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Original Articles

# An ecosystem service-disservice ratio: Using composite indicators to assess the net benefits of urban trees

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ABSTRACT

Considering ecosystem disservices (EDS) of urban forests alongside the services (ES) can lead to better-informed decisions about tree species selection and placement in cities. Finding a common assessment framework, that does not rely on a financial model, can be tricky, and many studies consider, but do not include, EDS in their tree appraisals. Compound indicators represent a means to neatly combine disparate ecosystem data into one meaningful metric. In this study quantitative field measurements, model outputs, and categorical data relating to some of the major ES and EDS of the urban forest of Meran, Italy, were successfully compressed into a single unit, overcoming epistemological boundaries surrounding different urban ecosystem valuation methods. Several methods of compound indicator construction were considered and uncertainty and sensitivity analysis carried out on the species rankings which were produced. Significant differences in ES/EDS provision were observed between trees on public and private land. Spatial analysis revealed hotspots of high ES provision and low EDS provision, and vice versa. With correct use, compound indicators can stand alongside other methods of measuring and valuing positive and negative aspects of urban ecosystems.

## 1. Introduction

Many cities around the world are promoting and implementing tree planting schemes in order to capitalize on the ecosystem services (ES) that urban forests provide (Jim and Chen, 2009; Pincetl, 2010). These ES range from the biophysical – storm-water modification (Berland et al., 2017), air pollution capture (Escobedo et al., 2011), and phytoremediation of contaminated land (Dadea et al., 2017), to the socio-economic – raising property values (Escobedo et al., 2015), and improving the aesthetic appeal of urban landscapes (Weber et al., 2008). Interactions between urban ecosystems and urban residents are not always positive, however, and these ecosystem disservices (EDS) (Lyytimäki and Sipilä, 2009; Von Döhren and Haase, 2015) are increasingly the subject of research (Pataki et al., 2011; Swain et al., 2013).

This surge in research interest is partly to try and address the imbalance which has been identified within the field of ES research (Lyytimäki and Sipilä, 2009). In a review of urban tree ES literature (Roy et al., 2012) only 15.6% of 115 papers discussed hazards alongside the benefits. There is currently a controversy in the use of the EDS concept in that many feel it only serves to highlight the harm to humans which may be caused by ecosystems, and thus hamper conservation efforts, or justify exploitation of natural resources (Lyytimäki, 2015). Shapiro and Báldi (2014) note that ES and EDS frequently come from the same provider, but society is often quicker to acknowledge the EDS. The concept of EDS thus may exaggerate the harms caused by nature. However, it has sensibly been argued that the controversy surrounding the complexity of ecosystem functions can only be resolved by taking into account the complete bundle of positive and negative functions as perceived by beneficiaries (Lyytimäki, 2015). The goal is to put ES and EDS under the same assessment framework, or bundle, allowing decision makers to weigh the benefits of urban forests against the costs, leading to better-informed decisions (Dobbs et al., 2011).

A common assessment framework utilized is financial (Mullaney et al., 2015). This approach is appealing because it allows tree benefits to be easily communicated to, and understood by, policy makers and corporate entities. Tree-scaping can increase spending in retail outlets (Wolf, 2005), decrease household electricity consumption for cooling via shading effects (Pandit and Laband, 2010), and increase house prices (Donovan and Butry, 2010). When such financial benefits are weighed against the planting, establishment (200–1500 euros per tree (Pauleit et al., 2002)) and maintenance costs, the results can be a very

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persuasive argument for tree planting. The annual net benefit per tree in the US, when financial EDS such as repairing damage to pavement by tree roots are taken into account, is between US$21 and $159 (Mullaney et al., 2015).

Several tools and applications use tree inventory data to quantify the monetary and non-monetary value of the environmental and aesthetic benefits of urban trees (i-Tree STREETS, 2017; Vogt et al., 2017). Often, these models account for ecosystem functions that are detrimental to human well-being and the related costs of management, thus allowing for a better understanding of the urban forest and strategic planning, but unfortunately, they do not consider any specific EDS to balance against the ES (i-Tree STREETS, 2017). Gómez-Baggethun and Barton (2013) describe several valuation methods used in urban ecosystems, such as direct and indirect methods (e.g. hedonic modelling, travel cost, contingent valuation), and other non-monetary methods. They propose that it is possible to obtain a monetary estimation for a wide range of ES, however, again, EDS are not considered in this typology.

A different approach is to consider trade-offs between ES and EDS, which inherently acknowledges that urban tree impacts are complex and dynamic and one cannot simply deal with single impacts separately. Dobbs et al. (2014) spatially quantified a broad range of plot-level ES alongside two EDS - pollen and damage to infrastructure potential. The supply of landscape-level Disservices were higher in the streets, and a moderate trade-off between maintenance of natural heritage and habitat provision was revealed.

Andersson-Sköld et al. (2018) proposed a cascade model of ES which links measured green space structures to ES delivery by means of functional traits – a quantification based method of assessing ecosystems. The model is comprehensive in that it strives to include (often difficult-to-measure) cultural ES and considers multiple ES arising from measurable ecosystem components, however it does not include EDS and thus only shows the gross benefits.

The aim of this paper is to develop an overall ratio that accounts for several EDS alongside some of the major ES in order to assess the net benefits of urban trees. The two major EDS considered are pollen allergenicity (Cariñanos et al., 2014), and Biogenic Organic Volatile Compound (BVOC) production, which can lead to the formation of tropospheric $O_3$ with consequent negative impacts on human respiratory health (Calfapietra et al., 2013). These urban EDS can be highly specific to cities i.e. BVOC production by trees is not a problem for human health in rural areas unpolluted by car exhausts. Urban EDS are important to study because they affect city residents daily, where they live, work and commute.

The approach to construct the overall ratio will utilize Composite Indicators (CIs) which have not been previously applied to ecosystem services or disservices. CIs have been criticized for over-simplifying complex issues and being open to misinterpretation or misuse, but as long as they are constructed in a transparent, statistically sound manner they can be very useful (Saisana et al., 2005). They lend themselves particularly well to the problem of considering multiple ES and EDS, which act on different scales and have been measured using different units. The main objective of this research is thus to assess whether simple, disparate measurements of the urban forest can be combined into a single assessment framework. Once a sensitivity analysis has been used to choose the best final metric, tree species will be ranked in order of simultaneous high ES provision and low EDS provision, and spatial patterns in ES and EDS provision will be interpreted. The research is unique as it incorporates a full inventory of public trees alongside extensive fieldwork on private land, because there is a need to identify which trees are favourable in different settings (Churkina et al., 2015).

## 2. Methodology

### 2.1. Study site

Meran, a city of about 40,000 inhabitants (ISTAT, 2017), is located in the Autonomous Province of South Tyrol in Northern Italy. The climate is of sub-Mediterranean influence with a mean annual precipitation of ca. 760 mm and the minimum and maximum average temperatures of 5.0 °C and 18.1 °C, respectively (Meteo Alto Adige, 2017). It covers approximately 661 ha, however the actual area available for study was 608 ha, due to the presence of a large military base within the city where fieldwork was prohibited. The city was classified into 17 land types following the i-Trees land classification scheme (i-Tree ECO, 2017) but using subdivisions of the 'commercial' and 'institutional' land types.

Since the year 2000, the Meran municipality has maintained a detailed street-tree inventory containing over 5000 trees in streets and parks, with an interactive online map (Comune di Merano, 2010). In addition to species and location, the inventory contains information on height, trunk diameter at breast height (DBH) and trees' health condition.

### 2.2. Tree sampling

Fieldwork took place during autumn 2016. Selection of areas to sample was guided by a desire to sample the land types proportionally to their areal coverage of the city. Sampling thus followed an ecological relevé style whereby all trees are sampled within parcels of urban land. This non-random sampling strategy has been shown to be acceptable for capturing the species diversity and tree characteristics of urban forests (Speak et al., 2018). Initially, 964 trees from the three major public spaces included in the city inventory – streets, parks, and cemetery – were re-measured. The measurements in the inventory were not used because some trees had not been measured for several years, DBH had been measured at 1 m above ground instead of 1.37 m and additional measurements consisting of total tree height, height to crown base, crown width, percent canopy missing, and tree-crown condition were required. DBH was measured with calipers and height was measured with a Blume-Leiss BL6 hypsometer from a distance of 30 m. Remaining measurements were recorded according to the i-Tree field guide (i-Tree ECO, 2017). An additional 1215 trees were measured on private land. Table 1 shows the main characteristics of the tree inventory.

Permission was always sought from the landowner. On the infrequent occasions where permission was not granted, the field worker moved to the next neighbouring unit. The patch (urban land parcel) sizes range from 250 $m^2$ (a single house and garden) to 5.9 ha on public land (cemetery) and 5.5 ha on private land (several adjacent apartment blocks). Tree species were identified mostly to species level and occasionally to genus level using Phillips (1978). Trees were drawn on a map of the area in the field and transferred to a geodatabase within ArcMap 10.4.1 using high-resolution aerial photography from 2013 obtained from the online Geocatalogue (Geocatalogo, 2017). Hourly air pollution concentration and meteorological data for Meran for the year 2013 (Meteo Alto Adige, 2017) were submitted to the i-Trees database and included in the latest software update (v. 6.0.7).

**Table 1**
Main characteristics of the tree inventory.

| | |
|---|---|
| Area covered hectares | 101.2 |
| Area covered % of total city – excluding military | 16.6% |
| Total trees | 6371 |
| Trees private | 1215 |
| Trees public | 5156 |
| Number of species | 222 |
| Number of genera | 92 |
| Number of families | 40 |

### 2.3. Indicator selection

Composite Indicators (CIs) are a means of providing simple comparisons between entities, such as countries, which reduces the complexity of considering trends in multiple indicators by agglomerating them into one index (Freudenberg, 2003; Nardo et al., 2005). Dobbs et al. (2011) developed indicators of many ES and a few EDS and used a 1 to 3 scale. Exceedance of literature thresholds, subjective decisions related to health impacts in that area, and percentile distributions of measured data were used for ranking. Our method uses individual tree data within an inventory for a specific analysis of the urban forest of Meran, but also looks at the suitability of the compound indicator method for more general situations using species averages and literature data for situations where extensive tree data may be lacking.

Lists of ES and EDS from the literature were consulted (Dobbs et al., 2011; Von Döhren and Haase, 2015) and suitable metrics were chosen for each ES and EDS variable to be included in the CI. Whether an ecosystem function is an ES or EDS will depend on context and the demand by beneficiaries (Soto et al., 2018). The final choice of variables was guided by inclusion of ES and EDS with considerable impacts on human health and comfort in the urban environment. Pollen allergenicity of each of the 222 tree species in the inventory was obtained using the 1-10 Ogren Plant Allergy Scale (OPALS). This scale not only considers the allergenicity of the pollen but also the amount produced, length of pollen season, and specific gravity of pollen grains (Ogren, 2015). Regarding the risk, there are several factors that can stimulate an allergic reaction, such as airflow, rainfall frequency and intensity, air temperature and possible pollen grains' microflora (Sikora et al., 2013). We acknowledge that other factors should be considered for example if a person is in close proximity to a blooming tree and also the minimum pollen amount that can cause an allergic reaction but this is a novel area for future research. For dioecious tree species (20% of the total species) the pollen score was added randomly to only 50% of the trees, assuming the proportions of pollen-producing males and non pollen-producing females (OPALS score of 1) are equal in the inventory. Tree damage potential was estimated by reversing the field measurement of tree canopy condition. The higher the percentage of damage found on a tree, the more likely it is for a branch to fall and cause damage (Dobbs et al., 2014; Soto et al., 2018). To measure the disservice of BVOC emissions and the services of $CO_2$ sequestration, $O_3$ capture, $PM_{2.5}$ capture, avoided rainfall runoff, and evapotranspirative cooling, the i-Tree ECO model was used (i-Tree ECO, 2017) because it is a well-known, comprehensive and reliable tree impact model. The model, which computes annual data for each individual tree, was run with the 6371 trees as a full inventory.

Tree crown volume is a vital component of tree functional models because of the direct correlation between tree size and functional trait levels (Andersson-Sköld et al., 2018). Crown volume was calculated for each tree in the inventory by first calculating canopy height by subtracting height to crown base from the total tree height. The volume of a cylinder is then calculated using this height with tree crown width as the radius. Trees in the pinales order were treated as a cone, with half the volume of this cylinder and the remaining deciduous tree crown volumes were treated as an ovoid which has 2/3 the volume of a cylinder. Adjustments were made to the volume using the field measurements of percent canopy missing and canopy condition to provide a more realistic assessment of crown volume. The volume was manipulated to fit into the 'general' model (see Composite Indicators section below) by dividing into 10 size classes using the Jenks natural breaks method. The provisioning ecosystem service of fruit production was then estimated by giving fruit trees a score of 1 and multiplying this by the crown volume size class, as fruit production is proportional to crown volume. Fruit-fall can also be considered a disservice but this was not included in the current model (Russo et al., 2017). Finally, the pollen score was given some weight for individual tree crown volume by adding the crown volume size class to the Ogren score.

The indicators derived from field data represent the ES and EDS provision bundle for the trees measured in Meran and specifically its geographical and socio-political context. In order to assess the performance of CIs when only general species-specific data from the literature are available, a second set of indicators was created, named the 'general' model to distinguish it from the 'field' model. This can be a useful method for practitioners with only a basic field dataset of species and height class, and when moving from a tree-level analysis to species-level. The ten crown volume size classes were used as species height bracket estimates and added to both the ES and EDS scores. To obtain general species level data for the services and disservices modelled with i-Tree, the ECO model was run using a dummy Meran tree inventory consisting of 100 individuals of each of the species found in the city with uniform measurements for DBH, height etc. The i-Tree model VOC and pollution removal estimates take into account leaf dry weight biomass and air temperature in their calculations (Hirabayashi, 2012). The only variable that changes is species and every other aspect in the model is kept the same, therefore the outputs can be considered general species characteristics. They reflect, however, the underlying parameters used by the i-Trees model and are based on Meran specific weather and pollution data. Frequently the outputs were the same across genera, as a consequence of the limited species-specific parameters in i-Trees. The frequency distributions of each variable used in the 'general' model are shown in Fig. 1.

### 2.4. Composite indicators

Technical guidelines for constructing CIs in a transparent manner are available in Nardo et al. (2005). The protocol used for their development is presented in Fig. 2. To avoid issues with mixing units and scales, indicators are first standardized or normalized (Nardo et al., 2005). The method chosen for standardization should depend on the particular dataset characteristics, and an a priori analysis of the frequency distributions of the raw data should be made. In Fig. 1 it can be seen that the data are not normally distributed, and BVOC production has extreme values which are a result of considerably higher BVOC output from trees in the *Picea* genera. Incidentally, the distributions of the field data all resemble the positively skewed tree crown volume data, reflecting the influence of tree crown volume at the tree-level of analysis. Each indicator was linearly re-scaled using equation 1:

$$I = \frac{\mathrm{x} - \min(\mathrm{X})}{\max(\mathrm{X}) - \min(\mathrm{X})}$$

where $I$ is the rescaled indicator value, x is the tree variable value and X is the entire range of x. The rescaled indicators have values between 0 and 1. This method has been found to be appropriate for dealing with variables with extreme values, as long as they are not unreliable outliers, however it can increase the range of indicators with low variation (Freudenberg, 2003). It essentially calculates the distance from the best and worst performers for that particular datsaset, and is suitable for this dataset. Another common normalization method is to use z-scores (subtracting the variable mean and dividing by the standard error) which avoids aggregation distortions stemming from differences in variable means (Freudenberg, 2003).

The ES and EDS indicators are summed separately and the positive/negative nature of these values is dealt with in two ways. The first way is to reverse the polarity of the EDS indicators, meaning a high score reflects a low provision of disservices, and derive a CI by adding this to the ES score. The second method is simply to subtract the original (negative polarity) EDS score from the ES score.

To assess the impact of different methods for calculating the CI from the separate indicators, a total of ten methods for deriving CIs were used on both the 'field' and 'general' datasets. Fig. 2 provides a summary of these methods. The first two methods are simply addition (CI1) or subtraction (CI2) of the sums of indicators. The next two methods rescale the summed indicators, using the same formula in equation 1,

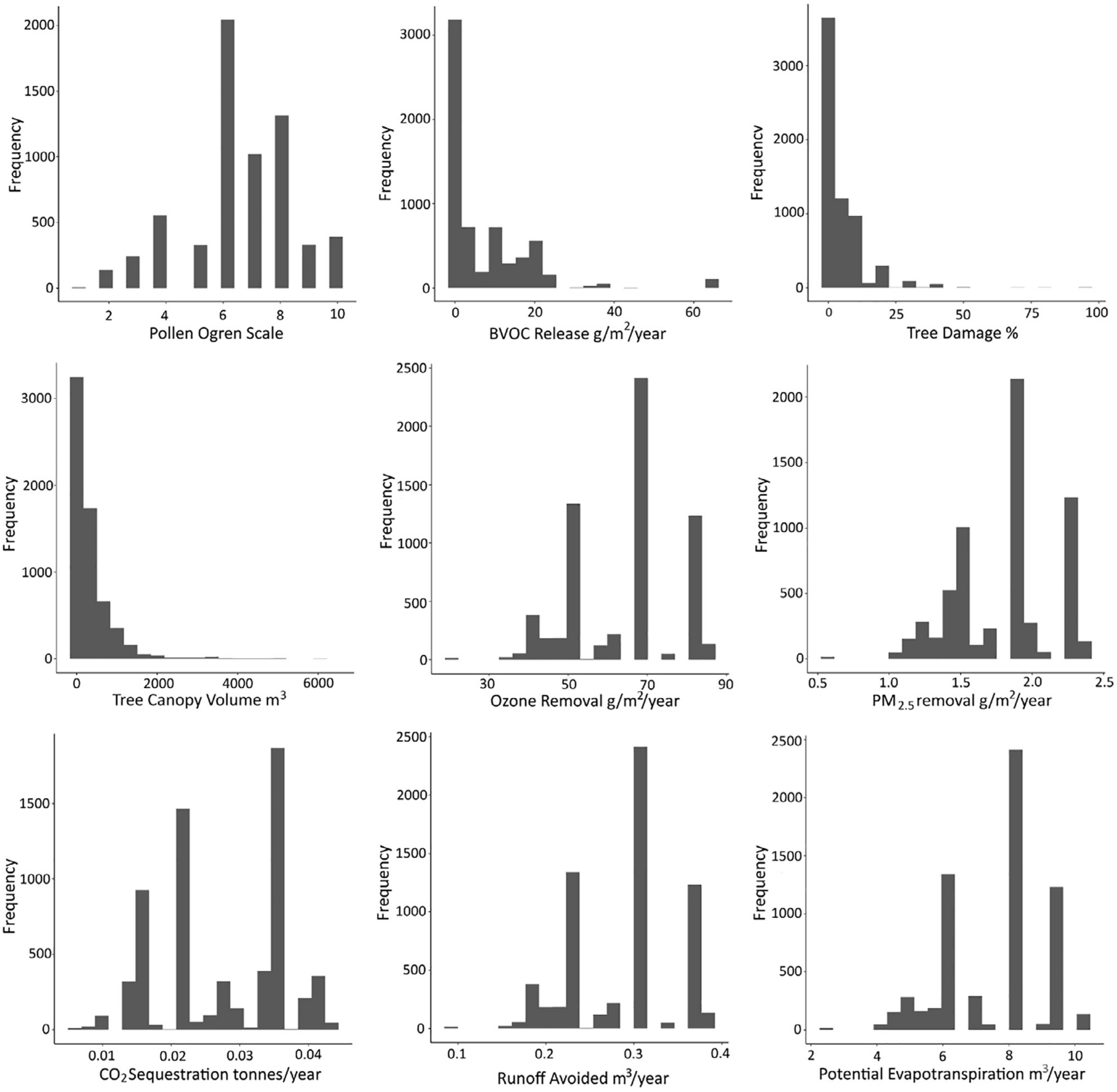

**Fig. 1.** Frequency distributions of the ES and EDS (top row) used in the general composite indicator model. BVOC = Biogenic Volatile Organic Compounds, $PM_{2.5}$ = Particulate Matter smaller than 2.5 µm.

before addition (CI3) or subtraction (CI4). Methods five and six (CIs 5 and 6) divide the summed indicators by the relevant number of indicators that went into their creation. The final four methods (CIs 7–10) repeat methods one to four but first the ES score is weighted. Weights given to an indicator can greatly influence the final CI value, and they are usually allocated to reflect the significance, or reliability of the underlying data (Freudenberg, 2003). In this case, the indicators which are highly correlated to each other (all $r = 0.99$, $p < 0.001$), were reduced in weight by division by four (the number of correlated indicators). Specifically these are ozone and particulate capture, runoff reduction, and evapotranspiration, which are all highly linked to the functional trait of leaf biomass in their action. This weighting method was chosen for its simplicity, however, in practice, weights are often based on stakeholder values.

### 2.5. Ranking species

We used a ranking system to better elucidate the relative benefits among tree species in the study area. The data from the 'general' model can generate ranks of tree performance with regards tree benefit/hazard combinations, therefore the 'general' model is exclusively used in this section Tree damage EDS was not included, however, a species average score for fruit production was. Uncertainty and sensitivity analysis is strongly recommended when using CIs (Saisana et al., 2005). To this end, the mean and variability of the rank positions for each species obtained when using the ten CI methods was plotted. Finally, to assess the effect of adding a tree crown volume class to the CIs, we recorded the magnitude and direction of rank position changes for the different methods.

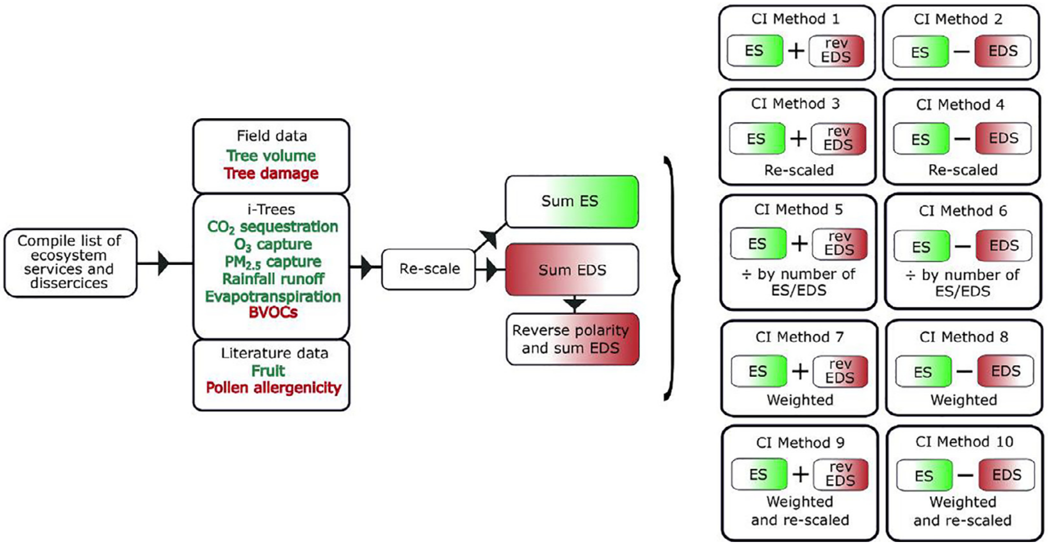

**Fig. 2.** Protocol for developing the ten different composite indicator (CI) methods. Green and red color indicate ecosystem services (ES) and disservices (EDS), respectively. Reverse polarity (rev) means a high score reflects a low provision of disservices. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

### *2.6. Analysis and spatial modelling*

After creation of the CIs, they are compared to each other by a correlation matrix and by examining how well the indicators correlate with the summed ES and EDS separately, and with tree crown volume. The most suitable CI is then chosen to be the final ES/EDS ratio. The distribution of ES/EDS ratio by land type will also be considered because assessing ecosystem functions at the landscape scale is important for landscape management and decision-making (De Groot et al., 2010). Clusters of high (hotspots hereafter) and low (coldspots hereafter) final metric values were mapped using ArcMap version 10.4.1 and the Getis Ord statistic, with a zone of indifference of 25 m (Getis and Ord, 1992).

## 3. Results

### *3.1. Similarity between composite indicator methods*

The ‘field’ CIs all correlate well with each other as do the ‘general’ CIs (Fig. 3). Regardless of whether the CI was constructed from addition of reversed EDS (even numbered CIs) or subtraction of EDS (odd numbered CIs), the most suitable compound indicator is one which simultaneously correlates positively with ES, and negatively with EDS. This shows both of the trends of interest – an increase in ES and a decrease in EDS as the CI rises. For the ‘field’ data, the best indicators in this respect are CI6 and CI7. Ultimately CI6 was chosen as the final metric because it has simultaneously a significant positive correlation with the summed ES ($r = 0.20$, $p < 0.001$) and a larger negative correlation with the summed EDS ($r = -0.50$, $p < 0.001$) than CI7 ($r = -0.28$, $p < 0.001$). An indicator that correlates better with EDS is preferred for a study with a specific interest in the distribution of EDS. CI6 also had the best correlations between the ‘field’ and all the ‘general’ indicators. Accordingly, CI6 will be used as the final Ecosystem Service/Disservice (ES/EDS) metric in subsequent spatial analyses.

With the ‘general’ indicators, CI3 to CI6 have unexpected negative correlations with the summed ES so the simpler indicator construction methods of CI1 and CI2, or weighting, are advised for the ‘general’ model. The ‘field’ model generally has a higher correlation with tree crown volume because the crown volume of the individual trees went into the production of ‘field’ CI values, whereas with the ‘general’ model, volume information is lost in the process of converting to a categorical variable.

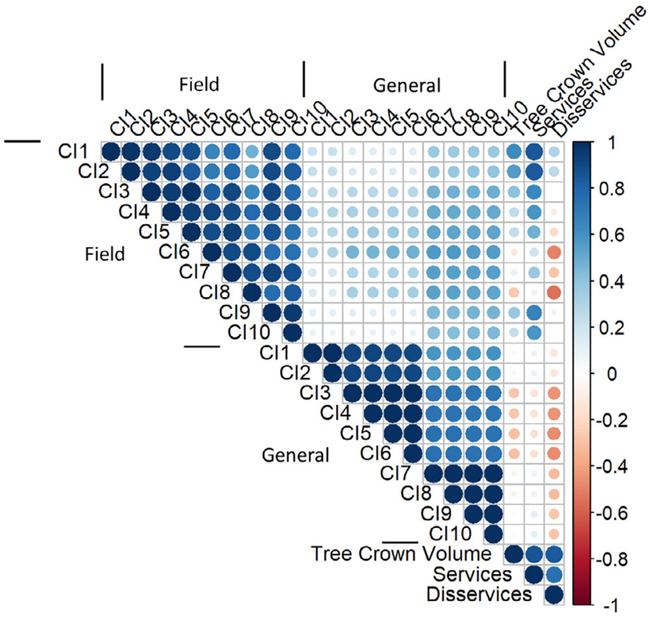

**Fig. 3.** Correlation matrix for the 10 different composite indicator (CI) methods with both the ‘field’ and ‘general’ models. Blue and red indicate positive and negative correlation respectively. Size of circle indicates correlation strength. Services are the summed ES indicators and disservices are the summed EDS indicators. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

### *3.2. Sensitivity analysis*

The different methods used to calculate the CI affected the ranking positions of the tree species (Fig. 4, full data in Appendix). The mean average difference between the lowest and highest ranks obtained with the different CI calculation methods was 61, and 15% of the species had differences over 100. The importance of tree crown volume in the construction of the ‘general’ CIs is demonstrated in Fig. 5. Note that with the ‘general’ CIs, the two methods of combining ES and EDS into one CI are effectively the same. The CI construction methods that involve rescaling after the initial rescaling of component variables (CI methods 3–6, 9, and 10) have the greatest changes in rank position

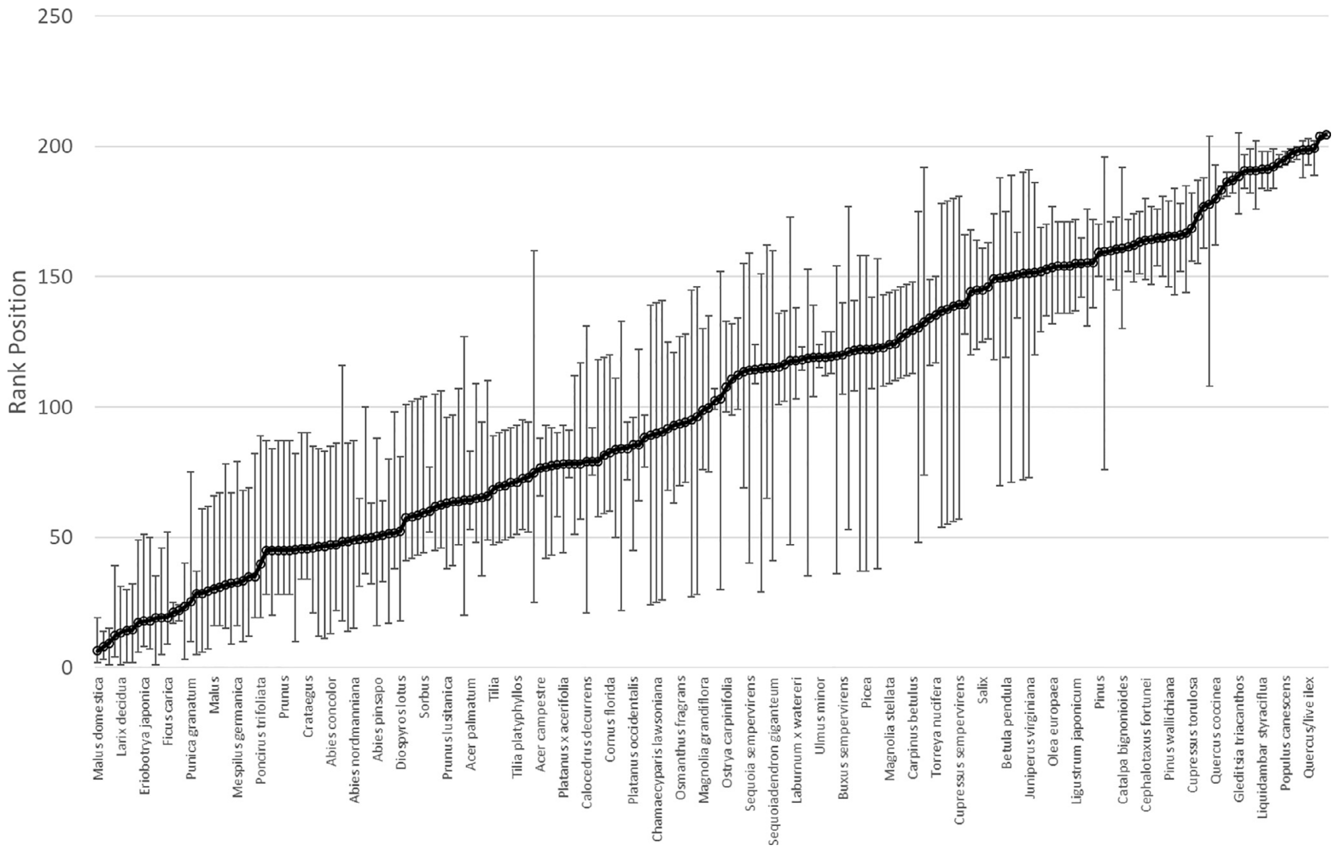

**Fig. 4.** Mean rank position for each species from the 10 different CI methods using the 'general' model. Upper and lower error bars represent the lowest and highest rank achieved respectively (all species names not shown). Lower rankscores indicate simultaneous high ES provision and low EDS provision.

when tree crown volume is added.

### 3.3. Land-use patterns

Trees on private land tenure are on the whole very similar to trees on public land tenure in terms of ES provision, however the species on private land appear to have a lower Ogren score on average, significantly higher BVOC production, and are approximately four times smaller on average than the trees on public land (Table 2). Private land trees are also more likely to be fruit producers, but also to show signs of damage.

Fig. 6 shows the spatial arrangement of individual trees in the 'field' model in relation to the results of the hotspot analysis performed on the final metric (CI6). Some areas of relatively low ES/high EDS include a large part of Meran's cemetery consisting of high numbers of *Thuja* spp., *Cupressus* spp. and *Cedrus* spp. trees, a row of *Populus alba* tree alongside the river, and a row of *Ligustrum lucidum* as street trees in the eastern residential area of the city. Conversely, areas of high ES/low EDS include a street of *Aesculus hippocastanum* near the city centre, and the equestrian centre to the south of the city dominated by *Tilia americana*. The tree species rankings, along with species abundance data, can be found in the Appendix. The top half of the list are labelled 'above the median average' and the following spatial patterns were found. 66% of all the public trees and 56% of the private trees are classed as above average. The land types with the highest proportion of above average species are street (80%) and piazza (70%), with cemetery (40%) and parks (49%) having the lowest proportions.

## 4. Discussion

An approach using compound indicators to represent a final tree-level ES/EDR ratio, offers a suitable method for combining ES and EDS into one metric, despite their inverse impact on human well-being at a localized scale. It also provides a way of overcoming the difficulties of combining biophysical impacts measured using different units. The 'field' data CI allows site-specific assessments of ES and EDS provision from the tree level potentially up to the urban ecosystem level, provided enough high-quality data can be collected from a tree inventory, especially tree crown volume given its importance for local ES and EDS provision. The 'general' data CI allows for a better understanding of the local-level net benefits and costs of different tree species, given species data from the literature and basic tree inventory data.

### 4.1. Application of the method

The species rankings highlight the tree species which may be better than others for urban planting schemes in the context of Meran, Italy. For example, *Juglans regia* and *Celtis australis* have fairly high Ogren pollen scores (low reverse pollen score) but are low BVOC emitters and high ES providers. At the other end of the scale, *Quercus* and *Populus* genera are high pollen producers and relatively poor ES providers. *Gleditsia triacanthos*, near the bottom of the list, also had the lowest shading factor in a list of 47 common urban trees (McPherson, 1984). The pinnate compound leaf structure means it is outperformed by many species with larger leaves, however, it is included in many urban tree planting schemes for its high aesthetic appeal, which underlines the importance of the relative importance of ES and EDS depending on the point of view.

The high proportion of above average ES/EDS ranking species in the city of Meran is good news for the municipality, especially as two-thirds of the trees on public land are above average. The cold and hotspots observed in Fig. 6 can be used to target areas where improvements in species selection and subsequent plantings or preservation may be beneficial, or simply to highlight areas where ES outweigh EDS in

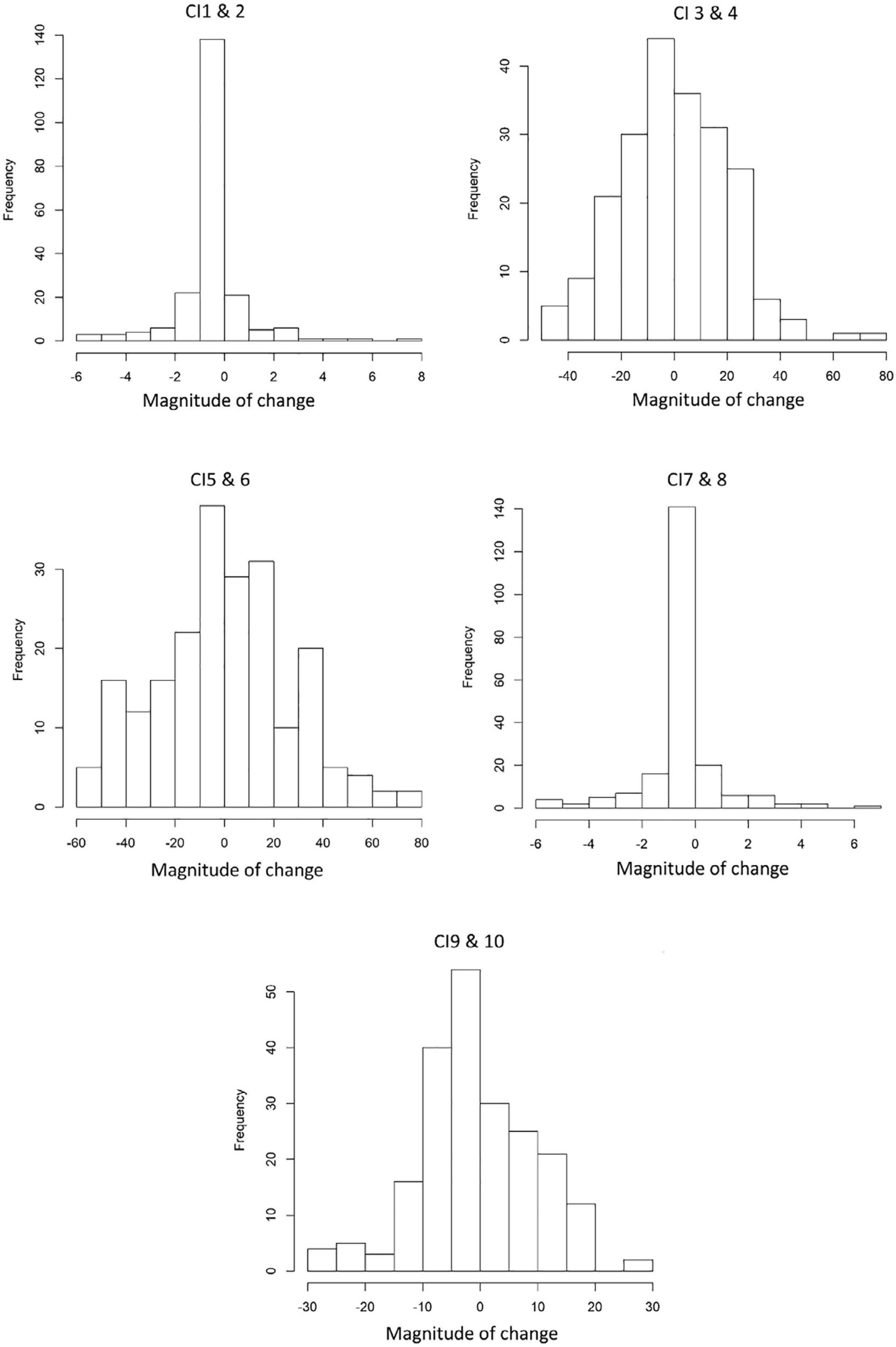

**Fig. 5.** Frequency distributions of the magnitude of the change in rank of each species when tree crown volume size class is included with ES and EDS in the different CI methods.

general. For example, the monospecific plantings which can occur on public land lead to areas of high or low relative ES provision depending on the constituent species. Interestingly the opposite pattern was found to Dobbs et al. (2014) who noted EDS were lower in parks and higher in streets.

### *4.2. Method limitations*

The species rankings from this study should be applied to other cities with caution, because of the specificity of the data which went into their creation, such as the i-Trees model output using Meran

**Table 2**
Mean average (and SD) values for the ecosystem services and disservices, and tree crown volume for public and private land tenures using the field data. * = Significant at 0.00125 after Bonferroni correction added to the familywise error rate of 0.01, using Kruskal-Wallis test.

| | Public (n = 5156) | Private (n = 1215) |
|---|---|---|
| Particulate Matter capture (g/yr) | 1.79 (0.4) | 1.84 (0.4) |
| Ozone capture (g/yr) | 63.5 (12.7) | 64.7 (13.8) |
| Runoff avoided ($m^3$/yr) | 0.28 (0.1) | 0.29 (0.1) |
| Carbon (tonne/yr) | 0.03 (0.01) | 0.03 (0.01) |
| Potential evapotranspiration ($m^3$/yr) | 7.6 (1.5) | 7.7 (1.6) |
| Volatile Organic Compounds (g/yr) | 6.4 (9.6) | 10.8 (15.2)* |
| Pollen (Ogren) | 6.6 (1.6) | 6.3 (2.4) |
| Tree Crown Volume ($m^3$) | 411.4 (609.5) | 107.7 (190)* |
| Fruit trees | 3% | 18.9% |
| Trees with damage 30% and over | 2.5% | 14.1% |

climate and pollution data. Calculating tree-level CIs and mapping the final ES/EDS ratio is a step toward standardizing a metric for all cites, however it is heavily reliant on the quality and wide-ranging applicability of the underlying data. For example, i-Trees model variables can be very US-specific. The Dobbs et al. (2011) ES and goods supply indicator method was also very specific to the Gainesville, Florida study site. They suggested rescaling of the indicators for use in new areas using context-specific data. Additionally, as new data become available for an area, this may also change the CI values or tree rankings. Similarly, Soto et al. (2018) noted the need to account for beneficiary demand when quantifying and mapping ES across different scales.

Collinearity of field data could be considered a problem, for example the high correlation between ozone and runoff reduction due to these properties being highly dependent on the same functional trait (i.e., leaf area). Accordingly, weighting can deal with this issue, however weighting schemes may be based on overly complex multivariate methods that could potentially have little practical management applications. Future studies may need to incorporate expert opinions, citizen demand, and change the weights for the purposes of the study (Saisana et al., 2005), or simply perform a sensitivity analysis on the use of different weights. Weights could be related to the spatial scale that ES and EDS operate on, or added to evergreen species to reflect year-round provision of leaf-related services and disservices.

The next thing to consider when calculating CIs is what will happen when more specific ES and EDS, at different scales (i.e., individual tree versus watershed-scale) are added to the model, culminating in a

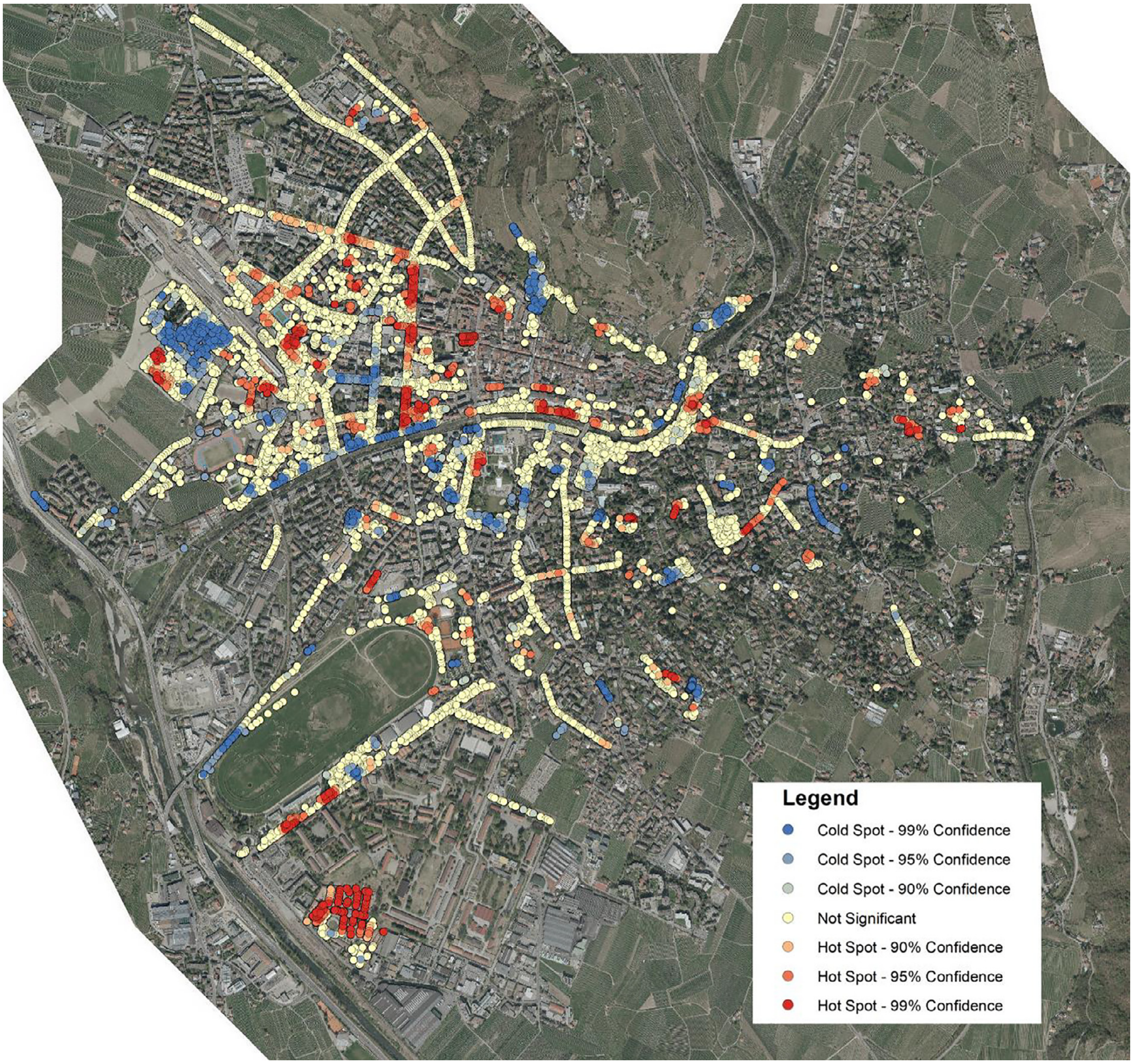

**Fig. 6.** Hotspot analysis for the studied trees. Hot and cold spots indicate clusters of high and low composite indicator values for the final ES/EDS ratio.

theoretically complete picture of all the ES and EDS possible for a tree or location. There is the chance that too many indicators and scaling effects combined can mask the existence of strong or important ES, which deserve more attention, with average ones. Equally, considering large numbers of EDS against a single ES may distort the overall picture. This is where CI construction transparency and sensitivity analysis is important (Saisana et al., 2005). The sensitivity analysis (Fig. 4) showed that the choice of CI aggregation method can greatly influence the rank position so there is a need to be clear about the reasons for the choice of method. In the case of this dataset it was CI6 which most captured the simultaneous positive and negative trends of the underlying ES and EDS data.

Finally care must be taken with interpretation of CIs. A low CI does not necessarily identify a tree or species as “bad” or more damaging to the environment than others. Instead, it is simply drawing attention that, given certain contexts, some local-scale sites might need more attention, for example, location of high pollen producing trees next to potentially sensitive human receptors. Once a poor performing tree or area has been identified, one should return to the detail of the underlying parameters in the CI. The CI does not indicate net benefits as this depends on the range of ES and EDS considered and also the CI is a relative scale based on the specific dataset that went into its construction. As Escobedo et al. (2011) suggest, urban forest management decisions should describe ES and EDS as a continuum; not just an “either/or” decision.

The following lists the steps required in order to create accurate and credible composite indicators. The reader is referred to Nardo et al. (2005) for an in-depth treatment:

- Build a theoretical framework – which ES and EDS to include
- Collect context-specific data on ES and EDS and make sure they are relevant and accurate
- Impute missing data, if needed. This can affect accuracy and credibility
- Choose weighting and aggregation methods
- Perform a sensitivity analysis on indicator inclusion, weighting methods etc.
- Presentation and visualization – provide clear messages without obscuring data points

An important decision to make, specific to ecosystem service CIs is how to account for tree crown volume effects. When tree crown volume is included in the CI construction it can have low or high impact on the resulting tree ranks depending on the CI method (Fig. 5). Omitting crown volume from the CI can give relative species information, which must then be modified when applying to the field with community tree size data.

### *4.3. Implications of research*

This assessment of the relative benefits of urban trees once EDS have been accounted for will allow a proactive tree management i.e. working with the complexity of ecosystems to assess trade-offs at different scales or directly minimize EDS through management (Shackleton et al., 2016). Tree planting schemes are often fast-track and thus do not take into account the subtleties of tree species selection or placement (Churkina et al., 2015). High BVOC emitting species should not be planted in areas of high traffic density for example. Online databases, such as Citree, have been created to assist in such tree selection efforts for urban areas (Vogt et al., 2017). The selection tool allows users to choose trees based on several ES, including aesthetic characteristics, and aims to help avoid removal of trees due to EDS or non-optimal tree placement. The EDS, termed ‘risk and interference potential’, consist of allergenicity, allergen period, toxicity, limb breakage, invasion risk, damage by roots, fruitfall, odour, and thorns. Such tool allows for a more skillful selection of urban tree species (Vogt et al., 2017) by allowing the user to at least consider, on a yes/no basis, the potential risks associated with some trees. The CI method offers an opportunity to improve this tool by allowing a more refined assessment of benefits and hazards associated with a particular species.

The next step for constructing CIs for urban ecosystems is to ensure high quality data availability for the multitude of ES and EDS. Growing tree functional trait databases should include cultural services alongside the biophysical ones, and should experiment with different measuring techniques. For example, Hofmann et al. (2017) created a 1–100 tree preference scale for measuring public perceptions of tree aesthetics. More refined models should consider the full range of associated services such as ES and EDS of the understorey soil ecosystems, or incorporate impacts on different scales such as weights added for continuous stands as opposed to isolated trees.

In conclusion we propose that compound indicator metrics be used as the catalyst for a hierarchy of systematic activities and practices related to identifying ES and EDS and investigating the relative magnitude, importance and distribution of EDS.

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## Appendix A. Supplementary data

Supplementary data ‘Tree species abundance and ranking statistics’ associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ecolind.2018.07.048.

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