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Total urban tree carbon storage and waste management emissions estimated using a combination of LiDAR, field measurements and an end-of-life wood approach

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Abstract

Climate action plans, with goals for carbon neutrality of cities, often rely on estimates of urban forest biomass and related annual carbon sequestration balanced against citywide carbon emissions. For these estimates to be successful, there is a need both for accurate quantification of urban tree populations and structure, and consideration of the net carbon sequestered when the fate of wood waste is factored in. This study provides a novel approach to providing a full city tree inventory for the city of Meran in northern Italy, using a combination of Light Detection and Ranging (LiDAR) and field techniques. Allometric equations, and the i-Tree application quantified the carbon storage in Meran as 8,923 and 9,213 Mg respectively, with an average carbon storage of 13.5 t/ha (5.47kg C/m^2). The percentage of traffic emissions sequestered annually is 0.61% falling to 0.17% when all emissions are considered. Differences between end-of-life wood management techniques were revealed, with burning with energy recovery for electricity being the most efficient with a carbon emissions/input ratio of 0.5. Landfill was the least efficient with a ratio of 121.9. The fate of this end-of-life wood has significant implications for carbon budget calculations in cities worldwide.

Keywords

Urban tree inventory, LiDAR, carbon sequestration, missing value imputation, urban tree growth, IPCC waste model, i-Tree

1. Introduction

Anthropogenic emissions of greenhouse gasses since the industrial revolution have led to global temperature rises and an increase in extreme climatic events, with an associated rise in threats to ecosystems, human health, and biodiversity (IPCC, 2013). Cities play a substantial role in the global carbon cycle, as they are a primary source of CO_2 emissions from energy consumption and transportation (Churkina, 2008). Land cover conversion in the form of urbanization is increasing worldwide as the result of an increasing proportion of the global population that now lives in cities (UN, 2011). Urban areas, in particular, are where the impacts of climate change may be exacerbated (Nowak and Crane, 2002). Therefore, cities have to be targeted as sites of action for mitigation and adaptation techniques (Dhakal, 2010).

Urban tree conservation and planting as nature-based solutions are considered effective and low energy-intensive strategies of both mitigating greenhouse gas emissions directly via photosynthesis and carbon storage in woody tissues, and indirectly by providing cooling via shading and evapotranspiration which reduce subsequent energy use and CO_2 emissions (Stone, 2012). Additionally, urban forests (tree and forest resources within urban ecosystems) provide a host of other ecosystem services, e.g. pollution mitigation (Escobedo et al., 2011). Urban forests can also be a consistent source of biomass (McKeever and Skog, 2003), and many studies have sought to quantify this biomass and their carbon storage potential, often balancing the carbon stored against the carbon emitted from the city under consideration (McPherson and Kendal, 2014; Vaccari et al., 2013; Zhao et al., 2010; Timilsina et al., 2014). Studies such as these are of great interest to local governments who play a crucial role in climate change mitigation activities, and who adopt climate action plans with goals for carbon neutrality of a city (Damsø et al., 2017; Kennedy and Sgouridis, 2011).

Mitigation of carbon emissions by sequestration in urban tree biomass has been shown to vary greatly in scope globally. Jo (2002) demonstrated that greenspace (including soils) in three cities in South Korea was able to annually offset an amount of C-equivalent of 0.5 to 2.2% of total emissions from energy consumption. Two cities in Florida, USA, were able to sequester 3.4% and 1.8% of total annual carbon emissions in their trees (Escobedo et al., 2010). Vaccari et al. (2013) showed that green space in Florence, Italy offsets 6.2% of direct carbon emissions, or 1.1% when greener peri-urban areas are not considered. The urban forests of Shenyang, China, were able to offset 0.26% of the annual emissions (Liu and Li, 2012). This variation is a product of both the urban forest extent, density, growth rates as well as the allometric biomass estimation methods used for calculating carbon sequestration and emissions (Timilsina et al., 2014). A number of studies only consider public or street trees in their assessments with consequent reduced carbon offset estimates. Reynolds et al. (2017) showed that 0.06% of total and 0.07% of transportation emissions were sequestered by 182,044 public trees in Medellin, Colombia. Russo et al. (2015) revealed public trees in Bolzano, Italy, could offset 0.08% of transportation associated carbon emissions. Finally, in an assessment of 35 Chinese cities, which only considered public urban greenspace, a collective figure of 0.33% of carbon emissions from fossil fuel combustion could be offset (Chen, 2015).

Variation also exists in the methods used to estimate the tree population using inventories and sampling protocols (species, numbers, areal coverage) as these form the basis for these biomass-carbon accounting estimates. The studies which consider only public trees rely on existing tree inventories created and managed by municipalities (Russo et al., 2014; Chen, 2015). The difficult task of estimating tree populations for entire urban areas, including private land which is often difficult to access, has necessitated a methodological sampling approach which aims to minimize estimation errors. By far the most popular sampling method is adapted from conventional forest sampling protocols and uses randomly allocated, fixed size, 0.04 ha circular plots as prescribed by the i-Tree methodology (Nowak et al., 2008a; Escobedo et al., 2010; McPherson et al., 2013; Timilsina et al., 2014). These can also be combined with visual assessments of tree cover from satellite imagery (Liu and Li, 2012; Nowak et al., 2013). The low sampling size, and spatial coverage of these plot-based estimates, however, has been highlighted as a potential source of error in species richness and diversity estimates, as it will miss many species, especially in larger cities (Speak et al., 2018). Similarly the time and effort involved with travel, plot location, permissions, and actual tree measurements can also be costly (Speak et al., 2018).

More recently, the increased availability and quality of high resolution Light Detection and Radar (LiDAR) data can be exploited to produce more accurate and cost-effective estimates of urban forest coverage (Alonzo et al., 2016) and biophysical parameters such as crown height and width (Shrestha and Wynne, 2012). MacFaden et al. (2012) for example undertook a time and labour intensive analysis of LiDAR data from New York City's five boroughs, which allowed evaluation of height and texture of above-ground features to be assessed, and resulted in a fine-scale map of the tree canopy within a complex urban environment.

An additional consideration with urban tree carbon sequestration studies is whether tree maintenance related carbon emissions from pruning, planting, and fertilizing activities are accounted for. This net carbon sequestration is considered the difference between overall, or gross, C sequestration minus maintenance-related and other biotic C emissions such as decomposition. Horn et al. (2015) found these maintenance-related emissions to be 0.1% of total gross C sequestration in Florida, USA.

The life cycle assessment (LCA) approach is another carbon estimation method that was used by McPherson and Kendall (2014) to assess the impact of a large-scale tree planting program with a time period of 40 years in Los Angeles, USA. They found that the total emissions associated with the project outweighed the amount of carbon projected to be stored in biomass. The program only became a carbon sink when the reduced CO_2 emissions from energy savings were factored in. LCA is advantageous because it considers all the linked sinks and sources of carbon over the entire lifespan of the system under observation, which most C sequestration studies tend to ignore. LCA is also sensibly applied to the management of the wood waste generated from prunings, and indeed what happens to dead trees, which dictates the fate of the carbon stored over the tree's lifetime and whether it remains sequestered or released (Boschiero et al., 2015).

We know of few studies that combine LiDAR and field sampling to assess urban forest structure on both public and private lands, and that also use LCA techniques to estimate carbon dynamics. Thus the overall aim of this study is to undertake a realistic assessment of a city's carbon sequestration potential. The specific objectives of the study are to:

- characterise a full city tree inventory with a more accurate species richness and tree measurement component,
- quantify the gross carbon storage and annual sequestration of the urban forest, and
- evaluate the impact of different end-of-life tree management scenarios on the fate of the stored carbon.

2. Methodology

2.1 Study Site

Meran, a city of about 40,000 inhabitants (ISTAT, 2019), 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. 760mm and minimum and maximum average temperatures of 5.0 ^{O}C and 18.1 ^{o}C, respectively (Meteo Alto Adige, 2019). It covers approximately 661 hectares (Figure 1). Meran is one of the many global cities that have joined the Covenant of Mayors initiative, and pledges to reduce CO_2 emissions by 20 % by 2020 (SYNECO, 2013). We worked closely with employees of the municipal gardens and civil protection departments, who provided us with information on public and riverside tree removal rates, and procedures for dealing with wood waste.

The city was classified into 17 land types following the i-Tree land classification scheme (i-Tree ECO, 2017) but using subdivisions of the 'commercial' and 'institutional' land types. Figure 1 shows that the city has a central commercial centre surrounded by mostly multi-occupancy apartment blocks, with smaller houses situated in the more affluent east. The large park to the south is an equestrian park, which mostly consists of frequently mowed grass with peripheral trees. Figure 2 displays the following methodological steps, outlined below, in a schematic diagram.

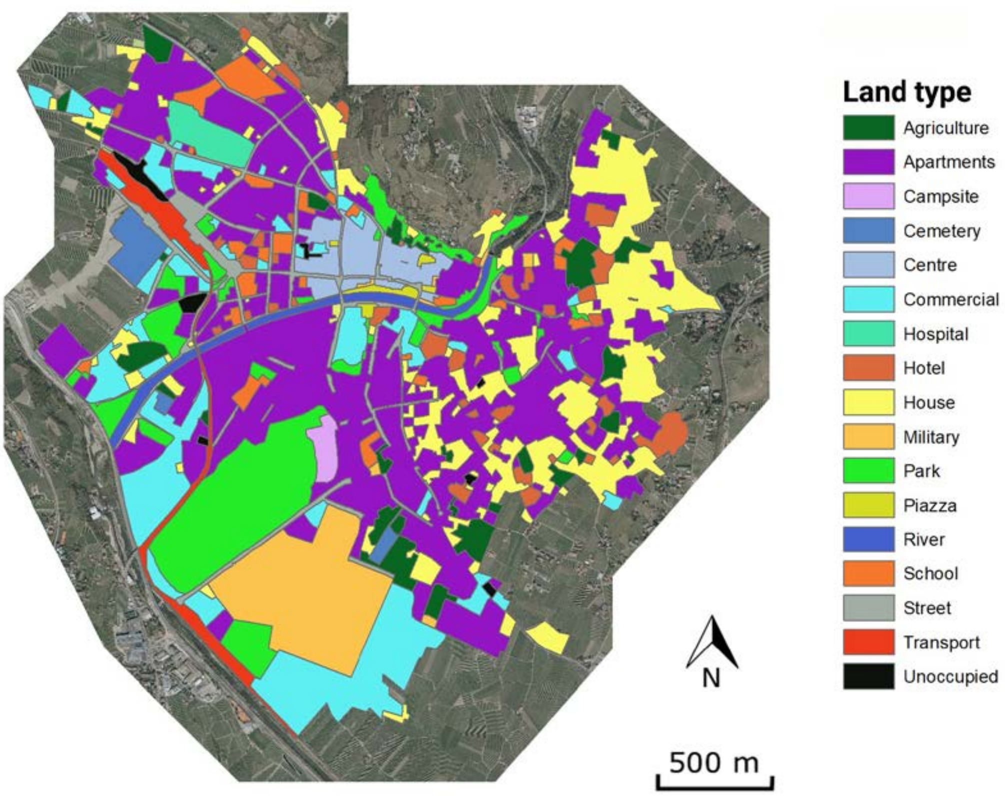

Figure 1 – Land type classification map for Meran, Italy

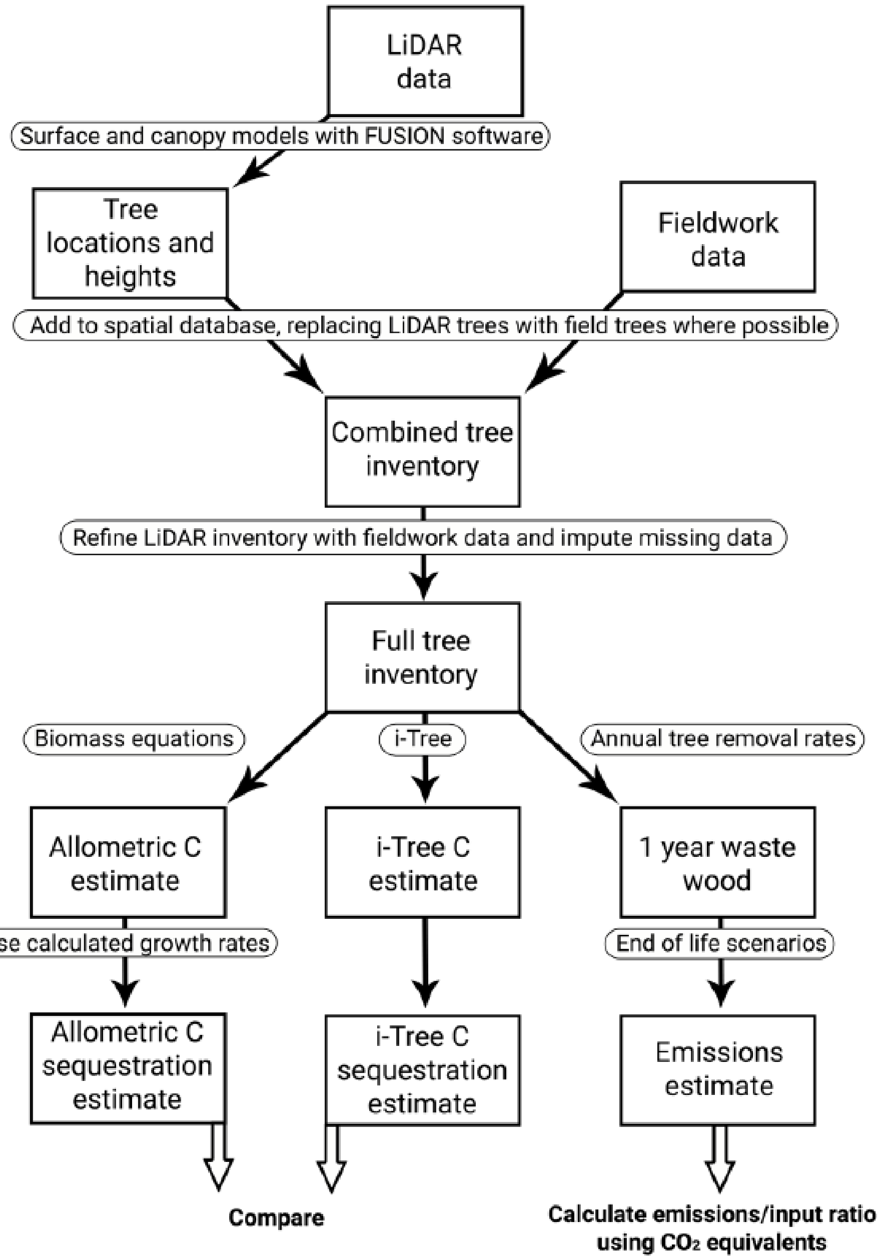

Figure 2 – Schematic diagram of the methodological steps

2.2 Field methods

The study uses data from an extensive fieldwork campaign, which took place during autumn 2016 (see Speak et al. (2018) for a full description). 964 trees on public land and 1,215 trees on private land were identified mostly to species level and occasionally to genus level using Phillips (1978). Diameter at breast height (DBH, 1.37 m) was measured with calipers, and height was measured with a Blume-Leiss BL6 hypsometer from a distance of 30 m. Diameter at 1 m was also measured as this was the height at which diameter was measured for the municipal tree inventory. Additional data for the i-Tree Eco application were collected, following the guidelines of Nowak et al. (2008b), which included crown-base height, crown width, percent crown dieback, percent missing canopy, and crown light exposure.

Individual 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, 2019). Tree species, location, height and DBH for an additional 4,192 trees on public land were obtained from the Meran municipality street-tree inventory (Comune di Merano, 2019). Finally, a further 543 trees were identified to the species level on targeted land types such as the military zone, riverside and commercial. This additional fieldwork was intended to enhance the species accuracy of the full city inventory described below.

2.3 LiDAR Inventory

Airborne LiDAR data was collected in 2016 with a high resolution of 4 pulses/m^3 for the entire study area (Geocatalogo, 2019). LiDAR processing software FUSION version 3.60 (McGaughey, 2016) was used to create a bare earth surface model by filtering the point cloud to identify bare earth points. A canopy model was then computed from the highest returns, and canopy maxima were derived by subtracting the bare earth model from the canopy model. The local maxima algorithm employed to identify tree peaks was similar to that reported in Popescu et al. (2002). The individual tree locations and heights were then exported to ArcGIS. A lower threshold for tree height was set at 5 m to avoid complications associated with false classification of small urban structures and shrubs. However, several building features such as turrets and gables were still mistakenly classified as trees. These were removed by deleting all points which overlapped with a building plan shapefile for the city.

Deciduous trees with broad crowns are frequently classified as multiple local maxima, leading to a potential overestimation of tree number, despite the method failing to capture the infrequent presence of smaller trees under larger trees (Popescu et al., 2002). To overcome this, tree density was calculated from the field data for each land type and this was used to derive a correction factor to apply to the unmeasured areas. The assumption is that each land type has a characteristic tree density, which was captured by the field sampling. This is similar to the land class-based transfer function proposed by McPherson et al. (2013). Each land type then had a fixed number of tree points to remove manually from the point shapefile in ArcGIS by targeting the deciduous trees with multiple peaks easily identified by eye.

Field measured trees were matched to LiDAR trees using the near neighbor tool in ArcGIS with a radius of 4 m followed by removal of any superfluous peaks captured by this radius. Finally, 1,400 individuals of *Cedrus spp*. and *Cupressus sempervirens* in the whole city inventory were easily visually identified, using texture, colour and shape of shadow, using the aerial orthophotograph. This systematic visual analysis of the city was time consuming, but increased the species richness accuracy of the final tree inventory, especially as Cedar trees are very common in Meran.

2.4 Missing Data Imputation

The next step was to estimate species and tree size and crown attributes (DBH, tree condition) for the remaining LiDAR-derived tree points on private land for which only height data exist, thus creating a full city inventory estimation. Missing value imputation was undertaken using the MICE (Multivariate Imputation by Chained Equations) package version 2.3 in R (Van Buuren and Groothuis-Oudshoorn, 2011). Missing species names were imputed with predictive mean matching, DBH with norm.predict (predicted values from linear regression), and crown width, height to crown base, crown light exposure, canopy condition and canopy missing values imputed with Classification and Regression Tree (CART), all using height as the predictor variable.

To improve the accuracy of the imputation, trees are first separated into three height classes using the Jenks natural breaks classification method in ArcGIS, and imputation carried out on the separated datasets. This ensures that species labels are imputed onto relevant tree heights. Additionally, two land types with very characteristic species assemblages (riverside, unoccupied land) were imputed separately. It is assumed that the tree species mix for each land type was captured adequately and the remaining unmeasured areas have the same species diversity. This is reasonable given the ability of the convenience sampling methods employed to sample a city’s species richness (Speak et al., 2018). Correlations of field-measured tree abundance and trait measurements against LiDAR and imputed were carried out using R.

2.5 Tree Allometrics

Once the full city inventory is estimated, allometric equations for calculating above-ground biomass from DBH and/or tree height, are used within a spreadsheet to calculate the carbon storage capacity. The mostly Europe-specific equations are the same as those used in a similar urban tree carbon storage study which took place in Bolzano, a nearby city (Russo et al., 2014). The current study featured more species, however, and the full list of allometric equations can be found in Appendix A. The dry weight above-ground biomass is multiplied by 0.5 to obtain carbon storage (Nowak and Crane, 2002).

In order to calculate annual carbon sequestration, we first estimated diameter and height increments. The diameter growth was calculated using field measured DBH at 1 m data and the historical DBH at 1 m from the public tree inventory. The annual growth rate is calculated as:

$$AGR = \left(\frac{DBH2 - DBH1}{t}\right) * 12$$

Where AGR is the annual growth rate in cm/year. DBH1 is the DBH from the inventory, DBH2 is the field measured DBH from 2016, and t is the time difference between DBH1 and DBH2 in months. AGR were calculated at the taxonomic order level, as by Russo et al. (2014). Previous DBH information was not available for five tree orders on private land, which were not included in the municipal tree inventory. In order to get the AGR for these trees, re-measurements of the DBH of a subselection of 26 individuals were made in autumn 2018 and the AGR calculated by the increase in DBH divided by 2.

Height increments were estimated using the LiDAR dataset from 2016 in conjunction with a LiDAR dataset from 2007, to which the same process for deriving tree positions and heights was applied as described above. Trees in the two datasets were matched using near neighbor analysis with a radius of 1 meter in ArcMap. Only the trees for which species information was known (i.e. excluding those estimated with imputation), and which were able to be matched using the 1 m radius, were used to derive species specific height increments, and these numbered 1,305.

The annual DBH and height growth rates are applied to all the trees in the inventory for a time step of one year, and carbon storage re-calculated. Carbon sequestration is simply the carbon stored in the first year's estimate subtracted from that of the second year's estimate (Russo et al., 2014).

We compared the carbon storage and sequestration estimates derived from the allometric equation-based approach with estimates produced by the available i-Tree Eco application. The tree species, DBH and height data, from the full tree inventory, along with the necessary additional measurements mentioned previously were uploaded to i-Tree, and climate data specific to Meran were selected. An i-Tree estimate based on 200 random circular plots from Speak et al. (2018) was also included for comparison. The i-Tree estimate takes into account below-ground biomass, therefore to make the estimates comparable by only considering above-ground biomass, we subtracted an amount from the allometric estimate based on a root-to-shoot ratio of 0.26 as used by Russo et al. (2014). The i-Tree estimates also adjust growth rates based on the tree condition, therefore we adjusted our allometric tree volume estimates using the canopy missing percentage, and used tree condition to adjust AGR estimates according to Nowak et al. (2008b), i.e. no adjustment for trees in fair to excellent condition, multiply trees in poor condition by 0.76, critical trees by 0.42, and dying trees by 0.15. Emissions estimates for traffic only and for traffic, energy and heat generation in Meran were obtained from the carbon management plan (SYNECO, 2013).

2.6 End-of-life Carbon

In order to derive a quantity of wood waste for subsequent modeling, appropriate tree removal rates were applied to trees on public land (4%), and riverside and abandoned land (4.3%) based on data from the municipality of Meran, and to trees on residential/hotel property (4.6%) and all remaining private land types (5.1%) based on Hilbert et al. (2018). The mortality rates were applied to the inventory trees randomly 1,000 times and the average total above-ground biomass taken as input to the assessment of end-of-life processes. We consider only the end- of-life disposal activities, as this determines the ultimate fate of the sequestered carbon. A full LCA approach, which considers emissions from the entire lifetime of a tree (Strohbach et al., 2012), including fuel used for pruning equipment and transport vehicles, is beyond the scope of this research. The planting of new juvenile trees to replace those removed is assumed to confer only a limited amount of carbon storage over the 1 year time span considered in this study, therefore it is not included in calculations.

Trees from urban areas are not normally turned into wood products, a form of long-term sequestration (McKeever and Skog, 2003). Therefore the scenarios assess the net release of CO_2 equivalent (including CH_4 and N_2O where appropriate) using different methods of treatment of waste wood. Appendix 2 details the different general wood-waste treatment techniques and the calculations for net carbon release. The IPCC waste model (IPCC 2006) was used to calculate methane generation from landfill. The waste wood biomass is entered for one year's input and the sum of 50 years' worth of methane generation is summed (IPCC, 2016). The production of biochar is a growing soil amendment technology which is reported to have a 20 % carbon sequestration efficiency over mulching alone (Lehmann, 2007).

Two real-world scenarios, which consider actual treatments used in Meran are simulated. Dead trees in Meran are usually chipped and the woodchips are sold as mulch. Little research exists on the decay and carbon release dynamics of woodchips but, McPherson et al. (2015) propose that all the carbon within mulch is released within a year. The municipality operates a small wood energy boiler which generates some energy and heat from 40 tonnes of the public land wood waste annually, with the rest going to woodchip. The wood waste from private land is modelled in scenario one as going into the municipal waste stream with the average waste treatment proportions for Italy of 40 % landfill, 30 % incineration, and 30 % compost (when recycling is omitted) (IPCC, 2006). The second scenario models a situation where all the wood waste from private land is collected by private garden maintenance companies and turned into woodchips for mulch.

3. Results

3.1 Tree Inventory

The full estimated tree inventory, comprising field measured trees, public trees registered by the municipality of Meran, and trees located by LiDAR, contained 25,497 individuals. Species lists for field-measured and municipal trees can be found in the supplementary data of Speak et al. (2018). 7,017 trees were identified taxonomically in total, which is 27.5% of this estimated inventory. The field-measured land surface area comprised 15.3 % of the total city area. The heights of trees measured in the field correlate well with the LiDAR derived heights ($r = 0.95$, $p < 0.001$, $n = 2,179$).

The abundances of the species correlate well between private land measured and imputed ($r = 0.78$, $p < 0.001$). Mean DBH by species correlates well between measured and imputed ($r = 0.55$, $p = 0.01$), and also for height to crown base ($r = 0.60$, $p < 0.001$) and crown width ($r = 0.35$, $p < 0.001$). For the categorical variables, the proportions of data in each category correlated very well for condition ($r = 0.99$, $p < 0.001$), crown light ($r = 0.94$, $p < 0.01$), and canopy missing ($r = 0.92$, $p < 0.001$).

3.2 Allometrics

The mean AGR in Table 1 have a fairly wide range, from 0.29 cm/year for the Myrtales (mainly *Lagerstroemia indica*) to 1.85 cm/year for the Saxifragales (mainly *Liquidambar styraciflua*). The overall mean AGR for all the trees that were able to be re-measured is 1 cm/year, which is higher than the 0.78 cm/year found in the nearby city of Bolzano (Russo et al., 2014). Table 2 shows the height increments for the species whose allometric equations required height measurements. The average for all the trees, 0.36 m/year is higher than the average of 0.26 m/year recorded by Russo et al. (2014).

Table 1 – Mean annual growth rate (AGR) of urban trees in Meran. Note: n, number; SD, Standard Deviation.

Taxonomical order	n	Mean AGR (cm/year)	SD
Aquifoliales	3	0.70	0.56
Dipsacales	2	1.00	0.67
Ericales	8	0.94	0.57
Fabales	14	0.97	0.47
Fagales	43	1.01	0.74
Ginkgoales	6	1.30	0.24
Lamiales/Scrophulariales	4	0.81	0.56
Laurales	11	1.42	0.50
Magnoliales	13	0.62	0.34
Malpighiales	11	1.49	0.54
Malvales	192	0.84	0.56
Myrtales	8	0.29	0.28
Pinales	354	0.78	0.64
Proteales	15	1.46	0.85
Rosales	37	0.86	0.62
Sapindales	45	0.66	0.54
Saxifragales	2	1.85	0.64

Table 2 – Mean annual height increments calculated from LiDAR data from different years. Note: n, number; SD, Standard Deviation.

Tree species	n	Mean (m/year)	SD
Abies spp., *Araucaria* spp., *Larix* spp., *Picea* spp., *Pinus* spp.	80	0.27	0.22
Acer spp.	123	0.31	0.25
Alnus spp., *Carpinus* spp., *Ostrya* spp.	18	0.44	0.30
Cupressus spp., *Cupressocyparis* spp., *Juniperus* spp.	58	0.35	0.33
Fagus spp.	13	0.45	0.36
Fraxinus spp., *Olea* spp.	29	0.26	0.19
Populus spp., *Salix* spp.	52	0.45	0.45
Prunus spp., *Pyrus* spp.	65	0.27	0.27
Robinia spp.	15	0.44	0.26
Tilia spp.	758	0.31	0.25
Thuja spp., *Platycladus* spp.	63	0.23	0.24
Ulmus spp., *Zelkova* spp.	31	0.48	0.38

3.3 Carbon Storage

The allometric equation method produced a carbon storage estimate not too dissimilar (within 4% of the value) from the i-Tree methods (Table 3) and the highest annual sequestration estimate. There are differences between the two i-Tree methods, with the full inventory estimate giving higher storage and sequestration than the statistical estimate based on random plots.

Table 3 – Total carbon stored and sequestered calculated using three methods

	Allometric equations	**I-tree full inventory**	**I-tree 200 plots**
C storage Mg	8,923	9,213	8,644
C sequestration Mg/year	370.4	216.2	106.5
C storage per tree Kg	349.9	361.3	339.0
C sequestration per tree Kg	14.5	8.5	4.2
% of annual traffic emissions sequestered	0.61	0.35	0.17
% of total annual emissions sequestered	0.17	0.10	0.05

There are clear differences among the different land types in Meran (Table 4). The higher storage and gross sequestration per hectare is observed on public land types such as street, park, and cemetery. The campsite had a similar tree composition to a public park. Over half of all trees in Meran are located on the private land types of house and apartments, yet these areas have relatively average storage and sequestration values. The lowest sequestration was observed on the wasteland (unoccupied), the highly maintained hospital and commercial grounds, and in the city centre and vineyards (the vines are not included in the carbon estimates). The overall average carbon storage for Meran is 13.5 t/ha. Taking the 24.7 % tree cover estimate for Meran from Speak et al. (2018) the carbon storage per area tree cover is 5.47 kg C/m^2. This equates to 40.3 m^2 of tree cover per inhabitant of Meran, with approximately 2 trees for every 3 inhabitants. The percentage of the traffic emissions sequestered, using the allometric method, is just 0.61% falling to 0.17% when total emissions are considered.

Table 4 – Tree abundance, average height, and carbon storage calculated for the estimated city- wide tree inventory, and gross sequestration over one year, within different land-type classifications in Meran, calculated using the allometric equations

Land Type	**Number of trees**	**Average tree height m (SD)**	**Storage tC / ha**	**C sequestration t/ year**	**Sequestration tC / ha / year**
Street	2,725	14.54 (6.51)	52.65	64.17	1.96
Park	2,439	16.90 (7.36)	25.99	60.89	0.95
Campsite	97	15.81 (6.72)	28.37	2.83	0.81
Cemetery	525	12.12 (6.50)	25.46	6.67	0.79
Hotel	1,202	12.60 (7.04)	20.27	16.61	0.76
House	4,797	10.84 (5.86)	16.91	59.51	0.74
Piazza	147	10.80 (5.42)	19.83	1.78	0.71
River	933	10.63 (3.84)	8.65	10.09	0.62
School	519	12.99 (6.05)	14.68	8.82	0.51
Military	1,048	16.13 (6.31)	8.22	19.40	0.43
Apartments	8,908	11.68 (6.17)	8.86	91.92	0.40
Transport	304	10.98 (3.88)	8.57	5.03	0.39
Unoccupied	129	9.26 (3.76)	8.03	1.25	0.32
Commercial	1,278	11.31 (5.23)	4.57	16.75	0.23
Hospital	153	11.39 (6.96)	5.18	1.70	0.22
Centre	84	10.60 (5.59)	1.78	1.19	0.07
Agriculture	209	8.32 (3.09)	1.42	1.75	0.07

3.4 Waste Management Emissions

The average annual biomass generated from dead trees in Meran is 1,002.2 tonnes (SD 44.7), which is 501.1 tonnes of carbon. Table 5 reveals the differences between end-of-life wood management techniques with burning with energy recovery for electricity being the most efficient with a carbon emissions/input ratio of 0.5, and landfill being the least efficient with a ratio of 121.9. Of the modelled real world scenarios, the second one is far better than the first with a ratio lower than 1.

Table 5 – Total emissions of carbon dioxide equivalents for different end-of-life wood management techniques

Technique	**Total CO_2 equivalent (tonnes)**	**Carbon ratio emissions/input**
Open burn	2,037.6	1.1
Burn with energy recovery:		
All electricity	1,006.9	0.5
All heat	1,236.6	0.7
50:50	1,121.7	0.6
Landfill	224,336.9	121.9
Landfill with methane recovery	99,138.9	53.9
Compost	1,837.3	1
Biochar	1,469.8	0.8
Real world scenario 1	27,215.3	14.8
Real world scenario 2	1,809.0	0.9

4. Discussion

4.1 Inventory Estimate

LiDAR data have been shown in this study to be very useful for estimating a whole city tree inventory for Meran, demonstrated by the high correlation between field and LiDAR-measured tree heights (r = 0.95). The ability to sample inaccessible land is undoubtedly a major benefit, and was useful in this study to locate, and measure, the height of trees within a large military zone in addition to the large privately-owned areas of the city.

The significant correlations between imputed and field-measured data show the community structure measures taken from 15.3 % of the city area were replicated with satisfaction. Species and height information for 27.5 % of the trees was enough to provide a basis for the imputation methods. In fact, an epidemiological study found that differing proportions of missing data, up to 90%, were not detrimental in terms of imputation efficiency, as long as sufficient auxiliary information is available (Madley-Dowd et al., 2019). A drawback of this approach is the length of time needed for both the fieldwork (21 days) and the data analysis (30 days). However, a full city inventory using fieldwork alone would have taken 140 days at the rate taken for this study. The image analysis to identify *Cedrus* spp. and *Cupressus sempervirens* trees, the refining of the tree point file to better reflect land-type tree densities, and the removal of building features falsely identified as trees, all required significant amounts of desk time and were only feasible given the moderate size of Meran.

4.2 Carbon Storage

The carbon storage in Meran, at 13.5 tonnes/ha (using the allometric equation method), is lower than the average for urban areas in the USA of 25.1 (Nowak and Crane, 2002) determined from a mix of field measures and extrapolation with tree cover data. The average carbon storage per area of tree cover of 5.47 kg C/m^2 is also lower than the average of 7.69 for US cities (Nowak et al., 2013). This could reflect cultural differences in urban landscaping, with a preference for smaller, manageable trees on private land. Meran also lacks the sprawling, and often tree-rich, suburbs of US cities, favouring medium-rise apartment blocks with small communal gardens. The breakdown by land type in Table 4 reveals expected patterns in carbon storage, with taller and denser trees lining streets and populating the park-like land types. Street tree carbon storage can be substantial, however, with the 52.7 tonnes C/ha not far behind the 87.6 t above-ground C/ha reported for mountainous forest ecosystems in the nearby Trentino region of Italy (Rodeghiero et al., 2010).

The difference in sequestration rates between the land types is quite large with streets sequestering 28 times as much carbon as the agricultural land type, where trees tend to be solitary trees around the perimeter of orchards and vineyards. The sequestration figures are not too dissimilar from those found in Barcelona, with 1.24 tonnes C/ha for urban forests, 0.3 for multi-family residential (0.4 apartments land type) and 0.03 for commercial land (0.07 for city centre) (Chaparro and Terradas, 2009).The higher sequestration from the allometric equations estimate could be explained by the higher AGR and height increment estimates observed, in comparison to the values recorded by Russo et al. (2014) in nearby Bolzano. This may be due to warmer urban climate conditions in Meran accelerating tree growth (Pretzsch et al. 2017), or different planting strategies which facilitate growth.

The percentages of carbon emissions from traffic and energy/heat generation that were able to be sequestered in trees in Meran were generally lower than those reported for other cities mentioned in the introduction (cf. 0.17% with 3.4 and 1.8% (Florida), 1.1% (Florence), and 0.5- 2.2% (Korea, including soils)), but higher than the estimates based on public trees alone (cf. 0.61% for traffic emissions with 0.08% (Bolzano) and 0.07% (Medellin)). This could be simply due to differences in how the carbon emissions are calculated or modelled, in addition to sequestration estimation differences. At present, there is a lack of a standard method for estimating and reporting emissions from urban forestry related activites. A study by Timilsina et al., (2014) found that urban tree C storage models such as i-Tree can have standard errors of up to 40%. Consequentially, the generally low figures for sequestration potential for city trees indicate that tree planting is perhaps not the optimum method for attaining carbon neutrality of a city. In fact in some situations, urban vegetation may act as a net source of emissions (Velasco et al., 2016).

Trees and urban forests, respectively, have a multitude of benefits in cities and should be promoted for their ecosystem services or nature based solutions. However, carbon neutrality is better achieved through comprehensive policies which reduce emissions at source. This becomes especially true when the fate of the stored carbon is considered.

4.3 Waste Management

The simple modelling of end-of-life tree management techniques has demonstrated that trees can effectively be a net emitter of CO_2 equivalents when the processing of the wood releases the more potent greenhouse gasses CH_4 and N_2O, as happens with landfill and burning (IPCC, 2006). This undermines the notion that urban forests are able to mitigate the accumulation of atmospheric carbon. It is true, however, that urban trees can help to reduce emissions associated with energy for air conditioning, by providing local cooling, as demonstrated by McPherson and Kendall (2014). Their study, which revealed the importance of considering emissions related to tree maintenance and decomposition of dead wood, only considered wood-chipping for mulch as a technique for dealing with dead trees. Our study has shown that more realistic municipal waste-management scenarios can have a far greater impact. The optimum waste treatment technique we considered was burning with energy recovery for electricity, while the worst method was landfill without methane recovery, which is unsurprising given the fact that CH_4 is considered to be 25 times as potent a greenhouse gas as CO_2 (IPCC, 2006). The real world scenario model with the better results was the second one, in which the dead trees from private land are chipped and turned into mulch instead of entering the municipal waste stream.

Landfill should be avoided, while energy recovery technologies and circular economy approaches, which consider the waste wood as an important and marketable resource, should be promoted. An example of the latter is using pruning material for organic insulation (Grohmann et al., 2019).

4.4 Study Limitations

The biggest limitation with this kind of study is the cumulative variation in accuracy of the underlying techniques used to quantify biomass. LiDAR based estimates of tree height tend to be an underestimation, given the fact that LiDAR pulses can miss the actual tree top (Zhang et al., 2015). Using allometric biomass equations developed from forest trees can over or underestimate urban tree biomass, given that urban trees have different growing environments relative to forest trees (McHale et al., 2009). Variability declines at coarser scales, however, reaching as low as 60% for street tree communities (McHale et al., 2009). Finally, the equations used for calculating emissions from wood waste may be an over simplification of complex decay processes in urban systems. Additionally we did not consider carbon storage in small trees, under-storey vegetation or soils (Dorendorf et al., 2015), therefore we underestimate the carbon sequestration potential of the urban forest. Future research could aim to better refine these urban carbon sequestration estimates, preferably utilizing urban-developed biomass equations (McHale et al., 2009). LCA studies which look at the entire life cycle and maintenance related emissions will also provide more realistic estimates of the carbon sequestration potential of urban forests (MacPherson and Kendall, 2014).

5. Conclusion

Our study has demonstrated the usefulness of LiDAR data for estimating a full city tree inventory for a moderately sized city. Spatial heterogeneity in urban areas is a challenge and hinders the development of fully automated urban canopy analysis software. However, with a combination of land type stratified fieldwork and some readily available GIS tools, we were able to create a comprehensive inventory estimate, which can form the basis of carbon storage models. The main drawback was the time-consuming aspect of some of the techniques, as has also been noted in other studies (MacFaden et al., 2012). Our methodology is only suggested for cities of a similar size to Meran, or for the analysis of selected boroughs of larger cities.

Large spatial differences in carbon storage and sequestration between urban land types indicates the challenges and opportunities that exist for municipalities hoping to achieve carbon neutrality by means of increasing the urban forest. This study also revealed that, even without considering maintenance activity related emissions and wood waste from pruning, end- of-life wood waste management practices can be very significant when determining the net carbon storage of urban-grown wood. However, the urban forest does partially offset CO_2 emissions from the traffic sector, and more research is needed to find technical solutions and sustainable planning strategies (e.g. minimization of unnecessary grass and paving area) to incorporate more trees into the dense built environment in Meran and other compact cities worldwide.

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Highlights

- LiDAR and field data successfully combined to create a full city tree inventory
- Carbon storage and sequestration estimates created for the city
- 0.61% of annual traffic emissions are sequestered by urban trees
- The fate of end-of-life wood waste is important within city carbon budgets

Credit Author Statement

Dr Andrew Speak undertook the methodology creation, data curation, analysis, writing and visualization. Dr Alessio Russo and Prof Francisco Escobedo assisted with data analysis and conceptualization, and Prof Stefan Zerbe undertook project administration and funding acquisition. All authors were involved with

conceptualization, and review and editing of manuscripts.

Declaration of interests

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

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: