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URBAN SUSTAINABILITY: CO_2 UPTAKE BY GREEN AREAS IN THE HISTORIC CENTRE OF SIENA

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ABSTRACT

Nature provides free assets and ecological services essential for human health and economic activity. For this reason, our ecosystems need to be protected and managed without affecting their integrity in the long run.

The absorption of carbon dioxide (CO_2) by vegetation is one of the most important services provided by the ecosystem, which needs to be preserved over time, because it regulates the planetary energy and entropic balance. In the cities, population growth, together with progressive urbanization, often leads towards a reduction of green areas and related ecological systems. Therefore, urbanization processes should be planned, also keeping in mind maintenance of a right equilibrium between built and green areas.

In this study, the green areas in the historic centre of the city of Siena (Tuscany, central Italy) were identified and investigated. It was found that the total surface area of the historic centre was 169.64 *ha*, of which 71.54 *ha* was occupied by valleys and other green areas. The real contribution of this natural heritage to the CO_2 absorption capacity of the ecosystem, was 330.50 t CO_2 yr^{-1}, depending on the vegetation types present in the green areas (e.g. trees, olive groves, vineyards, bamboo, grass and vegetables). Data showed remarkable carbon-storage efficiency untypical of a highly populated urban area (1.95 t CO_2 $ha_{overall}^{-1}$ yr^{-1}).

In an urban system, the presence of large green areas and their proper management are necessary to ensure its sustainability.

Keywords: CO_2 uptake, green areas, Siena, urban ecosystem.

1 INTRODUCTION

Every living and organized system (e.g. a city, an economic system or a society) depends inexorably on nature's ability to regenerate resources and absorb entropic wastes [1]. The exploitation of nonrenewable energy sources, specifically the overuse of water, soil, mineral and biological resources, is contributing to climate change and biodiversity reduction [2].

Following the industrial revolution, the demand for fossil fuels grew exponentially. This aspect, combined with deforestation, led to increased amount of carbon dioxide (CO_2) and other greenhouse gases released to the atmosphere, resulting in negative consequences to the planetary climate system [3]. Today, although the atmospheric CO_2 concentration is increased by 40% compared to the pre-industrial period, the oceans have absorbed only about 30% of it, accelerating the process of acidification of marine waters and altering many of the global biogeochemical cycles. In recent years, important international studies about these issues have been published, considering the effects, feedbacks and threshold values, specifically focusing on the importance of not exceeding the threshold values, in order to avoid the integrity of the Earth being compromised [4, 5]. Another factor to take into consideration is the exponential growth of the population, which is located mainly in urban areas. Fifty four percent of the world's population already lives in cities, a value that is expected to reach 66% by 2050, with an increase mainly in Asia and Africa. For this reason, the sustainable management of urban areas will be one of the main challenges of the future years [6].

CO_2 absorption is one of the services that are provided free by ecosystems, which allows to adjust the energy balance of the Earth, through plant photosynthesis and carbon storage in various environmental compartments, e.g. the oceans and soils. It is therefore essential to

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have a detailed understanding of the greenhouse gas emission and removal dynamics, both at global and local scales.

Ecosystem services are defined as 'the benefits that humans obtain from ecosystems', e.g. resources and processes that allow the development and the survival of all living systems [7]. The ecosystem services have been classified in the Millennium Ecosystem Assessment into four categories [8]:

1. *provisioning services*, which include all the biomass produced by ecosystems and directly used by humans in the form of food, water, timber and fibre;
2. *regulating services*, which sustain the functioning of the ecosystems, normalizing important elements such as climate, floods, diseases, wastes and water quality;
3. *supporting services*, which are needed to sustain all the other ecosystem services, such as soil formation, photosynthesis, and nutrient or water cycling;
4. *cultural services*, which provide recreational, aesthetic and spiritual benefits, affecting all intangible values derived from contact with nature.

The present study quantifies the regulating service provided by nature by way of photosynthetic activity that is able to maintain the Earth's climate in favourable conditions for life. In particular, the aim of this study was to quantify the CO_2 absorption capacity of an urban system characterized by a high population density: the historic centre of the city of Siena, the capital of the same province (Tuscany, central Italy). The historic centre, surrounded by Middle-Age walls, has preserved its medieval mark over centuries, maintaining its urban historic structure intact.

The work was aimed to:

1. evaluate the total surface area of the historic centre of the city of Siena by Geographic Information System (GIS) measurements, and organization in areas both able and unable to capture CO_2;
2. estimate the CO_2 uptake by green areas, according to their specific capacity;
3. provide comparative scenarios of CO_2 absorption among different local territorial systems.

2 MATERIALS AND METHODS

2.1 Study area: the historic centre of the city of Siena

Siena is located in southern Tuscany, with a famous medieval historic centre, surrounded by Middle-Age walls of about 7 km. Due to its integrity, the historic centre was declared an UNESCO World Heritage in 1995: it was defined as 'a masterpiece resulting from inventiveness and dedication in the way architecture is designed and embedded into the urban structure' [9].

The municipality of Siena is characterized by a total area of 11,853 *ha* with 53,903 inhabitants [10]; the population density is 4.54 inhabitants ha^{-1}. The historic centre covers 169.64 *ha* and accommodates 10,531 inhabitants [11] with a population density of 62 inhabitants ha^{-1}. Around 20% of the municipal population is concentrated here, despite the surface being only 1% of the municipality of Siena.

2.2 Geographic Information System (GIS)

To identify and quantify the green areas in the historic centre, Arc-GIS software (version 10.4) was used. This software allows to create and manage maps through the use of Geographic Information System (GIS) [12].

In this study, vector data was applied through polygons of different colours, composing the map of the green areas enclosed within the historic centre.

To identify the green areas, high-resolution orthophotos were used, taken from an aerial view, in the year 2007. The analysis was based mainly on photo-interpretation, which was followed by site inspections. This second phase was important to verify the actual consistency of the vegetation.

The total green area in the studied system was identified, drawing orange polygons in the map (Fig. 1a). Within the green areas, valleys (represented by light green polygons) play an important role in the city, due to their relevant size (Fig. 1b).

The subdivision in CO_2 absorption levels was made, according to the degree of carbon (C) accumulation in the plant biomass present in the identified green areas. The CO_2 absorption levels were defined by grouping vegetation species with similar growth rates.

The built areas (buildings, roads and cemented spaces) had zero CO_2 absorption and were identified with the code 0 and grey polygons. Zero CO_2 absorption was also expected for the reversible areas (clay and gravel spaces); for reversible, we consider all those areas currently not active in CO_2 absorption, but that could easily be converted to green areas. These were identified with the code 1 and black polygons. The level of high CO_2 absorption (represented by trees) was identified with the code 4 and red polygons. Lawns with shrubs and scattered trees were classified by the level of medium CO_2 uptake and identified with code 3 and yellow polygons. Lawns and vegetable gardens were included in a level of low CO_2 uptake, assigning the code 2; this level was determined by difference (Table 1 and Fig. 2).

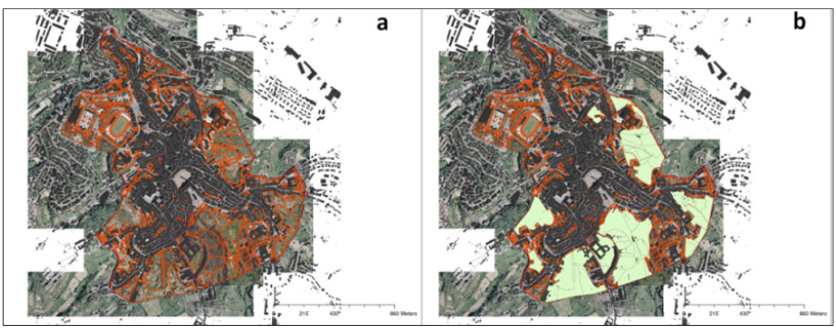

Figure 1: a) Map of green areas; b) Valleys highlighted by light green polygons.

Table 1: Identified levels of CO_2 uptake.

Code	Category	Level of CO_2 uptake	Vector data (Polygons)
0	Built areas (buildings, roads, cemented spaces)	Zero	Grey
1	Reversible areas (clay and gravel spaces)	Zero	Black
2	Lawns and vegetable gardens	Low	Determined by difference
3	Lawns with shrubs and scattered trees	Medium	Yellow
4	Trees	High	Red

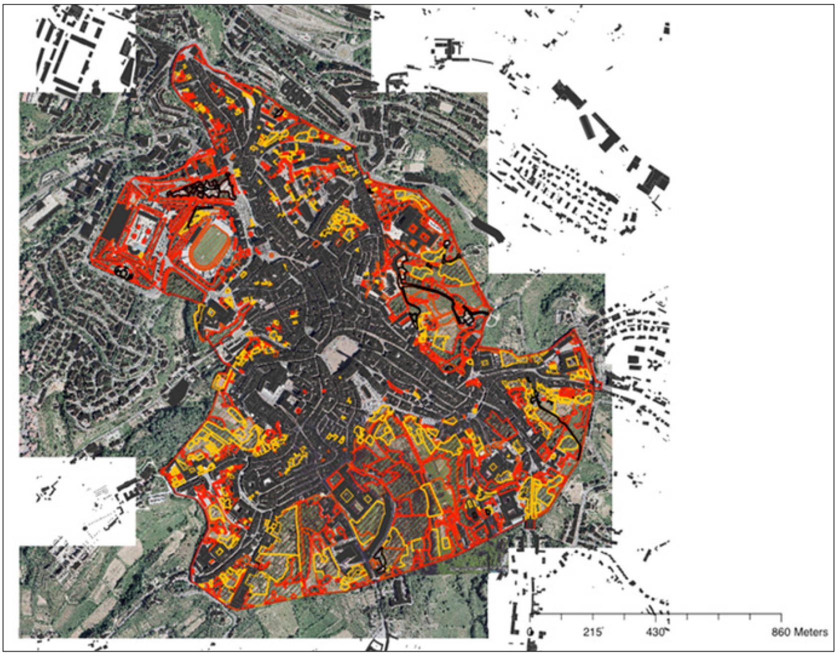

Figure 2: Map of the levels of CO_2 uptake in the historic centre.

2.3 CO_2 uptake accounting

The Gain-Loss method, presented in the 2006 IPCC methodology [13], was applied to evaluate the annual carbon stock change, by subtracting the carbon removed from the biomass (Carbon Loss) from the carbon stored (Carbon Gain), in the same year. The Carbon Gain was calculated by applying the equation (1):

$$\Delta C_G = \sum \left\{ A_i \times \left\lfloor I_V \times BCEF_I \times \left(1 + R\right) \right\rfloor \times CF_i \right\} \quad (1)$$

where:

ΔC_G = annual increase in biomass carbon stock due to biomass growth, t C yr^{-1};

A_i = area of specific vegetation type, *ha*;

I_V = average annual increment for specific vegetation type, m^3 ha^{-1} yr^{-1};

$BCEF_I$ = biomass conversion and expansion factor for conversion of net annual increment in volume to above-ground biomass growth for specific vegetation type, t above-ground biomass growth (m^3 net annual increment)$^{-1}$;

R = ratio of below-ground to above-ground biomass for a specific vegetation type, t dry matter below-ground biomass (t dry matter above-ground biomass)$^{-1}$;

CF_i = carbon fraction of dry matter, t C (t dry matter)$^{-1}$.

For orchards, olive groves and vineyards, a biomass pruning equal to 32% of the annual growth of the plant was considered [14].

The carbon absorbed by grass in lawns was equal to 0.879 t C *ha*$^{-1}$ yr^{-1} [15, 16]. The amount of carbon stored in the gardens, planted with vegetables, showed a carbon accumulation equal to 0.61 t C *ha*$^{-1}$ yr^{-1} [17].

For bamboo (species *Phyllostachys viridiglaucescens*), a carbon annual absorption equal to 1.42 t C ha^{-1} yr^{-1} was used [18, 19].

As the last step, the amount of annual carbon stock was converted to CO_2, multiplying by 3.67, a value which expresses the ratio between the molecular weight of CO_2 (44) and the atomic weight of carbon (12).

To calculate the real amount of CO_2 absorbed in the historic centre, the vegetation types in CO_2 absorption levels were grouped and for each level an annual average absorption rate per hectare was estimated. These CO_2 absorption levels were calculated by averaging the values obtained with the application of the Gain-Loss method, assuming that each plant type was present and distributed evenly in the territory.

Comparisons between the historic centre of the city of Siena and that of various territorial systems, at different organizational and productive vocations, were performed. For each territorial system, the required data were extrapolated from the REGES Project, promoted by the Province of Siena Administration to regulate its greenhouse gas balance over time [20]. The REGES project was developed by the Ecodynamics Group of the University of Siena, in collaboration with the certification agency RINA Services S.p.A. and the provincial agency for energy, environment and sustainable development, taking into account scientific, legislative and political issues [21].

3 RESULTS AND DISCUSSION

3.1 Green areas and CO_2 uptake in the historic centre of the city of Siena

Of the overall surface area occupied by the historic centre (169.64 *ha*), 58% was classified as built and reversible areas, while 42% corresponded to green areas. The latter constituted valleys (25% of the historic centre) and parks and private and vegetable gardens (17% of the historic centre) (Table 2).

The annual carbon and CO_2 uptake per hectare by the vegetation types present in the historic centre of the city of Siena are shown in Table 3, listed in decreasing order.

The level of high CO_2 absorption was characterized by trees, which showed a capacity between 3.98 and 12.20 t CO_2 ha^{-1} yr^{-1}. The level of medium CO_2 absorption was shown by lawns with shrubs and scattered trees; the specific average annual uptake value quantified per hectare was obtained from those vegetation types that absorb within a range of 3.22 to 3.98 t CO_2 ha^{-1} yr^{-1}. Finally, the level of low CO_2 uptake was shown by lawns and vegetable

Table 2: Areas of the historic centre, classified by surface types.

Surface type	**Area** *ha*	**Percentage**
Total area of the historic centre of the city of Siena	169.64	
Built and reversible areas	98.10	58%
Builts areas (buildings, roads, cemented spaces)	*96.23*	*57%*
Reversible areas (clay and gravel spaces)	*1.87*	*1%*
Green areas (valleys, parks and private and vegetable gardens)	71.54	42%
Valleys	*42.18*	*25%*
Parks and private and vegetable gardens	*29.36*	*17%*

Table 3: Annual CO_2 uptake per *ha* by vegetation types.

		C uptake per hectare per year	CO_2 uptake per hectare per year
Vegetation type	**Management**	**t C ha^{-1} yr^{-1}**	**t CO_2 ha^{-1} yr^{-1}**
Poplar	Arboriculture	3.33	12.20
Silver fir	High forest	3.05	11.17
Red fir	High forest	3.01	11.03
Other coniferous tree	High forest	2.68	9.84
Austrian pine and larch	High forest	2.46	9.01
Chestnut	Coppice	2.41	8.83
Other evergreen broadleaf	Coppice	2.27	8.32
Hornbeam	Coppice	2.08	7.63
Chestnut	High forest	2.06	7.54
Hygrophilous tree	Coppice	2.05	7.53
Hygrophilous tree	High forest	2.05	7.53
Other evergreen broadlef	High forest	1.96	7.16
Beech	Coppice	1.93	7.07
Beech	High forest	1.89	6.91
Other broadleaf	Coppice	1.84	6.75
Other broadleaf	High forest	1.84	6.75
Turkey and valonia oak	Coppice	1.74	6.38
Holm oak	Coppice	1.63	5.97
Turkey and valonia oak	High forest	1.61	5.90
Cembra	High forest	1.54	5.64
Scotch pine	High forest	1.46	5.35
Bamboo	Spontaneous	1.42	5.19
Orchards	Agriculture	1.38	5.06
Pinaster	High forest	1.36	4.98
Hornbeam	High forest	1.31	4.80
Durmast, downy and pedunculate oak	Coppice	1.18	4.32
Durmast, downy and pedunculate oak	High forest	1.09	3.98
Vineyard	Agriculture	1.08	3.95
Holm oak	High forest	1.05	3.84
Maquis and shrub	Spontaneous	0.95	3.47
Olive grove	Agriculture	0.94	3.43
Grass	Spontaneous	0.88	3.22
Cork tree	Coppice	0.81	2.97
Cork tree	High forest	0.67	2.47
Vegetable garden	Agriculture	0.61	2.24
		Weighted average absorption	**6.24**

gardens; this level included all the vegetation types that absorb between 2.24 and 3.22 t CO_2 ha^{-1} yr^{-1}, such as grass, cork trees and vegetables. The built and reversible areas had zero CO_2 absorption.

The total CO_2 absorption calculated for the historic centre of the city of Siena amounted to 330.50 t CO_2 yr^{-1} (Table 4). The green areas were composed of 37% by plant types with high CO_2 uptake, 36% by vegetation with low uptake and 27% by plants with medium uptake.

A wide green area, as in the historic centre of Siena, is very relevant and quite particular for a city with high population density [22, 23]. Furthermore, the plants present in valleys, parks and private and vegetable gardens, were homogeneously distributed within the three levels of CO_2 absorption. They were well managed and therefore selected for the study of climatic area and adaptation characteristics.

Thirty seven percent of the green areas consist of plant types at the level of high CO_2 absorption, such as some conifer species, oaks and other broadleaves, present both in the valleys and in the public/private parks. In the valleys, mainly vegetation types at the level of low CO_2 absorption, such as lawns, orchards, olive groves, vineyards and vegetables (36%) were detected, while plants at the level of medium CO_2 absorption were mainly located within the private gardens, where shrubs and scattered trees could be found (27%).

In this work, a precautionary approach has been used for the identification of the green areas within the historic centre. Only sure surfaces, excluding marginal spaces corresponding to roads and buildings were selected. Moreover, a level of low CO_2 absorption was attributed to the shaded areas, to avoid problems associated with the photo-interpretation.

The analysis was conducted indirectly with orthophotos; thus, subsequent site inspections were necessary in order to reduce the uncertainty associated with analysis based on only cartographic interpretation. The inspections were useful to verify whether the land use system had remained almost constant over time, considering that the used orthophotos were collected in 2007.

3.2 Comparison with other territorial systems

Comparisons with other territorial systems were also performed and the results presented in Table 2 and 4 were discussed, considering the features of each. It has been evaluated as follows:

1. territorial systems at different scale (historic centre, municipality and province of Siena);
2. territorial systems at the same scale (municipal) within the same province (Siena), with both similar (Poggibonsi and Colle di Val d'Elsa) and opposite (Radicondoli and Monticiano) characteristics.

The municipalities of Siena, Poggibonsi and Colle di Val d'Elsa have a prevailing administrative and managerial vocation, while Radicondoli and Monticiano present wide rural landscape and forestland, with a prevailing agricultural- and wood-based economy.

The parameters, plant composition of green areas and the average annual CO_2 absorption per hectare, were used to determine the absorption efficiency. Note that the overall surface of the urban systems (instead of just green areas) was used to obtain a more representative value.

Figure 3a shows that the historic centre of the city of Siena had a CO_2 absorption efficiency that coincided with that expected for the municipality of Siena, assessing a minimum difference (−0.11 t CO_2 $ha_{overall}^{-1}$ yr^{-1}). Moreover, the historic centre and the municipality of Siena

Table 4: Annual CO_2 uptake by the vegetation types of the historic centre.

Code	Category	Level of CO_2 uptake	Average CO_2 uptake per hectare per year	Area	CO_2 uptake per year
			$t\ CO_2\ ha^{-1}\ yr^{-1}$	*ha*	$t\ CO_2\ yr^{-1}$
0	Built areas (buildings, roads, cemented spaces)	Zero	0.00	96.23	-
1	Reversible areas (clay and gravel spaces)	Zero	0.00	1.87	-
2	Lawns and vegetable gardens	Low	2.73	25.87	70.52
3	Lawns with shrubs and scattered trees	Medium	3.65	18.95	69.13
4	Trees	High	7.14	26.72	190.86
	Total			**169.64**	**330.50**

were characterized by a CO_2 absorption efficiency equal to half of that estimated for the province of Siena (around 2 *vs* 4 t CO_2 $ha_{overall}^{-1}$ yr^{-1}). Results suggested that the green area composition was quite similar for the historic centre and the municipality, while the province was characterized by a higher prevalence of high-absorption plants, and lesser prevalence of those with medium CO_2 uptake. In fact, the province of Siena had large areas of forestland (almost 77% of the total surface).

Regarding comparison at the same scale (Figure 3b), the obtained results showed that the CO_2 uptake per hectare in the municipalities of Poggibonsi and Colle di Val d'Elsa (2.16 and 2.71 t CO_2 $ha_{overall}^{-1}$ yr^{-1}, respectively) were very similar to that of the municipality of Siena (2.06 t CO_2 $ha_{overall}^{-1}$ yr^{-1}). In fact, they are the three administrative systems most densely populated in the province and with similar economic vocations. The total green area was rather limited, when compared to other municipalities in the Siena district, considering also their high population density. By contrast, the CO_2 absorptions per hectare of the

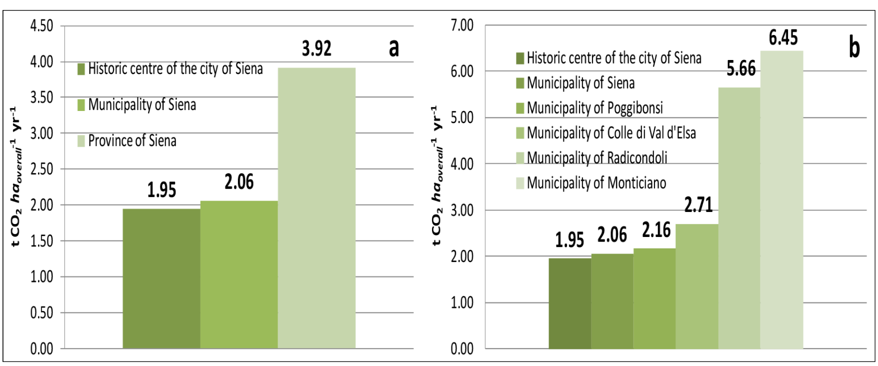

Figure 3: a) CO_2 absorption efficiency per hectare of territorial systems at different scales. b) CO_2 absorption efficiency per hectare of territorial systems at the same scale. CO_2 data for province and municipalities were extrapolated from the report related to the REGES Project at the year 2009 [24].

municipalities of Radicondoli and Monticiano were quite similar and double of that of the historic centre and the municipality of Siena. The CO_2 absorption efficiency per hectare was therefore very high in the municipalities of Radicondoli and Monticiano, exceeding 4 t CO_2 $ha_{overall}^{-1}$ yr^{-1} the calculated value for the municipality of Siena.

Other references about the CO_2 absorption of the vegetation at urban scale were available. Some of these studies were developed using GIS for the identification of green areas in cities [25–27]. Various methods were applied for the calculation of CO_2 stored in the plant biomass: the IPCC Guidelines, or mathematical models developed with software, aimed at quantifying the variation over time of the carbon stocks and flows (e.g. STELLA and Urban Forest Effects – UFORE) [15, 23]. The comparison of the results with those cited in other papers should be drawn keeping in mind the differences in CO_2 uptake estimations, assumptions for raw data collection and some missing information that are not explicated. Nowak and Crane [23] estimated that the annual uptake of the city of Chicago (Illinois, USA) is equivalent to 0.73 t CO_2 $ha_{overall}^{-1}$, while the value obtained for the historic centre of Siena is almost double, 1.95 t CO_2 $ha_{overall}^{-1}$.

The CO_2 uptake measured for the historic centre of Siena indicated that the present green areas were characterized by considerable structural complexity (presence of species at high CO_2 absorption and in harmony with each other) and consequently greater efficiency in the photosynthetic activity than other urban systems. This aspect affects other ecosystems services. Although in this study only the CO_2 uptake by plants was recorded, other ecosystems services also exist (e.g. preservation of biodiversity, water and nutrient cycle adjustment, soil formation and availability of recreational areas).

4 CONCLUSION

In this study, the green areas of the historic centre of the city of Siena were measured for the first time and the associated levels of CO_2 uptake were calculated. The green areas, including valleys, parks and private and vegetable gardens, covered 71.54 *ha*, within a total surface area of the historic centre equal to 169.64 *ha*. The green areas had an absorption capacity of 330.50 t CO_2 yr^{-1}.

These good values were due to a combination of at least two factors:

1. the orographic conformation of the city;
2. the management practices which, starting from the Middle Ages, demonstrate environmental sensitivity in system governance.

The annual CO_2 absorption efficiency per hectare of the historic centre was almost half of that of the Province of Siena; on the other hand, the efficiency per hectare of green area, considering its vegetation composition and management, was higher for the historic centre than that of the province of Siena (4.72 t CO_2 $ha_{green\ area}^{-1}$ yr^{-1} for the province *vs* 6.24 t CO_2 $ha_{green\ area}^{-1}$ yr^{-1} for the historic centre).

It is hoped that the management of the city of Siena, will further improve with regard to environmental actions, which should always be in favour of sustainable choices.

The presence of a wide green area in an urban system and its efficient management, are two essential conditions for urban sustainability, contributing positively to the welfare of the population.

CO_2 uptake by vegetation is one of the most important ecosystem services provided free by Nature: it must be absolutely preserved over time, because it regulates the energy and entropic balance of the Earth. This, with many other ecosystem services, are increasingly tangible but often neglected by traditional disciplines because it cannot be easily quantified in economic terms.

As underlined by Rockström *et al.* [4] and Steffen *et al.* [5] 'climate change and the integrity of the biosphere are two core boundaries', that should never be exceeded. When they were significantly altered, the Earth will inevitably lead to a new state characterized by greater vulnerability and welfare depletion. For this reason, the urbanization processes should be planned taking into consideration the balance between built and green areas.

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