How effective are the vegetated surfaces for the CO_2 sequestration? Analyzing parameters and methods

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***Abstract*— Human activities are severe sources of greenhouse gases and, particularly, of CO_2. This trend, according with the highly demanding criteria released by the international institutions, must be suitably cut, in order of turning the pollutant emissions within limits that will guarantee a sustainable and environmentally safe development of the human species. Apart the measures that are since long time usually implemented in the technological systems, other interventions should be properly adopted in supporting the sustainability of the anthropic activities. These actions mainly apply to the so-called bioclimatic and passive measures and, particularly, could usefully refer to the plantation of proper surfaces of trees that, thanks to their metabolic mechanisms, are able to sequester relevant amounts of greenhouse gases. In this paper, after a description of a simple method for evaluating the quantities of CO_2 sequestered by trees, the availability of the main parameters on which the sequestration of CO_2 by urban trees is based will be discussed.**

Keywords—Energy efficiency, buildings, passive actions, vegetated surfaces

I. Introduction

The methods for the evaluation of the CO_2 sequestration and cutting are acquiring a rising importance among the policies aimed at limiting the use of fossil fuels and improving the environmental performances of the anthropic activities. In fact, at international as well at country levels, the standards and the suggestions concerning the proper use of the energy (and material) resources are becoming more and more demanding, in this way obliging each single State to adopt effective measures able to put the human activities towards a decarbonisation path.

In this regard, in order to limit the recourse to primary energy sources that are cause of carbon releases which, in turn, generate dangerous amounts of greenhouse gases, the target proposed by the EU [1, 2] should be properly taken into account. Such recommendations call for a 40% decrease, by the year 2030, of the CO_2 emissions, compared to those of the year 1990. Anyway, it seems that these targets are going to be missed by member states, since the most plausible goal is only a 30% reduction of the EU emissions at that date, which is far from the desired target [3].

Moreover, apart the European suggestions, at a world scale, the well-known United Nations' Sustainable Development Goals – SDGs [4] can be additionally considered. Particularly, with the aim of pursuing energy efficiency, environmental sustainability, safety and resilience of the anthropic systems, SDGs 7 "Affordable and clean energy" [5] and 11 "Sustainable cities and communities" [6] should be suitably addressed.

Anyway, this complex situation calls for a deep program of interventions, at European scale, involving the most important sectors of the countries. The building sector is supposed to be responsible for relevant amounts of pollutant releases, to resort to a high rate of the fossil fuels' consumption and to use a significant volume of raw materials. In order of steering this crucial sector toward sustainable paths, several studies and actions have been proposed. Among them, one of the most effective tries to change the energy profile of buildings into a "nearly zero" one, in search of the so-called nZEB (nearly Zero Energy Buildings) [7, 8, 9]. Obviously, this goal should be acquired by maintaining, at the same time, a proper level of the indoor comfort conditions available to occupants [10]: it is well evident that this target – being sometimes energy spending – could conflict with the purpose of limiting the use of energy for climatization of buildings equipping them with appliances that may confer to people pleasant lighting and acoustics microclimatic conditions [11]. On purpose, a suitable rethinking of the design criteria of buildings is nowadays involving methods and schemes for their proper energy certification and classification [12].

Recently, despite these practices certainly originated from past times, buildings are more often equipped with passive components that use vegetated species and natural essences: green roofs are undoubtedly the most known and widely

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spread examples of this type of equipment [13]. Their effectiveness in reducing the energy demand for climatization of buildings is largely recognized, although huge differences can be observed between their seasonal behaviors, particularly in mild climates [14, 15]. In fact, in these climatic zones though the reduction of the annual demand for climatizing a given building by means of the adoption of green roofs is widely recognized (thanks to their suitability in cutting the cooling demand in summer) [16, 17], some authors argue a positive contribution of these components also in the winter season [18, 19]; some authors [20] find a neutral contribution to the climatization in winter, while others [21] indicate an adverse contribution.

Apart the above cited differences in the energy performances of these vegetated building-coupled surfaces, researchers are since several years putting an increasing attention on two further features of such systems: on one hand, their capability of reducing the Urban Heat Island phenomena [22] and, on the other hand, their attitude to sequestration of part of the CO_2 present in the air, included that released by the human activities.

As for the CO_2 sequestration, recently also the impact of the urban trees on the mitigation of the carbon dioxide concentration in cities has received a rising consideration because an extensive use of trees in the urban context might provide a positive contribution to the transition of cities toward sustainable and decarbonized paths.

In this paper, after describing a simple method for the evaluation of the quantities of CO_2 sequestered by trees, a discussion on the availability of the main parameters on which the sequestration of CO_2 by urban trees is based on will be made.

II. Assessing the Amount of CO_2 Sequestered by a Tree

The amount of CO_2 sequestered by a tree is quite difficult to be evaluated. In fact, such quantity depends on several parameters that, obviously, must take into account that these biological entities are living beings, subjected to growth, decay and death phenomena. During these events, trees absorb different amounts of CO_2, depending on their rate of the photosynthesis mechanism. On the other hand, it should be properly considered that the actual quantity of CO_2 absorbed by a tree is given by a balance considering that, other than absorbing a certain amount of CO_2, in the same time, a tree releases a quantity of this gas in the decay phase and embodies another portion during the maintenance phase.

A. Computing CO_2 Sequestration Rates

The evaluation of the carbon dioxide sequestered by a given tree can be simply computed by means of a method based on the knowledge of some parameters referring to the physical properties of these vegetated essences [23]. The scheme of calculation on which the method relies is synthetically depicted in Fig. 1.

The scheme aims to assess the weight of carbon dioxide, YW_{CO2}, that a tree is supposed to sequester annually, starting from the so-called green weight, W_G, of the same tree. More in general, within this simplified scheme, the amount of CO_2 entrapped in the tree is a function of the diameter of the tree, Φ, of its height, h, and of its age, T_A. These physical parameters refer to the "mature" age of the tree. That is:

$$YW_{CO2} = f(\Phi, h, T_A) \quad (1)$$

In details, the green weight W_G of a tree can be computed starting from its diameter, Φ, its height, h, and its age in years, T_A [24]:

$$W_G = \alpha \cdot \Phi^2 \cdot h \cdot \beta \quad (2)$$

The parameter α depends on the diameter of the trunk and can be set to 0.25 or 0.11 for diameter of the trunks lesser or higher of 29 cm. The parameter β enables to take into account the weight of the root system (it generally increases the weight of the tree of 20%).

The dry weight of the same tree, W_D, depends on its green weight and on the ratio between its dry matter and its moisture content. The first one is assumed to be equal, on average, to 0.725 of the whole weight of the tree [25]:

$$W_D = W_G \cdot 0.725 \quad (3)$$

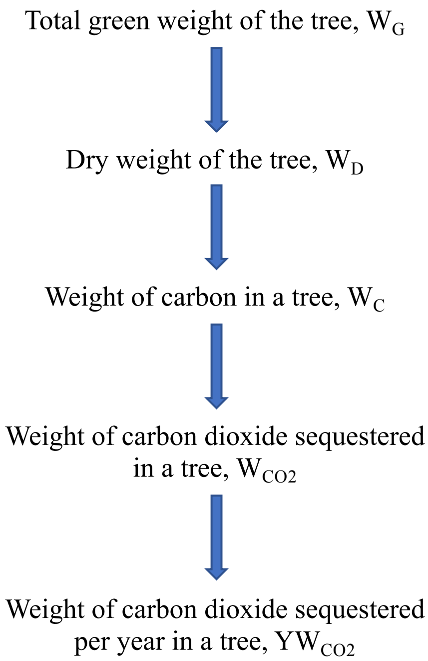

Fig. 1. Scheme of calculation of the CO_2 sequestered by a tree

The assessment of the dry weight of a tree enables the evaluation of the weight of carbon, W_C, embodied in it. Generally, it is assumed that 50% of the total tree's volume corresponds to its carbon content [26, 27, 28]. That is:

$$W_C = W_D \cdot 0.5 \quad (4)$$

In turn, the total amount of CO_2 sequestered by the tree, W_{CO2}, is simply given by:

$$W_{CO2} = W_C \cdot 3.6663 \quad (5)$$

Finally, taking into account the age T_A of the tree, its yearly sequestered content of CO_2, YW_{CO2}, can be computed as follows:

$$YW_{CO2} = W_{CO2} / T_A \quad (6)$$

When applying Equations (1) through (6), it should be properly considered that their parameters are mainly available for forest trees, while only few data are available for urban trees, despite the assessment of the number of trees needed for the sequestration of a given urban context should usefully refer to urban trees. In fact, in the rural forests the density of trees is intense; therefore, the rate of carbon dioxide sequestered by a forest is about double than the one referring to the urban trees [29]. On the other hand, urban trees grow faster than rural ones and, as a consequence, they can be imputed to a higher rate of carbon dioxide sequestration [30].

In order to provide some useful data for the effective design of the suitable areas of vegetated surface for the neutralization of the CO_2 emissions in a given urban context, in Fig 2 the amount of carbon dioxide sequestered by typical urban trees species is reported. Along with the amount of CO_2 yearly sequestered by the trees (kg/year) reported in the vertical axis, their relative heights (m) are indicated on the horizontal axis, in order of also indicating the level of growth of some of the tree species most widely used in the urban context.

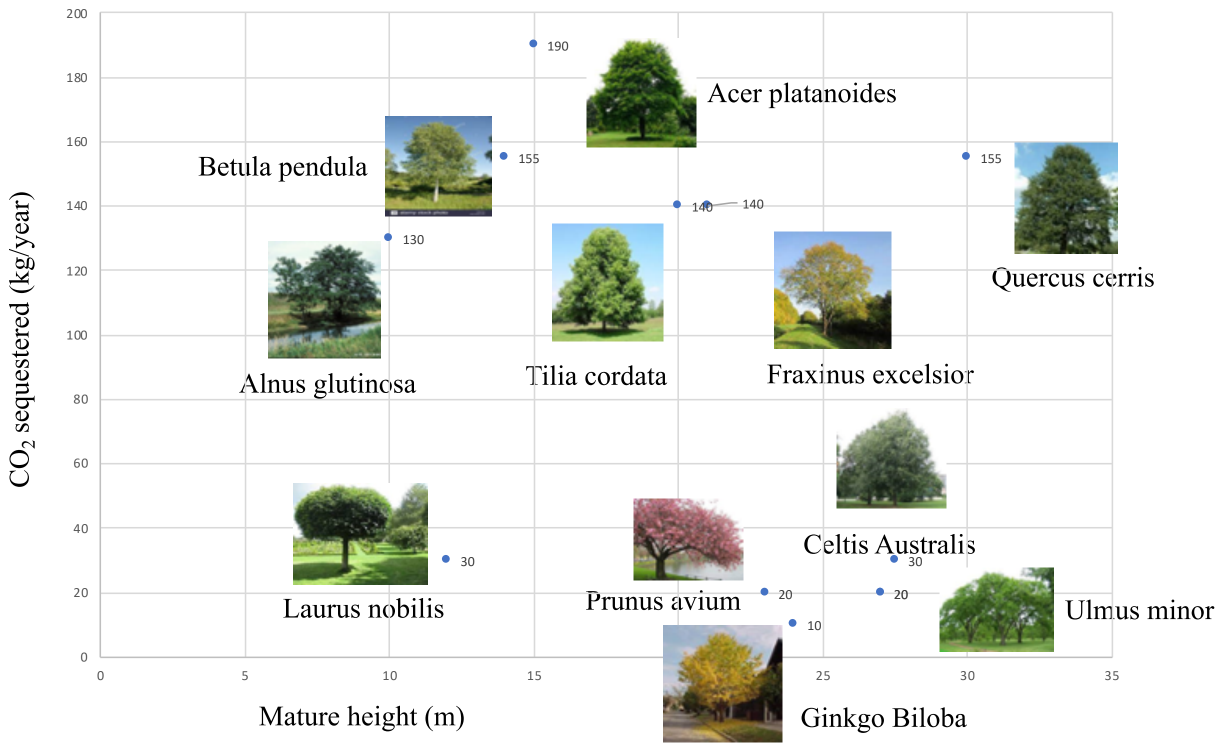

Fig. 2. Yearly amount of CO_2 sequestered by some typical urban trees, as a function of their mature height

B. *Available parameters*

The main parameters on which a calculation of the CO_2 absorbed by a given tree may relay, are directly connected with the physical growth of the vegetated species under analysis. On purpose, in Equations (1)-(6) one of the most relevant physical parameter is represented by the height of the considered trees. Obviously, this value should be directly measured in the field. Anyway, when technicians are under design processes, the availability of literature data concerning the trees is the only way to get this parameter.

Some researchers [31] have proposed a simple analytical model for computing the height of a given tree as a function of its trunk diameter at breast height. That is:

$$h = \alpha_3 \cdot {D_T}^{\alpha_4} \qquad (7)$$

In the previous equation, D_T represents the trunk diameter, that is modeled with a sigmoid growing trend. That is:

$$D_T = \alpha_0(1 - e^{\alpha_1} \cdot A_T) \cdot \alpha_2 \qquad (8)$$

where A_T is the tree age.

Equations (7) and (8) depend on parameters (α_i) that obviously are related to the type of trees, with their dimensions and growth and with the zone where they are developing. In Table 1 the parameters α_i are reported [31] for deciduous and evergreen plants living in a south growing zone and for three main dimensions of these urban plants, that is small, medium and large.

Another important parameter for suitably addressing the design of urban trees surfaces is the area of their crown spread.

TABLE I. COEFFICIENTS USED IN EQUATIONS (7) AND (8).

Plant Species	Tree Dimension	Growth Parameters				
		α_0	α_1	α_2	α_3	α_4
Deciduous	Small	15.50	-0.07	1.90	6.50	0.61
	Medium	26.00	-0.07	1.90	6.50	0.65
	Large	33.50	-0.07	1.90	6.50	0.72
Evergreen	Small	18.70	-0.10	1.90	6.50	0.59
	Medium	33.00	-0.06	1.70	8.40	0.60
	Large	40.00	-0.06	1.70	8.40	0.66

In fact, in order of removing a given amount of the released CO_2 in an urban context, it is necessary to compare the number of trees needed for sequestering that quantity of carbon dioxide with the available area supposed to host these trees. The evaluation of this important physical parameter is, of course, really complex to be achieved, due to the large differences among the same type of trees. Anyway, as a tentative approach, it is possible to refer to mean data released in the literature [32] for some typical urban trees. In Table 2 the average area of the crown is reported for such plants, considered in their mature stage of growth. These draft data can be used for steering towards the singling out of the number of trees, for each selected species, to be planted in a given area.

TABLE II. MATURE CROWN SPREAD OF SOME TYPICAL URBAN TREES (LONGEVITY. L: >50 YEARS; M: 25-50 YEARS; S: <25 YEARS)

Tree Species (Figure 2)	Mature Crown Spread (m)	Longevity
Acer platanoides	11	L
Betula pendula	9	S
Quercus cerris	20	L
Ginkgo Biloba	17	L
Celtis australis	14	L
Tilia cordata	13	M
Ulmus minor	12	M
Fraxinus excelsior	23	L
Alnus glutinosa	9	M
Prunus avium	10	M
Laurus nobilis	5	L

However, when the decarbonisation of large areas is in context (let us say, at urban levels), and therefore a wide number of trees is involved, a further parameter should be properly taken into account. That is the average survival of the plants that is directly related with the need of re-implanting the dead trees. This information is difficult to be achieved at the design stage as well, since survival depends, among other things, on the local conditions and on the adaptability of the vegetated species to such conditions. Nevertheless, even in this case, some literature data can be tentatively used [33, 34] when local data concerning the typical survival rates of the plants are not available.

III. DISCUSSIONS

The above described data and methods for computing the rate of carbon dioxide sequestered by a given tree (or by a group of trees) must be properly adjusted considering the CO_2 emitted by the trees during their life. In fact, trees are subjected to a decomposition process (linked with their survival rates); moreover, the proper management of trees by the anthropic activities unavoidably results in an emission of carbon dioxide that affect the net value of the rate sequestered by trees. That is:

$$NC_{CO2} = BS_{CO2} - DE_{CO2} - MR_{CO2} \tag{9}$$

where NC_{CO2} is the net captured CO_2, BS_{CO2} is the CO_2 sequestered by biomass, DE_{CO2} is the CO_2 emitted for decomposition and MR_{CO2} is the CO_2 released for maintenance activities.

As for the decomposition process, it must be considered that trees release a certain quantity of carbon dioxide after death. It is really complicated to assess such rate of CO_2 emissions. On the other hand, it must be observed that biomass of dead trees is partially recycled, usually as landscape mulch. Literature researches estimate that as far as 80% of the biomass of dead trees – on the basis of their carbon content - is released in the atmosphere in the form of carbon dioxide emissions. Clearly, parameters such as the survival rate of the considered trees are crucial for the assessment of the CO_2 releases due to decomposition processes.

As for the tree maintenance, it must be observed that the management of the urban vegetated surfaces involve a certain use of energy, which is responsible of a given release of carbon dioxide in the atmosphere; this release of CO_2, in turn, will limit the absolute values of the carbon dioxide avoided by means of the plantation of an urban forest. These values are generally low: literature studies [23] indicate that the activities related to the maintenance of urban trees account for rates of CO_2 comprised between 1% and 5% of the total carbon dioxide balance of these trees. Anyway, it is well evident that a deep effort of research is required in this field.

More in general, it must be underlined that the values of sequestered CO_2, as obtained using the equations previously reported, are certainly approximated, since the actual dimensions and level of development of the trees under consideration could significantly differ from the values assumed by the equations. In addition, the modelling adopted for predicting the survival rates of trees and the growing of their crown of leaves rely on a general categorization of the tree (deciduous or evergreen; large, medium or small sizes): this simplification could easily lead to parameters of the vegetated species different from those pertinent to the trees under analysis.

IV. CONCLUSION

The interest of researchers and technicians toward the effect produced by trees in sequestering the urban CO_2 emissions is more and more increasing. Particularly, despite until now a preeminent attention was paid to the role played by green roofs and, generally, to vegetated surfaces related to buildings, recently the impact of the urban trees on the mitigation of the carbon dioxide concentration in cities has received a rising consideration. A large campaign of plantation of trees in the urban context could, in fact, positively contribute to the transition of cities toward sustainable and decarbonized paths.

Unfortunately, although many data are available about the CO_2 sequestration properties of forest trees, only few data can be found in the scientific literature concerning the urban trees. This represents a limitation in the modelling of the carbon dioxide balance in cities, since urban trees usually are subjected to growing processes quite different to those involving the forest trees.

In order of providing a contribution for the overcoming of this problem, in the present paper a review of literature data regarding the urban trees has been reported. Moreover, the most effective mathematical models aimed at the simulation of the carbon dioxide sequestration by these vegetated species have been cited and discussed.

A significant lack in the actual availability of reliable data to be applied to urban trees still remains and a big effort of research should be made to this aim.

REFERENCES

[1] European Commission, 2014. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A policy

framework for climate and energy in the period from 2020 to 2030. COM(2014) 15 final. Brussels.

[2] European Commission, Climate strategies & targets: 2050 long-term strategy of the European Commission. https://ec.europa.eu/clima/policies/strategies/2050_en (accessed 21 May 2021)

[3] EEA, 2019. Total greenhouse gas emission trends and projections in Europe. https://www.eea.europa.eu/data-and-maps/indicators/greenhouse-gas-emission-trends-7/assessment (accessed 21 May 2021).

[4] United Nations, The UN Sustainable Development Goals. https://www.un.org/sustainabledevelopment/ (accessed 21 May 2021)

[5] United Nations, Sustainable Development Goal 7: Ensure access to affordable, reliable, sustainable and modern energy for all. https://www.un.org/sustainabledevelopment/energy/ (accessed 18 February 2021).

[6] United Nations, Sustainable Development Goal 11: Make cities inclusive, safe, resilient and sustainable. https://www.un.org/sustainabledevelopment/cities (accessed 18 February 2021).

[7] S. Charisi, "The role of the building envelope in achieving nearly-zero energy buildings (nZEBs)", Procedia Environmental Sciences 38, pp. 115–120, 2017.

[8] L. Cirrincione, M. La Gennusa, G. Peri, G. Rizzo, G. Scaccianoce, "Towards Nearly Zero Energy and Environmentally Sustainable Agritourisms: the Effectiveness of the Application of the European Ecolabel Brand", Applied Sciences, 10, 5741, 2020.

[9] C. Marino, A. Nucara, M.F. Panzera, M. Pietrafesa, "Towards the nearly zero and the plus energy building: Primary energy balances and economic evaluations", Thermal Science and Engineering Progress, 13,1004, 2019.

[10] C. Marino, A. Nucara, G. Peri, M. Pietrafesa, A. Pudano, G. Rizzo. "An MAS-based subjective model of indoor adaptive thermal comfort", Science and Technology for the Built Environment (formerly HVAC&R Research Journal, ASHRAE), 21, pp. 114-125, 2015.

[11] M. La Gennusa, R. Macaluso, F. Massaro, M. Mosca, G. Scaccianoce and L. Cirrincione, "An experimental study on relationship between LED lamp characteristics and non image-forming," 2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Milan, Italy, June 2017. Doi: 10.1109/EEEIC.2017.7977546.

[12] G. Peri, G. Rizzo, "The Overall Classification of Residential Buildings: a Possible Role for the Tourist Ecolabel-Award Scheme", Building and Environment, Vol. 56, pp. 151-161, October 2012.

[13] P. Ferrante, M. La Gennusa, G. Peri, G. Rizzo, G. Scaccianoce, "Vegetation growth parameters and leaf temperature: Experimental results from a six plots green roofs' system", Energy, Vol. 115, Part 3, pp. 1723–1732, 2016.

[14] F. Fantozzi, C. Bibbiani, C. Gargari, R. Rugani, G. Salvadori, "Do green roofs really provide significant energy saving in a Mediterranean climate? Critical evaluation based on different case studies", Frontiers of Architectural Research, Vol. 10, Issue 2, pp. 447-465, 2021.

[15] P. Bevilacqua, R. Bruno, N. Arcuri, "Green roofs in a Mediterranean climate: energy performances based on in-situ experimental data", Renewable Energy, Vol. 152, pp. 1414-1430, 2020.

[16] P. Bevilacqua, D. Mazzeo, R. Bruno, N. Arcuri, "Experimental investigation of the thermal performances of an extensive green roof in the Mediterranean area", Energy and Buildings, Vol. 122, pp. 63-69, 2016.

[17] F. Ascione, N. Bianco, F. de' Rossi, G. Turni, G. Peter Vanoli, "Green roofs in European climates. Are effective solutions for the energy savings in air-conditioning?", Applied Energy, Vo. 104, pp. 845–859, 2013.

[18] C.M. Silva, M.G. Gomes, M. Silva, "Green roofs energy performance in Mediterranean climate", Energy and Buildings, Vol. 116, pp. 318-325, 2016.

[19] A. Niachou, M. Papakonstantinou, M. Santamouris, A. Tsangrassoulis, G. Mihalakakou, « Analysis of the green rof thermal properties and investigation of its energy performance", Energy and Buildings, vol. 33, pp. 719-729, 2001.

[20] I. Jaffal, S.E. Ouldboukhitine, R. Belarbi, "A comprehensive study of the impact of green roofs on building energy performance", Renewable Energy, Vol. 43, pp. 157-164, 2012.

[21] M. Santamouris, C. Pavlou, P. Doukas, G. Mihalakakou, A. Synnefa, A. Hatzibiros, P. Patargias, "Investigating and analysing the energy and environmental performance of an experimental green roof system installed in a nursery school building in Athens, Greece", Energy, Vol. 32, Issue 9, pp. 1781-1788, 2007.

[22] H. Akbari, S. Konopacki, M. Pomerantz, "Cooling energy savings potential of reflective roofs for residential and commercial buildings in the United States", Energy, Vol. 24, pp. 391-407, 1999.

[23] E. Gregory McPherson James R. Simpson. Carbon Dioxide Reduction Through Urban Forestry: Guidelines for Professional and Volunteer Tree Planters (1999). United States. Department of Agriculture, Forest Service, Pacific Southwest Research Station. General Technical Report PSW-GTR-171.

[24] A. Clark III, J. R. Saucier, W. H. McNab. Total-Tree Weight, Stem Weight, and Volume Tables for Hardwood Species in the Southeast (1986). Research Division, Georgia Forestry Commission.

[25] S. DeWald, S. Josiah, B. Erdkamp (2005). Heating With Wood: Producing, Harvesting and Processing Firewood. University of Nebraska – Lincoln Extension, Institute of Agriculture and Natural Resources.

[26] R. A. Birdsey (1992). Carbon Storage and Accumulation in United States Forest Ecosystems. General Technical Report W0-59. United States Department of Agriculture Forest Service, Northeastern Forest Experiment Station, Radnor, PA.

[27] Whittaker, R.H.; Likens, G.E. (1973). Carbon in the biota. In: Woodell, G.M.; Pecans, E.V., eds. Proceedings of the 24th Brookhaven Symposium in Biology; May 16-18, 1972; Upton, NY. Washington, DC: U.S. Atomic Energy Commission. Technical Info. Services. Office of Information Services; 281-302.

[28] H. Leith, "Modeling the primary productivity of the world", Ecological Studies, Vol. 14, pp. 237-263, 1995.

[29] R. Birdsey. 1992. Carbon storage and accumulation in United States forest ecosystems. Gen. Tech. Rep. WO-GTR-59. Radnor, PA: Northeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture.

[30] H.K. Jo, E.G. McPherson, "Carbon storage and flux in urban residential greenspace", Journal of Environmental Management, Vol. 45, pp. 109-133, 1995.

[31] L.E. Frelich. 1992. Predicting dimensional relationships for Twin Cities shade trees. St. Paul, MN: University of Minnesota, Department of Forest Resources.

[32] E.F.Gilman, H.W.Beck, D.G.Watson, P. Fowler, D.L.Weigle, N.R. Morgan. 1996. Southern trees. Gainesville. University of Florida.

[33] R.H. Miller, R.W. Miller, „Planting survival of selected street tree taxa", Journal of Arboriculture, Vol. 17, issue 7, pp. 185-191, 1991.

[34] R.W. Miller, 1997. Urban forestry: planning and managing urban greenspaces. 2nd. ed. Upper Saddle River: Prentice-Hall.