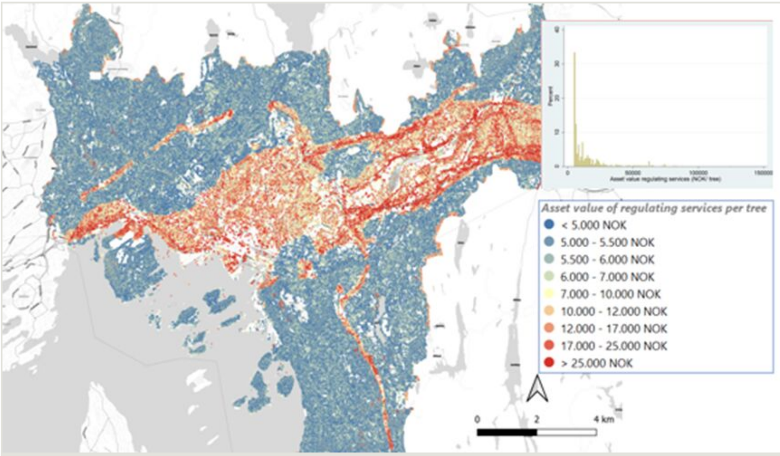

Figure 5.

Asset value of regulating services generalised to all city trees in Oslo’s built zone (2014).

	EXTENT-CONDITION ACCOUNT			(SMÅHUSPLAN SUBURBS - TREES)					
	Tree height (elevation bands)								
Crown cover	2.5-5m	5-10m	10-15m	15-20m	20-25m	25-30m	30-35m	35-40m	Total
Total 2011 (daa)	55	955	1501	2034	1540	547	102	14	6747
Additions (daa)	74	810	156	0	0	0	0	0	1040
Losses (daa)	0	0	0	-14	-314	-341	-76	-11	-756
Total 2014 (daa)	129	1765	1656	2020	1226	206	26	3	7031
Additions (daa)	6	0	0	0	0	0	0	1	8
Losses (daa)	0	-72	-20	-210	-51	-8	0	0	-361
Total 2017(daa)	136	1693	1637	1809	1175	197	26	5	6677
Total change 2011-2017(daa)	80	738	136	-225	-365	-350	-76	-9	-70

Figure 6.

Extent-condition account for tree assets in Oslo's Small House Regulation Plan area (2011 to 2017). Source: derived from Hanssen et al. (2021).

		2.5-5m	5-10m	10-15m	15-20m	20-25m	25-30m	30-35m	35-40m	Total
	5%(Asset value)(NOK/m2)	20	24	25	24	24	24	23	22	
	Mean(Asset value) (NOK/m2)	172	166	160	157	144	156	435	435	
	95%(Asset value)(NOK/m2)	281	427	540	540	406	438	1587	1569	
Mean	**Total 2011 (NOK)**	9 475 480	158 554 900	240 123 200	319 352 130	221 705 280	85 335 120	44 165 550	6 042 150	1 084 753 810
	Additions (NOK)	12 764 120	134 428 460	24 907 200	-	-	-	-	-	172 099 780
	Losses (NOK)	-	-	-	- 2 274 930	- 45 220 320	- 53 228 760	- 32 964 300	- 4 611 000	- 138 299 310
Mean	**Total 2014 (NOK)**	22 239 600	292 983 360	265 032 000	317 077 200	176 484 960	32 106 360	11 201 250	1 431 150	1 118 555 880
	Additions (NOK)	1 080 160	-	-	-	-	-	-	535 050	1 615 210
	Losses (NOK)	-	- 12 001 800	- 3 174 400	- 32 999 830	- 7 303 680	- 1 299 480	-	-	- 56 779 190
Mean	**Total 2017(NOK)**	23 319 760	280 979 900	261 856 000	284 077 370	169 181 280	30 806 880	11 201 250	1 966 200	1 063 388 640
Total change 2011-2017(NOK)		13 844 280	122 425 000	21 732 800	- 35 274 760	- 52 524 000	- 54 528 240	- 32 964 300	- 4 075 950	- 21 365 170

Figure 7.

Monetary Asset Account for Urban Trees in the Small House Regulation Plan area in Oslo. Source: derived from Hanssen et al. (2021) and Cimburova and Barton (2020). The top part of the Table shows the mean and 5%-95% confidence interval for the marginal canopy asset values in NOK/m^2 per tree derived from the Bayesian network machine-learning of the iTree Eco model results. The asset account below is based on the expected total asset values per tree height class, based on the mean of the marginal canopy asset value.

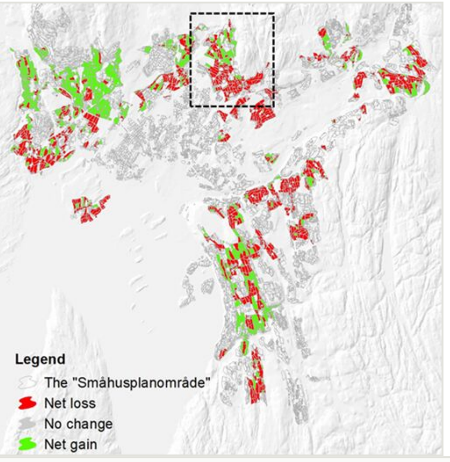

Figure 8.

Distributional analysis of the gains and losses in the monetary value of tree assets in Oslo between 2011 and 2017. Source: Hanssen et al. (2019).

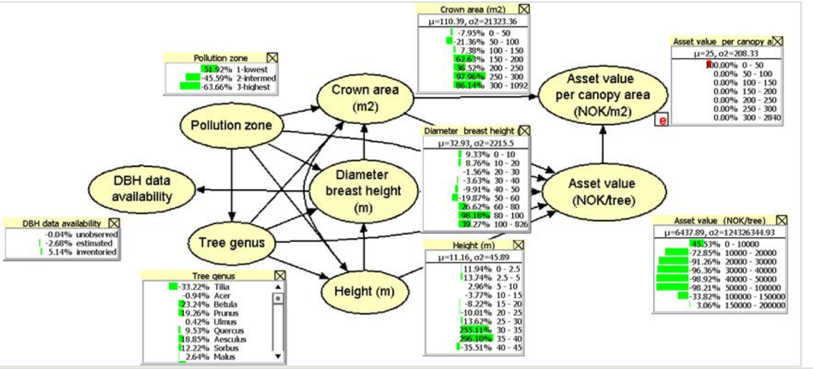

Figure 9.

Diagnostic of asset value per canopy trees using the Bayesian Network emulation of the iTree Eco model. In the node “Asset value per canopy area”, we selected the lowest asset value category (0-50 NOK/m^2). The network nodes show the changes in likelihoods of input variables relative to the likelihood distribution for all trees. This uses the inductive reasoning feature of BNs made possible by Bayes theorem.

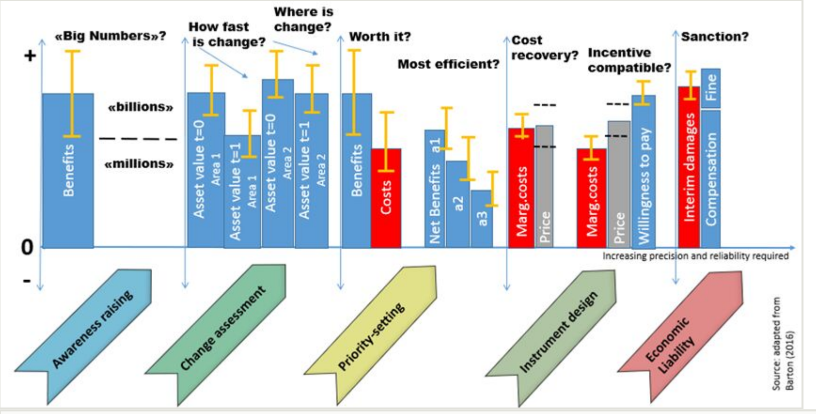

Figure 10.

Required accuracy of ecosystem service valuation depends, inter alia, on the policy analysis purpose. Error bars in yellow illustrate increasing requirements for accuracy (precision and reliability) across different policy questions from left to right. Source: adapted from Barton (2016).

Supplementary material

Suppl. material 1: Bayesian Belief Network

Authors: David N. Barton
Data type: Hugin Expert software. https://www.hugin.com/
Brief description: Source: BBN model used for value transfer is available as a Hugin Expert file. Model nodes are documented in supplementary material to Cimburova and Barton 2020, available here https://ars.els-cdn.com/content/image/1-s2.0-S161886672030618X-mmc2.docx
Download file (25.91 MB)