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**Russo, Alessio ORCID logoORCID: <https://orcid.org/0000-0002-0073-7243>, Escobedo, Francisco J., Timilsina, Nilesh and Zerbe, Stefan (2015) Transportation carbon dioxide emission offsets by public urban trees: A case study in Bolzano, Italy. Urban Forestry and Urban Greening, 14 (2). pp. 398-403. doi:10.1016/j.ufug.2015.04.002**

Official URL: <http://dx.doi.org/10.1016/j.ufug.2015.04.002>

DOI: <http://dx.doi.org/10.1016/j.ufug.2015.04.002>

EPrint URI: <https://eprints.glos.ac.uk/id/eprint/6594>

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# Transportation carbon dioxide emission offsets by public urban trees: A case study in Bolzano, Italy

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## **Keywords:**

Climate change  
CO<sub>2</sub> accounting  
CO<sub>2</sub> sequestration  
Streetscapes Transportation emissions

## **Abstract**

Increased carbon dioxide (CO<sub>2</sub>) emissions in urban areas due to rapid population growth and consequent increased energy use and vehicular traffic is a worldwide problem contributing to an altered 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 similar emissions from the transportation sector. Therefore, the aim of this study was to develop a method to calculate 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 annual vehicular CO<sub>2</sub> emissions from a city in the Italian Alps to determine the CO<sub>2</sub> offset potential of urban streetscapes. We found that the trees in Bolzano's streetscapes through sequestration annually offset 0.08% of the amount of CO<sub>2</sub> emitted by the transportation sector. Results, applications, and a potential indicator are discussed and compared against other studies. Findings from this study can be used as indicators and to better understand the potential role of urban streetscapes in reducing urban atmospheric CO<sub>2</sub> emissions.

## **Introduction**

Currently, the increased greenhouse gas concentrations in the atmosphere are one of the most pressing environmental problems (Valsta et al., 2008). Carbon dioxide (CO<sub>2</sub>) is an important greenhouse gas and a major driver of climate change effects (Nusbaumer and Matsumoto, 2008), as a result the predicted global temperature rise will be proportional to the total amount of CO<sub>2</sub> emitted (Skippon et al., 2012). In recent years, increases in carbon dioxide concentrations are mostly due to rapidly increasing population, energy

use, and emissions from vehicular traffic (Sharma et al., 2010; Uherek et al., 2010). In fact, half of the world's population is living in cities and 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 also predicted that by 2030, 5 of the 8.5 billion people in the globe will be urban dweller (Vauramo, 2011). As a result, the anthropogenic and transportation-related sectors comprise more than 80% of all CO<sub>2</sub> emissions into the urban environment (Gratani and Varone, 2005; Koerner and Klopatek, 2002). Thus, increasing population and urbanization in the world are a major cause of CO<sub>2</sub> and other greenhouse gases that are affecting the global climate. As urbanization increases globally, it is becoming important to better understand the carbon dynamics of these urban ecosystems (Gratani and Varone, 2013; McHale et al., 2009; Weissert et al., 2014).

Although, cities are a primary source of CO<sub>2</sub> emissions, remnant and planted vegetation in urban forests and green spaces can sequester and store carbon dioxide (Díaz-Porrás et al., 2014; Strohbach et al., 2012). For example, at the time of writing, several studies have demonstrated that urban trees in particular can play an important role in offsetting humans carbon dioxide (CO<sub>2</sub>) emissions (Escobedo et al., 2010; Nowak et al., 2013; Poudyal et al., 2010; Timilsina et al., 2014; Weissert et al., 2014; Zhao et al., 2010). Urban forest carbon offset standards and protocols are currently being developed to better account for the CO<sub>2</sub> mitigation potential of urban trees and to incentivise tree preservation and plantings (CalFIRE and USFS, 2014).

In Asia, Zhao et al. (2010) calculated that urban forests in Hangzhou, China offset 19% 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. Jo (2002) quantified carbon (C) emissions from energy consumption and C storage and uptake by green space for three cities in South Korea and 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% (Jo, 2002). In north America, Escobedo et al. (2010) studied two cities in Florida, USA, and showed that urban tree sequestered 3.4% and 1.8% of the total annual carbon emission in Gainesville and Miami Dade, respectively. However, McPherson and Kendall (2014) found that the total amount of CO<sub>2</sub> emitted from modeled, large scale tree plantings in Los Angeles, USA was slightly greater than the CO<sub>2</sub> stored by these trees over 40 years.

Studies that have quantified the offset potential of urban trees are less common in Europe (Roy et al., 2012; Weissert et al., 2014). Russo et al. (2014), in Bolzano, Italy found that a subsample of urban trees sequestered 5.73 Mg/year of carbon per year, but the study did not consider the potential CO<sub>2</sub> offset of anthropogenic emissions. Davies et al. (2011) in the United Kingdom found that 231 521 t of carbon are stored within the above-ground vegetation of Leicester, equating to 3.16 kg/C/m<sup>2</sup> of urban area, with 97.3% of this carbon pool being associated with trees rather than herbaceous and woody vegetation. To our knowledge, only in Florence, Italy has Vaccari et al. (2013) found that urban green spaces offset 6.2% of the total direct anthropogenic CO<sub>2</sub> emissions.

Given the above studies, quantifying carbon storage and sequestration by urban trees is necessary for the development of low-neutral carbon cities or climate friendly cities (Cao and Li, 2011; European Commission – Directorate General for Regional Policy, 2011; Kennedy and Sgouridis, 2011; Lehmann, 2013). As part of this initiative, European cities and towns are sharing their knowledge and their experience in climate policy initiatives with others. For example, London, Paris, Berlin, and Rome have signed the Covenant of Mayors (Covenant of Mayors, n.d.) that includes commitments to implementing sustainable energy policies (e.g. increased energy efficiency and development of renewable energy sources) that meet and exceed the EU's 20% CO<sub>2</sub> reduction objective. In addition to energy efficiency and renewable energy sources, CO<sub>2</sub> reduction can also be achieved via CO<sub>2</sub> sequestration from vegetation.

Indeed, a framework that integrates existing and available tree inventory data with existing region-specific allometric equations to quantify the role of urban trees in offsetting CO<sub>2</sub> in European cities can be used to promote the integration of urban green and trees towards these efforts. Therefore, the aim of this study was to analyze the CO<sub>2</sub> offsetting potential of treed streetscapes in a European city by incorporating available methods and information. The specific objectives of this case study in Bolzano, Italy were to: (1) quantify carbon dioxide storage and sequestration by urban streetscapes and (2) to determine the amount of CO<sub>2</sub> 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. For this short communication, we built on past studies and developed a region-specific approach that European cities can use to calculate carbon dioxide offsetting using available tree inventories, allometric equations, and city-specific anthropogenic CO<sub>2</sub> emission information. 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 et al., 2010), our study can not only contribute to the development of a methodology and indicator applicable to other cities such as Bolzano, but also will enhance the sustainable development of cities elsewhere in Europe.

## Methods

The study was conducted in Bolzano situated in the Autonomous Province of Bolzano-South Tyrol in Northern Italy (46°29'28"N, 11°21'15"E). The average annual rainfall is 740 mm (Bonatti, 2008), average annual temperature is 12.3 °C, average annual minimum temperature is 6.8 °C and the average maximum temperature is 17.9 °C (Provincia Autonoma di Bolzano, 2012). The population of Bolzano is about 100,000 people and covers an area of more than 50 square kilometers and is divided into five quarters (Ufficio, 2012). Compared to other European cities, Bolzano depends little on fuel burning vehicles in regards to the mobility of its inhabitants within the city (Ufficio, 2010) since on average only 27.2% move by car, 6.7% used motorcycle, 7.6% used public transportation, 29% used bicycle, and 29.5% moved by foot (Ufficio, 2010). Everyday approx. 150,000 vehicles (HGVs 14%) are used (Ufficio, 2010).

We calculated above-ground biomass using Bolzano's tree inventory data (Russo, 2013) and allometric equations from the literature (Jenkins et al., 2003; Liu and Li, 2012; Muukkonen and Mäkipää, 2006; Ruiz-Peinado et al., 2012; Tabacchi et al., 2011a,b; Zianis et al., 2005). Allometric equations are usually based on diameter measured at breast height (i.e. DBH). However, the diameter of Bolzano's tree inventory was measured at 1 m above the ground. Using field data from a previous study in Bolzano in 2011 that contained information on several urban forest structural characteristics, among them diameter at 1 m and at 1.37 m (DBH) for a subsample of 475 trees (Russo, 2013; Russo et al., 2014), we calculated the DBH for all the species in the Bolzano's tree inventory by multiplying the diameter at 1 m (DH) by the ratio of DBH/DH that was averaged at the taxonomic order and division level (Russo, 2013). Specifically, we calculated the diameter at 1 m for year 2011 ( $DH_{Y2}$ ) by adding the initial diameter ( $DH_{Y1}$ ) to the product of the annual growth rate and the number of years between two time periods (year of the initial diameter ( $DH_{Y1}$ ) and year 2011).

We then converted the  $DH_{Y2}$  to  $DBH_{Y2}$  by multiplying the diameter ( $DH_{Y2}$ ) by the ratio ( $R$ ) of DBH/DH:  $DBH_{Y2} = [DH_{Y1} + (AGR \times n)] \times R$ ; where  $DBH_{Y2}$  = diameter at breast height year 2011,  $DH_{Y1}$  = diameter at 1 m (years change with different location),  $AGR$  = annual growth rate,  $R$  = ratio DBH/DH, and  $n$  = number of years between two time periods. 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). Carbon dioxide sequestration was estimated based on Bolzano's annual growth rates as reported by Russo et al. (2014) and the difference of  $CO_2$  stored between year  $y$  (i.e. 2011) and year  $y + 1$  (i.e. 2012).

We also developed an urban tree- $CO_2$  offset indicator to estimate  $CO_2$  sequestration per square meter of tree cover for every streetscape ( $CO_2/year/m^2$ ). We first calculated the tree canopy cover across our different streetscapes using ground-plot measurements, photo-interpretation, and i-Tree Canopy V 6.1 (<http://www.itreetools.org/canopy/>). Using QGIS 2.2.0 and Bolzano's tree inventory data, we created 38 unique ESRI shapefiles representing the boundary of each streetscape in the study area and the ESRI shapefiles were then used in the i-Tree Canopy analysis. A total of 100 random points (standard error <5%) were photo interpreted for each streetscape for a total of 3800 points. The percentage of each streetscape cover class ( $p$ ) was calculated as the number of sample points ( $x$ ) interpreted as tree cover divided by the total number of non-tree sample points ( $n$ ) within the area of analysis ( $p = x/n$ ) (Nowak and Greenfield, 2012). The standard error of the estimate (SE) was calculated by i-Tree Canopy. Finally, the  $CO_2$  sequestration per square meter of tree cover for every streetscape, was calculated dividing the total  $CO_2$  sequestration (kg/year) by the estimated tree canopy cover ( $m^2$ ). The  $CO_2$  off- set was estimated as the  $CO_2$  sequestered by a streetscape ( $St_{SQ}$ ) divided by the  $CO_2$  produced from transportation by one person ( $TR_{em}$ ):  $v = St_{SQ}/TR_{em}$ .  $v$  = number of people offsetting,  $St_{SQ}$  =  $CO_2$  sequestered by a streetscape ( $t/year$ ), and  $TR_{em}$  =  $CO_2$  produced from transportation by one person ( $t/year$ ).

Transportation emissions were derived from data of Sparber et al. (2010), that estimated carbon dioxide ( $CO_2$ ) emissions for the City of Bolzano using ECO2Regio software (<http://ecospeed.ch/eco2region/it>). The authors estimated emissions at 9.7 Mg  $CO_2$  per person for the year 2007, out of which 3 Mg of  $CO_2$  were emitted from the transportation sector. This study determined that the majority of transportation  $CO_2$  emissions were from commuter traffic and transportation of goods by road (Sparber et al., 2010). Finally, we stratified our street tree inventory-based  $CO_2$  results by streetscape types based on tree location information as reported in Bolzano's tree inventory. Based on Russo (2013), we developed a typology that results in six types of streetscapes in Bolzano, Italy: boulevard, cycle path, park, piazza, promenade and street. Fig. 1 provides representative photos for each of the six streetscape types.

## Results and discussion

The total  $CO_2$  storage for Bolzano's tree population was 6352.47 Mg and the  $CO_2$  sequestration was 229.66 Mg/year. Our  $CO_2$  storage estimates were greatest in parks accounting for 2415.48 Mg and our lowest estimates were found in cycle paths (34.76 Mg). This is because the greatest number of trees in Bolzano were located in parks (1417 trees). The average  $CO_2$  storage and sequestration per tree was greatest in piazzas at 397.79 kg and 94.14 kg/year. The lowest average  $CO_2$  storage and sequestration per



**Fig. 1.** Representative streetscape types in Bolzano, Italy: (1) boulevard, (2) street, (3) cycle path, (4) park, (5) promenade, (6) piazza.

tree was in cycle paths (Table 1). Overall, differences in the average CO<sub>2</sub> storage and sequestration by streetscape type depended on species composition, DBH size, growth, and presence of monumental trees. For example in piazza, *Platanus × hispanica* stored more than five times the atmospheric carbon dioxide stored by *Cedrus atlantica*; the most frequent species in piazzas. Our indicator for CO<sub>2</sub> sequestration by trees per m<sup>2</sup> of canopy cover ranged from 0.56 kg/year/m<sup>2</sup> in cycle paths to 0.92 kg/year/m<sup>2</sup> in streets (Table 1).

Overall, we calculated that the trees in Bolzano's streetscapes through their sequestration, annually offset 0.08% of the total amount of carbon dioxide emitted by the transportation sector (300,000 Mg/year). On average, treed boulevards in Bolzano can offset the annual CO<sub>2</sub> emissions from transportation-related activities of about 14 inhabitants, treed cycle paths can offset about one inhabitant, treed parks 25 inhabitants, treed urban places (piazza) 5 inhabitants, treed promenades 12 inhabitants, and street trees about 20 inhabitants.

**Table 1**  
Bolzano (Italy) urban structure: streetscape type and carbon dioxide (CO<sub>2</sub>) stores and sequestration by different streetscape types.

Streetscape	Characteristics	No of trees	Most common	DBH		CO <sub>2</sub> storage			CO <sub>2</sub> sequestration			CO <sub>2</sub> sequestration
type			species	$\bar{x}$ (cm)	SE	Tot. (Mg)	$\bar{x}$ (kg)	SE	Tot. (Mg/yr)	$\bar{x}$ (Kg/yr)	SE	per tree cover (kg/year/m <sup>2</sup> )
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 Total area: 10.13 ha	715	<i>Sophora japonica</i> (28.1%) <i>Prunus cerasifera</i> (9.5%), <i>Platanus</i> × <i>hispanica</i> (7.6%)	36.22	0.63	997.35	1394.89	56.57	41.35	57.84	1.50	0.84
Cycle path	Green bicycle, minimum width 1.50 m, maximum width 3.0 m Total area: 1.69 ha	89	<i>Carpinus betulus</i> (13.5%) <i>Tilia</i> × <i>europaea</i> (9.0%) <i>Populus alba</i> (9.0%)	20.91	1.41	34.76	390.61	87.86	2.18	24.49	2.65	0.56
Park	Includes urban parks delimited by buildings, with paved roads and street-related infrastructure Total area: 22.13 ha	1417	<i>Cedrus deodara</i> (7.8%) <i>Acer pseudoplatanus</i> (5.4%) <i>Acer platanoides</i> (5.3%)	39.30	0.61	2415.48	1704.64	65.26	76.42	53.93	1.30	0.62
Piazza	Includes squares with urban trees Total area: 3.77 ha	154	<i>Cedrus atlantica</i> (19.5%) <i>Sophora japonica</i> (13.6%) <i>Tilia americana</i> (11.0%)	59.10	2.03	612.60	3977.95	480.96	14.50	94.14	7.11	0.61
Promenade	Areas of high landscape value, forest land use, periurban Total area: 7.67 ha	1072	<i>Quercus pubescens</i> (41%) <i>Cupressus sempervirens</i> (13.7%) <i>Celtis australis</i> (11.1%)	24.61	0.37	585.93	546.58	26.00	35.46	33.08	0.76	0.61
Street	Tree-lined streets having a total cross-section up to a maximum of 20 m could include sidewalks and bike paths Total area: 21.28 ha	1125	<i>Acer pseudoplatanus</i> (9.9%) <i>Liquidambar styraciflua</i> (9.2%) <i>Platanus</i> × <i>hispanica</i> (9.1%)	33.62	0.60	1706.34	1516.75	81.86	59.74	53.11	1.87	0.92

$\bar{x}$  = average; SE = standard error; Tot. = total; DBH = diameter at breast height; yr = year; SE = standard error.



**Table 2**  
Carbon dioxide offsets in several urban forestry studies.

Study	City	Urban green type	Sector	Emissions	Offset* (%)
This study	Bolzano, Italy	Treed Streetscapes	Transportation	300,000 t/CO <sub>2</sub> /y	0.1
Vaccari et al. (2013)	Florence, Italy	Trees, shrubs, lawns, forest at the city scale	Total anthropogenic	1161.5 (±136) kt/CO <sub>2</sub> /y	6.2
Zhao et al. (2010)	Hangzhou, China	Urban trees at the city scale	Industrial	7000,000 t/C/y	18.6
Escobedo et al. (2010)	Miami-Dade, USA	Urban trees at the city scale	Total anthropogenic	31967,000 t/CO <sub>2</sub> /y	1.8
Escobedo et al. (2010)	Gainesville, USA	Urban trees at the city scale	Total anthropogenic	2097,627 t/CO <sub>2</sub> /y	3.4
Jo (2002)	Chuncheon, Kangleung, and Seoul, Korea	Woody plants and soils at the city scale	Total anthropogenic	37.0–264.9 t/C/ha/y	0.5–2.2

C = carbon; y = year.

\* We rounded off decimal to be consistent.

Since CO<sub>2</sub> estimates are based on individual trees and streetscape type and these results represent about 40% of all Bolzano's public trees, care is needed when discussing our results with other studies at a city-level scale. Specifically, these results are difficult to compare with other studies from vastly different setting and climates because of differences in urban forest structures and composition, soils, climatic condition, land used and in particular because of the use of different methodologies such as disparate forest or urban derived tree allometric equations, the use of different available urban forest carbon models, root-to-shoot-ratios and different remote sensing techniques and resolutions (Aguaron and McPherson, 2012; Strohbach and Haase, 2012; Weissert et al., 2014).

Therefore, CO<sub>2</sub> offsets in Bolzano were lower than other studies (see Table 2). The low value offsets in Bolzano are due to several factors including: study area size, number of urban trees and omission of shrubs and grasses from our calculation. For example, Vaccari et al. (2013) focussed on the total CO<sub>2</sub> urban green spaces offset considering lawn, forest, mixed vegetation and lawn with shrubs, and a total number of 52,551 trees. The study area size is significant in the CO<sub>2</sub> offset calculation as in Florence the total urban green spaces (city and semi-rural peri-urban area) offset 6.2% of the direct carbon emissions while the green spaces in the densely built-up city only offset 1.1% of the emissions (Vaccari et al., 2013).

These CO<sub>2</sub> offset indicators and findings could easily be integrated into existing initiatives and policies. For example, they can be used to complement or integrated into carbon offset accounting protocols (CalFIRE and USFS, 2014) or national urban forest carbon stock assessments (Nowak et al., 2013). Also, according to the Italian Law on urban green spaces (LEGGE, 2013), Italian municipalities have to plant a new tree for every resident child born or adopted in the municipality. Therefore, tree plantings can partially offset the annual CO<sub>2</sub> emissions of every child born. For example, information from the Registry of the Municipality of Bolzano indicates 972 births (+1.6% increment) in 2012, that equates to 972 new tree plantings. Thus, new tree plantings in parks would result in an additional carbon sequestration of 52.42 Mg/year with a CO<sub>2</sub> offset of 0.09%. But, this would need to account for future CO<sub>2</sub> emissions from these new generations as well. Also, Life Cycle Assessments have indicated that the total amount of CO<sub>2</sub> emitted from large scale urban tree plantings, because of their maintenance and biological related emissions, might be slightly greater than their CO<sub>2</sub> offsets (McPherson and Kendall, 2014).

Additional research is needed to develop site-specific urban tree biomass equations and to quantify the effect of shrubs, grasslands and urban soils on overall carbon dynamics. In addition, we need to consider the CO<sub>2</sub> emissions from tree removals and maintenance- related operations. If fuel burning machinery were used to maintain vegetation structure and health, the urban forest ecosystem eventually will become a net emitter of carbon (Nowak et al., 2002). Hence, managers should consider the types of equipment that are used to plant, maintain, and remove vegetation (Nowak et al., 2002). To conclude, this study provides an improved and current approach and indicator for assessing the role of urban green in mitigating CO<sub>2</sub> cities. Findings could also be used to advocate city planners, politicians and urban green 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 effects.

## References

- Aguaron, E., McPherson, E.G., 2012. Comparison of methods for estimating carbon dioxide storage by Sacramento's urban forest. In: Lal, R., Augustin, B. (Eds.), *Carbon Sequestration in Urban Ecosystems*. Springer, The Netherlands, pp. 43–71, [http://dx.doi.org/10.1007/978-94-007-2366-5\\_3](http://dx.doi.org/10.1007/978-94-007-2366-5_3)
- Bonatti, M., 2008. Il clima di Bolzano nell'era di Internet, [http://www.marcobonatti.it/nuovo/scarica/CLIMABZ\\_nuovo.pdf](http://www.marcobonatti.it/nuovo/scarica/CLIMABZ_nuovo.pdf) (accessed 12.10.12) [WWW Document].
- CalFIRE, USFS, 2014. Urban Forest Project Protocol Revision, <http://www.climateactionreserve.org/how/protocols/urban-forest/rev/> (accessed 7.3.14) [WWW Document].
- Cao, S., Li, C., 2011. The exploration of concepts and methods for low-carbon eco-city planning. *Proc. Environ. Sci.* 5, 199–207, <http://dx.doi.org/10.1016/j.proenv.2011.03.067>
- Covenant of Mayors, n.d. Covenant Map [WWW Document]. URL (<http://www.covenantofmayors.eu/participation/covenant-map-en.html>).
- Davies, Z.G., Edmondson, J.L., Heinemeyer, A., Leake, J.R., Gaston, K.J., 2011. Mapping an urban ecosystem service: quantifying above-ground carbon storage at a city-wide scale. *J. Appl. Ecol.* 48, 1125–1134, <http://dx.doi.org/10.1111/j.1365-2664.2011.02021.x>
- Díaz-Porras, D.F., Gaston, K.J., Evans, K.L., 2014. 110 Years of change in urban tree stocks and associated carbon storage. *Ecol. Evol.* 4, 1413–1422, <http://dx.doi.org/10.1002/ece3.1017>
- Dobbs, C., Escobedo, F.J., Zipperer, W.C., 2011. A framework for developing urban forest ecosystem services and goods indicators. *Landsc. Urban Plan.* 99, 196–206, <http://dx.doi.org/10.1016/j.landurbplan.2010.11.004>
- Escobedo, F., Varela, S., Zhao, M., Wagner, J.E., Zipperer, W., 2010. Analyzing the efficacy of subtropical urban forests in offsetting carbon emissions from cities. *Environ. Sci. Policy* 13, 362–372, <http://dx.doi.org/10.1016/j.envsci.2010.03.009>
- European Commission – Directorate General for Regional Policy, 2011. Cities of tomorrow – Challenges, visions, ways forward. Publications Office of the European Union, European Commission, Luxembourg, <http://dx.doi.org/10.2776/41803>
- Gratani, L., Varone, L., 2005. Daily and seasonal variation of CO in the city of Rome in relationship with the traffic volume. *Atmos. Environ.* 39, 2619–2624, <http://dx.doi.org/10.1016/j.atmosenv.2005.01.013>
- Gratani, L., Varone, L., 2013. Atmospheric carbon dioxide concentration variations in Rome: relationship with traffic level and urban park size. *Urban Ecosyst.* 17, 501–511, <http://dx.doi.org/10.1007/s11252-013-0340-1>
- Jenkins, J.C., Chojnacky, D.C., Heath, L.S., Birdsey, R.A., 2003. National-scale biomass estimators for United States tree species. *For. Sci.* 49, 12–35.
- Jo, H., 2002. Impacts of urban greenspace on offsetting carbon emissions for middle Korea. *J. Environ. Manage.* 64, 115–126, <http://dx.doi.org/10.1006/jema.2001.0491>
- Kennedy, S., Sgouridis, S., 2011. Rigorous classification and carbon accounting principles for low and Zero Carbon Cities. *Energy Policy* 39, 5259–5268, <http://dx.doi.org/10.1016/j.enpol.2011.05.038>
- Koerner, B., Klopatek, J., 2002. Anthropogenic and natural CO<sub>2</sub> emission sources in an arid urban environment. *Environ. Pollut.* 116 (Suppl.), S45–S51.
- LEGGE, 2013. LEGGE 14 Gennaio 2013, No. 10, <http://www.gazzettaufficiale.it/eli/id/2013/02/01/13G00031/sg> (accessed 2.6.14) [WWW Document].
- Lehmann, S., 2013. Low-to-no carbon city: lessons from western urban projects for the rapid transformation of Shanghai. *Habitat Int.* 37, 61–69, <http://dx.doi.org/10.1016/j.habitatint.2011.12.014>
- Liu, C., Li, X., 2012. Carbon storage and sequestration by urban forests in Shenyang, China. *Urban For. Urban Green.* 11, 121–128, <http://dx.doi.org/10.1016/j.ufug.2011.03.002>
- McHale, M.R., Burke, I.C., Lefsky, M.A., Peper, P.J., McPherson, E.G., 2009. Urban forest biomass estimates: is it important to use allometric relationships developed specifically for urban trees? *Urban Ecosyst.* 12, 95–113, <http://dx.doi.org/10.1007/s11252-009-0081-3>
- McPherson, E.G., Kendall, A., 2014. A life cycle carbon dioxide inventory of the Million Trees Los Angeles program. *Int. J. Life Cycle Assess.*, <http://dx.doi.org/10.1007/s11367-014-0772-8>
- Muukkonen, P., Mäkipää, R., 2006. Biomass equations for European trees: Addendum. *Silva Fenn.* 40, 763–773.
- Nowak, D.J., Greenfield, E.J., 2012. Tree and impervious cover change in U.S. cities. *Urban For. Urban Green.* 11, 21–30, <http://dx.doi.org/10.1016/j.ufug.2011.11.005>
- Nowak, D.J., Greenfield, E.J., Hoehn, R.E., Lapoint, E., 2013. Carbon storage and sequestration by trees in urban and community areas of the United States. *Environ. Pollut.* 178, 229–236, <http://dx.doi.org/10.1016/j.envpol.2013.03.019>
- Nowak, D.J., Stevens, J.C., Sisinni, S.M., Luley, C., 2002. Effects of urban tree management and species selection on atmospheric carbon dioxide. *J. Arboric.* 28, 113–122.
- Nusbaumer, J., Matsumoto, K., 2008. Climate and carbon cycle changes under the overshoot scenario. *Glob. Planet. Change* 62, 164–172, <http://dx.doi.org/10.1016/j.gloplacha.2008.01.002>
- Poudyal, N.C., Siry, J.P., Bowker, J.M., 2010. Urban forests' potential to supply marketable carbon emission offsets: a survey of municipal governments in the United States. *For. Policy Econ.* 12, 432–438, <http://dx.doi.org/10.1016/j.forpol.2010.05.002>
- Provincia Autonoma di Bolzano, 2012. Servizio meteorologico della Provincia Autonoma di Bolzano, Dati storici, <http://www.provincia.bz.it/meteo/datistorici.asp> (accessed 12.20.12) [WWW Document].
- Roy, S., Byrne, J., Pickering, C., 2012. A systematic quantitative review of urban tree benefits, costs, and assessment methods across cities in different climatic zones. *Urban For. Urban Green.* 11, 351–363, <http://dx.doi.org/10.1016/j.ufug.2012.06.006>
- Ruiz-Peinado, R., Montero, G., Del Rio, M., 2012. Biomass models to estimate carbon stocks for hardwood tree species. *For. Syst.* 21, 42–52, <http://dx.doi.org/10.5424/fs/2112211-02193>
- Russo, A., (Ph.D. Thesis) 2013. Quantifying and Modeling Ecosystem Services Provided by Urban Greening in Cities of the Southern Alps, N Italy. University of Bologna, Bologna.



- Russo, A., Escobedo, F.J., Timilsina, N., Schmitt, A.O., Varela, S., Zerbe, S., 2014. Assessing urban tree carbon storage and sequestration in Bolzano, Italy. *Int. J. Biodivers. Sci. Ecosyst. Serv. Manage.* 10, 54–70, <http://dx.doi.org/10.1080/21513732.2013.873822>
- Sharma, A.R., Kharol, S.K., Badarinath, K.V.S., 2010. Influence of vehicular traffic on urban air quality – a case study of Hyderabad, India. *Transp. Res., D Transp. Environ.* 15, 154–159, <http://dx.doi.org/10.1016/j.trd.2009.11.001>
- Skippon, S., Veeraraghavan, S., Ma, H., Gadd, P., Tait, N., 2012. Combining technology development and behaviour change to meet CO<sub>2</sub> cumulative emission budgets for road transport: Case studies for the USA and Europe. *Transp. Res., A Policy Pract.* 46, 1405–1423, <http://dx.doi.org/10.1016/j.tra.2012.05.021>
- Sparber, W., Fedrizzi, R., Avesani, S., Exner, D., Mähknecht, H., 2010. Calcolo e valutazione delle emissioni di CO<sub>2</sub> e definizione di scenari di riduzione per la città di Bolzano. EURAC, Bolzano.
- Strohbach, M.W., Arnold, E., Haase, D., 2012. The carbon footprint of urban green space – a life cycle approach. *Landsc. Urban Plan.* 104, 220–229, <http://dx.doi.org/10.1016/j.landurbplan.2011.10.013>
- Strohbach, M.W., Haase, D., 2012. Above-ground carbon storage by urban trees in Leipzig, Germany: analysis of patterns in a European city. *Landsc. Urban Plan.* 104, 95–104, <http://dx.doi.org/10.1016/j.landurbplan.2011.10.001>
- Tabacchi, G., Di Cosmo, L., Gasparini, P., 2011a. Aboveground tree volume and phytomass prediction equations for forest species in Italy. *Eur. J. For. Res.* 130, 911–934, <http://dx.doi.org/10.1007/s10342-011-0481-9>
- Tabacchi, G., Di Cosmo, L., Gasparini, P., Morelli, S., 2011b. Stima del volume e della fitomassa delle principali specie forestali italiane. Equazioni di previsione, tavole del volume e tavole della fitomassa arborea epigea. Consiglio per la Ricerca e la Sperimentazione in Agricoltura, Unità di Ricerca per il Monitoraggio e la Pianificazione Forestale, Trento.
- Timilsina, N., Staudhammer, C.L., Escobedo, F.J., Lawrence, A., 2014. Tree biomass, wood waste yield, and carbon storage changes in an urban forest. *Landsc. Urban Plan.* 127, 18–27, <http://dx.doi.org/10.1016/j.landurbplan.2014.04.003>
- Ufficio, 2010. Ufficio Mobilità del Comune di Bolzano. Piano urbano della mobilità 2020–2010, vol. 36. Atlas, Bolzano, pp. 81.
- Ufficio, 2012. Ufficio Statistica e Tempi della Città, 2012. Bolzano. Ufficio, Bolzano.
- Uherek, E., Halenka, T., Borken-Kleefeld, J., Balkanski, Y., Berntsen, T., Borrego, C., Gauss, M., Hoor, P., Juda-Rezler, K., Lelieveld, J., 2010. Transport impacts on atmosphere and climate: land transport. *Atmos. Environ.* 44, 4772–4816, <http://dx.doi.org/10.1016/j.atmosenv.2010.01.002>
- Vaccari, F.P., Gioli, B., Toscano, P., Perrone, C., 2013. Carbon dioxide balance assessment of the city of Florence (Italy), and implications for urban planning. *Landsc. Urban Plan.* 120, 138–146, <http://dx.doi.org/10.1016/j.landurbplan.2013.08.004>
- Valsta, L., Lippke, B., Perez-Garcia, J., Pingoud, K., Pohjola, J., Solberg, B., 2008. Use of forests and wood products to mitigate climate change. In: Bravo, F., Jandl, R., LeMay, V., Gadow, K. (Eds.), *Managing Forest Ecosystems: The Challenge of Climate Change, Managing Forest Ecosystems*. Springer, The Netherlands, pp. 137–149, [http://dx.doi.org/10.1007/978-1-4020-8343-3\\_8](http://dx.doi.org/10.1007/978-1-4020-8343-3_8)
- Vauramo, S., (Ph.D. Thesis) 2011. Urban Ecosystem Services at the Plant–Soil Interface. University of Helsinki, Helsinki.
- Weissert, L.F., Salmond, J.A., Schwendenmann, L., 2014. A review of the current progress in quantifying the potential of urban forests to mitigate urban CO<sub>2</sub> emissions. *Urban Clim.* 8, 100–125, <http://dx.doi.org/10.1016/j.uclim.2014.01.002>
- Zhao, M., Kong, Z., Escobedo, F.J., Gao, J., 2010. Impacts of urban forests on offsetting carbon emissions from industrial energy use in Hangzhou, China. *J. Environ. Manage.* 91, 807–813, <http://dx.doi.org/10.1016/j.jenvman.2009.10.010>
- Zianis, D., Muukkonen, P., Mäkipää, R., Mencuccini, M., 2005. Biomass and stem volume equations for tree species in Europe. *Silvia Fenn. Monogr.* 4, 1–63.