Alma Mater Studiorum – Università di Bologna

DOTTORATO DI RICERCA IN

Colture Arboree ed Agrosistemi Forestali Ornamentali e Paesaggistici

Ciclo XXV

Settore Concorsuale di afferenza: 05/A1 – BOTANICA

Settore Scientifico disciplinare: BIO/03 - BOTANICA AMBIENTALE E APPLICATA

TITOLO TESI

Quantifying and modeling ecosystem services provided by urban greening in cities of the Southern Alps, N Italy

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Esame finale anno 2013

To my family

ACKNOWLEDGMENTS

In the first place, I would like to thank my Ph.D. supervisor, Prof. Dr. Stefan Zerbe, for his supervision, advice and guidance in writing this thesis. I would also like to show my gratitude to Prof. Dr. Massimo Tagliavini, Dean of the Faculty of Science and Technology - Free University of Bozen – Bolzano, through which I was able to take part in a joint PhD program between the Free University of Bozen – Bolzano and the University of Bologna.

I am heartily thankful to Prof. Dr. Francisco Escobedo and Dr. Nilesh Timilsina, during my period at the University of Florida for their friendship, help, guidance and suggestions.

I would also like to thank Prof. Dr. Giustino Tonon and Dr. Armin Otto Schmitt for their valuable support and suggestions provided during the course of my research.

I would also like to extend thanks to Pasquale Gigliotti, Raimondo Gallo and Gabriele Pezzani for helping with field work.

Finally, I would like to thank all those people who helped during the development of this thesis, in particular, this thesis could not have been written without the support of Dr. Ulrike Buratti from the City of Bolzano and Dr. Mauro Tomasi.

CONTENTS

ABSTRACT

Population growth in urban areas is a world-wide phenomenon. According to a recent United Nations report, over half of the world now lives in cities. Numerous health and environmental issues arise from this unprecedented urbanization. Recent studies have demonstrated the effectiveness of urban green spaces and the role they play in improving both the aesthetics and the quality of life of its residents. In particular, urban green spaces provide ecosystem services such as: urban air quality improvement by removing pollutants that can cause serious health problems, carbon storage, carbon sequestration and climate regulation through shading and evapotranspiration. Furthermore, epidemiological studies with controlled age, sex, marital and socio-economic status, have provided evidence of a positive relationship between green space and the life expectancy of senior citizens.

However, there is little information on the role of public green spaces in mid-sized cities in northern Italy. To address this need, a study was conducted to assess the ecosystem services of urban green spaces in the city of Bolzano, South Tyrol, Italy. In particular, we quantified the cooling effect of urban trees and the hourly amount of pollution removed by the urban forest. The information was gathered using field data collected through local hourly air pollution readings, tree inventory and simulation models. During the study we quantified pollution removal for ozone, nitrogen dioxide, carbon monoxide and particulate matter (<10 microns). We estimated the above ground carbon stored and annually sequestered by the urban forest. Results have been compared to transportation CO_2 emissions to determine the CO_2 offset potential of urban streetscapes. Furthermore, we assessed commonly used methods for estimating carbon stored and sequestered by urban trees in the city of Bolzano. We also quantified ecosystem disservices such as hourly urban forest volatile organic compound emissions.

ABBREVIATION AND CONCEPTS USED IN THIS THESIS AND THER DEFINITIONS

AGR	Annual Growth Rate
C	Carbon
CLE	Crown Light Exposure
CTCC	CUFR (Center for Urban Forest Research) Tree Carbon Calculator (CTCC)
DBH	Diameter at Breast Height
PMV	Predicted Mean Vote
STRATUM	Street Tree Resource Analysis Tool for Urban Forest Managers
UFORE	Urban Forest Effects model
VOCs	Volatile Organic Compounds

CHAPTER 1

Quantifying ecosystem services provided by urban green streetscapes in a city of the Southern Alps, Italy.

Abstract

Urban green spaces have the potential to offer multiple ecosystem services to people. Specifically, urban green spaces provide ecosystem services such as air pollution removal, carbon sequestration, and climate regulation through shading and evapotranspiration. Urban vegetation in transportation rights of ways also reduces temperatures in pedestrian areas, affects local-scale air quality and indirectly reduces CO_2 emissions. However, there is little information about the role of these localized public green spaces, or streetscapes on the urban environment of mid-sized cities of northern Italy. Thus, a holistic approach is needed to better design and plan urban streetscapes for improved localized environmental quality. To address this need, we explored the effects of different streetscape types on mitigating local-scale temperatures and air pollution in Bolzano, Italy using the ENVI-met and Urban Forest Effects model. Field data and simulation models were used to quantify the ecosystem services provided by urban trees and streetscape types. Specifically, we quantified ecosystem services at the individual tree and streetscape level including total air pollution removed and the cooling effect provided by trees and streetscapes. Results can be used to assess the role of urban streetscapes in improving human well-being and mitigating the effects of climate change.

Keywords: UFORE model, ENVI-met model, ecosystem disservices, thermal comfort.

1. Introduction

Increased urbanisation is altering the natural and non-natural ecosystem causing the loss of vegetation and open spaces and changing the hydrologic systems and the biogeochemical cycles (Grimm et al., 2008). Average temperatures in large metropolitan areas of 100,000 to 1 million people can be 5 - 10°C warmer than surrounding rural areas and results in a phenomenon known as the urban heat island (UHI) effect (Bonan, 2000; Holderness, Barr, Dawson, & Hall, 2013; Taleb & Abu-Hijleh, 2013). Also, incidences of longer and warmer summer temperatures are increasing and this is likely due to climate change (Hansen, Sato, & Ruedy, 2012). Additionally, increased temperatures are resulting in increased mortalities during summer heat waves (Conti et al., 2005; D'Ippoliti et al., 2010; Hajat et al., 2006; Son, Lee, Brooke Anderson, & Bell, 2012). A number of health and environmental issues are arising from these ecosystem modifications. In this human-modified ecosystem, urban green spaces play a key role in improving the aesthetics, environment and the overall quality of life of its residents. In particular, urban green spaces provide ecosystem services and goods that benefit human health and well-being such as: urban air quality improvement by removing pollutants (F. J. Escobedo, Kroeger, & Wagner, 2011; F. J. Escobedo & Nowak, 2009; David J Nowak, Crane, & Stevens, 2006; Tallis, Taylor, Sinnett, & Freer-Smith, 2011) that can cause serious health problems and mortality (Cheng, Jiang, Fajardo, Wang, & Hao, 2012; Sicard, Lesne, Alexandre, Mangin, & Collomp, 2011; Yang & Omaye, 2009), carbon storage and sequestration (David J Nowak & Crane, 2002; Strohbach & Haase, 2012) thereby offsetting CO_2 emission from cities (F. Escobedo, Varela, Zhao, Wagner, & Zipperer, 2010; H.-K. Jo & McPherson, 1995; Liu & Li, 2012; Zhao, Kong, Escobedo, & Gao, 2010) and climate regulation through altering the albedo of surfaces and shading and evapotranspiration (Akbari, 2002; J. N. Georgi & Dimitriou, 2010; N. J. Georgi & Zafiriadis, 2006; Hardin & Jensen, 2007; Rosenfeld et al., 1995).

Furthermore, urban green spaces provide human health benefits. For example, epidemiological studies with controlled age, sex, marital and socio-economic status, have provided evidence of a positive relationship between green space and the life expectancy of senior citizens (Takano, Nakamura, & Watanabe, 2002; Tanaka, Takano, Nakamura, & Takeuchi, 1996; Tzoulas et al., 2007). Urban green spaces also provide economic, aesthetic and architectural benefits (Tyrväinen, Pauleit, Seeland, & Vries, 2005). Recent studies have demonstrated that urban green spaces can also result in decreased well-being, or ecosystem disservices (Escobedo, Kroeger, &

Wagner, 2011), such as costs to the community including social problems e.g. fear of crime and health problems e.g. increasing allergy from pollen, environmental problems e.g. volatile organic compounds (VOCs), economic e.g. maintenance costs (F. J. Escobedo et al., 2011; Roy, Byrne, & Pickering, 2012).

According to the EU Biodiversity Strategy 2020, by 2014 European member states are required to map and assess the state of ecosystem services in their national territory (Maes et al., 2012). Several approaches to map and assess ecosystem services exist, however they are generally only appropriate for large scales (Maes et al., 2012). Within a city, the ecosystem services quantification should be done at an urban area scale so as to be useful for policy and planning purposes, since acquiring information at a local or micro scale might be prohibitively expensive. Recently, ecosystem services of urban green spaces have been assessed using various methods including computer models such as ENVI- met, i-Tree (UFORE, STRATUM), and CITYgreen (Roy et al., 2012). But, most of these studies were developed in the United States (Roy et al., 2012) with relatively few originating in Europe or Italy. Most of these studies conducted in Italy have examined just one aspect of ecosystem services provided by urban green spaces and urban trees for example Siena & Buffoni (2007) have examined the air quality improvement of a small park in Milan, while some authors have focused on O_3 removal (Manes et al., 2012; Paoletti, 2009). Other studies by Gratani & Varone (2007) and Baraldi, Rapparini, Tosi, & Ottoni (2010) have examined CO_2 sequestration at the species level, and social aspects have been studied by Sanesi & Chiarello, (2006). Picot (2004) for example studied the thermal comfort provided by trees in a typical Italian piazza in Milan and health benefits have been studied by Lafortezza, Carrus, Sanesi, & Davies, (2009).

Overall, few studies in Italy and Europe overall have examined more than one aspect of ecosystem services related to urban trees and green spaces (Loretta Gratani & Varone, 2006; Paoletti, Bardelli, Giovannini, & Pecchioli, 2011). Specifically, there is little information about ecosystem services provided by the urban green in localized area of mid-sized cities in the Southern

Alps, N Italy. Therefore, the objective of this study is to develop a methodology to quantify more than one ecosystem service provided by urban trees in different streetscape types using biometric data, site-specific meteorological and pollution concentration data, using two simulation models (Urban Forest Effects and ENVI-met), and an existing tree inventory with spatial data. In particular, this study estimates the mitigation role of urban trees on streetscape-scale temperature and air pollution removal of ozone (O_3), particulate matter less than 10 microns, (PM_{10}), nitrogen dioxide (NO_2), and carbon monoxide (CO) in a northern Italian city's different streetscapes. In addition, we model the biogenic emissions of these trees as a proxy for the ecosystem disservices that are produced from these streetscapes.

2. Material and methods

2.1 Study area

This study was conducted in the city of Bolzano, in northern Italy (Figure 1). The City of Bolzano is situated in the autonomous region of Trentino-Alto Adige/South Tyrol in northern Italy (46° 29' 28" N, 11° 21' 15"E), with a population of roughly 100,000 inhabitants and covers an area of over 50 square kilometres (Ufficio Statistica e Tempi della Città, 2012). Green areas represent about 3.9% of the city's territory which accounts for approximately 20 square metres of green space per person (Chiesura & Mirabile, 2012). The city of Bolzano has an estimated urban tree population of 12,000 trees (City of Bolzano, 2011, personal communication). According to the Köppen classification Bolzano's climate type is moist continental "Dfb" characterized by cold winters and warm summers with no dry season (Energy plus weather data, n.d.) with mean annual precipitation of 740 mm and a mean average maximum and minimum temperature of 17.9°C and 6.8 °C respectively (Servizio meteorologico della Provincia Autonoma di Bolzano, n.d.). In this study, we define "streetscape" as any area with paved roads, street furniture, roadside buildings and vegetation. We identified six streetscapes typologies in Bolzano: boulevards, cycle paths, parks, piazzas, promenades and streets (see Chapter 3).

Figure 1: The city of Bolzano in northern Italy.

2.2 Ecosystem services quantification

In this study, we followed the definition of Escobedo et al. (2011) for an ecosystem service as the components of urban greening that are directly enjoyed, consumed, or used to produce specific, measurable human benefits. Therefore, we focused on measurable benefits such as air pollutant removal and microclimatic regulation. The workflow of our methodology was: 1) To use existing tree inventory data in a Geographical Information System (GIS) format; 2) Select the appropriate mathematical, functional and simulation models; 3) Field sample streetscapes in order to obtain information required by the models; and 4) Apply the output of the simulation model to the tree inventory in order to map ecosystem services as required by the European Commission. The specific methods for quantifying each service are summerized in Table 1.

Table 1. Methods for quantifying ecosystem services in Bolzano.

Ecosystem Services	Method	Input data
Air pollutant removal	UFORE outputs of PM_{10}, O_3, CO, and NO_2 removal values by DBH classes have been assigned to Bolzano´s tree inventory single tree by DBH class	Species, number of DBHs recorded, DBH (cm) , height to crown base (m), crown width (m), percent canopy missing, dieback, crown light exposure, hourly weather data, hourly pollution data (the concentration of the pollutant in ppm for CO, NO_2, O_3 and in $\mu g/m^3$ for PM_{10}) (D J Nowak et al., 2008)
Temperature reduction	ENVI-met model using aerial photographs, Vector data combined with Bolzano´s tree inventory	Wind Speed in 10 m above ground (m/s), Roughness Length z0 at Reference Point, Wind Direction, Initial Temperature Atmosphere (K), Specific Humidity (g Water/kg air), Relative Humidity (%),Walking Speed (m/s), Heat transfer resistance cloths, Building height (m), vegetation and materials information (Bruse, 2012)
Ecosystem Disservices		
Biogenic Volatile Organic Compound (VOC) Emissions	UFORE outputs of isoprene, monoterpenes, and other VOC emissions that contribute to O_3 formation	Hourly weather data, species and field data (D J Nowak et al., 2008)

UFORE = Urban forest effects model; DBH = diameter at breast height (1.37 m)

2.3 Tree inventory

Inventories provide data on various ecosystem structural components relevant to this types of assessment (Millennium Ecosystem Assessment, 2005). Many countries routinely conduct inventories of their natural resources at regional or continental scales (Millennium Ecosystem Assessment, 2005). Because ecosystem services of urban green spaces are necessary at the local scale, local biometric data such as a tree inventory can be used to assess these services (D J Nowak et al., 2008). To this end, we used Bolzano' City's tree inventory as the inital step in our framework for assessing ecosystem services in Bolzano. Specifcally, the data provided in Bolzano's tree inventory relevant to our framework included: species, diameter (cm), height (m), health condition (in classes), streetscape type and global positioning system location (latitude, longitude). Further information required by the UFORE model is provided in D J Nowak et al. (2008).

2.4 Numerical Functional and Simulation Models

Models are useful tools for quantifying and assessing ecosystem assessments (Millennium Ecosystem Assessment, 2005). Urban ecosystems provide a variety of benefits to people, some models and methods are available to quantify some of these services (Escobedo et al., 2011).

We used two available models to quantify our ecosystem services of interest. First, we used the Urban Forest Effects (UFORE-ACE Version 6.5) because of its previous use in Italy (Paoletti et al., 2011; Siena & Buffoni, 2007) and other European cities such as: Zurich (Wälchli, 2012); Barcelona (Chaparro & Terradas, 2009), London (Tallis et al., 2011) and Torbay (Rogers, Hansford, Sunderland, Brunt, & Coish, 2011). Rather than analyzing urban forest-level functions we modeled at the individual tree-level. Additionally we modeled temperature effects using the ENVI-met model because it was developed in Europe (Bruse, 2012).

2.5 ENVI-met input data and methods

ENVI-met (Version 3.1) is a three-dimensional non-hydrostatic model for the simulation of surface-plant-air interactions within urban environments. It is designed for microscales with a typical horizontal resolution from 0.5 to 10 m and a typical time frame of 24 to 48 hours with a time step of 10 seconds at maximum. This resolution allows for the analyses of small-scale interactions between individual buildings, surfaces and plants and the model calculation includes:

- Shortwave and longwave radiation fluxes with respect to shading, reflection and re-radiation from building systems and the vegetation;
- Transpiration, evaporation and sensible heat flux from the vegetation into the air including

full simulation of all plant physical parameters (e.g. photosynthesis rate);

- Surface and wall temperature for each grid point and wall;
- Water- and heat exchange inside the soil system;
- Calculation of biometeorological parameters like Mean Radiant Temperature or Fanger's Predicted Mean Vote (PMV) –Value;
- Dispersion of inert gases and particles including sedimentation of particles at leafs and surfaces (Bruse, 2012; Wania, Bruse, Blond, & Weber, 2012).

We chose a site in Bolzano's historic center for our simulation. Therefore, the ENVI-met model was constructed according to the actual geometry of the site using aerial images and vector data from our GIS. The ENVI-met parameters were set up according to Bolzano´s streetscape using city-specific data such as climatic information (wind speed and direction; roughness length; initial temperature atmosphere; specific humidity in 2500 m, relative humidity), vegetation, building and surface materials. Two 24 h simulation scenarios were run:

- first scenario, existing situation;
- second scenario, without vegetation.

In order to quantify the human thermal comfort and discomfort, the ENVI-met results of the PMV (predicted mean vote) for the two scenarios was used. In particular, the predicted mean vote (PMV) created by Fanger in the late 1960s was used since it is used worldwide as an outdoor comfort index (Honjo, 2009; van Hoof, 2008). The PMV scale is defined between −4 (very cold that means extreme cold stress) and +4 (very hot that means extreme heat stress) where 0 is the thermal neutral (comfort) value (Berkovic, Yezioro, & Bitan, 2012; Honjo, 2009).

2.6 UFORE input data and methods

The UFORE model was developed in the late 1990s by researchers at the United States Department of Agriculture (USDA) Forest Service, to quantify urban forest structure and its effects on function and values. The UFORE model has five model components that quantify:

- Urban forest structure (e.g., species composition, tree density, tree health, leaf area, leaf biomass);
- Hourly pollution removal by the urban forest for ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide, and particulate matter (PM_{10});
- Hourly urban forest volatile organic compound (VOC) emissions and the relative impact of tree species on net ozone and carbon monoxide formation throughout the year;
- Total carbon stored and net carbon annually sequestered by the urban forest.
- Energy Conservation, which estimates effects of trees on building energy use and consequent emissions of carbon from power plants.

Readers are referred to Hirabayashi, Kroll, & Nowak, 2011; David J Nowak et al., 2006 for a more complete description of the model.

We did not estimate effects of trees on building energy use and consequent emissions of carbon from power plants because the UFORE-ACE V 6.5 complete tree inventory option does not quantify this and this component of the UFORE model is designed for US building types, energy use and emissions factors, limiting its use in international applications (Rogers et al., 2011).

The UFORE model was used to quantify air pollution removal during no precipitation periods, in which hourly dry deposition of CO, NO_2, O_3 and PM_{10} is estimated with hourly meteorological and pollutant measurements, location information, and urban forest parameters (Hirabayashi et al., 2011). In addition to assess the ecosystem disservices of these streetscapes we estimated annual VOCs emitted by trees in the streetscapes. The hourly meteorological data for Bolzano necessary to run the UFORE model were obtained from the NOAA's National Climatic Data Center (NCDC) (NOAA, 2012).

Hourly pollutant concentrations (CO, NO_2, O_3, PM_{10}) were obtained from the Laboratory of Physical Chemistry of the Autonomous Province of Bolzano that has three stations distributed within the city of Bolzano.

In June 2011, using ArcGIS (Version 10), we used a stratified random sample- according to land-cover classes (Figure 2) - in order to obtain tree level data required by the UFORE model for the different streetscape types.

During June and July 2011, trees were sampled and data recorded for each tree diameter at 1 m above ground surface and at breast height (DBH). Other data collected included: species, total tree height, height to live top, height to crown base, percent canopy missing, crown dieback, crown light exposure (CLE). This data have been used in the UFORE model to estimate the ecosystem services of streetscapes.

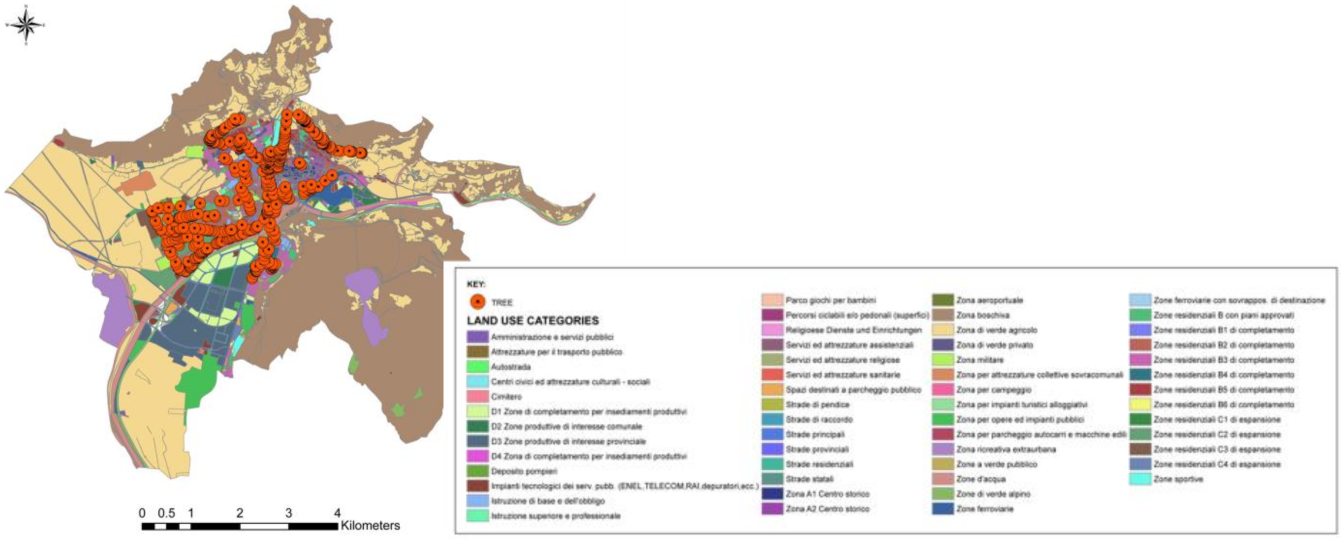

Figure 2: Bolzano - stratified sampling. (Land use categories, Source: PUC Comune di Bolzano).

The aim of our research was to quantify total pollution removal using an existing tree inventory. Therefore the outputs of the UFORE model were specific to the measured 475 trees. We estimated the average pollutants removed of CO, NO_2, O_3 and PM_{10} for the measured trees according to tree DBH classes (see Table 3) and in doing so assign average air pollution removal values of every individual tree in Bolzano's inventory. For example, we assigned an average CO removal value of 4.70 g to every individual tree with a DBH of 20 cm in the Bolzano´s tree inventory.

3. Results and discussions

3.1 Envi-met simulations

The first simulation shows that during the summer (July) the potential temperature is slightly lower (<1°C) in a piazza than in a street (Figure 3). This little difference is due to the greater tree density and canopy cover in a piazza than in a street.

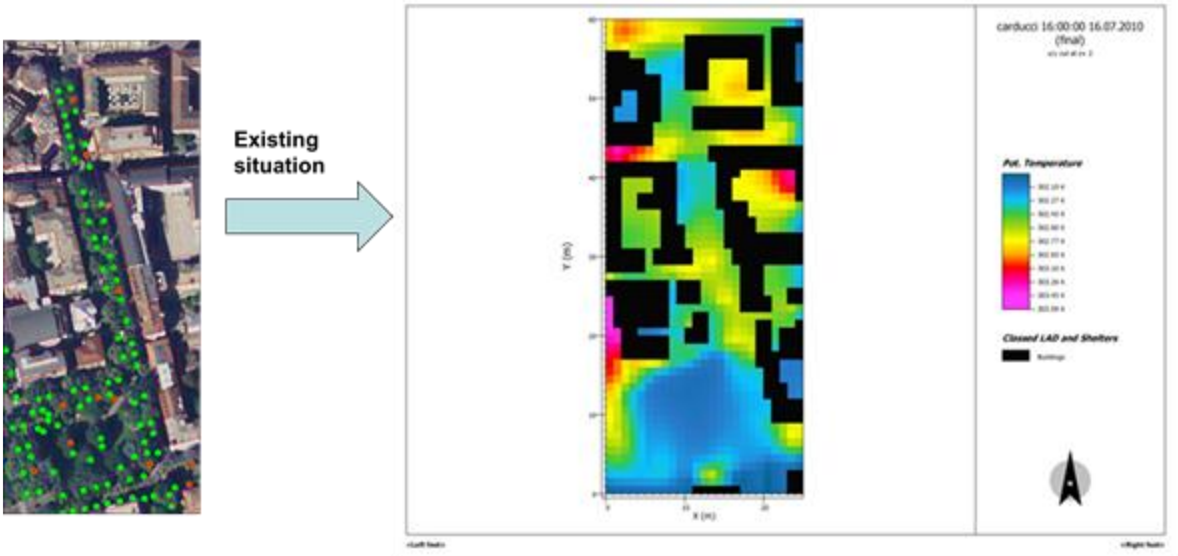

Figure 3: ENVI-met simulation: Potential temperature is lower in a piazza than in a street, dark blue colour represents low temperature.

The comparison between scenario 1 and scenario 2 shows a clear difference in potential temperature (Figure 4). These results highlight the role of trees in reducing urban temperatures. For example, inside the Piazza with vegetation (scenario1) has lower temperatures (about 302° K = 28,85°C) compared to scenario 2, piazza without vegetation and with hard landscape materials (temperature about 304°K =30,85°C). Overall, the higher temperature in scenario 2 is due to the fact that hard landscape materials have lower albedos and higher heat capacities that absorb solar energy during the day (Brown & Gillespie, 1995).

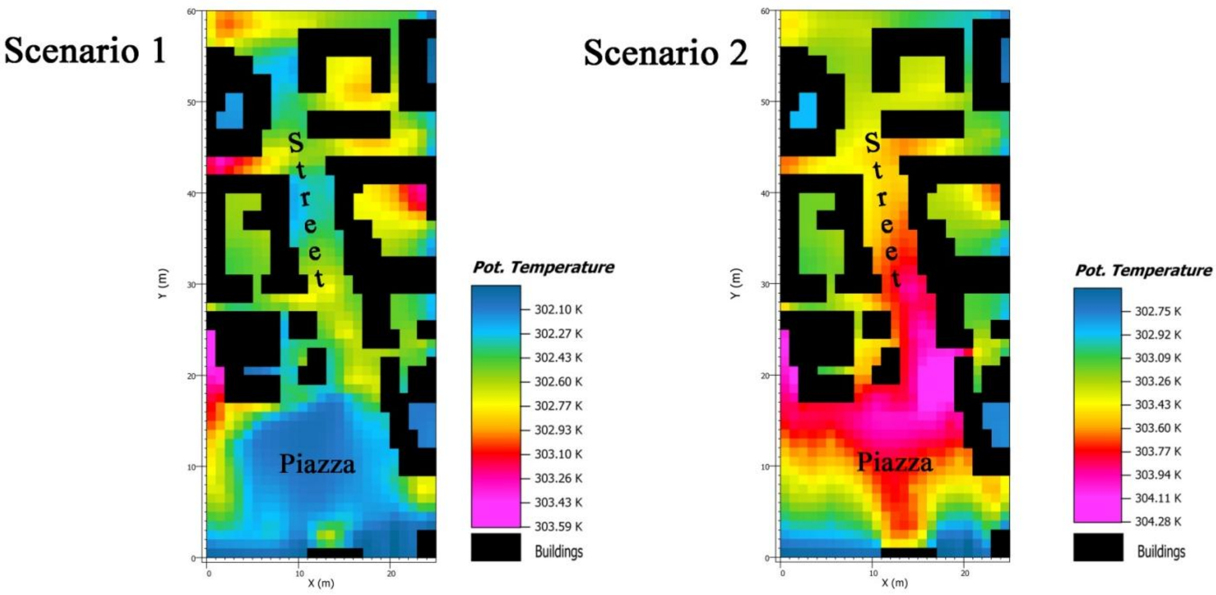

Figure 4: ENVI-Met Potential temperature simulations at 2 m level and at 04:00 pm.

The PMV values in this study (Figure 5) are not in the acceptable comfort range but scenario 1 has the highest amount of shade provided by trees consequently less solar irradiation. Therefore, scenario 1 is the most comfortable at 4:00 pm. In particular PMV is between 1.5 and 1.9 inside the piazza (scenario 1) that means a thermal perception of warm while scenario 2 has a PMV value inside the piazza > 4.5 that means a thermal perception of very hot.

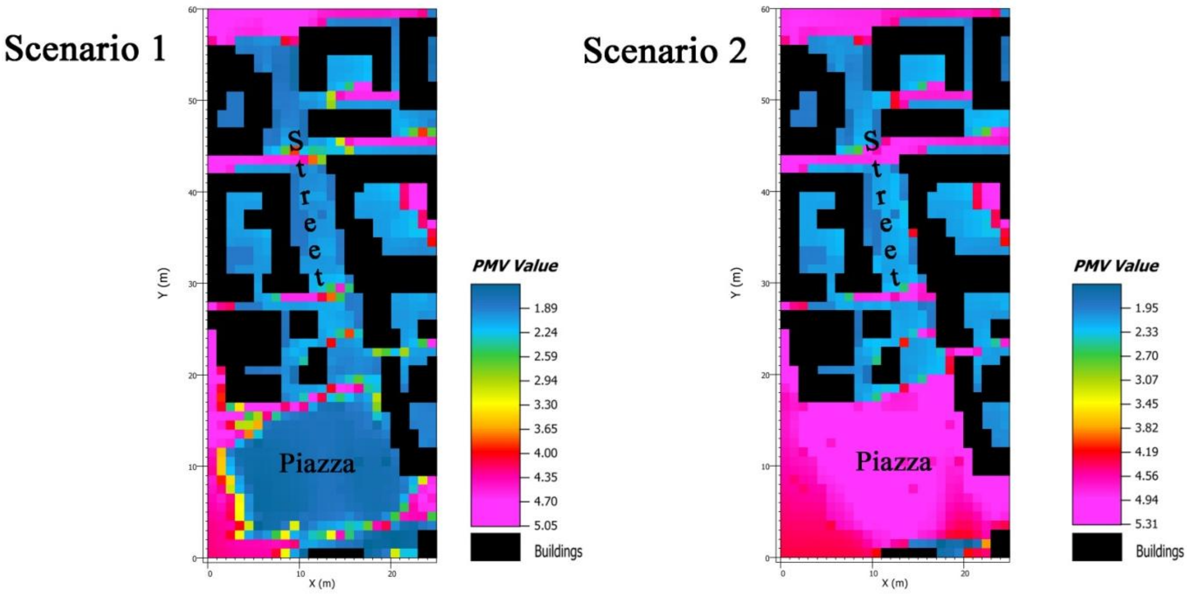

Figure 5: Spatial distribution of PMV (predicted mean vote) biometeorological index at 4:00 pm.

3.2 UFORE outputs

Total estimated pollution removal by trees in Bolzano was 2.42 metric tons with O_3 (1.2 t) being the pollutant that is removed the most and CO (0.03 t) removed the least. Differences in removal rates per tree by diameter classes (Table 2) are due to differences in the average amount of healthy leaf area per tree among the diameter classes (City of Grants Pass, n.d.). Figure 6 shows pollution removed by different streetscape types, therefore pollution removal was greatest for all pollutants in parks due to the higher number and size of trees. Annual pollutant removal per unit tree cover area ranged from 0.1 g m^{-2} for CO to 4.2 g m^{-2} for O_3. Total pollutant removal per unit tree cover area was 8.4 g m^{-2} for all 4 pollutants. These values were lower than have been estimated by other studies in the United States (David J Nowak et al., 2006) see Table 3.

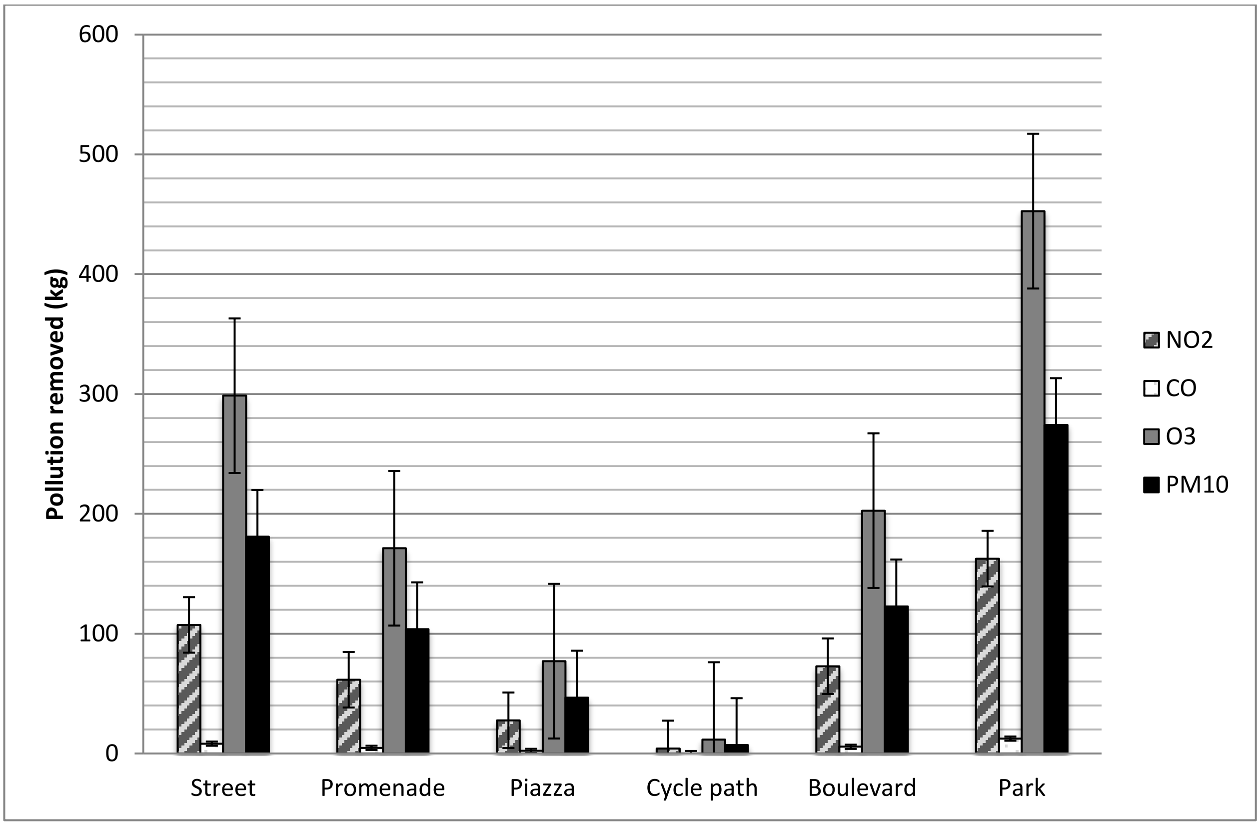

Figure 6: Pollution removed (NO_2, CO, O_3, PM_{10}) by different streetscape types. Error bars represent ± one standard error of the mean.

Table 2. Average individual tree pollution removal estimates (gram) for Bolzano by various diameter (DBH) classes

DBH Class (cm)	CO	NO_2	O_3	PM_{10}
0.00 -7.62	0.49	6.49	18.08	10.95
7.63 - 15.24	1.44	19	52.89	32.03
15.25 - 22.86	2.43	32.05	89.23	54.04
22.87 - 30.48	4.70	61.99	172.57	104.5
30.49- 38.10	7.41	97.68	271.94	164.7
38.11- 45.72	9.11	120.1	334.38	202.5
45.73 -53.34	11.52	151.8	422.59	255.9
53.35 - 60.96	16.82	221.6	617.01	373.7
60.97 -68.58	16.38	215.9	601.01	364
68.59 - 76.20	19.41	255.8	712.03	431.2
76.21 - 83.82	20.81	274.3	763.70	462.5
83.83 -91.44	19.28	254.1	707.34	428.4
91.45- 99.06	20.72	273.1	760.27	460.4
99.07 -106.68	7.94	104.7	291.39	176.5
106.69 - 114.30	32.75	431.7	1201.84	727.8
114.31 - 121.92	16.68	219.9	612.13	370.7
121.93 - 129.54	32.97	434.6	1209.91	732.7

Table 3. Annual pollution removal by trees and associated value in Bolzano and US cities (David J Nowak et al., 2006).

Cities	O_3 (g/m^2)	PM_{10} (g/m^2)	NO_2 (g/m^2)	CO (g/m^2)
Bolzano	4.2	2.6	1.5	0.1
Los Angeles, CA	6.9	8.0	6.3	1.2
Miami, FL	5.5	4.6	1.7	0.5
New York, NY	3.7	3.7	3.6	0.7
Sacramento, CA	4.9	3.8	1.4	0.4
Washington, DC	3.9	3.3	2.0	0.5

For more USA cites see David J Nowak et al. (2006)

The difference of these values depend on several factors such as pollution concentration, length of in-leaf season, percent of evergreen leaf area, amount of precipitation and other meteorological variables (David J Nowak et al., 2006). Therefore, the size, growth form and health condition of individual plants could affect the amount of pollutant removal per tree (Jim & Chen, 2008). The UFORE model has a number of assumptions (Tiwary et al., 2009), however, the model does not take into account occult or wet deposition and therefore likely to underestimate the total deposition (Tiwary et al., 2009).

Apart from their ability to mitigate urban temperatures and air pollution concentrations, there are many other ecosystem services provided by urban trees that have not been considered in this study. Other ecosystem services not included are cultural services such as aesthetic, educational and recreational.

Urban trees also provide ecosystem disservices, in fact the UFORE model estimated a total volatile organic compounds (VOCs) emissions of 5.61 mg C/m^2/hour in Bolzano, which may contribute to ozone formation (Benjamin & Winer, 1998; Paoletti, 2009).

The emission of these organic chemicals varied throughout the year and the day (David J Nowak, Crane, Stevens, & Ibarra, 2002) with the highest emission in August and at 2 pm.

The tree genera in Bolzano with the highest VOCs emissions were *Cedrus* (0.36 kg of isoprene, 29.0 kg of monoterpene, 31.7 kg of other VOCs) and *Platanus* (35.5 kg of isoprene, 0.24 kg of monoterpene, 4.17 kg of other VOCs). To reduce O_3 level in Bolzano, managers should change species composition using low VOC-emitting species.

4. Conclusions

Urban trees provide many social, recreation and beautification benefits. However, recent studies, including this one, have examined the effects of urban trees on environmental quality. Although most existing studies are from North American cities and have been conducted at the city-wide scale, ours is one of the few studies on the effects of treed streetscape on air pollution, ambient temperature in European cities. This study used field, pollution, and meteorological data and simulation models to quantify the role of urban greening in improving environmental quality in an Italian city. Models results can be used to provide information on air pollution removal at the tree and streetscape scale, temperature mitigation by different streetscape types. In addition, it explored the effect of VOC emission or ecosystem disservices associated with streetscapes. Specific, findings can be used to better design and plan for urban streetscapes for improved environmental quality and mitigation the urban island effect.

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CHAPTER 2

Assessing tree carbon storage and sequestration in an Italian, Southern Alps city

Abstract

Recent studies and policies have shown that the quantification of carbon storage and sequestration by urban trees is essential for the development of “low carbon cities”. Indeed, the current trend for new urban developments or existing cities is to substantially offset and reduce anthropogenic emissions of carbon dioxide (CO_2) in order to become ‘‘carbon neutral”. Several studies in North America and East Asia have used available models and tools to quantify this CO_2 offsetting effect of trees. But, little information on urban tree carbon storage and sequestration exist from the European Southern Alps and the use of these North America models in Europe has not been assessed. Therefore, the objectives of this study were to quantify carbon (C) storage and sequestration by urban trees in Bolzano, Italy and assess existing and available methods that are commonly being used. In particular, C storage and sequestration were estimated using three different methods: allometric biomass equations from a review of the European literature, the United States UFORE (Urban Forest Effects Model), and the CUFR Tree Carbon Calculator (CTCC). This study quantified gross C sequestration; using field measured stem growth rates and predicted tree height increments. To approximate net C sequestration, dendrometric equations were also used to calculate the biomass removals due to pruning operations. Results from this study can be used to inform cities on the potential of urban trees to provide ecosystem services to and in developing carbon neutral policies.

Keywords: low carbon cities, UFORE, growth rate, allometric equations, ecosystem services.

1. Introduction

Climate change is one of the most important environmental, economic and security issues our world faces today (Barnett, 2003; Karagiannis & Soldatos, 2010; IPPC, 2007). Urban-industrialized areas are steadily growing throughout the world (Grimm *et al*., 2008). By 2030, it is expected that 60% of the world's population will be living in cities (Rydin *et al.*, 2012). Thus, as urban environments become more important as living space for humans, they are an increasing source of carbon emissions. The Intergovernmental Panel on Climate Change (IPPC) Working Group 1 Fourth Assessment (IPPC, 2007), has pointed out that the primary sources of increased atmospheric CO_2 are indeed from the emission of carbon dioxide from increased fossil fuel use and from the effects of land use change. In fact, the global atmospheric concentration of CO_2 has increased from a pre-industrial value of about 280 ppm (Solomon *et al*., 2007) to around 393 ppm in 2012 (Conway & Tans, 2012*)*. Accordingly several climate change mitigation policies such as the Kyoto protocol, have called for stabilization of the atmospheric concentrations of greenhouse gases at a level that would prevent dangerous anthropogenic interference with the climate system (UNFCCC, 2008). These policies also recognize forests and trees as a CO_2 sink (Grace & Basso, 2012).

Several studies in North America, China, and Australia (Nowak & Crane, 2002; Dobbs et al., 2011; Zhao *et al*., 2010; Brack, 2002; Roy *et a*l., 2012) and more recently in the United Kingdom and Germany (Davies *et al*., 2011; Strohbach & Haase, 2012; Strohbach *et al*., 2012) have shown that trees in urban environments remove carbon dioxide from the atmosphere through growth and photosynthesis, and store excess carbon as biomass in roots, stems, and branches. Indirectly, urban trees through their shade and climate amelioration effects also reduce building energy used for cooling thereby reducing CO_2 emissions from decreased energy production (Akbari *et al*., 2001).

The estimation of carbon sequestration depends on the mortality and growth characteristics of the trees as well as their overall condition (Nowak & Crane, 1998; Escobedo *et al*., 2010; Staudhammer *et al*., 2011). Urban tree morality can be influenced by site and tree characteristics such as land use, natural disturbance (e.g. pests, fire and drought), human activities and urbanization effects (Iakovoglou *et al*., 2002; Lawrence *et al*., 2012). Similarly, tree growth is influenced by genetics, climate, soil, moisture, light, and competition (Peper & McPherson, 1998; Bühler *et al*., 2007). These effects on tree growth and mortality are well known in European forests, but the majority of studies of urban trees growth rates have been conducted in the USA (Jo & McPherson, 1995; Iakovoglou *et al*., 2002; Lawrence *et al*., 2012). Therefore, there is little information on urban tree growth rates in Europe.

Recently, Semenzato *et al*. (2011) developed models to predict the growth for five tree species in north-eastern Italy. According to these models, *Acer platanoides* L. attained the largest average annual diameter at breast height (DBH; tree stem diameter at 1.37m above the surface) growth with values ranging from an average of 1.25 cm/year during the first 15 years after planting and 1.52 cm/year 15 to 25 years after planting. Also, *Lagerstroemia indica* L. with smaller DBHs had growth rates ranging from 0.34 cm/year during the first 15 years after planting and 0.48 cm/ year in the second period (25 years after planting). Overall, *Acer platanoides* L. was the tallest tree, had the largest crown diameter, and the largest average annual growth. This species was closely followed by *Fraxinus angustifolia* Vahl and *Tilia x vulgaris* Hayne that showed similar growth patterns (Semenzato *et al*., 2011).

Several European cities have begun to formulate CO_2 mitigation policies and this is exemplified by the city of Bolzano, Italy which decided to become carbon neutral by 2030 (Sparber *et al*., 2010). This carbon sequestration mitigation potential of urban trees is considered a regulating ecosystem service (Escobedo *et al*., 2011; Niemelä *et al*., 2010; MA, 2005) and according to the EU Biodiversity Strategy 2020, by 2014, all European member states should map and assess the state of ecosystem services in their national territory (Maes *et al*., 2012). However, with the exception of studies in Germany and the United Kingdom (Davies *et al*., 2011; Strohbach & Haase, 2012) and assessments using the Urban Forest Effects (UFORE) model developed in the United States of America, Spain, Switzerland, and the United Kingdom (i-Tree Reports, 2012); we know of no studies of regulation ecosystem services of urban trees in the southern Italian Alps in the peer reviewed literature.

The UFORE model was developed in the late 1990s by researchers at the United States Department of Agriculture's Forest Service to quantify urban forest structure, function and value (Nowak & Crane, 1998). A recent user interface version is available for use and is referred to as i-Tree ECO. Using field measurements, study area characteristics, hourly annual meteorological data, and hourly annual pollution concentrations data the model quantifies:

- Urban forest structure, e.g. species composition, tree density, tree health, leaf area, leaf biomass, and information on shrubs and ground cover types;
- Hourly pollution removal by the urban forest for ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide, and particulate matter (PM_{10});
- Hourly urban forest volatile organic compound (VOC) emissions and the relative impact of tree species on net ozone and carbon monoxide formation throughout the year.

The UFORE/ i- Tree ECO model calculates urban forest and individual total tree (above and below ground) carbon storage using forest-grown tree allometric biomass equations (Nowak 1994; Nowak *et al.* 2002). Dry weight biomass estimates for open-grown street trees are multiplied by a factor of 0.8 (Nowak *et al*., 2002) since these trees tend to have less above ground biomass than predicted by these forest-derived biomass equations for trees of the same DBH (Nowak, 1994; Nowak & Crane,1998). Total tree biomass estimates are then multiplied by 0.5 to obtain total stored carbon. Specific details can be found in Nowak *et al.* (2008).

For example, annual gross C sequestration is estimated by the UFORE model as the difference in estimates of carbon storage between year x and year x + 1 (Nowak *et al*. 2002). Once C storage is obtained for year x, a growth rate is used for each trees to obtain an DBH and subsequent C storage at year x+1 for the same trees. The model uses average DBH growth rates obtained from a few cities in the United States (Nowak & Crane,1998). For example, for trees in forest stands the model uses an annual growth rate of 0.38 cm/year (Smith & Shifley, 1984; Nowak *et al*., 2002), for park-like structure the model uses 0.61 cm/year (Nowak *et al*., 2002). Average height growth is calculated based on formulas from Fleming (1988) as reported by Nowak *et al*. (2002) and the specific DBH growth factor used for the tree. According to Nowak *et al*. (2002) growth rates are then adjusted based on tree condition (i.e. no adjustment for trees in fair to excellent condition, trees in poor condition are multiplied by 0.76, critical trees by 0.42, dying trees by 0.15, and dead trees by 0). Adjustment factors are based on percent crown dieback and the assumption that less than 25% crown dieback had a limited effect on DBH growth rates. The more recent ECO version also adjusts the growth rate based on the study area's average annual plant growing period.

Another available model is the Center for Urban Forest Research's Tree Carbon Calculator (CTCC) (Urban Forest Project Reporting Protocol, 2008) that was developed by the USDA Forest Service, Pacific Southwest Research Station. The CTCC is a MS Excel spreadsheet that estimates urban tree carbon dioxide sequestration and building heating/cooling energy savings. The model estimates CO_2 sequestration for single trees located in one of sixteen climate zones of the United States (Aguaron & McPherson, 2012). The CTCC requires climate zone, species, and DBH or age input data to calculate individual tree CO_2 sequestration (kg/tree), total CO_2 stored (kg/tree), above ground biomass (dry weight) (kg/tree). Tree size and growth data were developed from samples of about 1000 urban trees and approximately 20 predominant species in each of the 16 United States reference climate zone cities (Aguaron & McPherson, 2012). Many of the biomass equations used to derive total CO_2 stored and sequestered are derived from open-grown city trees (Aguaron & McPherson, 2012).

These United States models and modeling approaches are currently the basis for tools that are becoming increasingly available for use in not only north America, but Europe as well (e.g. UFORE, i-Tree Eco, i-Tree Streets, i-Tree Vue, CUFR Tree Carbon Calculator (CTCC)) (i-Tree Applications, 2012). Aguaron & McPherson (2012) have compared the UFORE and other North American C storage estimation models with tree data from a United States city. But, to our knowledge, the appropriateness of these models for European trees has not been assessed. For example, according to Ferrini & Fini (2011) errors of modeled carbon estimates can be substantial. In addition, Nowak (1994) performed an analysis of carbon sequestration for individual trees as a function of tree diameter measured at breast height (DBH). In this study that is a basis for the UFORE/ECO model, the author estimates that an average tree with a DBH of 31–46 cm and approximately 50 m^2 in crown area sequesters carbon at a rate of 19 kg/year. However, Akbari (2002) quantified the rate of carbon sequestration for a similar tree using data by Frelich (1992) and the average sequestration rate for this 50 m^2 tree was estimated at about 11 kg/year.

As such, C storage and sequestration methods that are developed using local or regional allometric equations and site specific growth rates and dendrometrics should provide for more consistent and context-specific information. Therefore, the two specific objective of this study were to: (1) estimate carbon storage and sequestration for Bolzano Italy's public trees using Italian and European allometric equations and local growth rates obtained from remeasurements, and (2) to assess the performance of our method against the use of North American carbon storage and sequestration models that are commonly being used in Europe. The role of tree maintenance related carbon emissions and the application of this study for carbon dioxide offsetting objectives by Italian cities will also be discussed.

2. Material and methods

2.1 Study area

The study area was the City of Bolzano located in the autonomous region of Trentino-Alto Adige/South Tyrol in Northern Italy (46° 29' 28" N, 11° 21' 15" E). Bolzano is the capital of the province of Alto Adige/South Tyrol and in its 2011 census; showed a population of about 100,000 people (Comune di Bolzano, 2012). The city of Bolzano covers an area of over 50 square kilometers with approximately 12,000 public urban trees (Comune di Bolzano, 2010, personal communication). According to climatic data (1926-2011) reported by the weather station in

Bolzano, Italy (Servizio meteorologico della Provincia Autonoma di Bolzano, 2012), the annual temperature average is 12.3°C and average annual rainfall is 740 mm (Bonatti, 2008). The coldest month of the year is January with a minimum of -3.8°C, a maximum of 5.6°C, and an average of 0.9 °C. The warmest month is July with a minimum of 16°C, a maximum of 29.2, and an average of 22.6°C. The extreme records range from -17°C to +40 °C.

2.2 Allometric equations and carbon storage

The use of group allometric equations to estimate biomass and subsequent C storage is an internationally accepted approach and is indeed the basis of models such as the UFORE and CTCC (Strohbach & Haase, 2012; Jo & McPherson, 1995). The vast majority of these allometric equations are derived from non-urban, forest-grown trees that are destructively sampled (i.e., felled and weighed on site; Basuki *et al*., 2009). However, due to local regulations, liability and public perceptions and safety, destructive sampling is expensive and difficult in an urban environment. McHale *et al.* (2009) found that these allometric equations for forest-grown trees yield similar biomass estimates of urban-grown trees. However, these allometric equations produce very different results when applied to sites outside the region where the equations were originally developed (Zapata-Cuartas *et al*., 2012).

Therefore, since the UFORE model CTCC models use North American equations and this study was conducted in Europe, we used tree species, tree stem circumference (subsequently converted to diameter), tree height data and European-specific allometric equations derived from the literature (Appendix A) to better approximate urban tree C storage estimates for Europe. These equations in Appendix A were used specifically to calculate dry weight above ground biomass of each measured tree and not total dry weight biomass due to the complexity in estimating the belowground portion as reported by Strohbach & Haase (2012) study of urban tree carbon in Germany. Dry weight above ground biomass, obtained from equations in Appendix A, were multiplied by 0.5 to obtain C storage.

2.3 Field sampling

Our study is based on data from an existing tree inventory from the City of Bolzano (Giardineria Comunale di Bolzano, 2012). As is the case for most cities, Bolzano's urban tree inventory was developed to assess tree condition, hazards and risks, and overall public safety. Therefore, Bolzano's tree inventory did not contain specific input data required by the UFORE and CTCC models. However, this same tree condition and hazard data can be used to derive specific input data required by the forest-grown tree biomass allometric equations and the UFORE and CTCC models. Consequently, in order to obtain this data, we used ArcGIS (Version 10) and we obtained a subsample of tree in the tree inventory using a stratified random sample- according to land-cover classes and selected individual trees in the tree inventory's spatial database (PUC - Piano Urbanistico Comunale, 2012).

During June 2011, we measured selected trees and collected data for 475 trees. Specific measurements included: tree species, total and crown base height (m), crown width in two directions (m), percent crown dieback, percent missing canopy, and crown light exposure. Specific field methods are outlined in Nowak *et al*. (2008). We also measured tree circumference (cm) at 1 meter above the surface, which was then converted to Diameter (DH) by dividing by π (Figure 1).

Furthermore, assuming 0 cm in taper from 1.0 to 137 above the surface for individual stems and inherent variability in measuring tree stem diameters (Lawrence et al 2012), we assumed that DH (cm) was equivalent to diameter at breast height (DBH; 1.37 m above the surface). The DBH data were used in our European allometric equations and DBH and other data were used in the UFORE model to quantify carbon storage and sequestration. The CUFR Tree Carbon Calculator (CTCC) requires only information on tree species, DBH and an overall characterization of Bolzano's climate.

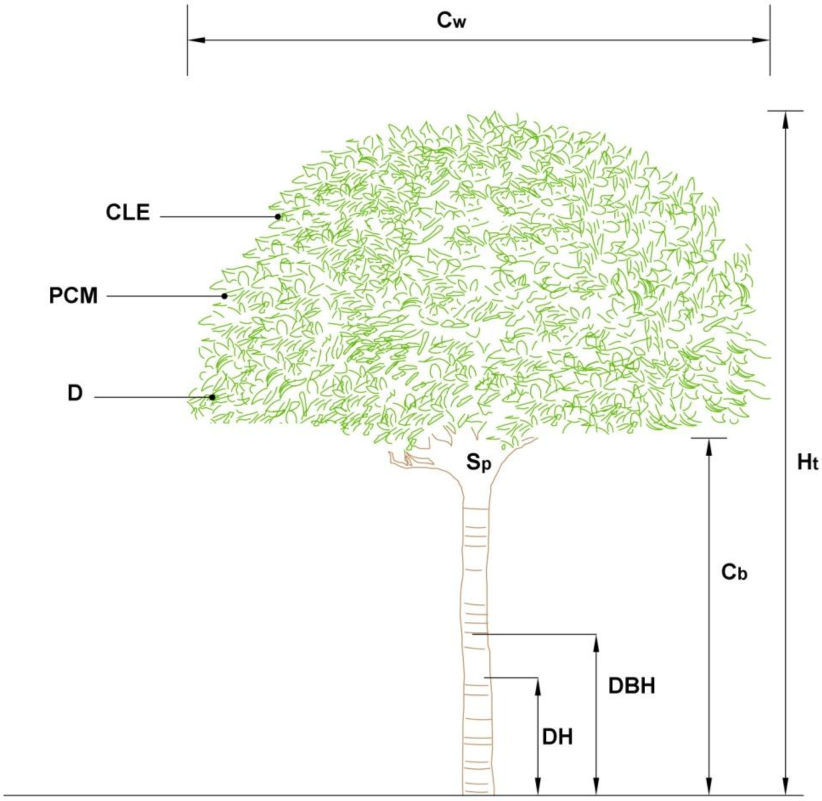

Figure 1: Urban trees parameters sampled in Bolzano, N Italy: Sp = species, DH = diameter at 1 m, DBH = diameter at breast height (1.37 m), Cb = crown base height, Ht = total height, Cw = crown width, CLE = crown light exposure, PCM = percent canopy missing, D = crown dieback (Nowak et al., 2003, 2008).

2.4 Estimated Height Increments and Growth rates

Several allometric equations in Appendix A require continuous data on tree height (m) in addition to DBH. However, Bolzano's tree inventory provided only tree height classes. To obtain necessary tree height increment data we used our 2011 subsample data to develop an Ordinary Least Squares predictive regression model *h = f(DBH)* based on the 2011 subsample's measured tree height (h; m) and DBH (cm) data to estimate the function parameters for the statistical relationship of DBH – h (Table 1; Pretzsch, 2009). The model was developed using the PROCREG procedure in the Statistical Application Software (Version 9.2).

Table 1. Tree height-diameter at breast height models for urban trees in Bolzano Italy. Note: y= height (m) and x=DBH (cm).

Genus	Models	R^2
Abies, Pinus, Picea	$y = 6.8788 \ln(x) - 10.131$	0.54
Acer	$y = 5.2586 \ln(x) - 5.1651$	0.81
Alnus, Carpinus, Ostrya	$y = 0.4717 x + 2.5591$	0.63
Betula, Fagus	$y = 0.3059 x + 3.4955$	0.64
Cupressus	$y = -0.004 x^2 + 0.5878x - 0.5975$	0.75
Fraxinus	$y = 4.732 \ln(x) - 3.621$	0.53
Prunus	$y = 0.0038 x^2 + 0.1054x + 4.8598$	0.58
Quercus	$y = 0.0045 x^2 + 0.0715x + 4.9053$	0.60
Robinia	$y = 5.0266 \ln(x) - 4.4342$	0.65
Salix, Populus	$y = 11.024 \ln(x) - 21.16$	0.96
Tilia	$y = 2.1438 x^{0.5301}$	0.63
Ulmus, Zelkova	$y = 12.837 \ln(x) - 30.193$	0.97

We then used the tree diameter- height models from Table 1 to estimated height in 2011 (H_{est1}) and height year 2012 (H_{est2}) by using measured 2011 DBH and the estimated growth rate that will be reported later in the results section. The mean annual tree height increment (H_i) was then calculated as the difference between the estimated height at year 2011 and the estimated height at year 2012 using Equation 1(Eq 1):

$$H_i = H_{est2} - H_{est1} \quad \text{(Eq 1)}$$

Where H_i is the mean annual tree height increment (m/year), H_{est2} is the estimated height (m) at year 2012 (m), and H_{est1} is the estimated height (m) at year 2011. The tree height in 2012 (H_2) was then derived using Equation 2 using the mean annual tree height increment (H_i; m/year) multiplied by the number of years (*n*) added to the height measured in 2011 (H_{1m}):

$$H_2 = (H_i \times n) + H_{1m} \quad \text{(Eq 2)}$$

Finally, diameter growth of the individual trees was calculated as the difference between the DH measured at the beginning and the end of a given time period (Laar *et al*., 2007). Specifically in this study, the annual growth rate (AGR; cm/year) was calculated using Equation 3 (Jalota & Sangha, 2000; Stoffberg *et al*., 2008; Stoffberg *et al*., 2009):

$$\text{AGR} = \left(\frac{DHY_2 - DHY_1}{t} \right) \quad \text{(Eq 3)}$$

Where, AGR is the annual growth rate (cm/year), DHY_1 is DH at a given year i.e. different DHs were measured during different years for different trees thus years change with different locations, DHY_2 is DH in 2011 and t is the time period (months) between measurements. To increase sample sizes for individual tree species, AGR and mean were averaged at the taxonomic order and division level. Trees that had a DHY_2 less than DHY_1 were excluded from the analyses.

2.5 Carbon sequestration and biomass removals from pruning operations

Annual carbon sequestration was the estimated amount of carbon a tree stem and its branches take up during one year of growth. Thus, in this study, annual gross carbon sequestration (kg/year) was estimated as the difference of C stored between year y (2011) and year y + 1 (2012) and was determined using an individual tree's annual growth rate (Liu & Li, 2012) and predicted height increment as explained in the previous section.

A report on municipal waste 2012 (ISPRA, 2012) shows the that the green waste biomass of from urban vegetation mowing and urban tree pruning operations in the Trentino-Alto Adige/SouthTyrol Region was 15,705 tons only in the year 2009. Hence, the amount of biomass waste from pruning operations can be substantial and should be accounted for when estimating net carbon sequestration effects from urban trees (Sajdak & Velazquez-Marti, 2012). Thus, to better estimate net annual carbon sequestration, we estimated the amount of annual biomass removals to account for maintenance-related C emissions associated with Bolzano's tree population. According to the Bolzano's Gardens Department (Personal communication, 2012), trees in parks are primarily pruned for tree health reasons. If there are no particular problems, the plants are not pruned and the only trees that are subject to periodic and systematic pruning are *Sophora japonica* L. trees that are pruned every 2 years and *Platanus hybrida* Brot. trees that are pruned every 7-10 years. However, the amount of biomass that is removed by tree pruning operations in Bolzano has never been measured. So to account for maintenance-related C emissions, we calculated the green waste biomass removal (y) obtained from pruning for *Sophora japonica* L. using the following linear Equation 4 derived from data from Sajdak & Velazquez-Marti (2012):

$$y = 1.352688(x) - 6.0096 \text{ (Eq 4)}$$

where y is the dry weight biomass obtained from annual pruning operations (y; kg) and x is the DBH (cm). This assumes one 2012 pruning intervention for *Sophora japonica* L. trees in our subsample.

2.6 UFORE and CTCC data input methods

Using tree data from our Bolzano tree inventory 2011 subsample, we adapted the input variables for use in the UFORE (Version ACE 6.5) model's complete tree inventory option based on methods outlined in Nowak *et al.* (2008 and 2002). We also formatted our subsample data for the use in the CTCC model. According to McPherson (2010) and McPherson & Peper (2012), the use of the CTCC and i-Tree Streets (formerly STRATUM) model is dependent on selecting an appropriate reference city in the United States. Therefore, due to the use of CTCC outside the United States, the limited number of species listed in the CTCC that matched Bolzano's tree inventory, and Bolzano climate; Bolzano's trees were matched to existing CTCC tree species and climates using similarities in tree taxonomy, growth forms and overall tree structure. Specific CTCC inputs for Bolzano are presented in (Appendix B) and are based on climate information from Bonatti (2008).

Finally to better assess our European-allometric based urban tree C storage and sequestration methods to the UFORE and CTCC model, we converted UFORE estimated total tree C estimates into above ground C by subtracting the below-ground portion using a root-to-shoot ratio of 0.26 as reported in Nowak *et al*., (2002) and Cairns *et al.* (1997). While the CTCC model was adjusted by dividing the total biomass by 1.28 since total biomass is 1.28 times the above ground biomass (Aguaron & McPherson, 2012).

2.7 Model Assessment

To assess the performance of the UFORE and CTCC model against our allometric equation-based approach, we tested for significant differences ($p<0.05$) between these 3 methods using the PROCTTEST procedures in SAS version 9.2. Specifically, we used a paired t-test to test the null hypothesis that there were no significant differences in carbon storage and sequestration between the 3 means from each method. Additionally, data were checked for normality using Q-Q plots and the Kolmogorov-Smirnov test. Data for the three model puts were then fitted to a linear regression and comparison made between variables (e.g. Allometric equations vs CTCC, Allometric equations vs UFORE, and CTCC vs UFORE) using a PROCGLM procedure in SAS and tested ($p<0.05$) to determine whether the slope differed from 1.0.

3. Results

3.1 Forest structure

Our subsample measured 475 individual trees and identified 91 different tree species. Overall, *Quercus pubescens* Willd, *Cedrus deodara* (Roxb.) G. Don, *Platanus hybrida* Brot., *Acer platanoides* L., *Acer pseudoplatanus* L. were the five most frequent tree species. In all, 89.7% of the trees sampled were in good to excellent condition, 6.5% were in fair, 2.3% in poor, and 1.2 % were dead or in critical condition. Table 2, presents the number of sampled trees, as well as the DBH and height for the ten most frequent tree species.

The mean AGR in the subsample are presented in Table 3 according to taxonomic "division" and "order". For example, the order *Fabales* includes the following species:
Cercis siliquastrum L., *Gleditsia triacanthos* L., *Gymnocladus dioicus* (L.) K. Koch, *Robinia pseudoacacia* L., *Sophora japonica* L. and *Wisteria sinensis* (Sims) DC. Overall, the order *Rosales* had the greatest mean AGR (1.02 cm/year) while the order *Magnoliales* had the lowest mean AGR (0.57 cm/year). Table 4 presents the mean annual height increments in m/year and shows that *Populus* spp. and *Salix* spp. had the greatest height increments (0.63 m/year), while *Tilia* spp.,

Robinia pseudoacacia L., *Gleditsia triacanthos* L. *and Sophora japonica* L. had the lowest (0.13 m/year).

Table 2. The ten most common public tree species in Bolzano, Italy and the number sampled in 2011 (n), mean diameter at breast height (DBH) and height, SE = standard error.

Tree species		**DBH**		**Height**	
	n.	Mean (cm)	SE	Mean (m)	SE
Quercus pubescens Willd.	46	21.8	1.12	9.2	0.52
Cedrus deodara (Roxb.) G. Don	22	66.1	4.44	22.4	1.38
Platanus hybrida Brot.	22	64.5	4.18	21.8	0.94
Acer platanoides L.	20	31.8	4.20	12.0	0.84
Acer pseudoplatanus L.	20	35.3	3.68	13.2	0.88
Sophora japonica L.	19	39.0	3.54	13.4	0.82
Betula pendula Roth	18	29.6	4.08	12.0	1.13
Aesculus hippocastanum L.	13	34.1	5.57	12.1	1.26
Cupressus sempervirens L.	12	29.7	3.79	12.4	1.27
Tilia americana L.	12	49.8	3.89	18.1	0.80

Table 3. Mean annual growth rate (AGR) of urban trees in the city of Bolzano; n = number of trees sampled, SE= standard error.

Order	**n**	**Mean AGR (cm/year)**	**SE**
Fabales	20	0.73	0.11
Fagales	50	0.77	0.08
Ginkgoales	6	0.80	0.27
Hamamelidales	30	0.89	0.10
Magnoliales	13	0.57	0.11
Malvales	27	0.62	0.10
Pinales	59	0.72	0.08
Rosales	17	1.02	0.14
Salicales	10	0.99	0.23
Sapindales	57	0.63	0.07
Scrophulariales	12	0.82	0.22
Urticales	11	0.85	0.26
Division			
Magnoliophyta	279	0.78	0.03

Table 4. Predicted mean annual height increments of urban tree species in the city of Bolzano; n = number of trees sampled.

Species	**n**	**Mean (m/year)**
Abies spp., *Picea* spp., *Pinus* spp.	23	0.20
Cupressus spp.	13	0.24
Acer spp.	52	0.15
Alnus spp., *Carpinus* spp., *Ostrya* spp.	16	0.36
Fagus spp., *Betula* spp.	21	0.24
Fraxinus spp., *Olea europea*	16	0.22
Populus spp., *Salix spp.*	9	0.63
Prunus spp., *Pyrus* spp.	25	0.23
Robinia pseudoacacia L., *Gleditsia triacanthos* L., *Sophora japonica* L.	22	0.13
Quercus spp.	67	0.24
Tilia spp.	30	0.13
Ulmus spp., *Zelkova carpinifolia* (Pall.) Dippel	9	0.25

3.2 Regional sources of the allometric equations

The allometric equations used in our dry weight and biomass C storage estimates were developed primarily for European, forest-grown trees and were applied to 60.3% of trees in our subsample. More specifically, Italian-specific equations were applied to 51.5 % of the trees in our subsample, equation from Spain and the UK were applied to 0.2% and 8.6 %, respectively, to tree in our subsample (Tabacchi *et al*., 2011a, 2011 b; Muukkonen & Mäkipää, 2006; Ruiz-Peinado *et al*.,2012; Bunce,1968; Zianis *et al*., 2005). Due to the presence of non-native trees and lack of European-specific equations for certain species, the remaining equations were from China (4 % of subsampled trees; Li *et al*., 1985 as cited in Liu & Li, 2012) and North America (35.7 % of subsampled trees; Jenkins *et al*., 2003).

3.3 Comparison of storage estimations

Using our allometric equation method we estimated that the total carbon stored by the 475 trees in our subsample was 179.14 Mg. Meanwhile, using our field measurement data as model inputs, we estimate 140.15 Mg of C storage using the CTCC model and 134.89 Mg using the

UFORE model (Figure 2). The amount of carbon stored for the five most frequent tree species using the 3 different methods are also presented in Figure (3).

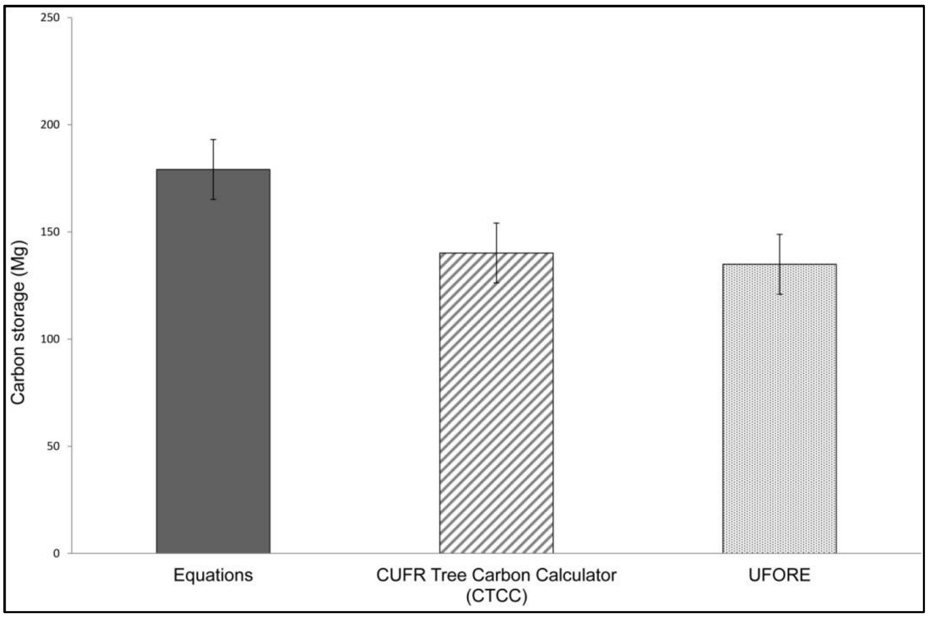

Figure 2: Total carbon stored (Mg) by 475 trees in Bolzano calculated using three different methods. Error bars represent ± one standard error of the mean.

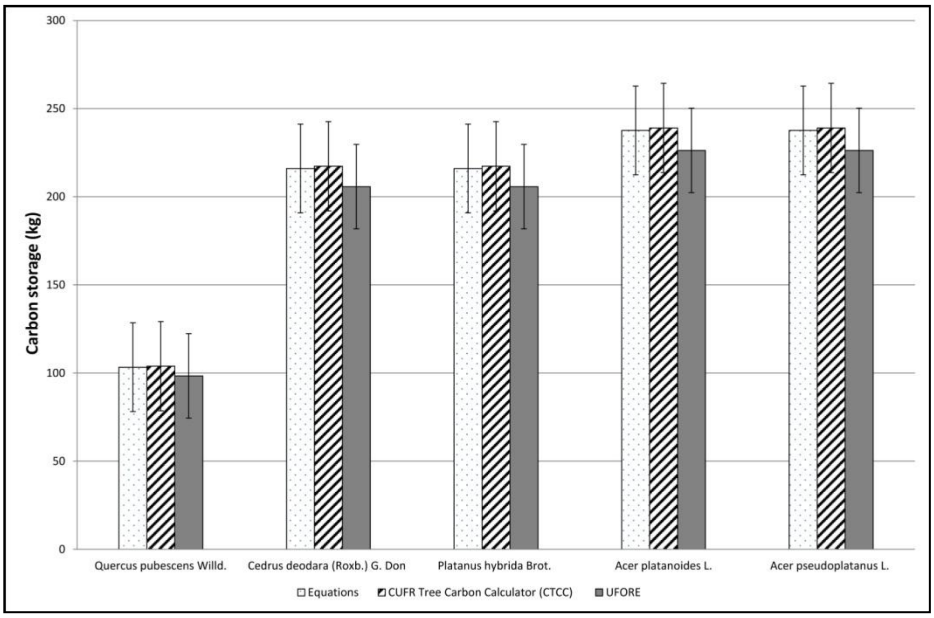

Figure 3: Average carbon storage (kg) estimates for the most common tree species calculated using three different methods. Error bars represent ± one standard error of the mean.

The paired t-test shows that predictions from our allometric equations are significantly higher than the CTCC (t= 4, P<0.0001) and UFORE (t=8.43, P<0.0001) models. But there was no significant difference in predictions between the CTCC and UFORE (t= -0.82, P=0.413). Additionally, a regression slope between our allometric equations and the CTCC model was significantly different than 1 (P=0.003), which suggests that predictions from two methods are also different. Similarly, the slope between our allometric equations, UFORE (P=<0.0001), and CTCC and UFORE (P=<0.0001) were also significantly different from 1 (P=<0.0001); therefore, we can say that predictions were different.

3.4 Comparison of C sequestration estimates

The total gross annual carbon sequestration for trees in our subsample was 5.71 Mg/year using the allometric equations and Bolzano´s growth rates and/or height increment predictions. However, 8.27 Mg/year were estimated using the CTCC model and 5.82 Mg/year using the UFORE model (Figure 4). The amount of carbon sequestered for the 5 most frequent tree species using the different methods is shown in Figure 5.

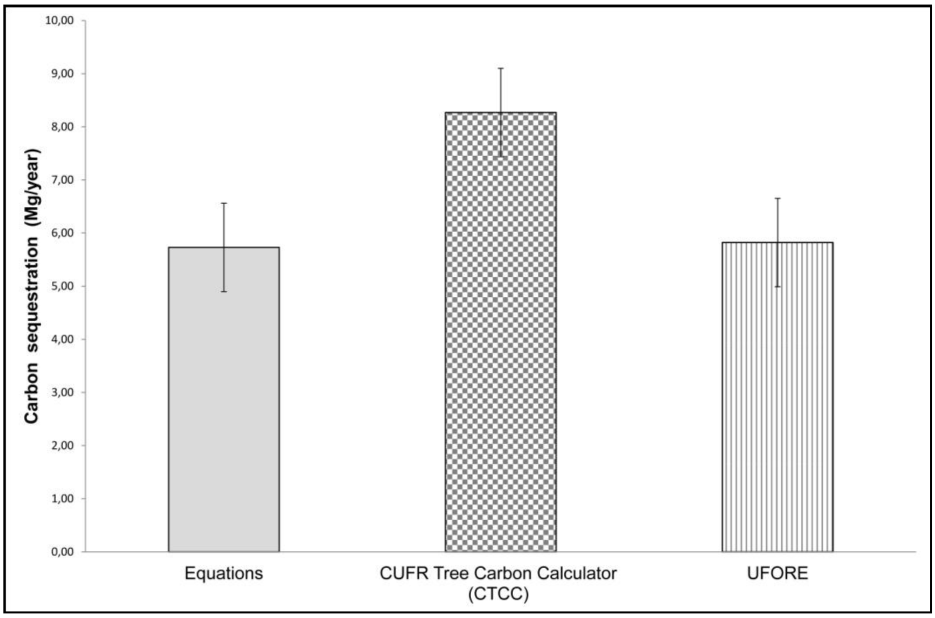

Figure 4: Annual carbon sequestration (Mg/year) by 475 trees in Bolzano calculated using three different methods. Error bars represent ± one standard error of the mean.

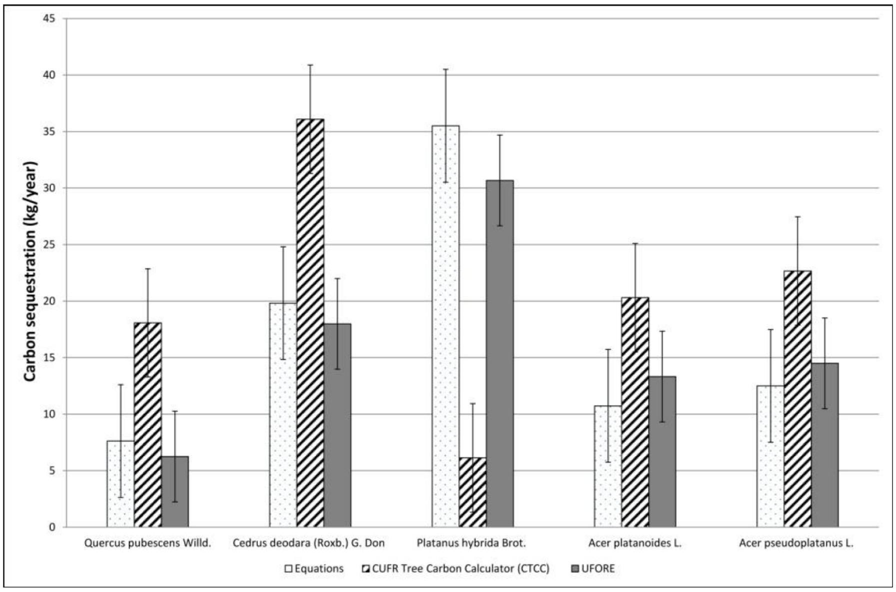

Figure 5: Average carbon sequestration (kg/year) estimates for the 5 most common tree species calculated using three different methods. Error bars represent ± one standard error of the mean.

A paired t- test showed that predictions from our allometric equations were significantly lower than the CTCC model (t= -7.71, P<0.0001). Also, there was no significant difference in estimates between the allometric equations and the UFORE model (t= -0.60, P=0.54). However, estimates from the CTCC model were significantly higher than UFORE model (t=7.30, P <0.0001) and the regression slope between the allometic equations and the CTCC model was significantly different than 1 (P<0.0001). This suggests that predictions from these two methods are also different. Similarly, the slope between the allometric equations and UFORE model (P=<0.0001) and the CTCC and UFORE models (P=<0.0001) were also significantly different from 1 (P=<0.0001); thus model predictions are also different.

The green waste biomass from annual pruning operations of *Sophora japonica* L. was estimated at 678 Kg per year. Assuming this biomass is burned and is emitted as C with the same year trees were pruned, this can be a potential of 339 kg C emitted per year. Since the gross annual c sequestration from trees in our subsample was 5,710 kg; our net annual C sequestration (i.e. gross C sequestration minus C emitted from maintenance) is 5371 kg/year. Additionally, the 678 kg/year of dry weight biomass can be used as biofuel or as compost and thus acts as a carbon sink.

4. Discussion and Conclusion

Our study provides a quantification of the C stored and sequestered by urban trees in an Italian city in the Southern Alps. As opposed to studies that estimate urban tree C storage and sequestration using North American models, we present an approach that primarily uses European allometric equations, measured growth rates and predicted tree height increments using field measurements that can be obtained from available urban tree inventories. In addition the study compiles a list of biomass equation that can be used to estimate C storage, mean annual growth rates and height increment prediction at the order, division and genera level, respectively. Finally, the study assessed the performance of two United States urban tree C models against our allometric equation approach.

Overall our growth rates are different than those reported by Jo & McPherson (1995) and Iakovoglou *et al.* (2002), and Lawrence *et al.* (2012) for trees in the United States. The Order *Fagales* for example, had an AGR estimated at 0.77 cm/yr which was lower than the 0.85 cm/yr (average growth rates of *Q. laurifolia, Q. nigra, Q. virginiana, O. virginiana*) reported by Lawrence et al. (2012). Also, our growth rates for hardwood trees estimated at 0.78 cm/yr (*Magnoliophyta*) was lower than the 1.09 cm/yr reported by Jo & McPherson, (1995), but greater for softwood trees 0.72 cm/yr (*Pinales*) instead of 0.51 cm/yr (Jo & McPherson, 1995). Our results also differ from those reported in Strohbach *et al*. (2012) in Leipzig, Germany and in Bühler *et al.* (2007) in Copenhagen, Denmark.

The C storage and sequestration results from this study are difficult to compare with other studies because of the use of different estimation methodologies, climatic condition, different species composition and urban forest structures (Strohbach & Haase, 2012; Aguaron & McPherson 2012). Our estimates are different from those reported in Table 5.

Table 5. Average per tree carbon storage and sequestration and estimation methods for case studies in Europe.

Study area	n. trees	C storage (kg) Average	C sequestration (kg/year) Average	Method	References
Bolzano, IT	475	377.14	12.06	Above - ground C in urban trees, European allometric equation and field data	Our study
Bolzano, IT	475	295.06	17.41	Above - ground C in urban trees, CUFR Tree Carbon Calculator (CTCC) and field data	Our study
Bolzano, IT	475	283.98	12.26	Above - ground C in urban trees, UFORE model and field data	Our study
Florence, IT	885	354.60	9.79	Above and below ground C in trees, UFORE model and field data	Paoletti et al. (2011)
Leicester, UK	267647	206.61	na	Above - ground C in public trees, stratified random sampling across land cover and land ownership	Davies et al. (2011)
Lisbon, P	41,247	509.86	43.06	Above- and below-ground C* in trees, STRATUM model and field data.	Soares et al. (2011)
Padua, IT	219	138.62	12.84	Above- and below-ground C* in trees, STRATUM model and field data.	Crema (2008)
Padua, IT	219	260.36	na	Above- and below-ground C in trees, N. American equation	Crema (2008)
Zurich, CH	130	348.88	12.97	Above- and below-ground C in trees, i-Tree Eco model and field data	Wälchli (2012)
Zurich, CH	130	375.46	30.69	Above- and below-ground C* in trees, i-Tree Streets model	Wälchli (2012)

*We converted CO_2 to carbon, na= not analyzed

In particular, the comparison between our C estimates with the UFORE model and other European studies that have used the UFORE/ i-Tree ECO model in Europe, show that the average carbon storage and sequestration per tree was higher in our study than estimates reported by Wälchli, (2012) in Zurich in Switzerland (about 235 km from Bolzano) and Paoletti *et al.* (2011) in Florence, Italy (about 300 km from Bolzano).

As discussed in Nowak *et al.* (2008), the UFORE model estimates gross C sequestration using a series of assumptions that include: non-measured root-to-shoot ratios, non-site specific growth rates adjusted by tree condition and landuse, and modeled removal and decomposition. Thus, our gross and net C sequestration estimates based on annual re-measurement data, AGR and predicted height increments values for Bolzano and accounting for maintenance related C emissions; presents and alternative methods based on fewer assumptions and parameters derived from United States trees.

Although according to Jo & McPherson (1995), the use of allometric biomass equations based on forest-grown trees can overestimate or underestimate urban tree biomass. For example an urban tree with the same DBH or height as a forest trees could have a different biomass due to the conditions of the urban environment relative to forest-grown trees (Jo & McPherson, 1995). In fact, the UFORE model reduces biomass estimates of open grown street trees by 20% based on a study of 30 street trees of 9 different species in Chicago USA (Nowak, 1994). However, in the case of Bolzano's urban trees, we observed urban trees were often not open-grown, were in overall good condition, were regularly fertilized and irrigated relative to forest-grown trees. Therefore given the uncertainty in this assumption and lack of information on the below ground C portion reported by Strohbach & Haase (2012) for trees in Germany, we do not subtract 20% for open grown trees using our allometric equation method.

Overall the UFORE model produced the lowest estimates (134.89 Mg) for carbon storage, and this might be because forest-based equations are used exclusively with application of the 0.8 multiplier to open-grown trees Aguaron & McPherson (2012). The CUFR Tree Carbon Calculator (CTCC), however, produced an intermediate estimate of 140.15 Mg while our allometric equations produced larger estimates of 179.14 Mg. Accounting for Nowak's (1994) and Peper & McPherson's (1998) correction factor for open-grown urban trees, multiplying the carbon storage from our allometric equation method by a factor of 0.8 results in a carbon storage of 143.3 Mg that is still greater than that estimated by the UFORE model. The CUFR Tree Carbon Calculator (CTCC) C sequestration estimates for our subsample was the greatest at 8.27 Mg/year, while the UFORE model (5.73 MG/year) and our equations (5.82 MG/year) produced similar estimates. These results corroborated by Aguaron & McPherson (2012) found that the UFORE model (i-Tree Eco) produced the lowest carbon storage estimate while the CUFR Tree Carbon Calculator (CTCC) produced the largest C sequestration estimates. In general, there are differences in these three methods for the calculation of C storage and sequestration. Table 6 shows the strengths and weaknesses of the three carbon calculation approaches.

Table 6. Strengths and weaknesses of various methods: UFORE, Allometric equations, and CUFR Tree Carbon Calculator (CTCC) for European C estimates.

	Allometric Equations	CUFR Tree Carbon Calculator (CTCC)	UFORE
Strengths	Local equations	User friendly	User friendly (i- Tree ECO)
	Species specific	Free available on internet	Free available on internet
	Requires only species, DBH and height	Requires only species, DBH or age	Species specific
	Local growth rates	Urban-based equations	Calculates also other ecosystem services
Weaknesses	Time consuming for literature review	North American urban-based equations	North American biomass equations
	Forest biomass equations	Limited number of species	Forest biomass equations
		North American growth rates	Requires too many data
		North American urban-based equations	North American growth rates
			Expensive, Field data costs 1000 euro per 100 trees.

There are several limitations that need to be acknowledged regarding the present study. The first limitation is the use of forest based equations. Further research is needed for accurate C measurements and for developing urban trees equations. For example it could be possible to develop urban tree equations using destructive sampling of trees removed in new development or reconstruction sites. Another limitation is the calculation of the annual height increments that are not based on felled tree measurements or remeasured height. Therefore, stem analysis of felled trees, is the most accurate method, but it is time consuming and expensive and not applicable for urban trees. On the other hand remeasurement of height on the same trees can have a large measurement error relative to the actual height increment (Hasenauer & Monserud,1997).

In conclusion, our methods, findings and model assessment can be used for integrating, and assessing, urban landscapes and trees in environmental design, planning and climate change initiatives and policies. For example, the use of Regional and European-specific biomass equations and local annual growth estimates can provide improved carbon storage and sequestration estimates like that of the commonly used north American models. Findings from this study on annual growth rates, annual height increments, and model assessments can be applied to existing tree inventories and used for the development of similar model/ tools for Italian cities or other urban areas in the southern Alps. Similarly, green and dry weight biomass from pruning operations can be estimated and used to predict green waste yield from urban landscape maintenance activities for use as biofuel and compost, and greenhouse gas emission information from maintenance operations can also be used in green space life cycle analyses. We propose that results from this study can be used to plan, design and manage cities to maximize the potential of urban trees to provide ecosystem services and for developing carbon neutral policies.

Appendix A: Allometric equations

Species sampled	Equation	Parameters	Region	Reference
Abies spp.	$dw_4=b_1+b_2d^2h+b_3d$	dw_4= Total aboveground dry weight b_1=-2.1386 b_2=1.8125 × 10^{-2} b_3=1.1089 h= total tree height d= diameter at breast height	Italy	*Abies alba* Mill. (Tabacchi et al., 2011a, 2011 b)
Acer spp.	$dw_4=b_1+b_2d^2h$	dw_4= Total aboveground dry weight b_1 = 6.4595 b_2 =2.6368 × 10^{-2} h= total tree height d= diameter at breast height	Italy	Acer spp. (Tabacchi et al., 2011a, 2011 b)
Aesculus spp., *Catalpa* spp., *Celtis* spp., *Cercis* spp., *Cornus spp*., *Diospyros* spp., *Ginkg biloba*, *Gleditsia* spp.,	bm = Exp(β_o + β_1 In dbh)	bm= total aboveground biomass β_o = -2.4800	North America	Mixed hardwood (Jenkins et al., 2003)

Gymnocladus spp., *Hibiscus* spp.,*Juglans* spp., *Koelreuteria spp., Lagerstroemia* spp., *Laurus* spp., *Liquidambar* spp., *Liriodendron* spp. , *Magnolia* spp., *Melia* spp., *Morus* spp., *Paulownia* spp., *Photinia* spp., *Platanus* spp., *Pterocarya* spp., *Tamarix spp., Toona spp., Wisteria* spp.		β_1= 2.4835 dbh = diameter at breast height		
Alnus spp.	$dw_4=b_1+b_2d^2h+b_3d$	dw_4= Total aboveground dry weight b_1= -1.6747×10 b_2=1.7930 × 10^{-2} b_3=2.6664 h= total tree height d= diameter at breast height	Italy	Alnus spp. (Tabacchi et al., 2011a, 2011 b)
Betula spp., *Corylus* spp.	$\log_e y = a + b (\log_e x)$	y = tree dry weight (trunk + branches) x = tree girth at 1.3 m a= -5.223864 b= 2.425436	UK	Birch Combined (Bunce,1968)
Carpinus spp., *Ostrya* spp.	$dw_4=b_1+b_2d^2h$	b_1= 3.2485 b_2=3.0167 × 10^{-2}	Italy	*Carpinus* spp., *Ostrya* spp. (Tabacchi et al., 2011a, 2011 b)
Cedrus spp., *Chamaecyparis* spp., *Cryptomeria* spp., *Metasequoia* spp., *Sequoiadendron* spp., *Taxodium* spp.	bm = Exp(β_o + β_1 In dbh)	bm=total aboveground biomass β_o = -2.0336 β_1=2.2592 dbh = diameter at breast height	North America	Cedar/larch (Jenkins et al., 2003)
Cephalotaxus spp.,*Taxus* spp.	bm = Exp(βo + β_1 In dbh)	bm= total aboveground biomass βo = -2.5384 β_1=2.4814 dbh = diameter at breast height	North America	True fir/hemlock (Jenkins et al., 2003)
Cupressus spp.	$dw_4=b_1+b_2d^2h+b_3d$	dw_4= Total aboveground dry weight b_1=-4.1345 b_2=2.4359 × 10^{-2} b_3=1.4156 h= total tree height d= diameter at breast height	Italy	*Cupressus spp.* (Tabacchi et al., 2011a, 2011 b)
Fagus spp.	$dw_4=b_1+b_2d^2h$	dw_4= Total aboveground dry weight b_1=1.6409 b_2= 3.0775 × 10^{-2} h= total tree height d= diameter at breast height	Italy	*Fagus sylvatica* L. (Tabacchi et al., 2011a, 2011 b)
Fraxinus spp.	$dw_4=b_1+b_2d^2h$	dw_4= Total aboveground dry weight b_1=2.1893 b_2= 3.2949 ×10^{-2} h= total tree height d= diameter at breast height	Italy	Fraxinus spp. (Tabacchi et al., 2011a, 2011 b)
Olea europaea L.	$W_s = 0.0114 \times d^2 \times h$ $W_{b7} = 0.0108 \times d^2 \times h$ $Wb_{2–7} = 1.672 \times d$ $Wb_{2+1} = 0.0354 \cdot\times d^2 + 1.187 \times h$	Ws: Biomass weight of the stem fraction (kg); W_{b7}: Biomass weight of the thick branches fraction (diameter larger than 7 cm) (kg); $Wb_{2–7}$: Biomass weight of medium branches fraction (diameter between 2 and 7 cm) (kg); W_{b2+1}: Biomass weight of thin branches fraction	Spain	(Ruiz-Peinado et al.,2012)

		(diameter smaller than 2 cm) with leaves (kg); Wr: Biomass weight of the belowground fraction (kg); d: diameter at breast height (cm); h: tree height (m)		
Picea spp.	$dw_4=b_1+b_2d^2h+b_3d$	dw_4= Total aboveground dry weight $b_1=1.4146 \times 10^{-1}$ $b_2=1.7620 \times 10^{-2}$ $b_3=5.6209 \times 10^{-1}$ h= total tree height d= diameter at breast height	Italy	*Picea abies* (L.) Karst. (Tabacchi et al., 2011a, 2011 b)
Pinus halepensis Mill.	$dw_4=b_1+b_2d^2h+b_3d$	dw_4= Total aboveground dry weight b_1= - 8.1012 $b_2=2.1559 \times 10^{-2}$ b_3=2.2591 h= total tree height d= diameter at breast height	Italy	*Pinus halepensis* Mill. (Tabacchi et al., 2011a)
Pinus nigra Arnold	$ABW= a+b \cdot D^2 \cdot H+c \cdot D^2$	ABW = Total aboveground woody biomass a= -3.5712 b=0.014429 c=0.068047 H= Height D= Diameter	Italy	*Pinus nigra* Arnold, Equation 739 (*Muukkonen & Mäkipää,* 2006)
Pinus pinea L.	$dw_4=b_1+b_2d^2h$	dw4= Total aboveground dry weight $b_1=4.5885\times 10^{-1}$ $b_2=2.5176 \times 10^{-2}$ h= total tree height d= diameter at breast height	Italy	(Tabacchi et al., 2011a, 2011 b)
Pinus strobus L.	$dw_4=b_1+b_2d^2h$	dw_4= Total aboveground dry weight b_1=5.6156 $b_2=1.5939 \times 10^{-2}$ h= total tree height d= diameter at breast height	Italy	Exotic pine group (Tabacchi et al., 2011a, 2011 b)
Pinus sylvestris L.	$dw_4=b_1+b_2d^2h$	dw_4= Total aboveground dry weight b_1=2.8848 $b_2=2.2080 \times 10^{-2}$ h= total tree height d= diameter at breast height	Italy	*Pinus sylvestris* L. (Tabacchi et al., 2011a, 2011 b)
Populus spp., *Prunus* spp., *Pyrus* spp., *Tilia* spp., *Ulmus* spp., *Zelkova* spp.	$dw_4=b_1+b_2d^2h+b_3d$	dw_4= Total aboveground dry weight b_1= -1.2825×10 b_2= 1.1993×10^{-2} b_3=3.1553 h= total tree height d= diameter at breast height	Italy	Other broadleaves group (Tabacchi et al., 2011a, 2011 b)
Pseudotsuga spp.	bm = Exp($\beta_o + \beta_1$ In dbh)	bm= total aboveground biomass β_o = -2.2304 β_1= 2.4435 dbh = diameter at breast height	North America	Douglas -fir (Jenkins et al., 2003)
Quercus palustris Münchh., *Quercus petraea* (Mattuschka) Liebl., *Quercus robur* L., *Quercus rubra* L.	$\ln(ABW) = a+b \cdot \ln(D)$	ABW= Total aboveground woody biomass	UK	*Quercus* spp., Equation n. 601 (Zianis et al.,

		a= -2.4232 b= 2.4682		2005)
Quercus pubescens Willd.	$dw_4=b_1+b_2d^2h+b_3d$	b_1=-7.1745 $b_2=3.3299\times10^{-2}$ b_3=1.2623	Italy	*Quercus pubescens* Willd. (Tabacchi et al., 2011a, 2011b)
Robinia pseudoacacia L.	$dw_4=b_1+b_2d^2h+b_3d$	$b_1=-1.0114\times10$ $b_2=2.4042\times10^{-2}$ b_3=2.2065	Italy	*Robinia pseudoacacia* L. (Tabacchi et al., 2011a, 2011b)
Salix spp.	$dw_4=b_1+b_2d^2h$	b_1= 9.0561 b_2= 2.1087×10^{-2}	Italy	*Salix* spp. (Tabacchi et al., 2011a, 2011b)
Sophora japonica L.	$Bs = 0.069 \times D^{2.54}$, $Bb = 0.068 \times D^{1.89}$	Bs=stem, Bb= branch	China	(Liu & Li, 2012)

Appendix B: Bolzano´s trees species assigned to CUFR Tree Carbon Calculator (CTCC) listed species and US climate zones.

Species Bolzano´s tree inventory	CTCC Climate zone	CTCC Assigned species
Abies spp.	8 - Temperate Interior West	*Pinus sylvestris* L.
Acer negundo L.	12 - Midwest	*Acer negundo* L.
Acer platanoides L., *Acer pseudoplatanus* L.	9 - Pacific Northwest	*Acer platanoides* L.
Acer rubrum L.	9 - Pacific Northwest	*Acer rubrum* L.
Acer saccharinum L.	4 - Central Valley	*Acer saccharinum* L.
Aesculus spp., *Toona sinensis* (A. Juss.) M. Roem.	7 - Northeast	*Aesculus hippocastanum* L.
Alnus incana (L.) Moench, *Betula pendula* Roth, *Corylus colurna* L.	9 - Pacific Northwest	*Betula pendula* Roth
Carpinus betulus L. , *Ostrya carpinifolia* Scop.	9 - Pacific Northwest	*Carpinus betulus* L. '*Fastigiata*'
Catalpa bignonioides Walter, *Paulownia tomentosa* (Thunb.) Siebold & Zucc. ex Steud.	8 - Temperate Interior West	*Catalpa speciosa* (Warder) Warder ex Engelm.
Cedrus spp.	2 - South Coast	*Cedrus deodara* (Roxb.) G. Don
Celtis australis L.	4 - Central Valley	*Celtis sinensis* Pers.
Cephalotaxus harringtonia (Knight ex Forbes) K. Koch	2 - South Coast	*Podocarpus macrophyllus* (Thunb.) Sweet
Cercis siliquastrum L.	13 - Lower Midwest	*Cercis canadensis* L.

Chamaecyparis lawsoniana (A. Murray) Parl., *Cryptomeria japonica* (L. f.) D. Don, *Cupressus* sempervirens L., *Taxodium disticum spp.*	9 - Pacific Northwest	*Calocedrus decurrens* (Torr.) Florin
Cornus mas L.	11 - Coastal Plain	*Cornus florida* L.
Diospyros kaki L. f.	4 - Central Valley	*Pyrus kawakamii* Hayata
Fagus spp.	9 - Pacific Northwest	*Fagus sylvatica 'atropunicea'*
Fraxinus spp.	7 - Northeast	*Fraxinus pennsylvanica* Marshall
Ginkgo biloba L.	4 - Central Valley	*Ginkgo biloba* L.
Gleditsia triacanthos L.	4-Central Valley	*Gleditsia triacanthos* L.
Gymnocladus dioicus (L.) K. Koch	6 - Mountains	*Gymnocladus dioicus* (L.) K. Koch
Hibiscus syriacus L., *Tilia cordata* Mill., *Tilia* × *europaea* L. (pro sp.) [*cordata* × *platyphyllos*]	9 - Pacific Northwest	*Tilia cordata* Mill.
Juglans nigra L.	8-Temperate Interior West	*Juglans nigra* L.
Koelreuteria paniculata Laxm., *Melia azedarach* L.	4 - Central Valley	*Koelreuteria paniculata* Laxm.
Lagerstroemia indica L.	4 - Central Valley	*Lagerstroemia indica* L.
Laurus nobilis L.	6 - Mountains	*Prunus* sp.
Liquidambar styraciflua L.	4 - Central Valley	*Liquidambar styraciflua* L.
Liriodendron tulipifera L.	3 - Inland Empire	*Liriodendron tulipifera* L.
Magnolia spp.	4-Central Valley	*Magnolia grandiflora* L.
Metasequoia glyptostroboides Hu & W.C. Cheng, *Sequoiadendron giganteum* (Lindl.) J. Buchholz	1 - North and Central coast	*Sequoia sempervirens* (Lamb. ex D. Don) Endl.
Morus alba L.	9 - Pacific Northwest	*Morus alba* L.
Olea europaea L.	5 - Desert	*Olea europaea* L.
Photinia serrulata Lindley	9 - Pacific Northwest	*Malus angustifolia* (Aiton) Michx.
Picea spp.	13 -Lower Midwest	*Picea pungens* Engelm.
Pinus halepensis Mill.	5 - Desert	*Pinus halepensis* Mill.
Pinus nigra Arnold, *Pinus pinea* L.	13 - Lower Midwest	*Pinus nigra* Arnold
Pinus strobus L.	13 - Lower Midwest	*Pinus strobus* L.

Platanus hybrida Brot.	4 - Central Valley	*Platanus hybrida* Brot.
Populus spp., Salix spp.	9 - Pacific Northwest	*Populus balsamifera* ssp. *Trichocarpa* (Torr. & A. Gray ex Hook.)
Prunus avium (L.) L., *Prunus laurocerasus* L.	6 - Mountains	*Prunus sp.*
Prunus cerasifera Ehrh.	1 - North and Central coast	*Prunus cerasifera* Ehrh.
Pseudotsuga menziesii (Mirb.) Franco	9 - Pacific Northwest	*Pseudotsuga menziesii* (Mirb.) Franco
Pyrus communis L.	6 - Mountains	*Pyrus sp.*
Quercus palustris Münchh., *Quercus petraea* (Mattuschka) Liebl.	12 - Midwest	*Quercus palustris* Münchh.
Quercus robur L., *Quercus rubra* L.	12 - Midwest	*Quercus rubra* L.
Robinia pseudoacacia L., *Sophora japonica* L.	1 - North and Central coast	*Robinia pseudoacacia* L.
Taxus baccata L.	2 - South Coast	*Podocarpus macrophyllus* (Thunb.) Sweet
Tilia americana L.	9 - Pacific Northwest	*Tilia americana* L.
Tilia tomentosa Moench	7 - Northeast	*Tilia tomentosa* Moench
Ulmus spp.	6 - Mountains	*Ulmus pumila* L.
Wisteria sinensis (Sims) DC.	4 - Central Valley	*Gleditsia triacanthos* L.
Zelkova carpinifolia (Pall.) K. Koch	4 - Central Valley	*Zelkova serrate* (Thunb.) Makino

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Assessing transportation CO2 emission offsets by urban green streetscapes in Bolzano, Italy

Abstract

Increased CO_2 emissions in urban areas due to the rapid population growth and consequent increment in energy use and vehicular traffic is a worldwide problem that is altering the global climate. Studies from North America and Asia have reported that urban trees can be used to mitigate these emissions. However, little is known about the role of European urban streetscapes in mitigating these emissions. Therefore, the aim of this study was to develop a method to calculate above ground carbon dioxide storage and sequestration at the streetscapes level using field data, an existing tree inventory and available region-specific allometric equations.

Results were compared to vehicular CO_2 emissions from a city in the Italian Alps to determine the CO_2 offset potential of urban streetscapes. We found that the trees in Bolzano's streetscapes through sequestration annually offset 0.08 % of the amount of carbon dioxide emitted by the transportation sector. Results can be used to better understand the potential role of urban streetscapes in reducing atmospheric carbon dioxide.

Keywords: carbon sequestration, carbon storage, climate friendly cities, ecosystem services, streetscapes

1. Introduction

Currently, the increased concentration of greenhouse gases in the atmosphere is one of the most severe environmental problems (Valsta et al., 2008). Carbon dioxide is an important greenhouse gas and a major agent of climate change (Nusbaumer & Matsumoto, 2008), and the predicted global temperature rise will be proportional to the total amount of CO_2 emitted (Skippon, Veeraraghavan, Ma, Gadd, & Tait, 2012). In recent years, increases in carbon dioxide concentrations are mostly due to rapidly increasing population, energy use, and emissions from vehicular traffic (Sharma, Kharol, & Badarinath, 2010; Uherek et al., 2010). In fact, half of the world´s population is living in cities. In Europe alone, it is estimated that around 70 % of the EU population – approximately 350 million people – live in urban agglomerations of more than 5000 inhabitants (European Commission - Directorate General for Regional Policy, 2011). It is predicted that by 2030, five billion out of the global population of 8.5 billion people will be urban dweller (Vauramo, 2011). Thus, the world's increasing population and urbanization of the landscape is a major cause of CO_2 and other greenhouse gases that are affecting the global climate. In addition, anthropogenic and transportation -related sectors comprise more than 80% al of all CO_2 emissions into the urban environment (L Gratani & Varone, 2005; Koerner & Klopatek, 2002). As urbanization increases globally, it is becoming important to more accurately evaluate carbon dynamics in these systems (McHale, Burke, Lefsky, Peper, & McPherson, 2009).

Although, cities are a primary source of CO_2 emissions, they can also sequester and store carbon dioxide in urban forests and green spaces (Strohbach et al., 2012). For example, several studies have demonstrated that urban trees can play an important role in offsetting humans carbon dioxide (CO_2) emissions (F. Escobedo et al., 2010; H. Jo, 2002; David J Nowak & Crane, 2002; David J Nowak, 1993; Poudyal, Siry, & Bowker, 2010; Zhao et al., 2010).

Zhao et al. (2010), have calculated that urban forests in the Chinese city Hangzhou offset 18% of the annual amount of carbon emitted by industrial enterprises through sequestration, and store an amount of carbon equivalent to 1.75 times the amount of annual carbon emitted by industrial energy uses within the city.

H. Jo (2002) quantified carbon (C) emissions from energy consumption and C storage and uptake by greenspace for three cities in middle Korea. He estimated that woody plants stored an amount of C equivalent to 6.0–59.1% of total C emissions within the cities, and annually offset total C emissions by 0·5–2·2% (H. Jo, 2002).

A study conducted by Escobedo et al. (2010) in two cities in Florida, USA, showed that urban tree sequestered 3.4% and 1.8% of the total annual carbon emission in Gainesville and Miami Dade, respectively. In addition to carbon, urban trees provide several other ecosystem goods and services to city dwellers such as air quality improvement, storm water attenuation, temperature reduction, energy conservation, production of woody biomass and food (Dobbs, Escobedo, & Zipperer, 2011; F. J. Escobedo et al., 2011; Roy et al., 2012).

Given the above studies, quantifying carbon storage and sequestration by urban trees is essential for the development of low - neutral carbon cities or climate friendly cities (Cao & Li, 2011; European Commission - Directorate General for Regional Policy, 2011; Kennedy & Sgouridis, 2011; Lehmann, 2013). According to the concept of "climate friendly cities", cities and town should integrate climate aspect into their strategies (European Commission - Directorate General for Regional Policy, 2011). Furthermore, cities and town should aspire to create compact urban structure, extend urban green spaces, and develop their quality. According to the European Commission - Directorate General for Regional Policy (2011), the three key pillars of climate friendly cities are governance, climate aware integrated strategic planning, and the proper spatial structure of the city supported by zoning policy. As part of this initiative, European cities and towns are recommended to share their knowledge and their experience of climate policy initiatives with others. For example, European cities such as London, Paris, Berlin, Rome have signed the Covenant of Mayors (Covenant of Mayors, n.d.) that are committed to implementing sustainable energy policies (increased energy efficiency and development of renewable energy sources) to meet and exceed the EU's 20% CO_2 reduction objective . But, in addition to energy efficiency and renewable energy sources, CO_2 reduction can also be achieved by CO_2 sequestration from vegetation. However, little is known on the carbon dioxide offset potential of urban trees in Italian cities.

At present, expensive and time consuming field sampling methods (Myeong, Nowak, & Duggin, 2006), models (Aguaron & McPherson, 2012; David J Nowak, 2006), and remote sensing techniques (Mariappan et al., 2012; Myeong et al., 2006) are used to quantify carbon storage and sequestration by urban trees . Furthermore, models and available allometric equations that are commonly used were developed in North America (Soares et al., 2011). However, the use of existing tree inventories can save time and money for the quantification of carbon storage and sequestration. These tree inventories are currently available in many European cities [Bolzano & Merano in Italy, Wien in Austria, Berlin in Germany, Oslo in Norway, Aarhus & Copenhagen in Denmark (Keller & Konijnendijk, 2012)]. Although studies that use street tree inventories to estimate CO_2 do exist, they are mostly for north American, South African, Australian, and Chinese cities (Brack, 2002; Maco & McPherson, 2003; E. Gregory McPherson & Simpson, 2002; E.G. McPherson, 2003; Ren et al., 2012). Also, the majority of studies on carbon storage and sequestration are at macro – scale level (city, province and regions) (Davies, Edmondson, Heinemeyer, Leake, & Gaston, 2011; Tratalos, Fuller, Warren, Davies, & Gaston, 2007) and related to land use (E. Gregory McPherson, Simpson, Xiao, & Wu, 2011; David J Nowak & Crane, 2002).

As an example of a framework that can be used to integrate existing and available inventory data with existing region-specific allometric equations, we focus on the city of Bolzano in South Tyrol, Italy where a comprehensive tree inventory is available. As in most cities in the world, Bolzano's tree inventory is used for tree maintenance and for monitoring of hazard trees. But for this framework, we built on past studies and developed a framework that European cities can use to calculate carbon dioxide storage and sequestration using the tree inventory and available allometric equations from Europe, N. America, and China. Additionally, we analyzed carbon storage and sequestration of urban structures by identifying different types of streetscapes (Asgarzadeh, Lusk, Koga, & Hirate, 2012; Fukahori & Kubota, 2003; Kazemi, Beecham, & Gibbs, 2011; White, Antos, Fitzsimons, & Palmer, 2005). Because of the importance of shaping climate friendly cities, it is of key importance to identify spatial urban structures (i.e. streetscapes) that can be implemented .

Therefore, the objectives of this study in Bolzano were to (1) quantify carbon dioxide storage and sequestration by urban streetscapes and (2) to determine the amount of CO_2 offset from the city's transportation sector. Although we use a city in the Italian Alps as our study area, this framework can be used by other European cities to quantify the potential carbon offsetting of urban trees.

Since the Bolzano City Council has taken part in the Covenant of Mayors in 2009 and decided to become a carbon neutral city by 2030 (Sparber, Fedrizzi, Avesani, Exner, & Mahlknecht, 2010), our study will not only contribute to the development of a methodology applicable to other European cities but also will enhance the sustainable development of a particular city in Northern Italy.

2. Materials and methods

2.1 Study area

The city of Bolzano is situated in the Autonomous Province of Bolzano-South Tyrol in Northern Italy (46° 29' 28'' N, 11° 21' 15''E). The climate of Bolzano can be defined as temperate-continental Central European (Bonatti, 1999), the average annual rainfall is 740 mm (Bonatti, 2008). The average annual temperature is 12.3°C, the average annual minimum temperature is 6.8°C and the average maximum temperature is 17.9°C (Servizio meteorologico della Provincia Autonoma di Bolzano, n.d.). The coldest temperature recorded in Bolzano was -17°C and the maximum record was 40°C (Servizio meteorologico della Provincia Autonoma di Bolzano, n.d.).

The population of Bolzano is about 100,000 people. Bolzano covers an area of more than 50 square kilometers and it is divided into five quarters (Ufficio Statistica e Tempi della Città, 2012). Urban greening represent about 3.9 % of the city's territory and account for approximately 20 m^2 of green space per person (Chiesura & Mirabile, 2012) . Public parks and gardens in Bolzano cover an area of 8.6 ha (1.5 % of the city's territory) and 6 more acres of new parks were added between 1999 and 2003 (Città di Bolzano, 2005). Compared to other European cities, Bolzano belongs to the most virtuous regarding the mobility of its inhabitants within the city (Ufficio Mobilità del Comune di Bolzano, 2010). On average, only 27.2% moved by car, 6.7% used motorcycle, 7.6% used public transportation, 29% used bicycle, and 29.5% moved by foot (Ufficio Mobilità del Comune di

Bolzano, 2010). Everyday approx. 150,000 vehicles (HGVs 14%) run on the roads leading to the city, of which 90,000 come and go from the urban areas (Ufficio Mobilità del Comune di Bolzano, 2010).

2.2 Tree inventory data

The City of Bolzano's Department of Garden and Parks conducted a tree inventory of the boulevards, streets, and urban park rights of ways. This specific tree inventory started in the year 2000 and since then has been updated every 2-3 years . As with most municipal tree inventories, Bolzano´s trees inventory was designed originally to document and identify regular tree maintenance operations as well as the identification of dead or hazardous trees. Overall, Bolzano´s trees inventory contains information for approximately 5000 trees that represent roughly 40 % of the trees on public spaces in Bolzano (City of Bolzano, personal communication, 2011). The tree inventory data includes: tree species and cultivar names, tree circumference at 1 meter above the surface of the ground, age classes (e.g. new planting, young, adult), height classes (e.g. < 5 m, 5-10 m, 10-20 m, and 20-30 m), crown condition as defined by five classes (e.g. healthy to dead trees) based on Roloff´s (2001) classes, and location based on a combination of Global Positioning System (GPS) coordinates, aerial photo interpretation, topographic measurements, and trigonometric calculations. Since Bolzano´s tree inventory does not contain precise information on tree growth and changes in height, we used predictive equations [h=f(DBH); see Chapter 2] for estimating tree height for the entire tree inventor.

2.3 Allometric and carbon dioxide estimates

Existing allometric biomass equations developed from forest trees (Bunce, 1968; Jenkins, Chojnacky, Heath, & Birdsey, 2003; Leonardi, Santa Regina, Rapp, Gallego, & Rico, 1996; Liu &

Li, 2012; Ruiz-Peinado, Montero, & Del Rio, 2012; G. Tabacchi, Di Cosmo, Gasparini, & Morelli, 2011; Giovanni Tabacchi, Di Cosmo, & Gasparini, 2011; Zianis, Muukkonen, Mäkipää, & Mencuccini, 2005) were used to calculate the dry weight above-ground biomass for each tree in Bolzano´s tree inventory. A literature review of over 9 publications produced 32 equations from mostly Italian and European sources (Appendix A). Mostly equations from forest grown trees (Appendix A) were applied to each appropriate tree. If there was no species specific biomass equation available for a particular species (like, e.g. *Albizia julibrissin*), the species' biomass was derived using equations for the same genera, family, or group (i.e. mixed hardwood) according to Jenkins et al. (2003).

Some studies report that urban street trees have 20 % lower biomass than similar sized forest-grown trees of the same species (D. J. Nowak, 1994). However, other studies such as Lawrence et al. (2012) found little difference between forest and urban grown trees of the same species and McHale et al. (2009) found that some of the forest allometric equations published in the literature produce similar estimates of biomass as compared to urban-based allometric equations developed for specific locations. Therefore, we did not reduce the 20% biomass to account for trees growing in streets and boulevards. Furthermore, we followed the approach of Strohbach & Haase, (2012) study of urban trees in Germany and we did not account for below-ground biomass in our calculation since urban root systems are likely very different from forest grown conditions due to urban soil conditions. Finally, dry weight of the above-ground biomass was converted to Carbon (kg) by multiplying by 0.5 and CO_2 equivalent was calculated by multiplying C by 3.67 (Dobbs et al., 2011; McPherson & Simpson, 1999). Carbon dioxide sequestration was estimated based on the annual growth rates or changes in tree diameter over a given time period (Liu & Li, 2012) and the difference of C stored between year y (i.e. 2011) and year y + 1 (i.e. 2012). Finally, CO_2 offset was estimated as the CO_2 sequestered by a streetscape (St_{SQ}) divided by the CO_2 produced from transportation by one person (TR_{em}):

$\nu = St_{SQ}/TR_{em}$

ν=number of people offsetting,

St_{SQ}= CO_2 sequestered by a streetscape, and

TR_{em}= CO_2 produced from transportation by one person

2.4 Growth rates

Trees remove carbon dioxide from the atmosphere through their growth process (Nowak et al., 2002); data on growth or information on changes in tree diameter over time are necessary to estimate changes in biomass and carbon storage over a defined time period (i.e. carbon sequestration). Some studies David J Nowak, Crane, Stevens, & Ibarra, (2002) , DeVries (1987)) have used average urban tree growth rates of species reported by previous studies of North American trees on various land-use types (Lawrence et al., 2012), Stoffberg et al., 2009). In this paper, we used tree growth rates data from a previous study in Bolzano (see Chapter 2).

2.5 Diameter at breast height (DBH)

Allometric equations are based on diameter measured at breast height (i.e. DBH). However, the diameter of Bolzano´s tree inventory was measured at 1 meter above the ground. Using field data from a previous study in Bolzano (see Chapter 2), we calculated the DBH by multiplying the diameter at 1m (DH) by the ratio of DBH/DH (Appendix B). In addition, DBH was measured for the year 2011 subsample. Specifically, we calculated the diameter at 1m by adding the initial diameter (DHY1) to the product of the annual growth rate and the number of years between measurements . We then converted the DH 2011 to DBH 2011 by multiplying the diameter (DH 2011) by the ratio (R) of DBH/DH:

$DBH_{2011} = [DHY_1+(AGR \times n)] \times R$

where DHY_1 = diameter at 1 meter (years change with different location), AGR = annual growth rate, R = ratio DBH/DH, and n = number of years between two time periods.

2.6 Carbon emissions by the transportation sector in Bolzano

Sparber et al. (2010) estimated carbon dioxide (CO2) emissions for the City of Bolzano at 9.7 Mg CO_2 per person for the year 2007, out of which 3 Mg of CO2 were emitted from the transportation sector (Figure 1). The study determined that the majority of transportation CO_2 emissions were from commuter traffic and transportation of goods by road (Sparber et al., 2010).

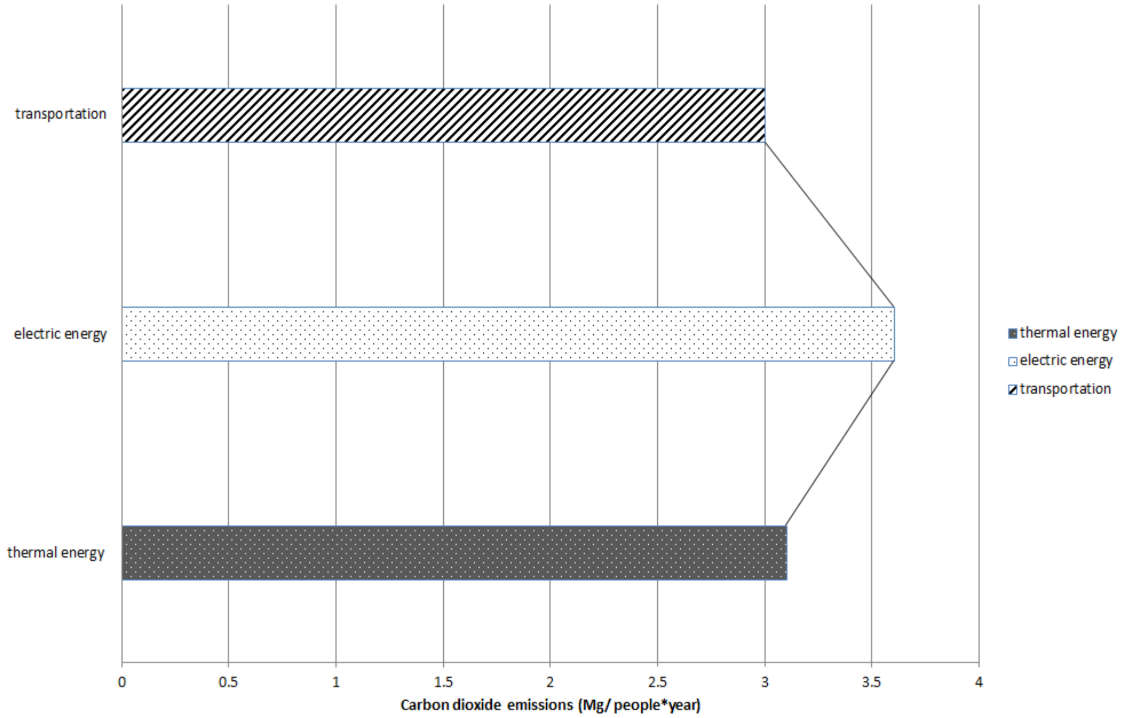

Figure 1: CO_2 emissions in Bolzano [data from Sparber et al. (2010)].

2.7 Streetscapes

We define “streetscape” as any area with paved roads, street infrastructure, and vegetation located in urban and peri-urban areas (Fukahori & Kubota, 2003; White et al., 2005; Zhang & Lin, 2011). We stratified our results by streetscape types based on tree location information as reported in Bolzano´s tree inventory. We identified 6 typologies of streetscapes: boulevard, cycle path, park, piazza, promenade and street (Figure 2).

Figure 2: Representative examples of streetscape types in Bolzano: (1) boulevard, (2) street, (3) cycle path, (4) park, (5) promenade, (6) piazza.

In general, “boulevards” were wide tree-lined avenues usually having trees and shrubs at both sides or at the center too, while cycle paths were bicycle facility normally separated from pedestrian paths by a hedge of shrubs and trees. “Parks” were open spaces used for recreation characterized by permeable land surfaces covered with trees, shrubs, and grass, and which is differentiated from “piazza” as the latter included public squares with hard and soft landscape elements created for the development of social relationships (Scudo & Ochoa de la Torre, 2003).

Finally, "promenade" included rights of way in forest land used in mostly peri-urban areas and streets were tree-lined street rights of way.

3. Results
3.1 Urban green spaces type and urban forest structure

Table 1 shows the streetscape types in Bolzano, number of tree individuals measured, and their characteristics. In all, we calculated 176 tree species in the Bolzano´s tree inventory and Figure 3 shows the most frequent tree species in Bolzano. Accordingly, *Quercus pubescens* was the most frequent tree species and represents 9.6 % of the total streetscape tree population in Bolzano (Figure 3). The CO2 storage for Bolzano´s tree inventory is 6352.47 Mg and the CO2 sequestration is 229.66 Mg/year.

Table 1. Bolzano´s urban structure: streetscape type.

Streetscape type	Characteristics	Number of trees	Most common species
Boulevard	Tree-lined avenues called in Italian "viali" having a total cross-section up to a maximum of 20 m including sidewalks and bike paths	715	*Sophora japonica* (28.1%), *Prunus cerasi fera (9.5%), Platanus x hispanica (7.6%)*
Cycle path	Green bicycle, minimum width 1.50 m, maximum width 3.0 m	89	*Carpinus betulus(13.5%), Tilia x europaea(9.0%), Populus alba (9.0%)*
Park	Includes urban parks	1,417	*Cedrus deodara (7.8%), Acer pseudoplatanus (5.4%), Acer platanoides (5.3%)*
Piazza	Includes squares with urban trees	154	*Cedrus atlantica (19.5%) Sophora japonica (13.6%)Tilia americana (11.0%)*
Promenade	Areas of high landscape value, forest land use, periurban	1,072	*Quercus pubescens (41%)Cupressus sempervirens(13.7%), Celtis australis (11.1%)*
Street	Tree-lined streets having a total cross-section up to a maximum of 20 m could include sidewalks and bike paths	1,125	*Acer pseudoplatanus(9.9%)Liquidambar styraciflua (9.2%), Platanus x hispanica (9.1%)*

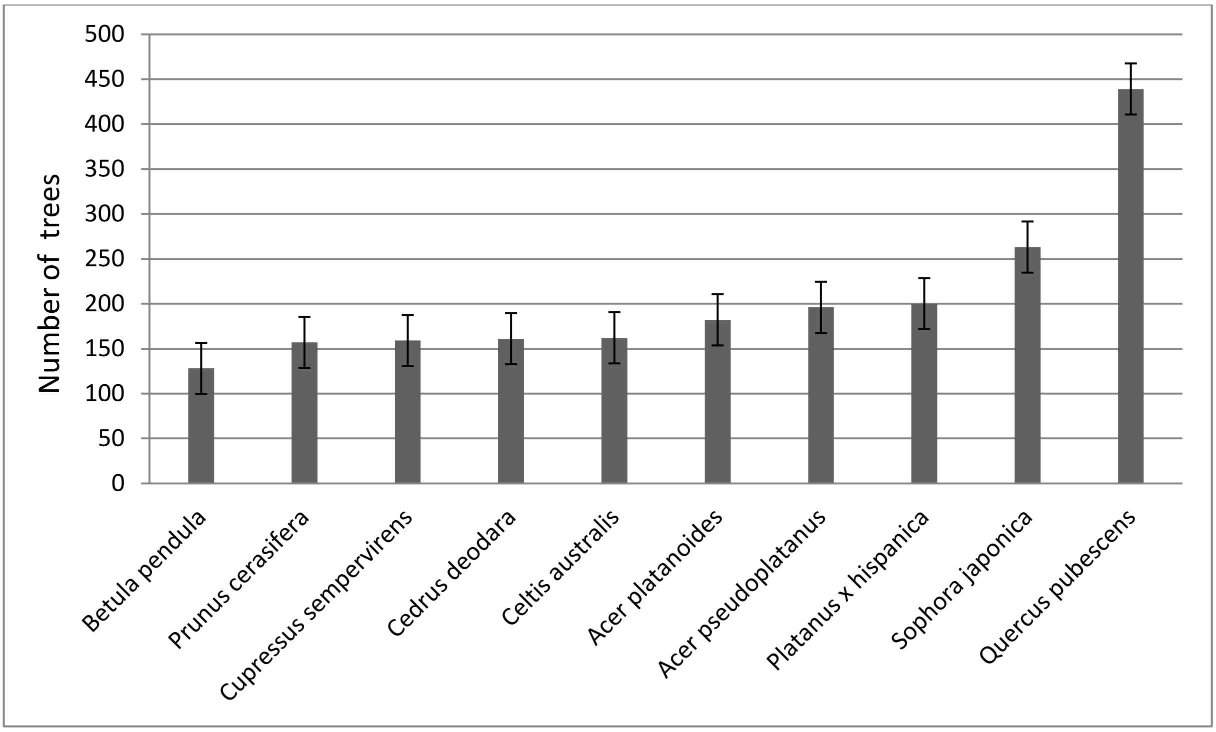

Figure 3: Most frequent tree species in Bolzano's streetscapes with individual numbers given according to the tree inventory of the city. Error bars represent ± one standard error of the mean.

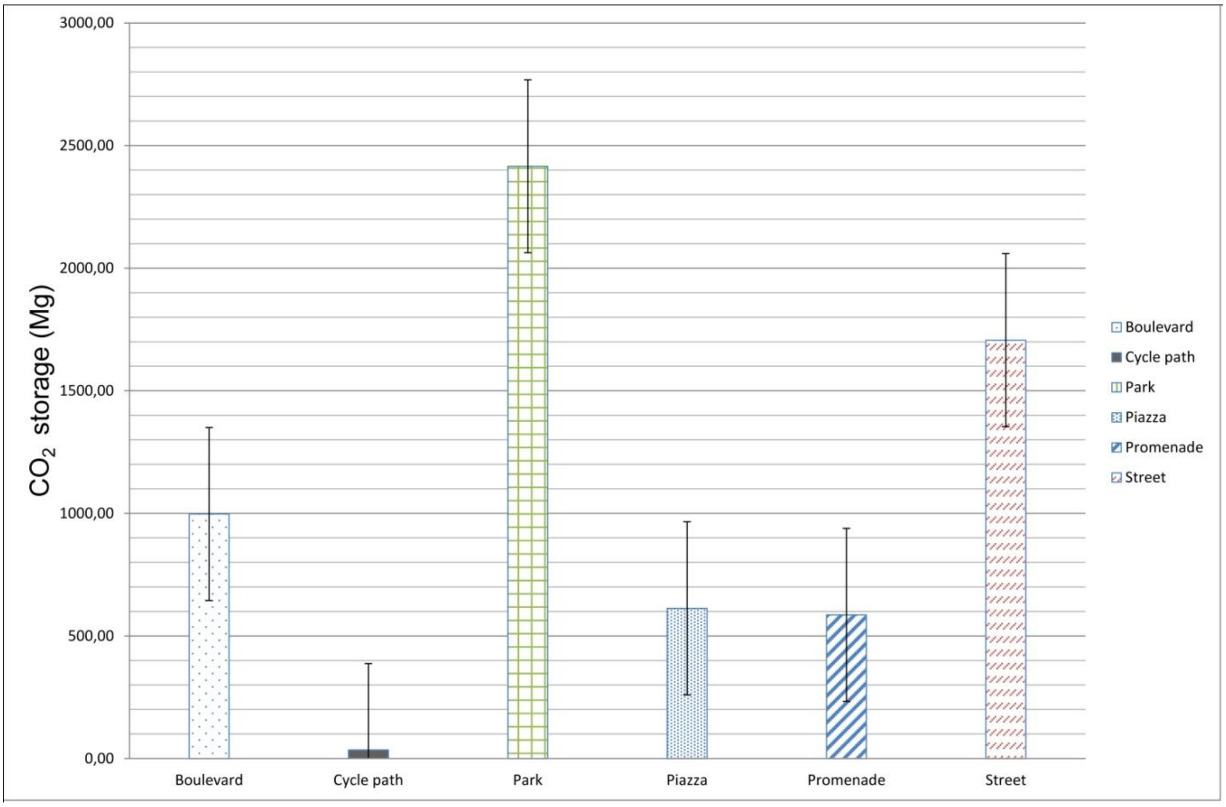

Figure 4: Total carbon dioxide stored by different streetscapes in Bolzano. Error bars represent ± one standard error of the mean.

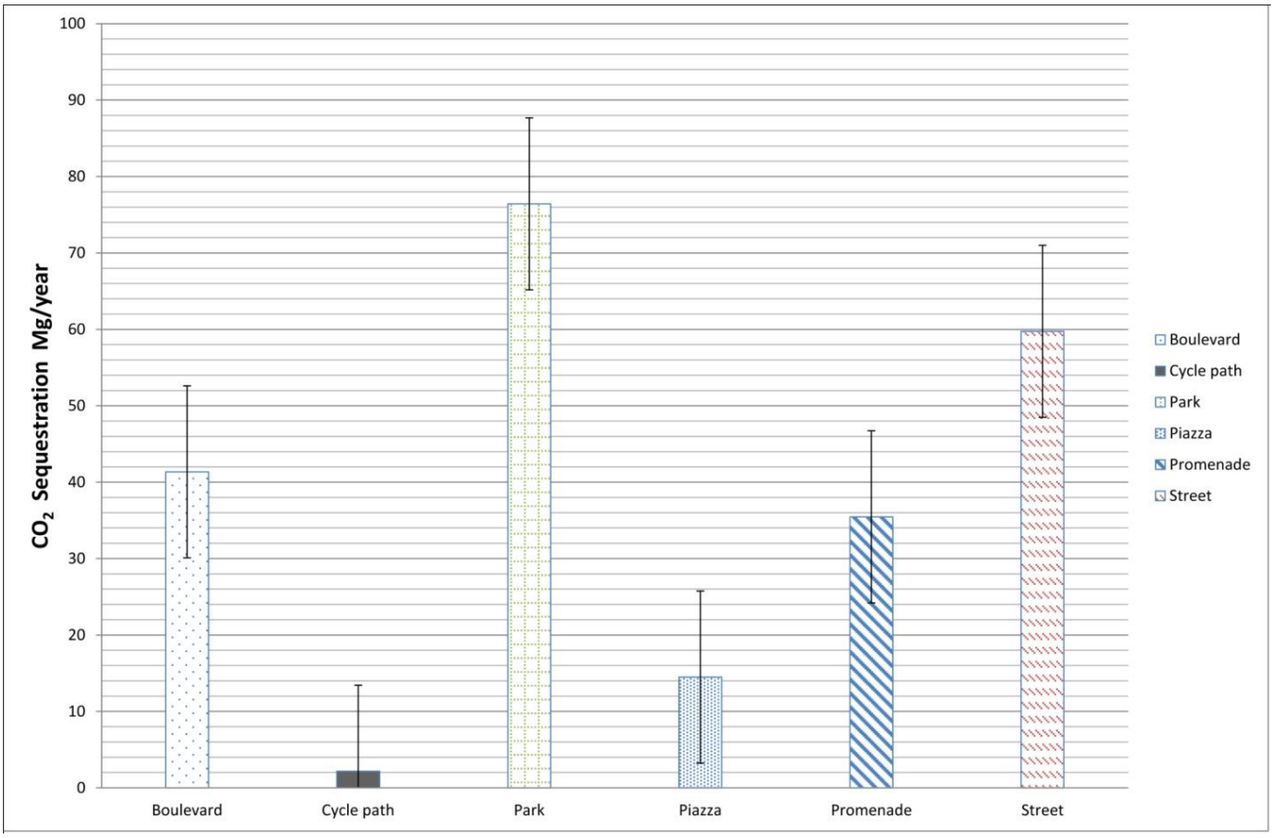

Figure 5: Total carbon dioxide sequestration by different streetscapes in Bolzano. Error bars represent ± one standard error of the mean.

Table 2. Average DBH and CO_2 stored and sequestration per tree by different streetscapes. SE= Standard error.

Streetscapes	n	DBH (cm)	SE	CO_2 storage (kg)	SE	CO_2 sequestration (kg/year)	SE
Street	1125	33.62	0.60	1516.75	81.86	53.11	1.87
Promenade	1072	24.61	0,37	546.58	26.00	33.08	0.76
Piazza	154	59.10	2.03	3977.95	480.96	94.14	7.11
Park	1417	39.30	0.61	1704.64	65.26	53.93	1.30
Cycle path	89	20.91	1.41	390.61	87.86	24.49	2.65
Boulevard	715	36.22	0.63	1394.89	56.57	57.84	1.50

3.2 Carbon offsetting

We calculated that the trees in Bolzano's streetscapes through sequestration annually offset 0.08 % of the amount of carbon dioxide emitted by the transportation sector (300,000 Mg/year). Boulevards in Bolzano can offset that annual CO_2 emissions from transportation-related activities of about 14 inhabitants, cycle paths can offset about one inhabitant, parks 25 inhabitants, urban places (piazza) 5 inhabitants, promenades 12 inhabitants, and streets about 20 inhabitants.

4. Discussion

4.1 Methodology

In this paper, we presented a methodology to calculate the potential CO_2 offsetting provided by urban streetscapes using an available tree inventory. The methodology and approach we applied used limited but available data from an existing tree inventory and more detailed field measurements from a subsample to calculate CO_2 storage and sequestration from urban trees. We estimated CO_2 sequestration using annual growth rates and forest based allometric equations that use DBH and tree height.

4.2 CO_2 storage and sequestration

We calculated the CO_2 storage and sequestration based on a tree inventory; we do not consider the amount of carbon stored in shrubs, grasslands and soil. CO_2 storage was greatest in parks amounting for 2,415.48 Mg. Lowest estimates were found in cycle paths (34.76 Mg). This is because the highest number of trees in Bolzano are in parks (1417 trees). The average CO_2 storage and sequestration per tree was greatest in piazza 397,79 Kg and 94,14kg/year. The lowest CO_2 storage and sequestration per tree was in cycle paths (Table 2). The capacity of urban trees to absorb CO_2 from the atmosphere depend on the annual growth rates. Since annual growth rates are influenced by several factor such as genetics, climate, soil, moisture, light, competition, disturbance, irrigation regime and stress (Bühler, Kristoffersen, & Larsen, 2007; Lawrence et al., 2012; Peper & McPherson, 1998), the growth rates used in this study were different from those reported by other North American and European studies (Bühler et al., 2007; Iakovoglou, Thompson, & Burras, 2002; H.-K. Jo & McPherson, 1995; Lawrence et al., 2012).

Since CO_2 estimates are based on individual trees and streetscapes types and these results represent about 40% of total public trees in Bolzano, it is hard to compare with other studies that are at city scale. Furthermore, these results are difficult to compare with other studies because of differences in urban forest structures and composition, soil, and climatic condition, use of different methodologies (Aguaron & McPherson, 2012; Strohbach & Haase, 2012) (forest or urban derived equations, North American models, remote sensing techniques). For example a study conducted by Paoletti et al., (2011) in a urban park in Florence, Italy, using the Urban Forest Effects (UFORE) model, found that the average C storage (above and belowground) per tree was 370.8 kg (CO_2), C sequestration was 9.10 kg (CO_2) in 1985. Estimates after 19 year found that the C storage was 354.6 kg (CO_2) and C sequestration was 9.79 kg (CO_2) (Paoletti et al., 2011). The average DBH was 27.22 cm in 1985 and in 32.31cm in 2004 (Paoletti et al., 2011) lower than our estimates (average DBH was 39.30 cm see Table 2) this means lower CO_2 storage in Florence's park than in Bolzano's parks. The average CO_2 sequestration per tree in Florence's park (Paoletti et al., 2011) was lower than our estimates in Bolzano's parks because the UFORE model uses growth rates based on land use types and adjusted on tree condition: fair to excellent condition, multiplied by 1 (no adjustment), poor condition - 0.76, critical condition - 0.42, dying - 0.15, dead – 0 (E.G. McPherson & Peper, 2012; D J Nowak et al., 2008; David J Nowak et al., 2002).

4.3 Limitations

The estimates given in this paper are based on forest biomass equations that can overestimate or underestimate the CO_2 stored and sequestered by urban trees (H.-K. Jo & McPherson, 1995). Furthermore, the use of North American and Asian forest based equations (Jenkins et al., 2003; Liu & Li, 2012) used for non-native species in this study can overestimate tree biomass. For example Annighöfer et al., (2012) found that *Prunus serotina* in the biosphere reserve ''Valle del Ticino'' in Northern Italy, like other species introduced from North America, is less productive in Europe when compared to North America, due to smaller achieved growth heights.

We did not consider the amount of CO_2 from maintenance activities, such as pruning, removals, irrigation, fertilization.

In order to improve this methodology, therefore to better understand the role of urban streetscapes in offsetting carbon emission in cities additional research is needed to develop urban tree biomass equations and investigate the effect of shrubs, grasslands and urban soils on carbon storage. In addition, we need to consider the carbon dioxide emissions from maintenance operations. If fuel machinery are used to maintain vegetation structure and health, the urban forest ecosystem eventually will become a net emitter of carbon (D J Nowak, Stevens, Sisinni, & Luley, 2002). Hence, managers should consider the types of equipment that are used to plant, maintain, and remove vegetation (David J Nowak et al., 2002).

Therefore, within a city, trees are not only important for CO_2 storage and sequestration but they provide several ecosystem services such as air pollutant removal, microclimatic regulation, noise reduction, mental and physical benefits and cultural services (F. J. Escobedo et al., 2011; N. J. Georgi & Zafiriadis, 2006; Roy et al., 2012; Tyrväinen et al., 2005; Tzoulas et al., 2007).

5. Conclusion

To conclude, the outcome of this study could convince city planners, politicians and managers to improve the number of urban trees and to plan sufficient sustainable and low maintenance green streetscapes in order to deal with climate change.

Appendix A: Allometric equations

Species	Equation	Parameters	Reference	Region
Abies spp.	$dw_4=b_1+b_2d^2h+b_3d$	dw_4= Total aboveground dry weight b_1=-2.1386 b_2=1.8125 × 10^{-2} b_3=1.1089 h= total tree height d= diameter at breast height	Abies alba (G. Tabacchi et al., 2011; Giovanni Tabacchi et al., 2011)	Italy
Acer spp.	$dw_4=b_1+b_2d^2h$	dw_4= Total aboveground dry weight b_1 = 6.4595 b_2 =2.6368 × 10^{-2} h= total tree height d= diameter at breast height	Acer spp. (G. Tabacchi et al., 2011; Giovanni Tabacchi et al., 2011)	Italy
Aesculus spp., *Ailantus* spp., *Catalpa* spp., *Celtis* spp., *Crateagus* spp.,*Cercis* spp., *Cornus* spp., *Davidia involucrate, Diospyros* spp., *Eriobotrya japonica, Firmiana simplex* (L.) W. Wight, *Ginkgo biloba, Ficus carica, Gleditsia* spp., *Gymnocladus* spp., *Hedera helix* L., *Hibiscus* spp., *Juglans* spp., *Koelreuteria* spp., *Laburnum anagyroides, Lagerstroemia* spp., *Laurus* spp., *Liquidambar* spp., *Ligustrum lucidum, Liriodendron* spp. , *Maclura pomifera, Malus* spp., *Magnolia* spp., *Melia* spp., *Morus.* spp., *Paulownia* spp., *Photinia* spp., *Pistacia terebinthus, Platanus* spp., *Pterocarya sp., Rhus taphrina, Sorbus* spp., *Tamarix* spp., *Toona* spp., *Wisteria* spp.,*Zanthoxylum americanum*	bm = Exp(βo + β_1 In dbh)	β_o = -2.4800 β_1= 2.4835 dbh = diameter at breast height Exp = exponential function In = log base e (2.7 18282)	Mixed hardwood (Jenkins et al., 2003)	North America
Alnus spp.	$dw_4=b_1+b_2d^2h+b_3d$	b_1= -1.6747*10 b_2=1.7930*10^{-2} b_3=2.6666	(G. Tabacchi et al., 2011; Giovanni Tabacchi et al., 2011)	Italy
Arbutus unedo L.	ABW= a+b·D^2	a= –2.8816 b= 0.2639 D=diameter ABW= Total aboveground woody biomass	equation n.29 (Zianis et al.,2005)	Italy
Betula spp., *Corylus* spp.	$\log_e$ y = a + b (loge x)	$\log_e$ y = a + b (loge x), where y = tree dry weight (trunk + branches) and x = tree girth at 1-3 m a= -5.223864 b= 2.425436	Birch Combined (Bunce, 1968)	UK
Carpinus spp., *Ostrya* spp.	$dw4=b_1+b_2d^2h$	b_1= 3.2485 b_2=3.0167*10^{-2}	(G. Tabacchi et al., 2011; Giovanni Tabacchi et al., 2011)	Italy
*Cedrus sp., Chamaecyparis sp., Cryptomeria sp., Cunninghamia lanceolata (*Lamb.) Hook. *Sequoia sempevirens, Metasequoia* spp., *Sequoiadendron* spp., *Taxodium sp. Thuja* spp.	bm = Exp(βo + β_1 In dbh)	β_o = -2.0336 β_1=2.2592 dbh = diameter at breast height Exp = exponential function In = log base e (2.7 18282)	Cedar/larch (Jenkins et al., 2003)	North America
Araucaria spp., Cephalotaxus spp.,*Taxus* spp. *Tsuga canadensis*	bm = Exp(βo + β_1 In dbh)	βo = -2.5384 β_1=2.4814 dbh = diameter at breast height Exp = exponential function	True fir/hemlock (Jenkins et al., 2003)	North America

		In = log base e (2.7 18282)		
Cupressus spp. *Calocedrus decurrens*	$dw_4=b_1+b_2d^2h+b_3d$	b_1=-4.1345 b_2=2.4359*10^{-2} b_3=1.4156	(G. Tabacchi et al., 2011; Giovanni Tabacchi et al., 2011)	Italy
Castanea sativa	Aboveground biomass= $0.137(DBH)^{2.247}$		(Leonardi et al., 1996)	Italy
Ceratonia siliqua L.	Ws=0.142*$d^{1.974}$ W_{b7}=0.104*d^2 W_{b2-7}= 0.0538*d^2	Ws= biomass stem (kg) W_{b7}=Thick branches biomass (Kg) W_{b2-7}= Medium branches	(Ruiz-Peinado et al., 2012)	Spain
Fagus spp.	$dw_4=b_1+b_2d^2h$	b_1=1.6409 b_2= 3.0775*10^{-2}	(G. Tabacchi et al., 2011; Giovanni Tabacchi et al., 2011)	Italy
Fraxinus spp.	$dw_4=b_1+b_2d^2h$	b_1=2.1893 b_2= 3.2949*10^{-2}	(G. Tabacchi et al., 2011; Giovanni Tabacchi et al., 2011)	Italy
Larix spp.	$dw4=b_1+b_2d^2h+b_3d$	b1=-1.4060*10 b_2=1.4664*10^{-2} b_3=3.2309	(G. Tabacchi et al., 2011; Giovanni Tabacchi et al., 2011)	Italy
Olea europaea L.	Ws = 0.0114 · d^2 · h Wb7 = 0.0108 · d^2 · h Wb2–7 = 1.672 · d Wb2 + l = 0.0354 · d^2 + 1.187 · h	Ws: Biomass weight of the stem fraction (kg); Wb7: Biomass weight of the thick branches fraction (diameter larger than 7 cm) (kg); Wb2–7: Biomass weight of medium branches fraction (diameter between 2 and 7 cm) (kg); Wb2 + l: Biomass weight of thin branches fraction (diameter smaller than 2 cm) with leaves (kg); Wr: Biomass weight of the belowground fraction (kg); d: diameter at breast height (cm); h: tree height (m)	(Ruiz-Peinado et al., 2012)	Spain
Picea spp.	$dw_4=b_1+b_2d^2h+b_3d$	b_1=1.4146*10^{-1} b_2=1.7620*10^{-2} b_3=5.6209*10^{-1}	(G. Tabacchi et al., 2011; Giovanni Tabacchi et al., 2011)	Italy
Pinus cembra	$dw4=b_1+b_2d^2h$	B_1= 3.3073 B_2=1.8848*10^{-2}	(G. Tabacchi et al., 2011; Giovanni Tabacchi et al., 2011)	Italy
Pinus halepensis Mill.	$dw_4=b_1+b_2d^2h+b_3d$	b_1=- 8.1012 b_2=2.1559*10^{-2} b_3=2.2591	(G. Tabacchi et al., 2011; Giovanni Tabacchi et al., 2011)	Italy
Pinus nigra Arnold	$a+b\cdot D^2\cdot H+c\cdot D^2$	a=–3.5712 b=0.014429 c=0.068047	Equation 738 (*Muukkonen, P.*	Italy

			& Mäkipää, R. 2006)	
Pinus pinaster Aiton	$dw4=b_1+b_2d^2h$	b1=1.9539 $b_2=2.0810*10^{-2}$	(G. Tabacchi et al., 2011; Giovanni Tabacchi et al., 2011)	
Pinus pinea L.	$dw_4=b_1+b_2d^2h$	$b_1=4.5885*10^{-1}$ $b_2=2.5176 *10^{-2}$	(G. Tabacchi et al., 2011; Giovanni Tabacchi et al., 2011)	Italy
Pinus strobus L., *Pinus wallichiana*, *Pinus taeda*, *Pinus coulteri*, *Pinus ponderosa*, *Pinus* spp.	$dw_4=b_1+b_2d^2h$	$b_1=5.6156$ $b_2=1.5939*10^{-2}$	(G. Tabacchi et al., 2011; Giovanni Tabacchi et al., 2011)	Italy
Pinus sylvestris L.	$dw_4=b_1+b_2d^2h$	$b_1=2.8848$ $b_2=2.2080*10^{-2}$	(G. Tabacchi et al., 2011; Giovanni Tabacchi et al., 2011)	Italy
Populus spp., *Prunus* spp., *Tilia* spp., *Ulmus* spp., *Zelkova* spp.	$dw_4=b_1+b_2d^2h+b_3d$	$b_1= -1.2825*10$ $b_2= 1.1993*10^{-2}$ $b_3=3.1553$	(G. Tabacchi et al., 2011; Giovanni Tabacchi et al., 2011)	Italy
Pseudotsuga spp.	bm = Exp(βo + β_I In dbh)	β_o = -2.2304 β1= 2.4435dbh = diameter at breast height Exp = exponential function In = log base e (2.7 18282)	Douglas -fir (Jenkins et al., 2003)	North America
Quercus ilex	$Ab= a*D^b$	a=0.2306 b=2.2791	Equation 556 (Zianis et al.,2005)	Italy
Q. palustris, Q. petraea, Q. robur, Q. rubra	a+b·ln(D)	a= –2.4232 b= 2.4682	Equation 601 (Zianis et al.,2005)	UK
Quercus pubescens	$dw_4=b_1+b_2d^2h+b_3d$	$b_1=-7.1745$ $b_2=3.3299*10^{-2}$ $b_3=1.2623$	(G. Tabacchi et al., 2011; Giovanni Tabacchi et al., 2011)	Italy
Albizia julibrissin, Robinia spp.	$dw_4=b_1+b_2d^2h+b_3d$	$b_1=-1.0114*10$ $b_2=2.4042*10^{-2}$ $b_3=2.2065$	(G. Tabacchi et al., 2011; Giovanni Tabacchi et al., 2011)	Italy
Salix spp.	$dw_4=b_1+b_2d^2h$	$b_1= 9.0561$ $b_2= 2.1087*10^{-2}$	(G. Tabacchi et al., 2011; Giovanni Tabacchi et al., 2011)	Italy
Sophora japonica L.	$Bs = 0.069 \times D^{2.54}$, $Bb = 0.068 \times D^{1.89}$	Bs=stem, Bb= branch	(Liu & Li, 2012)	China

Appendix B: Ratio DBH/DH, Std = standard deviation

Order	Ratio DBH/DH	Std
Fabales	0.97	0.09
Fagales	0.96	0.08
Ginkgoales	0.97	0.03
Hamamelidales	0.97	0.03
Juglandales	0.99	0.02
Magnoliales	0.96	0.05
Malvales	0.96	0.05
Myrtales	0.88	0.16
Pinales	0.95	0.09
Rosales	0.93	0.12
Salicales	0.94	0.08
Sapindales	0.97	0.04
Scrophulariales	0.97	0.02
Urticales	0.95	0.07
Violales	0.89	0.33
Division	**Ratio DBH/DH**	**Std**
Magnoliophyta	0.95	0.03

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