Science of the Total Environment 959 (2025) 178267

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Life Cycle Analysis and species-specific net CO_2 assimilation model to assess when a new urban forest becomes a carbon sink in a Mediterranean city

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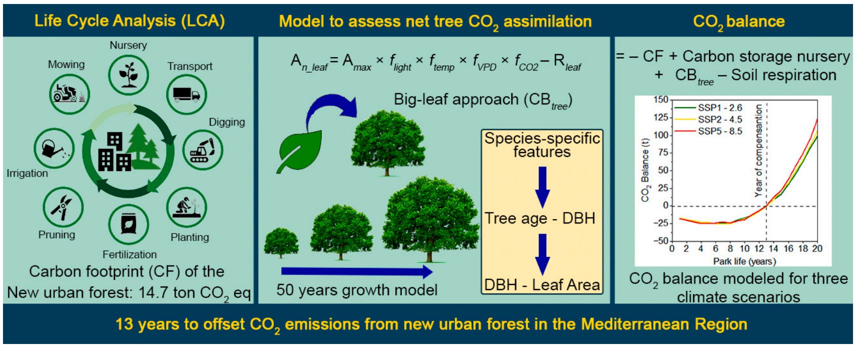
HIGHLIGHTS

- Species-specific leaf-level net photosynthetic CO_2 uptake were modeled.
- Life Cycle Analysis (LCA) was accomplished to calculate all CO_2 emissions.
- LCA highlighted that 62 % of CO_2 emissions are related to park maintenance.
- Soil respiration resulted a key CO_2 emission factor in the Mediterranean area.
- 13 years are needed for a new urban forest to become a real CO_2 sink in a Mediterranean city.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Jacopo Bacenetti

Keywords:
Carbon footprint
Carbon balance
Net photosynthesis
Urban trees
Urban greening
Urban forestry

ABSTRACT

Carbon dioxide (CO_2) is one of the most impactful greenhouse gases (GHG) leading to global warming. Planting urban forests can help to mitigate *climate change* effects as trees remove CO_2 from the atmosphere thanks to their photosynthetic activity. However, by setting up a new urban forest, GHG emissions occur during cultivation in the nursery, planting, and maintenance operations. A total of 170 urban trees belonging to four genera (*Tilia*, *Acer*, *Ulmus*, and *Cupressus*) were planted in Florence (Italy), and species-specific leaf-level net photosynthetic CO_2 uptake (A_{n_leaf}) was modeled considering A_{n_leaf} response to different environmental factors (i.e., light, air temperature, relative humidity, and atmospheric CO_2 concentration). A_{n_leaf} was scaled to canopy level and the total tree CO_2 balance was estimated considering the respiration rate of woody biomass too. Moreover, carbon storage by trees during nursery cultivation was assessed through allometric formulas. Regarding CO_2 emissions, a Life Cycle Analysis was accomplished to calculate the Carbon Footprint (CF) linked to nursery cultivation, tree

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https://doi.org/10.1016/j.scitotenv.2024.178267
Received 15 October 2024; Received in revised form 18 December 2024; Accepted 21 December 2024

planting, and maintenance over time. In addition, seasonal CO_2 soil respiration was measured. To run the model, tree growth over time was estimated, hourly meteorological data and soil temperature were recorded *in situ* for two consecutive years, while three future climatic scenarios were considered for the entire park-life span (50 years). Results showed that the CF was equal to 14.7 t CO_2 equivalent with maintenance over time as the most CO_2-emitting phase (62 %). The model highlighted that 13 years are needed to reach a positive CO_2 balance. This study allowed to determine when a new urban forest becomes a real carbon sink in a Mediterranean climate, thus helping to achieve the European goal of carbon neutrality.

1. Introduction

After the Industrial Revolution, anthropic activities led to a steady increase in carbon dioxide (CO_2) emissions (Yoro and Daramola, 2020). It was estimated that in 1750 the CO_2 atmospheric concentration was approximately 278 ppm (Gulev et al., 2021) while current values exceed 420 ppm and are predicted to further increase by the end of the century (NOAA, 2024). Together with water vapor, methane (CH_4), nitrous oxide (N_2O), tropospheric ozone (O_3), and halogenated compounds, CO_2 is the main greenhouse gas (GHG) leading to global warming (Sonwani and Saxena, 2022). Urban areas play a critical role in the carbon cycle (Luqman et al., 2023), as they emit large amounts of CO_2 due to fossil fuels burning for energy consumption and transport as well as waste decomposition and city expansion (Churkina, 2016). In addition to efforts to cut off the emissions, the implementation of mitigation strategies aiming to reduce current CO_2 concentrations is urgently needed in urban context.

The "green solution" is offered by the city green infrastructures that can significantly affect local CO_2 levels (Anderson and Gough, 2020). Indeed, trees and shrubs sequester CO_2 from the atmosphere through photosynthesis, to store carbon above and below the ground in their woody biomass (Weissert et al., 2014). Thus, the implementation of nature-based solutions (NBS) inside cities has the potential to cope with *climate change* and policies are taking actions in this direction worldwide. In this framework, the European Commission recently introduced its Green Deal, which aims to achieve climate neutrality by 2050 and reduce GHG by 55 % compared to the 1990 levels by 2030 (Wolf et al., 2021). At national level, governments aim to achieve environmental objectives set by the European Commission through NBS, particularly tree planting, and greening in urban and peri-urban areas, to create sustainable cities (e.g., Italian National Recovery and Resilience Plan). Addressing these considerations, within the European Life Project AIRFRESH (LIFE19 ENV/FR/000086), a novel urban forest was planted in Florence (Italy) to improve air quality and CO_2 sequestration from the atmosphere. As a drawback, the realization of a NBS, such as a new urban forest, has an environmental cost linked to the release of GHG due to the cultivation in nursery, tree planting, and subsequent maintenance. Therefore, to understand the real CO_2 mitigation potential, all CO_2 emission sources and the contribution offered by tree species in terms of CO_2 storage must be carefully accounted.

Life Cycle Assessment (LCA) is a standardized methodology used to assess the impact of a product, production process or a system on the environment (Hauschild et al., 2018). LCA was recently applied to ornamental tree production, urban forestry, and green spaces (Kendall and McPherson, 2012; Strohbach et al., 2012; McPherson et al., 2015; Petri et al., 2016; Nicese et al., 2021; Zhang et al., 2022; Muscas et al., 2024). LCA analysis allows to calculate the Carbon Footprint (CF), expressed in terms of CO_2 equivalent (CO_2eq), assuming the Global Warming Potential (GWP) as the impact category. In detail, the Intergovernmental Panel on Climate Change (IPCC), using CO_2 as a reference, provides GWP emission metrics for each GHG to quantify their amount of CO_2eq released during the entire process (Benedetti, 2023).

One of the most important components of the carbon cycle is the soil respiration carried out by root activity (autotrophic respiration) and heterotrophic microorganisms (Wei et al., 2010) which release CO_2 to the atmosphere. The magnitude of soil respiration can change along the season and space due to environmental factors (i.e., temperature and humidity) and soil physical and chemical properties (Ohashi and Gyokusen, 2007). In particular, soil temperature is the main factor of the temporal fluctuations in soil respiration (Chen et al., 2022), and the foreseen global warming can further exacerbate this negative CO_2 flux (Nissan et al., 2023).

Once all negative CO_2 emission components are considered, the tree capacity as carbon sink has to be assessed to obtain an accurate estimate of the CO_2 balance. Allometric biomass equations are applied to indirectly estimate tree species CO_2 storage in urban areas (Jo and McPherson, 1995; Nowak and Crane, 2002; Tang et al., 2016). Currently, i-Tree Eco model is widely used to account for carbon storage and annual carbon sequestration by species-specific allometric equations (Nowak, 2024), while the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model is applied to determine the CO_2 storage capacity of urban areas based on land use/cover changes (Sharma et al., 2024).

However, direct leaf-photosynthesis measurements that allow to upscale the actual net CO_2 assimilation at canopy level are still scarce for urban trees. CO_2 assimilation through photosynthesis is a highly species-specific trait that also depends on site-specific climatic conditions so *in situ* measurements are recommended to obtain reliable results. Light intensity, CO_2 concentrations, air temperature, relative humidity, and soil water content are the main environmental factors that affect stomatal opening (Driesen et al., 2020) and, consequently, CO_2 assimilation by trees. In addition, CO_2 assimilation undergoes diurnal variations with canopy uptake during daylight, when trees are photosynthetically active, while nocturnal cellular respiration translates into CO_2 emissions (Fares et al., 2017) that exponentially increase with temperature (Dusenge et al., 2019).

Since NBS currently have considerable political interest and are a source of noteworthy public investment, evidence-based effects on the carbon budget need to be demonstrated. So far, no comprehensive research has been conducted for urban area, especially in Mediterranean region where current and future climate conditions (e.g., high temperatures) can heavily impact CO_2 assimilation by urban vegetation and soil respiration, influencing the offset of CO_2 emissions.

Therefore, experimental and modeled data were combined in this innovative study to achieve the following two main goals: i) to quantify the actual species-specific CO_2 sequestration potential of a new urban forest and the years required to offset the CO_2 emissions associated with its setting-up and maintenance; ii) to simulate future CO_2 assimilation rates under different climatic scenarios characterized by increased temperature and CO_2 concentrations.

2. Materials and methods

2.1. Experimental site

The test area is a new urban forest located in the western suburb of the municipality of Florence, Italy (43° 46′ 38″ N, 11° 11′ 25″ E) and has an extension of approximately 0.55 ha. According to Köppen classification, the zone is characterized by hot-summer Mediterranean climate (Csa) with annual mean air temperature and precipitation of 15.5 °C and 821 mm, respectively (reference period 1991–2020; www.lamma.toscana.it/clima-e-energia/climatologia/clima-firenze). Before afforestation, the area was an urban flat grassland inside a park with scattered mature trees. After planting, it hosts 170 trees belonging to the following five species: *Tilia platyphyllos* Scop., *Acer rubrum* L., *Acer opalus* Mill., *Cupressus sempervirens* L. and the hybrid *Ulmus* 'Plinio' obtained from a crossing of the clone *Ulmus* 'Plantyn' (female parent) with *Ulmus pumila* L. clone 'S.2' (Santini et al., 2002). All trees are constantly watered during summer, thanks to an automatic irrigation system equipped with drippers.

2.2. Life cycle assessment (LCA)

The LCA was carried out following ISO 14040 and ISO 14044 guidelines (ISO, 2006a; ISO, 2006b). The boundary system followed a "cradle to gate" approach, considering the entire tree life from the nursery to the planting in the test area as well as its maintenance over time. As time span for the park life, we considered 50 years following the approach of Strohbach et al. (2012), while GWP100 (Myhre et al., 2013) was selected as the impact category, allowing the calculation of the equivalent CO_2 emissions (CO_2eq) generated by cultivation in the nursery, planting, and maintenance. GaBi software (Sphera Solution, Inc., Chicago, Illinois, USA), updated to version 10.6.0.110, was employed to perform the LCA analysis while CML 2001, updated to the August 2016 release, was considered as the impact characterization method. The entire test area (0.55 ha) was considered as functional unit to calculate the impacts in terms of kg of CO_2eq.

2.2.1. Life cycle inventory (LCI)

Energy inputs and machinery used during the cultivation of the trees in the nursery, as well as during the planting (transport of the trees, excavation for the planting holes, and the irrigation system) and the current and future maintenance of the test area (grass mowing, fertilization, pruning, irrigation) were considered. The LCI was carried out through interviews with public greenery operators, direct measurements, and by collecting data in the literature on the materials and operating machines used throughout the process.

2.2.2. Negative factors for CO_2 balance

2.2.2.1. Nursery phase. Potential factors for CO_2 emissions during the nursery period were considered. In the nursery phase, trees were grown in pots or in the ground (Table S1). Trees grown in high-density polyethylene (HDPE) pots were re-potted once (from a 10 L to a 25 L pot), and the potting mix had the following composition: peat (30 %), coconut fibre (25 %), pumice (25 %), and wood fibre (20 %). Furthermore, fertilization, electricity consumption for automatic irrigation, and support structures (including pipes for fertigation) were taken into account. For trees grown in the open field, the use of a tree spade machine for transplanting and removing trees, support structures as well as standard cultivation operations such as weeding, fertilization, and irrigation were considered.

2.2.2.2. Setting up of the new green area. Three round trips from the nursery were needed (total distance of 1200 km) to transport trees to the test area by a flatbed van (weight < 3.5 t). As regards the activities strictly linked to the plantation, a mini excavator was used both for the planting holes and the lines to lay the irrigation system pipes. The approximate size of each planting hole was equal to 0.08 m^3 (0.4 m × 0.4 m × 0.5 m), while the dig for irrigation was wide 0.3 m at a depth of 0.5 m for a total length of 1 km. The main pipes and driplines (1.5 m for each tree) were in HDPE. Each tree was supported with two debarked-chestnut poles (height 2 m) to avoid overturning problems due to wind. The trunks were tied to horizontal wooden crosspiece with a polyvinyl chloride (PVC) lace (0.5 m per tree), while a corrugated HDPE tube of about 25 cm was positioned at the bottom of the trees to protect the collar from grass cutting operations. The woody poles were purchased 250 km far away from Florence and were transported by van (< 3.5 t), while all the plastic materials, including irrigation system tubes, were transported to the test area with a van for a total distance of 10 km. Finally, the transport of the excavator with a flatbed van from the rental point also located 10 km away was considered.

2.2.2.3. Maintenance over time. The grass mowing is repeated 6 times in a year while the fertilization (0.15 kg/tree) was carried out only in the first two years after planting with a chemical granular fertilizer N-P-K (chemical formulation: 12-5-5). To calculate the amount of pruning for each tree, we considered a frequency of three interventions in 50 years, as proposed by Nicese et al. (2021), while for the volume lop, we considered 0.065 m^3/pruning as the average between the values of 0.04 m^3 and 0.09 m^3 proposed by Strohbach et al. (2012) for young and old trees, respectively. To establish the species-specific wood density (kg_{dw}/m^3), we used values included in a global database (Zanne et al., 2009) referring to the European region (Table S2). Based on Nowak et al. (2002), it was assumed that the pruning operations would be carried out using a 2.3-hp chainsaw for 1 h/tree. The transport of the total pruning to the landfill (distance of 10 km) was also considered. The irrigation was planned for the first 3 years after planting from mid-May to mid-September. The electrical consumption of the pump is equal to 1 kW/h, the area was split into 5 sectors, and each sector was irrigated 1 h/day.

2.2.2.4. Soil respiration. Combined instantaneous soil respiration (R_{soil}) and temperature (T_{soil}) measurements were performed by EGM-4 equipped with SRC-1 (PP-Systems, Herts, UK). Three sub-areas were randomly selected inside the new urban forest and nine PVC collars (∅ 10 cm) for plot were settled on the ground. A total of 300 measurements were carried out during all the seasons with different thermal conditions. The recorded CO_2 emissions (expressed in μmol m^{-2} s^{-1}) and temperatures allowed to obtain a relationship between R_{soil} and seasonal temperature variations.

2.2.3. Positive factors for CO_2 balance

2.2.3.1. Carbon storage of trees before planting. Before planting, diameter at breast height (DBH) and height (*h*) were measured for all trees and species-specific allometric equations for small trees (DBH < 5 cm) were applied to quantify the biomass. Above- and below-ground carbon storage (C_{tot}) was assessed as proposed by Ferrari et al. (2017) and according to the Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC, 2003), applying the following allometric equation:

$$C_{tot} = \text{Dry weight biomass} \times Cf \tag{1}$$

In detail, Dry weight biomass $= (V \times WDB \times BEF) \times (1 + R)$, where V is the stem tree volume calculated for each tree through the following allometric equations developed for Italian tree species (Tabacchi et al., 2011).

$$\text{Broadleaves species : } V\left(dm^3\right) = 0.599670 + 0.039619\ DBH^2 \times h\ [DBH\ cm, h\ m] \tag{2}$$

$$\text{Conifer species : } V\left(dm^3\right) = 2.1414 + 3.4914 \times 10^{-2}\ DBH^2 \times h\ [DBH\ cm, h\ m] \tag{3}$$

where WDB is Wood Basic Density (t m^{-3}), BEF is Biomass Expansion Factor, R is Root-to-Shoot Ratio and Cf is the carbon fraction of the dry biomass (0.5). Different BEF, WDB and R values were applied for broadleaves and conifers according to ISPRA (2014). In detail, we used WDB: 0.53; BEF: 1.53; R: 0.24 for broadleaves and WDB: 0.43; BEF: 1.41; R: 0.29 for *C. sempervirens*. Finally, to convert the carbon stored by a single tree to CO_2, a coefficient of 3.67 was used (Fini et al., 2023).

2.2.3.2. Net CO_2 tree assimilation modeling. Planted trees absorb CO_2 through photosynthesis at different rates depending on environmental factors (Liang et al., 2023). Species-specific leaf-level net photosynthetic CO_2 uptake (A_{n_leaf}) was modeled as:

$$A_{n\_leaf} = A_{g\_leaf} - R_{leaf} \tag{5}$$

where A_{g_leaf} and R_{leaf} are the leaf-level gross photosynthetic rate (μmol m^{-2} s^{-1}) and respiration rate (μmol m^{-2} s^{-1}), respectively. A_{g_leaf} is estimated by the following multiplicative formula:

$$A_{g\_leaf} = A_{max} \times f_{light} \times f_{temp} \times f_{VPD} \times f_{CO2} \tag{6}$$

where A_{max} is the maximum photosynthetic rate while f_{light}, f_{temp}, f_{VPD}, and f_{CO2} are species-specific limiting functions (scaled from 0 to 1) dependent on environmental factors i.e., photosynthetic active radiation (PAR), temperature (T), vapor pressure deficit (VPD), and CO_2 concentration.

f_{light} was assumed to be given by a hyperbolic function as:

$$f_{light} = 1\Big/(K_m + \text{PAR}) \tag{7}$$

where K_m is the value of PAR at 0.5 × A_{max} (Barton and North, 2001).

The temperature function (f_{temp}) considered the optimum (T_{opt} = 27 °C), the minimum (T_{min} = 0 °C), and the maximum temperature (T_{max} = 48 °C) for photosynthesis in urban environment, according to Zhang et al. (2017), and was expressed as:

$$f_{temp} = \left(\frac{T - T_{min}}{T_{opt} - T_{min}}\right)\left\{\left(\frac{T_{max} - T}{T_{max} - T_{opt}}\right)^{\left(\frac{T_{max} - T_{opt}}{T_{opt} - T_{min}}\right)}\right\} \tag{8}$$

Conversely, f_{VPD} and f_{CO2} were obtained by linear and quadratic regression, respectively, and calculated as:

$$f_{VPD} = -a \times \text{VPD} + b \tag{9}$$

$$f_{CO2} = -c(CO_2)^2 + d(CO_2) - k \tag{10}$$

where a, b, c, d, and k are species-specific constants.

Regarding leaf respiration, the response of R_{leaf} to temperature was described by an exponential function:

$$R_{leaf} = r \times exp^{\,sT} \tag{11}$$

where r and s are species-specific constant factors and we considered respiration at light (day respiration) as $R_{leaf}/2$ with PAR > 50 μmol m^{-2} s^{-1} according to Niinemets et al. (2005). For broadleaves, the in-leaf season was considered between the 15th April and the 31st October.

Based on Monsi-Saeki's model for the big-leaf approach and according to Oikawa (1986), A_{n_leaf} was scaled up to tree level photosynthesis (A_{tree}):

$$A_{tree} = \frac{A_{n\_leaf}}{k}\,\text{Ln}\left(\frac{1 + \sqrt{1 + \varphi \times \text{PAR} \times 1/k}}{1 + \sqrt{1 + \varphi \times \text{PAR} \times 1/k \times exp(-k \bullet \text{LAI})}}\right) \times CA \tag{12}$$

where φ is the initial slope of the light-photosynthesis relationship; k is the light extinction coefficient (≈ 0.6; Zhang et al., 2014), LAI is the Leaf Area Index, and *CA* is the crown area.

Finally, to assess the total CO_2 balance at the tree level (CB_{tree}) this simple formula was used:

$$CB_{tree} = A_{tree} - R_{tree} \tag{13}$$

where R_{tree} (μmol s^{-1}) is the respiration rate of above and below ground woody biomass defined by the following equation:

$$R_{tree} = R_{tref}\, Q_{10} \times (T - T_{ref})/10 \tag{14}$$

In detail, R_{tref} = 201.87 × (Fresh weight Biomass)$^{1.408}$ + 0.41 × (Fresh weight Biomass)$^{0.805}$, Q_{10} = 2 and T_{ref} = 20 °C according to Mori et al. (2010). The constants suggested by Nowak (2002) for the evergreen (0.48) and deciduous species (0.56) to convert fresh to dry weight were applied to derive Fresh weight Biomass.

To parameterize the Leaf-level photosynthesis model (Eqs. (5)–(11)), net CO_2 assimilation measurements were carried out *in situ* during summer (late June – mid July) using portable infrared gas analyzer systems (LI6800, Li-Cor, Lincoln, USA) equipped with a cuvette for broadleaves (size: 6 cm^2). For *C. sempervirens*, the projected leaf area was obtained using the Easy Leaf Area Free application (Easlon and Bloom, 2014). Six trees for each species were selected (total = 30 trees) and the measurements were made on 3 representative sun-exposed leaves. A-light response curves (PAR: 2000, 1500, 1000, 700, 400, 300, 200, 100, 75, 50, 25, 0 μmol m^{-2} s^{-1}) were measured to parametrize f_{light} whereas A-Ci curves (CO_2: 410, 200, 100, 50, 300, 600, 800, 1200, 1600, 2000 ppm) were accomplished to obtain the parameters *c*, *d*, and *k* for f_{CO2}.

To assess the midday depression of photosynthesis due to stomatal closure in the afternoon (photosynthetic limitation by higher VPD as f_{VPD}), instantaneous measurements were performed along the day with clear sky during mid-summer in 2022–2023 under various natural environmental conditions of T, RH, and PAR by setting the leaf cuvette to the track-ambient mode.

To evaluate the negative component for the leaf carbon assimilation as R_{leaf}, species-specific leaf dark respiration (PAR = 0 μmol m^{-2} s^{-1}) under summer temperature conditions (20, 25, 30, and 35 °C) was measured to derive the exponential function that links both variables as described in the previous paragraph. For cypress, we additionally performed dark respiration measurements at 15 °C.

For the validation of the leaf-level photosynthesis model, during the summer of 2024, additional instantaneous measurements were carried out in different conditions of PAR, T, and RH for each species. Measured data were then correlated with estimated values for the model validation of CO_2 tree assimilation.

2.3. Morphological measurements and simulations of trees growth over time

Since tree size is a determinant factor for the tree-level CO_2 uptake capacity (Eqs. (12) and (14)), simulations for tree allometries were carried out. For the first two years after planting (2022–2023), values of *h*, DBH, and LAI were recorded (Table S3). The *h* and DBH of each tree were measured by a graduated bar and a measuring wheel, respectively. LAI was estimated using a portable radiometer (LAI2000, Li-Cor, Lincoln, USA). Seven measurements were performed for each species (n = 9 trees): 1 reference outside the canopy +6 under the canopy in different directions (N; S; N-E; S-E; N-W; S-W). Moreover, species-specific Leaf Mass per Area (LMA) was assessed. For broadleaves, five leaf discs (area: 0.50 cm^2; diameter: ∅ 0.8 cm) from sampled leaves (n = 3 leaves × 9 trees) were obtained by a leaf punch (Fujiwara Scientific Company Co., Ltd.,Tokyo, Japan). For *C. sempervirens*, the projected twig area of the samples (n = 3 twigs × 9 trees) was assessed by the Easy Leaf Area application (Easlon and Bloom, 2014). Leaf discs and twigs were oven-dried at 70 °C for 5 days and then weighed (Sartorius, Germany, sensitivity: ± 0.01 g) to calculate LMA as the ratio between average dry-biomass (kg) and relative area (m^2).

Growth models of DBH and *h* considering tree age were performed for each species. Data of DBH and *h* across a range of tree ages were extrapolated from the Urban tree database (McPherson et al., 2016) and a nonlinear regression showed the best fitting curves for the two parameters (DBH-age or *h*-age). When species-specific data were missing, the same genus was used. Conifers data of DBH, *h* and age were used for *C. sempervirens*. Subsequently, the relationship between DBH and foliage biomass (kg) for European broadleaved and conifer species proposed by Forrester et al. (2017) was applied. Finally, to estimate the species-specific Leaf Area (LA, m^2) for each year, the foliage biomass was divided by LMA (kg/m^2). Concerning LAI, based on the data measured in the first two years, we hypothesized a linear growth up to a maximum species-specific average value inferred from a LAI global database (Iio and Ito, 2014). The crown area was calculated as LA/LAI (Cutini and Varallo, 2006). In addition, to predict the average annual woody biomass for each species (Table S4), the same formula reported in chapter 2.2.3.1 was used, but different species-specific allometric equations were applied to estimate tree stem volume when DBH ≥ 5 (see supplementary materials).

2.4. Environmental data and future climatic scenario

To run the tree-level CO_2 assimilation model and to estimate the soil respiration of the test area, environmental data were directly recorded for the first two years after planting (2022–2023) while three climatic scenarios (SSP1–2.6, SSP2–4.5, and SSP5–8.5) were considered to predict the future carbon fluxes during the park lifespan. The optimistic (SSP1–2.6), intermediate (SSP2–4.5), and pessimistic scenario (SSP5–8.5) of GHG emissions reflect the radiative forcing levels of 2.6, 4.5, and 8.5 W/m^2 by 2100, respectively (O'Neill et al., 2016).

For 2022 and 2023, hourly meteorological data were provided by a station located at CNR LaMMA/IBE (43° 50′ 56″ N, 11° 09′ 04″ E) close to the test area. The recorded environmental parameters were Photosynthetic Active Radiation (PAR, μmol m^{-2} s^{-1}), temperature (T, °C) and relative humidity (RH, %). Vapor pressure deficit (VPD, kPa) was calculated starting from T and RH, whereas CO_2 concentration was set to 410 ppm for both years. At the same time, hourly soil temperature was recorded by Decagon RT-1 sensors placed inside the experimental site at 10 cm depth.

Future meteorological conditions under the three climatic scenarios were obtained by the regional Earth System Model ENEA-REG (Anav et al., 2024), a fully coupled ocean-atmosphere-river model designed to downscale, over the Mediterranean basin, the models used in the Coupled Model Intercomparison Project phase 6 (CMIP6). The atmospheric component of the ENEA-REG has a spatial resolution of 12 km and provides six-hourly data of PAR, T, RH, and soil temperature, while future CO_2 concentrations were taken from CMIP6 scenarios. Further detail on ENEA-REG set-up, validation and climate sensitivity can be found in Anav et al. (2024).

2.5. Statistical analysis

The normality of the data was tested by Kolmogorov-Smirnov test. One-way ANOVA, followed by post-hoc Tukey's test was used to assess the significant difference of net CO_2 assimilation daily instantaneous measurements within each species. Simple linear regression analysis assessed the relationship between measured and estimated assimilation values. Results were considered significant at $p < 0.05$. All statistical analyses were conducted with OriginLab software®.

3. Results

3.1. CO_2 emissions

3.1.1. Carbon footprint

Total emissions during nursery cultivation, tree planting, and maintenance operations were 14.74 t of CO_2 equivalent (Table 1). As shown in Fig. 1, maintenance of the test area accounted for the highest percentage of CO_2 emissions (61.83 %), followed by the nursery phase (20.04 %) and tree planting (18.13 %).

Concerning maintenance over time, the highest CO_2 source resulted grass mowing that is repeated 6 times in a year (83 %). Emissions linked to pruning operations and their transport to the landfill were 10 % followed by the electrical consumption of the pump for the irrigation system (7 %). Conversely, a negligible impact derived from fertilization for the two years following tree planting. As regards the nursery phase, 98 % of emissions depended on the tree cultivation in pots, compared to only 2 % linked to open field production. For the potted nursery, 86 % of emissions were attributable to the use of HDPE plastic pots of different volumes (60 %) and the use of peat-based substrates (26 %). Fertilization, irrigation and structures accounted for 14 %. On the contrary, in open field cultivation, irrigation was the most impactful component followed by weeding, structures, mechanical operations (i.e., soil tillage and tree trans-planting), and fertilization. Finally, for the planting phase, the highest source of CO_2eq emissions was related to the tree transport to the experimental site (64.4 %). Excavations for planting holes and pipes accounted for 7 % while 6.3 % resulted for tree support structures (chestnut poles, trunk protectors, bindings for tying and their transport). The plastic irrigation system tubes (pipes and driplines) represented 22.3 % of CO_2eq emissions.

Table 1
CO_2 emissions related to the different inputs involved during nursery cultivation, tree planting, and maintenance operations.

Phases	Input	Emissions (kg CO_2eq.)
Nursery pot	Plastic pot 10 L	581.14
	Plastic pot 25 L	1168.69
	Potting mix	746.93
	Structures	49.16
	Fertilization	42.35
	Irrigation	310.59
Nursery open field	Weeding	13.32
	Mechanical operations	7.14
	Structures	9.05
	Fertilization	6.34
	Irrigation	19.10
Tree planting	Trees transport	1719.49
	Support structures	169.09
	Excavations	187.38
	Irrigation system	595.73
Maintenance	Pruning	889.90
	Mowing	7520.13
	Fertilization	17.15
	Irrigation	684.65
Total emissions (t CO_2eq.)		14.74

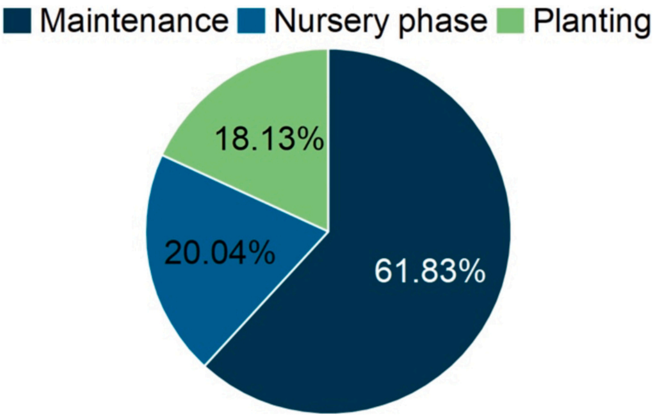

Fig. 1. Percentage distribution of CO_2 equivalent emissions for each process phase (Nursery phase, planting, and maintenance).

3.1.2. Soil respiration (R_{soil})

R_{soil} rate increased exponentially with increasing soil temperature (Fig. 2A). R_{soil} was highly variable during the year ranging from a minimum of 0.04 μmol CO_2 m^{-2} s^{-1} measured in winter (December–January), when the highest recorded value was 0.74 μmol CO_2 m^{-2} s^{-1}, to a maximum of 3.60 μmol CO_2 m^{-2} s^{-1} in deep summer (July–August), when the lowest recorded value was 1.08 μmol CO_2 m^{-2} s^{-1}. The soil temperature (Fig. 2B) showed a typical bell-shaped trend for

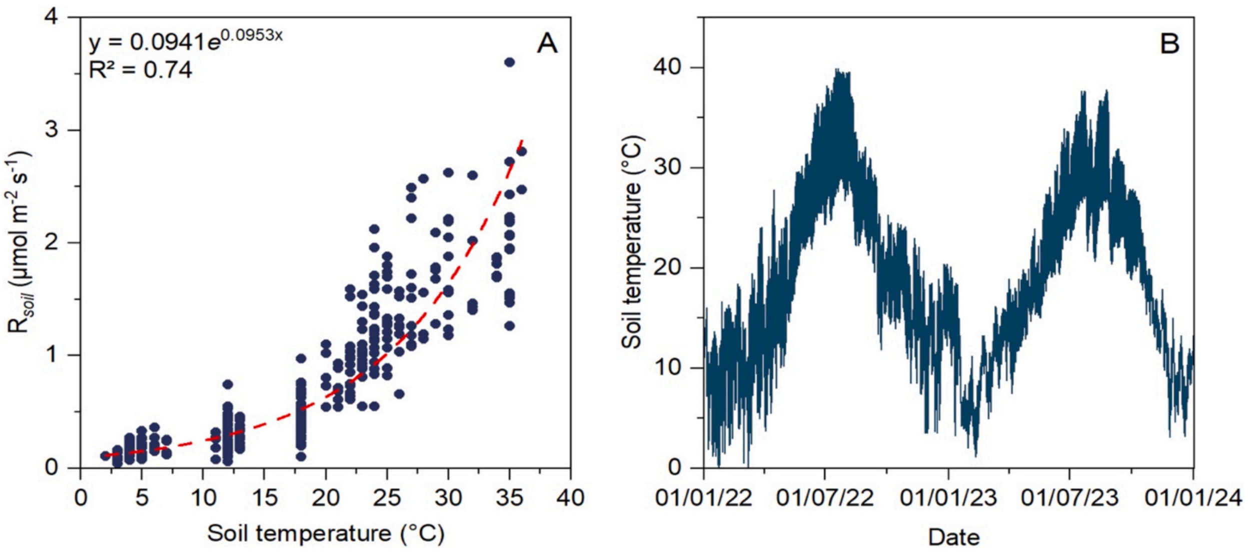

Fig. 2. A) Exponential relationship between soil respiration and temperature is indicated by the dotted-red line. R_{soil} measurements ($n = 300$) are expressed in µmol CO_2 m^{-2} s^{-1}. B) Seasonal variation of soil temperature (°C).

both years monitored (2022 and 2023). In the first year, the summer maximum temperature was slightly higher (39.9 °C versus 37.8 °C) while the minimum winter value was lower (− 0.3 °C) than in 2023 (1.1 °C).

3.2. CO_2 sinks

3.2.1. Carbon storage before plantation

Table 2 reported measured values of DBH and *h* before planting and the Carbon stored by trees during nursery cultivation. DBH and *h* were approximately included in a range between 2–3.5 cm and 2–3.5 m, respectively. The total carbon storage (C_{tot}), calculated as a sum of the species-specific value for each single tree, was 0.16 t equal to 0.58 t CO_2.

3.2.2. Net CO_2 trees assimilation after plantation

Species-specific parameters used to model net CO_2 assimilation are shown in Table 3. A_{max} was maximum for *Ulmus* 'Plinio' followed by *T. platyphyllos* and *C. sempervirens* while lower similar values were modeled for the maple species *A. opalus* and *A. rubrum*. The initial slope of the light-photosynthesis curve (φ) was the same for broadleaved species, while it resulted slightly lower for the evergreen conifer *C. sempervirens*. Conversely, the highest value of K_m was modeled for *C. sempervirens* followed by *Ulmus* 'Plinio' while the other three species showed lower values included in the range 220–280 µmol m^{-2} s^{-1}.

Regarding daily instantaneous measurements of net CO_2 assimilation, all five species showed a statistically significant photosynthesis decline ($p \leq 0.05$) during the afternoon compared to the morning (Fig. 3). Before midday, *T. platyphyllos* recorded the highest photosynthesis value (10.87 ± 0.61 µmol m^{-2} s^{-1}) as well as during afternoon (7.77 ± 0.83 µmol m^{-2} s^{-1}). The lowest photosynthesis values were detected for *A. rubrum* (7.93 ± 0.36 µmol m^{-2} s^{-1}) and *Ulmus* 'Plinio' (3.87 ± 0.39 µmol m^{-2} s^{-1}) during morning and afternoon, respectively. The highest photosynthesis daily reduction resulted for *Ulmus* 'Plinio' (−59.4 %) followed by *A. opalus* (−38.8 %), *A. rubrum* (−29.4 %) and *T. platyphyllos* (−28.5 %) while *C. sempervirens* highlighted the lowest decrease in net CO_2 assimilation equal to 17.2 %.

Table 2
Average values ± standard error of diameter at breast height (DBH) and height (*h*) before planting for each species. Species-specific carbon storage (C_{tot}) was obtained by summing values obtained for each single tree.

Species	Number of trees	DBH (cm)	*h* (m)	C_{tot} (t)
Tilia platyphyllos	70	3.11 ± 0.05	3.23 ± 0.03	0.0663
Acer opalus	15	2.77 ± 0.13	3.24 ± 0.09	0.0257
Acer rubrum	15	3.54 ± 0.08	3.51 ± 0.07	0.0117
Ulmus 'Plinio'	40	2.17 ± 0.18	2.38 ± 0.10	0.0178
Cupressus sempervirens	30	3.34 ± 0.27	2.23 ± 0.07	0.0385

The model estimates of A_n were in good agreement ($R^2 = 0.79$, $p < 0.001$) with the measured A_n values in the five species, although the model tended to slightly overestimate and underestimate the low and high A_n range, respectively (Fig. 4).

3.3. Total CO_2 balance

The total CO_2 balance was obtained as: – Carbon Footprint + C_{tot} – R_{soil} + CB_{tree}. The first two equation terms were fixed while R_{soil} and CB_{tree} followed a variable annual rate due to climatic conditions and tree growth. Results indicated that the new urban forest is a CO_2 source in the first 12 years considering the three climatic scenarios (Fig. 5A). Starting from the 13th year, the urban forest is able to offset all the emissions and becomes a real CO_2 sink. For all scenarios, an exponential positive trend in CO_2 removal was observed after the compensation year (Fig. 5B). At the end of park life, the highest CO_2 balance was modeled for SSP5–8.5 (2349.88 t) followed by SSP2–4.5 (1867.28 t) and SSP1–2.6 (1509.76 t).

4. Discussion

4.1. CO_2 emission sources

LCA analysis highlighted the CO_2eq emission hotspots related to the realization of an urban reforestation project. Based on the results, management strategies for the entire process can be refined and CF can be further reduced to faster achieve the time of compensation. Unless to replace fuel-powered machinery and tools with electrical ones, it is difficult to improve environmental performances from excavations during tree planting (Lind et al., 2023) as well as pruning operations (McPherson et al., 2015). On the other hand, nursery cultivation, the tree transport, and the lawn mowing frequency, can be optimised to limit CO_2 emissions. In detail, the potted nursery phase showed a much higher CF than when trees were obtained with open field cultivation, mainly due to the extensive use of plastic pots and peat-based substrates, as already stated by Lazzerini et al. (2016). The CO_2 emissions from using peat are attributable both to its extraction process and to the

Table 3

Summary of species-specific net CO_2 assimilation model parameters. In detail, A_{max} is the maximum assimilation rate; φ determines the initial slope of the light-photosynthesis relationship; f_{temp}, f_{light}, f_{VPD}, and f_{CO2} are the variation of A_{max} with temperature (T, °C), photosynthetic active radiation (PAR, μmol m^{-2} s^{-1}) vapor pressure deficit (VPD, kPa) and CO_2 concentration (ppm), respectively; R_{leaf} is the temperature-dependent leaf respiration. T_{max}, T_{opt}, and T_{min} are the maximum, optimal, and minimum air temperatures for photosynthesis; K_m is the value of PAR when A_{max} /2; *a, b, c, d, k, r, s* are species-specific constants.

Parameter		Unit	*Tilia platyphyllos*	*Acer opalus*	*Acer rubrum*	*Ulmus* 'Plinio'	*Cupressus sempervirens*
A_{max}		μmol m^{-2} s^{-1}	16.28	12.58	10.73	21.30	14.27
φ		Not dimensional	0.04	0.04	0.04	0.04	0.03
f_{temp}	T_{max}	°C	48	48	48	48	48
	T_{opt}	°C	27	27	27	27	27
	T_{min}	°C	0	0	0	0	0
f_{light}	K_m	μmol m^{-2} s^{-1}	280.7	261.6	222.9	347.5	515.3
f_{VPD}	*a*	Constant	1.1687	1.4229	0.9871	3.7706	3.2648
	b	Constant	13.261	12.086	9.749	20.345	13.418
f_{CO2}	*c*	Constant	0.000002	0.000002	0.000002	0.000002	0.000001
	d	Constant	0.003608	0.003909	0.003980	0.004088	0.003942
	k	Constant	0.230697	0.290640	0.282759	0.252225	0.384921
R_{leaf}	*r*	Constant	0.0226	0.0574	0.0324	0.0395	0.288
	s	Constant	0.1160	0.0950	0.1078	0.1063	0.0716

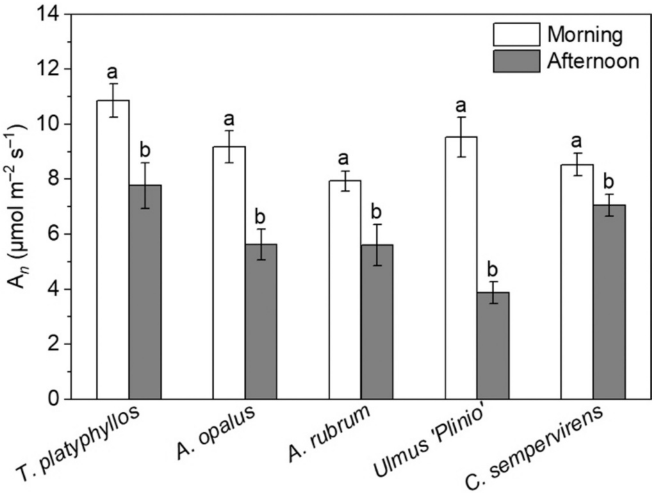

Fig. 3. Species-specific net CO_2-assimilation (average ± standard error) measured at saturated light (PAR = 1500 μmol m^{-2} s^{-1}) during the morning and the afternoon in mid-summer under various conditions of T and RH. Different letters indicate significant differences among A_{sat}, within each species, at $p \leq 0.05$ following Tukey's test.

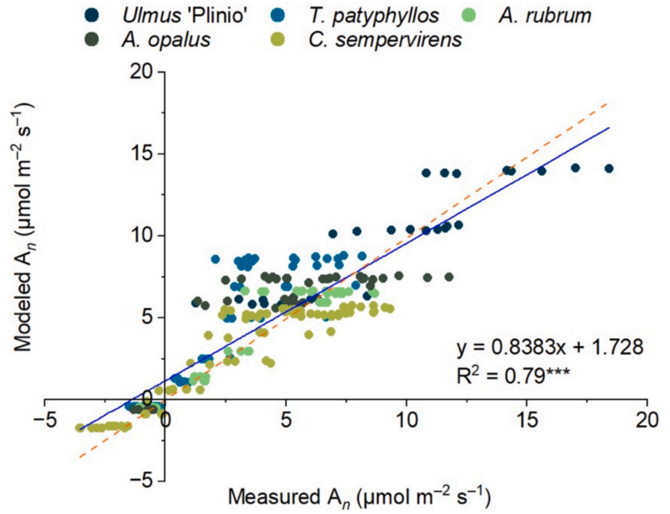

Fig. 4. Comparison between measured and modeled A_n ($n = 250$). All species were plotted together. The blue line represents the linear regression ($p < 0.001$). The yellow dotted line denotes the 1:1 line.

transport from peat bogs located in the Baltic countries (Hirschler and Osterburg, 2022). Moreover, peat is a depleting resource, and the continuous exploitation of peatland ecosystems that are natural carbon reservoirs (Wellock et al., 2011), is no longer sustainable. To reduce CF in nursery production, it is thus desirable to use alternative substrates and pots that can replace peat and plastic respectively, while ensuring comparable plant growth performance (Gupta et al., 2023; Nicese et al., 2024). Another CO_2 hotspot was the tree transport given the distance from the nursery to the test area (i.e., 200 km). Shortening the supply cultivation chain, for example, through the development of municipal tree nursery services, would significantly alleviate the CO_2 burden. Definitely, maintenance of the area over time is the main source of CO_2eq emissions, and the grass cutting is the activity with the greatest impact. Intensive lawn management is largely used in urban areas primarily for aesthetic reasons, but the reduction of mowing frequency can produce ecological and economic benefits (Watson et al., 2020). Alternatively, parts of park lawns could be left unmown with the double beneficial effect of reducing CO_2 emissions and promoting the presence and richness of pollinating insects (Rada et al., 2024). Noteworthy, this study innovatively showed that R_{soil} represents the most prominent emission source as negative factor for the CO_2 balance. This result pointed out that R_{soil} is an unavoidable factor to precisely calculate the CO_2 balance linked to a green area, but increasing the tree cover through reforestation projects is also essential to mitigate CO_2 soil emission that naturally occurs due to this biological phenomenon. As this carbon cycle component is strongly temperature-dependent, future changes in the thermal regime can amplify the CO_2 release from soil, especially in the Mediterranean area, while its effect may be slighter in colder regions (e.g., northern Europe). However, increased shading due to canopy cover growth could reduce the land surface temperature (Schwaab et al., 2021) and consequently R_{soil}. Autotrophic respiration rate is strictly related with temperatures and seldom limited by water availability (Jian and Steele, 2024). Conversely, Karvinen et al. (2024) highlighted that elevate soil temperature has a lower magnitude than wetness in the increase of heterotrophic component of R_{soil} over the growing season in urban green spaces. Similarly, Selsted et al. (2012) and Schindlbacher et al. (2012) have underlined that prolonged severe summer drought periods can decrease soil CO_2 efflux due to reduced soil water content. Hence, further measurements to assess the relationship between soil moisture and heterotrophic respiration should be considered to better estimate the soil CO_2 efflux. Ultimately, one of the novelties of the study was to parameterize the species-specific foliar dark respiration in response to high temperatures. The evaluation of this negative

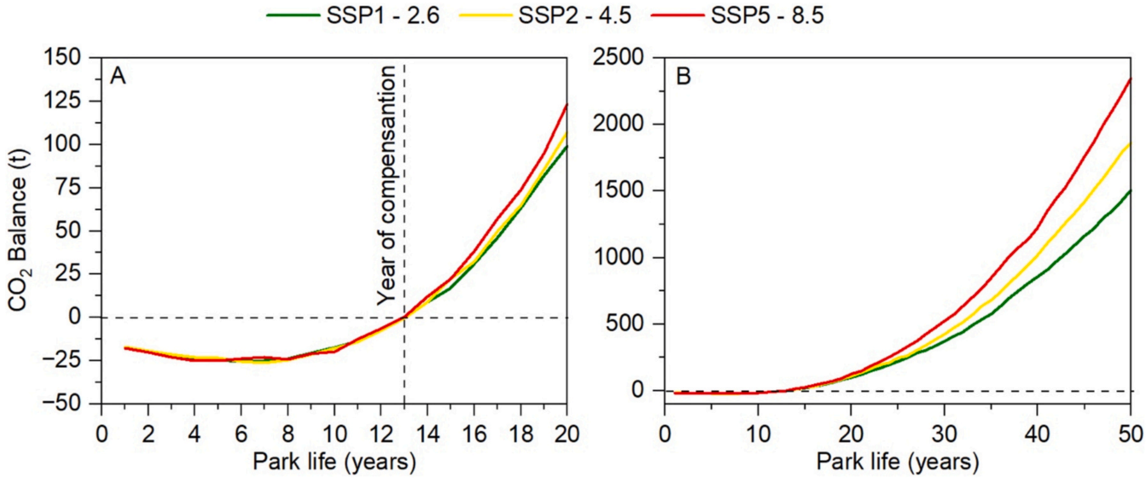

Fig. 5. A) CO_2 balance modeled for the first 20 years considering the three climate scenarios: SSP1–2.6 (green line), SSP2–4.5 (yellow line) and SSP5–8.5 (red line). B) CO_2 balance modeled for the entire park life (50 years).

component in the CO_2 assimilation model is mainly needed in the Mediterranean urban areas where tropical nights are increasingly widespread during summer (Yavaslı and Erlat, 2024).

4.2. *CO_2 sinks*

As suggested by Allen et al. (2017), the successful long-term survival of urban reforestation projects is directly linked to the selection of healthy and high-quality plant material in the nursery, site conditions, planting methods, and post-transplant cares. Particularly, the appropriate watering requirement is needed to develop a vigorous root system that can guarantee the ideal tree growth over time (Connellan, 2008). The net CO_2 assimilation model developed in this study considers an ideal tree growth in a city environment. However, abiotic stresses due to climate and soil *status*, e.g., drought, nutrient deficiency, heat, and sunlight excess, as well as pathogenic attacks, could heavily affect urban trees, leading to a lower CO_2 assimilation. Furthermore, air pollution such as atmospheric nitrogen deposition and elevated tropospheric ozone concentration would affect the growth of trees in urban ecosystems (Fares et al., 2013; Du et al., 2022), probably leading to an uncertainty in the net CO_2 balance of one new urban forest. Especially drought is a major concern in an urban context and can strongly affect the CO_2 uptake (Wang et al., 2019), as trees can act the strategy to close stomata to avoid dehydration (Agurla et al., 2018; Liang et al., 2023). Since trees were continuously irrigated during summer for the years of measurement in the experimental area, the response function of A_n to soil water content was not included in the CO_2 assimilation model. Therefore, the model could overestimate the actual CO_2 uptake for drought-avoiding species, especially in Mediterranean cities such as Florence, which will be increasingly characterized by prolonged dry periods. Nonetheless, with the introduction of the f_{VPD} function, the model evaluated the limitation of photosynthesis due to increasing values of VPD that were recorded in hot and dry climate during the afternoon (i.e., midday depression). As a matter of fact, as shown in Fig. 4, statistically significant good fitting ($R^2 = 0.79$) was found for modeled-measured photosynthesis values suggesting the high model predictiveness for this kind of environment. Since canopies of young trees were poorly developed during the first two years, measurements for parameterization of the leaf-level photosynthesis model were performed on fully sun-exposed leaves. Monsi-Saeki's approach was thus applied to also consider the shading of leaves inside the canopy, which occurs with tree growth.

Tree species biodiversity in urban forests is an essential factor to optimize multiple ecosystem services (Morgenroth et al., 2016), to face disease outbreaks (Tello et al., 2005) and to enhance resilience to local environmental alterations (St-Denis et al., 2024). Moreover, the mixture and richness of species can promote a greater CO_2 assimilation potential offered by the designed urban forest. Indeed, the selection of evergreen or coniferous species (e.g., *C. sempervirens*) allows a CO_2 sink even in winter when deciduous trees cannot carry out photosynthesis. On the other hand, broadleaved species belonging to *Tilia* and *Ulmus* genera demonstrated higher photosynthetic rate during in-leaf seasons, stoking greater amounts of CO_2 in woody tissues. For this reason, CO_2 sequestration capacity should be considered as an important additional criterion for tree selection to maximize the beneficial effects induced by an urban forest, as stated by Manzini et al. (2023).

4.3. *Total CO_2 balance*

To the best of our knowledge, this is the first study to comprehensively evaluate both CO_2 sources and sinks for a planted urban forest in the Mediterranean area. Although CF linked to nursery cultivation, planting, or maintenance were already calculated in previous studies (Ingram, 2012; Kendall and McPherson, 2012; Strohbach et al., 2012; McPherson et al., 2015; Zhang et al., 2022), the novelty of the research was to model, based on measured and modeled data, both the annual R_{soil} and species-specific CB_{tree} dependent on the city-specific climatic conditions. Moreover, the model proposed in this study is able to encompass the biophysical complexities and dynamics (e.g., tree growth) as well as consider the effect of *climate change* over time, contrary to i-Tree Eco and InVEST that significantly simplify ecosystem processes.

Following this original approach, it was possible to calculate an overall CO_2 balance and indicate precisely the year of compensation. Results underscored that the new urban forest needs 7–8 years to develop a tree canopy cover able to counterbalance the CF and CO_2 emitted by the soil reaching full emissions offset after 13 years. Interesting to note, an exponential capacity to remove CO_2 by the new urban forest was highlighted after the offset of CO_2 emissions. The same trend was reported by Strohbach et al. (2012) for an urban green space project in Germany, even though the compensation point was detected after c.a. 5 years of tree growth, mainly because annual soil respiration was not included among the CO_2 emission sources. Single-tree CO_2 storage 50 years after planting is higher but of the same magnitude as that estimated by Fini et al. (2023) for urban woody species growing in parks of Italy. However, higher atmospheric CO_2 concentrations represent a fertilizer for trees, leading to a more efficient photosynthesis process, as stated by Fares et al. (2017). For this reason, the function f_{CO2} was innovatively included in the assimilation model considering the future increase in atmospheric CO_2 concentration. Interestingly, it was observed that more CO_2 is absorbed in the pessimistic-intermediate scenarios, SPP5–8.5 and SSP2–4.5, than in SSP1–2.6. Nonetheless, higher CO_2 concentrations can reduce stomatal conductance (Xu et al., 2016; Liang et al., 2023) and consequently decrease the stomatal removal of gaseous pollutants. Furthermore, the partial stomatal closure, induced by the high CO_2 concentrations in the atmosphere, could also promote an increase in the leaf temperature (i.e., overheating) and the detrimental effect on CO_2 assimilation due to higher respiration rate.

Soil Organic Carbon (SOC) as well as grass photosynthesis were not encompassed in the CO_2 balance assessment. However, as Nicese et al. (2021) reported, urban parks have the potential to store a high quantity of SOC. Accordingly, the CO_2 break-even point would be reached earlier than estimated in this study if these two additional parameters are considered. In addition, the tree mortality rate was not contemplated, although failures commonly occur in the first years after planting due to wrong management practices, vandalism, soil features, and mechanical injury (Nowak et al., 1990). Finally, it should be considered that carbon storage and sequestration increase with tree density up to a saturation point. The tree density related to this case study (i.e., 309 trees/ha) is really close to the saturation value found by Drolen et al. (2023) and could be considered optimal to avoid delaying in the turning point.

5. Conclusions

This case study underlined that 13 years are needed for a new urban forest to become a real carbon sink in Southern Europe, thus helping municipalities and city planners to design carbon neutral cities in this climate zone. Firstly, LCA analysis clearly detected the hotspots linked to CO_2 emissions, suggesting that technological development should further decarbonize the production chain. Moreover, CF can be reduced by a smart management plan for urban forest maintenance. Among the emission sources, soil respiration emerges as a key factor that cannot be excluded from a CO_2 balance, especially in the Mediterranean area. Concerning the positive component of the balance, tree biodiversity proved to be a decisive aspect since woody species showed different capacity to store CO_2. Furthermore, tree selection should prefer a mixture of evergreen and deciduous species to extend the assimilation period and cover the entire year. Further research is needed to validate the obtained findings also in other climatic regions and sites in different urban ecosystems, where local environmental conditions may change CO_2 assimilation and soil respiration. In conclusion, this study demonstrated that planting a new urban forest can effectively help to mitigate the *climate change* effects by storing considerable tons of atmospheric CO_2, although tree selection and management play a critical role to maximize the positive effect offered by this NBS.

CRediT authorship contribution statement

Jacopo Manzini: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yasutomo Hoshika:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Pierre Sicard:** Writing – review & editing, Funding acquisition. **Alessandro Anav:** Writing – review & editing, Data curation. **Alessandra De Marco:** Writing – review & editing. **Beatrice Sorrentino:** Writing – review & editing. **Giovanni Trentanovi:** Writing – review & editing, Data curation. **Barbara Baesso Moura:** Writing – review & editing, Visualization. **Francesco Ferrini:** Writing – review & editing. **Lapo Azzini:** Writing – review & editing, Software. **Francesco Paolo Nicese:** Writing – review & editing, Software. **Elena Paoletti:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

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

Acknowledgments

We would like to thank Moreno Lazzara, Leonardo Lazzara, Sarah Demarty, Matheus Casarini Siqueira, Elena Marra, Andrea Viviano, Giorgia Guardigli, Arianna Biancalani, and Matilde Diani for support during field measurements. This work was carried out with the contribution of the LIFE financial instrument of the European Union (LIFE19 ENV/FR/000086) in the framework of the AIRFRESH project "*AIR pollution removal by FoRESts for a better human well-being*" and of the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.4 - Call for tender No. 3138 of 16 December 2021, rectified by Decree n.3175 of 18 December 2021 of Italian Ministry of University and Research funded by the European Union – NextGenerationEU, Award Number: Project code CN_00000033, Concession Decree No. 1034 of 17 June 2022 adopted by the Italian Ministry of University and Research, CUP B83C22002930006, Project title "National Biodiversity Future Center - NBFC" (Spoke 5).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.178267.

Data availability

The data that has been used is confidential.

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