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RESEARCH ARTICLE

Whether the carbon emission from green roofs can be effectively mitigated by recycling waste building material as green roof substrate during five-year operation?

Liangqian Fan[1,2,3] · Jingting Wang[2,4] · Xiaoling Liu[5] · Hongbing Luo[1,2,3] · Ke Zhang[1,3] · Xiaoying Fu[4] · Mei Li[6] · Xiaoting Li[7] · Bing Jiang[8] · Jia Chen[1] · Shuzhi Fu[8] · You Mo[1] · Lin Li[1] · Wei Chen[1] · Lin Cheng[1] · Fenghui Chen[1] · Lin Ji[1] · Dandan Ma[1] · Xiaohong Zhang[2] · Bruce C. Anderson[9]

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Abstract

Green roof (GF) as an important role of urban ecosystem services is more and more focused on carbon sequestration for the mitigation of climate change, which there is still a gap of longer period of investigation on carbon sequestration on GF. This work aims to quantify the carbon sequestration on green roofs from 2012 to 2017 by measuring and calculating parameter on substrate organic carbon and plant organic carbon, when using waste building material substrate (WBMS) as GF substrate for the recycling of waste solid. Green roof group 2 (waste building material substrate (WBMS) as substrate) and green roof group 1 (local natural soil (LNS) as substrate), planting same three native plants (*N. auriculata*, *L. spicata*, and *L. vicaryi*), were both three substrate depth of 20 cm, 25 cm, and 30 cm, respectively. Results show that both innovative WBMS and LNS were a great capability of carbon sequestration and carbon storage on green roofs. Carbon storage of green roof group 1 and green roof group 2 was 65.6 kg C m^{-2} and 72.6 kg C m^{-2}, respectively. Annual mean carbon sequestration of the WBMS was 1.8 times higher than LNS. The overall average carbon sequestration (12.8 kg C m^{-2} $year^{-1}$) in green roof group 2 using WBMS was 1.1 times than corresponding in green roof group 1 (11.4 kg C m^{-2} $year^{-1}$ using LNS). WBMS substrate and *L. vicaryi* could be considered as the most adaptable green roof configuration, which can be a recommendation to promote the carbon sequestration and the function of green roof for the better urban ecosystem services. Future work may focus on the GF carbon model, water interface, long-term monitoring, environmental impact, water quality and quantity, synthesized effect on GF ecosystem, low impact development (LID), management and simulation, and combination on intelligent urban system, based on LCA.

Keywords Waste building material substrate (WBMS) · Carbon sequestration · Green roof · Carbon storage · *L. vicaryi*

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Ke Zhang, Jingting Wang, Liangqian Fan contributed equally to this work.

✉ Hongbing Luo
hbluo@sicau.edu.cn

✉ Ke Zhang
zhangke@sicau.edu.cn

[1] College of Civil Engineering, Sichuan Agricultural University, Chengdu 611830, China

[2] College of Environmental Sciences, Sichuan Agricultural University, Chengdu 611130, China

[3] Sichuan Higher Education Engineering Research Center for Disaster Prevention and Mitigation of Village Construction, Sichuan Agricultural University, Chengdu 611830, China

[4] State Key Laboratory of Hydraulics and Mountain River Engineering, Sichuan University, Chengdu 610065, China

[5] Sichuan Water Conservancy Vocational College, Chengdu 611231, China

[6] School of Architecture and Civil Engineering, Chengdu University, Chengdu 610106, China

[7] Laboratory Center, College of Chemical and Material Science, Sichuan Normal University, Chengdu 610066, China

[8] College of Business, Sichuan Agricultural University, Chengdu 611830, China

[9] Department of Civil Engineering, Queen's University, Kingston K7L 3N6, Canada

Introduction

Carbon dioxide (CO_2) emission makes a significant contribution to the global climate change (IPCC 2007) and global warming has become a serious issue worldwide (Edenhofer and Seyboth 2013; IPCC 2013; IPCC 2014; Wang and Feng 2017). Cities consume the vast majority of global energy and account for about 60–80% of global greenhouse emissions. Meantime, some problems including the lack of green areas, lower humidity, urban heat land effect and decreasing of cultivated land also bring great pressure to the cities space and environment. These problems can relieved by green roof to a certain extent (Berndtsson 2010; Shafique et al. 2019).

Green roofs can promote CO_2 sequestration, increase urban wildlife habitats, and reduce the urban heat island effect (Ondoño et al. 2018; Catalano et al. 2016), carbon footprint reduction, and as an urban strategy for mitigation to climate change with providing multiple urban ecosystem services (Foudi et al. 2017). Green roofs, also named as vegetated roofs, eco-roofs, roof garden, or living roofs (Sailor 2008), have been defined as a practical and efficient approach to make sustainable buildings for urban ecosystem service in urban areas (Sailor 2008; Getter et al. 2009a; Voyde 2010; Francis and Lorimer 2011; Vijayaraghavan and Joshi 2015; Shafique et al. 2018). In the recent ten years, low impact development (LID) for green roof has increasingly concerned (Burszta-Adamiak and Mrowiec 2013; Krebs et al. 2016; Shafique and Kim 2017). Green roof, as one of low impact development (LID) strategies, has contribute hydrology and environment service for urban ecosystem, especially recent a decade in China for the "Sponge City." Green roof was designed and developed in western countries to promote the abundance of green vegetation on high-rise buildings and thereby provide aesthetical as well as environmental benefits (Vijayaraghavan 2016), while the USA, Canada, Germany, Britain, Switzerland Japan, Italy, and Australia have larger scale and advanced technology in this field. Some researchers have previously studied the ecological advantages of green roofs in various fields (Sailor 2008), but less research has been done on carbon sequestration potential of green roofs especially in long-term observation to judge green roof carbon sequestration ability.

Green roofs can make full use of its carbon sequestration associated with plants, substrate, green roof structure, and management (Durhman et al. 2007; Saadatian et al. 2013; Whittinghill et al. 2014), especially the organic carbon content of substrate (Rugh et al. 2006). Plants play large differences of carbon sequestration (Razzaghmanesh et al. 2014), such as plant density, ecosystem age (Matamala et al. 2008), and species diversity (Russelle et al. 2007). Plants add life to green roofs and success of any green roof depends on how healthy the plants are (Vijayaraghavan 2016). Diversity of plants improve green roof functioning, aesthetics, longevity (Macivor and Lundholm 2011) and native plant species adapting surrounding environment on green roof (Farrell et al. 2013; Macivor et al. 2013). Native species may be of interest due to potential ability to adapt and their characteristics to adverse conditions (Clary et al. 2015). Meantime, greater substrate moisture within deeper substrates of green roof allows for plants having greater biomass to survive based on substrate depth. The substrates, as part of the green roof, provide the chemical and physical properties necessary for plant growth (Williams et al. 2010). Green infrastructures including green roofs have been considered as one of the most effective method of mitigating global greenhouse emissions (Kamal-Chaoui and Robert 2009). Carbon sequestration is influenced by management regulations on the distributing of trees or the cutting cycle (Fang et al. 2007). However, green roofs are not favorable environment for plant growth due to the water limit and fluctuations in rainfall (Rowe 2011; Farrell et al. 2012). Therefore, it concluded to provide nutrition by substrates for the green roof life (Vijayaraghavan 2016).

Green roof substrates are usually designed to achieve desirable characteristics such as hydraulic conductivity, preparation cost, low bulk density, and high water holding capacity (Vijayaraghavan and Joshi 2015; Lata et al. 2018). Substrates on green roofs are a key factor in enhancing urban environments depending on their physical properties and water content (Coma et al. 2017). Organic carbon content of substrate influences the formation and stability of structure; moisture performance of the substrate can directly influence fertility and the growth of vegetation. Generally, substrates consist of sand, aggregates, and specific organic matter to produce better conditions for roof vegetation (Coma et al. 2017). However, few studies have shown recycle waste materials (such as demolition waste or broken bricks) used as green roof substrate to mimic natural brownfield areas in urban environments (Ishimatsu and Ito 2013; López-Uceda et al. 2018). Sewage sludge and clay, carbonated limestone, and paper ash have been used to produce useful substrates employing on extensive green roofs in the UK (Molineux et al. 2009). With the development of economy and social progress, the natural resources will become more and more withered, and the construction waste generated in industrial production is increasing. Construction waste is mainly composed of crushed stone, slag, brick and tile, waste mortar, asphalt block, concrete block, nonmetallic material, and other mixtures (Tam 2003).

Waste building material (WBM) belongs to main construction waste, which contains a certain amount of toxic substances, and the release of toxic substances on the environment impact will be a long process (Tam and Tam 2006). Demolition waste and construction, as a major source of urban solid waste, frequently accounts for 10–30% of the total waste disposed of at landfills in many cities (Li et al. 2016). The influence of WBM on the environment pollution is divided into four aspects: water pollution, air pollution and the destruction of the ecological environment, destruction of the appearance of the city. Therefore, if WBM can be used as a green roof substrates, that would be positive for energy conservation and emission reduction. The building sector of global carbon emissions is a major contributor and responsibility as much as one-third of global greenhouse gas emissions (UNEP 2009). Waste materials and by-products when producing building materials are useful solution to reduce the embodied carbon emissions (Höglmeier et al. 2013; Ingrao et al. 2014; Intini and Kühtz 2011; Malmqvist et al. 2018). However, there is no report that the green roof using waste building material substrate (WBMS) and sewage sludge together is knowledge gap of carbon sequestration. Consequently, it is also a significant meaning to explore available and economical methods to promote the carbon sequestration of green roof. In one of our report, the mix-sewage-sludge substrate (MSSS, sewage sludge and local natural soil with the volume ratio of 1:1) had been used the green roof substrate applied in green roofs operating for one year, and at 2012, it was found with a potential performance on carbon sequestration (3.81 kg C m^{-2} $year^{-1}$) (Luo et al. 2014). To date, it is worth to output our new findings of WBMS during a 5-year research period from 2012 to 2017 for carbon sequestration in green roofs in this study.

This study investigated the improvement of the resource utilization rate of waste materials in determining green roof as a carbon sink or source for the mitigation of climate change. The objectives of this study are (1) to utilize waste building material substrate (WBMS) to the construct and evaluation on several green roofs; (2) to explore the ability of carbon sequestration of WBMS substrate and native plants in green roofs; and (3) to assess the 5-year performance between 2012 and 2017 of green roofs carbon sequestration ability, and consequently provide a reference for the stability of substrate and selected native plants.

Material and methods

Green roof construction and engineering

Green roofs were built on the 2nd building top at College of Civil Engineering in the Sichuan Agricultural University at Dujiangyan City (103° 37′ 19.14″ E, 31° 0′ 16.67″ N) in China in this study. Dujiangyan City belongs to the Chengdu WMGC (World Modern Garden City) from 2009 to 2039 (Xu et al. 2012; Zhao 2012). Waste building material substrate (WBMS) was used in green roof group 1 (composed of green roof L1, green roof L2, and green roof L3), and local natural soil (LNS) was used in green roof group 2 (composed of green roof W1, green roof W2, and green roof W3) in this study (Fig. 1). WBMS was made up of tiny particles (3–5 cm). WBMS was artificial substrates produced by abandoned building waste from the "Wenchuan Earthquake on May 12th, 2008" in Dujiangyan City. This work used the artificial waste substrates to promote the good utilization of waste materials. There are three native plant (*L. vicaryi*, *N. auriculata*, and *L. spicata*) as green roof plant.

Figure 1 a in this study shows the two substrates used in the green roofs. Figure 1 b demonstrates the layouts of designed green roofs. The whole green roof was 6 m length and 4.5 width, and was divided into same area of two parts, where one part is green roof group 1 made up green roof L1, L2, and L3 with same size of 3 m length and 4.5 m widths, and another part is green roof group 2 composed of green roof W1, W2, and W3 with same size of 3 m length and 4.5 m width. The substrate depth of L1 and W1 was 30 cm, depth of L2 and W2 was 25 cm, and depth of L3 and W3 was 20 cm. In addition, these six individual areas respectively planted the *L. vicaryi*, *N. auriculata*, and *L. spicata*.

Vertical structures (Fig. 1c) are the same to the green roofs from Luo (Luo et al. 2014), including plant layer, substrate layer (20 cm, 25 cm, 30 cm), filter layer (5 mm), drainage layer (28 mm), and water proof layer (22 mm). Waterproof materials used polypropylene fiber and can make a good waterproof effect. Drainage layer was constructed by abandoned construction waste (size 5–8 mm) after the earthquake with excellent drainage geotextile lay above as filter layer. LNS and WBMS were as substrates for comparison. Due to the special conditions of roofs, local plants *N. auriculata*, *L. spicata*, and *L. vicaryi* were used as green roof plants which the application of these plants on green roof was less in the previous research. Total organic carbon and initial plants biomass of these three plants before building green roofs in 2012 were shown in Table 2. The total numbers of *N. auriculata*, *L. spicata*, and *L. vicaryi* were 180 plantlets (plant crown diameter, 20 cm; plant height, 35 cm; row×column, 25 cm×20 cm), 216 plantlets (plant crown diameter, 10 cm; plant height, 30 cm; row×column, 25 cm×16.7 cm) and 405 plantlets (plant crown diameter, 10 cm; plant height, 15 cm; row×column, 20 cm×13.6 cm), respectively.

Sample and pretreatment

Both substrate properties are manifested in Table 1 before building of the green roofs. The BD (bulk density), MC (moisture contents), and pH of WBMS were similar to LNS's. The TN, TP, and TK of LNS were more than twice in the WBMS. TC (total carbon) of WBMS was slightly higher than that of LNS and TOC (total organic carbon) of WBMS, more than twice as much as the TOC in LNS.

This experiment period was operated from July 2012 until July 2017. Table 2 shows the properties of initial biomass and total organic carbon (TOC) of green roof plant before planting. The sample points were set from each green roof in three substrate thickness (20 cm, 25 cm, and 30 cm). Each green roof was divided into three layers: bottom layer (20–30 cm), middle layer (10–20 cm), and surface layer (0–10 cm). The

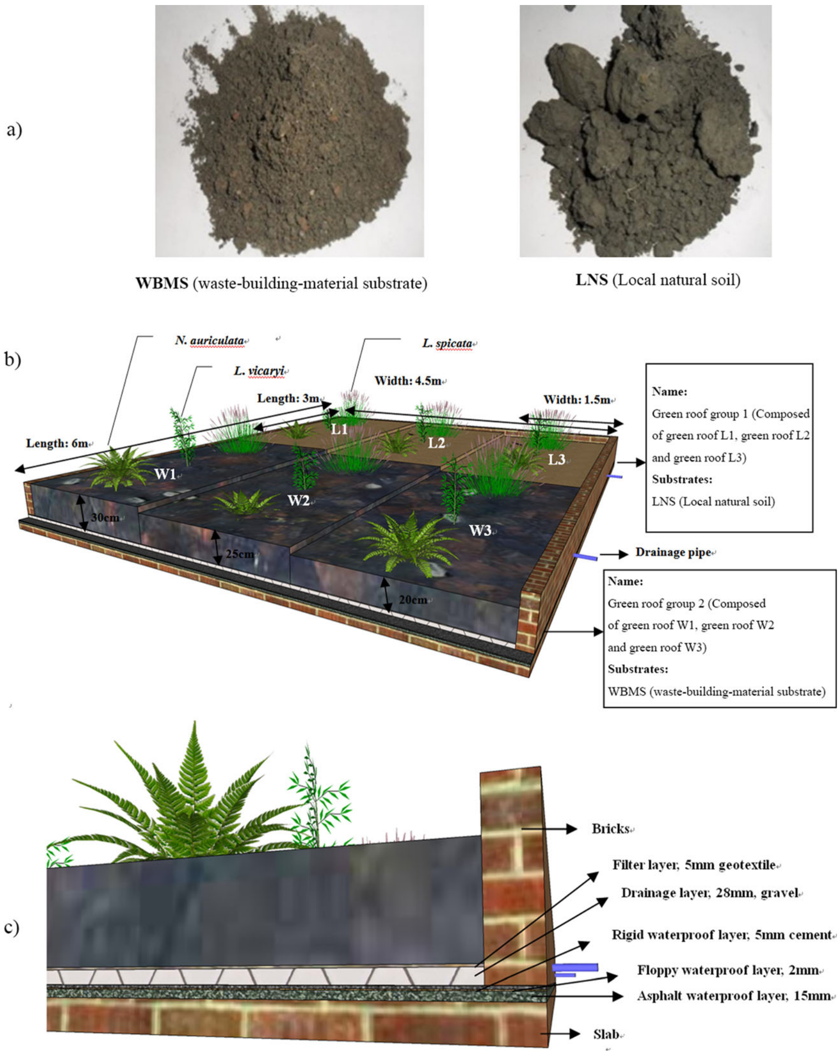


Fig. 1 Spatial distribution of green roofs. **a** Initial two substrates of green roof. **b** 3D layout of green roofs (LNS was in green roof group 1, WBMS was in green roof group 2. The green roof was divided into six equal area part: green roof L1, L2, L3, W1, W2, and W3, which every green roof planted three different plant (*L. spicata*, *N. auriculata*, and *L. vicaryi*). **c** The vertical structures of green roofs

green roof substrate layer ranges from 5 to 30 cm and TC (total carbon) and TOC content was measured at every 5-cm depth.. Fifteen samples from each substrate were collected each month (date 25 or 26), and a total of 30 soil samples per month consequently. Plants sampling (*N. auriculata*, *L. spicata*, and *L. vicaryi*) were sampled in early July 2017. After sieved through a 100-mesh sieve, all substrate samples were firstly air-dried, then secondly milled and thirdly preserved. Dry weighed for biomass of these three plants was oven-dried for 48 h at 80 °C. Before the measurement of TOC and TC, a stainless steel grinder was used to contain the oven-dried samples by passing through a 100-mesh sieve.

Sample testing and statistical analysis

TOC and TC of substrates and plants samplings were determined by carbon/nitrogen analyzer (Multi C/N 2100 and HT1300, Jena, Germany). TN and TP were measured by automated discrete analyzer (Seal Analytical and AQ2+, England). TK was analyzed using the photon absorption spectrophotometer (TAS-990, China). Wet weight of plants biomass and dry weight of plant biomass were measured by analytical balance instrument (Denver, T214). All data were fitted by the R Project for Statistical Computing (Version 3.02 for Windows) and statistical tests significance was considered at p values below 0.05.

Table 1 Properties of initial substrates local natural soil (LNS), waste building material substrate (WBMS) of green roof before planting

Substrates	BD (g cm^{-3})	MC (%)	pH	TC (g kg^{-1})	TOC (g kg^{-1})	TN (g kg^{-1})	TP (g kg^{-1})	TK (g kg^{-1})
LNS	1.3 ± 0.1	20.6 ± 3.1	6.4 ± 0.3	16.6 ± 3.2	12.2 ± 0.6	12.3 ± 1.3	2.3 ± 0.2	17.6 ± 2.2
WBMS	1.1 ± 0.1	22.1 ± 2.1	6.9 ± 0.2	35.5 ± 5.6	15.3 ± 1.2	14.3 ± 0.2	0.8 ± 0.1	6.4 ± 0.9

Table 2 Properties of initial biomass (g) and total organic carbon (TOC, g kg-1, ±S.E. (standard error)) of green roof plant before planting

Plant		Biomass		TOC	
	Wet weight	Dry weight	Belowground	Aboveground	Mean
L. spicata	32.8	8.7	450.1 ± 15.2	443.5 ± 3.5	446.8 ± 9.4
N. auriculata	49.0	13.9	486.7 ± 20.4	460.1 ± 5.6	473.4 ± 13.0
L. vicaryi	74.0	29.5	510.5 ± 15.6	466.1 ± 3.2	488.3 ± 9.4

Calculations of carbon sequestration

According to Lee (Lee et al. 2010) and Luo (Luo et al. 2014), carbon storage calculation and carbon sequestration calculation for green roof were connected with substrates and plants, especially by using the parameter on substrate organic carbon (SOC) and plant organic carbon (POC). Therefore, carbon calculation of six green roofs was as follows:

$$\begin{aligned}\mathrm{TC}_i &= \mathrm{Carbon}_{\mathrm{substrate}_i} + \mathrm{Carbon}_{\mathrm{plant}_i}\\ &= \mathrm{SOC}_{\mathrm{substrate}_i} \times D_{\mathrm{substrate}_i} \times H_{\mathrm{greenroof}_i} + \frac{1}{n}\sum_j^n \frac{SOC_{ij} \times DW_{ij}}{A_{ij}}\end{aligned} \tag{1}$$

Where,TC_i(g C m^{-2}) is the green roof's carbon storage of *i* green roof. $\mathrm{Carbon}_{\mathrm{substrate}_i}$ (g C m^{-2}) is the substrate carbon storage of *i* green roof. $\mathrm{Carbon}_{\mathrm{plant}_i}$ (g C m^{-2}) is the plant carbon storage of *i* green roof. $\mathrm{SOC}_{\mathrm{substrate}_i}$ (g kg^{-1}) is the substrate organic carbon of *i* green roof. $D_{\mathrm{substrate}_i}$ (g cm^{-3}) is the substrate's bulk density of *i* green roof. $H_{\mathrm{greenroof}_i}$ (*m*) is the substrate depth of *i* green roof. SOC_{ij}(g kg^{-1}) andDW_{ij}(kg) is the plant's organic carbon and plant's dry weight of *j* plant in green roof*No. i*, respectively. A_{ij}(m^2) is the plant area of *i* green roof.

Calculations of six green roofs carbon sequestration are as follows:

$$\begin{aligned}\Delta\mathrm{TOC}_i &= \Delta\mathrm{Carbon}_{\mathrm{substrate}_i} + \Delta\mathrm{Carbon}_{\mathrm{plant}_i}\\ &= \left(\mathrm{SOC}_{\mathrm{substrate}_{i-E}} - \mathrm{SOC}_{\mathrm{substrate}_{i-B}}\right) \times D_{\mathrm{substrate}_i} \times H_{\mathrm{greenroof}_i}\\ &\quad + \frac{1}{n}\sum_j^n \frac{\left(\mathrm{POC}_{ij-E} - \mathrm{POC}_{ij-B}\right) \times \mathrm{DW}_{ij}}{A_{ij}}\end{aligned} \tag{2}$$

Where, $\Delta\mathrm{TOC}_i$(g C m^{-2}) is the green roof's carbon sequestration of *i* green roof. $\Delta\mathrm{Carbon}_{\mathrm{substrate}_i}$ (g C m^{-2})and$\Delta\mathrm{Carbon}_{\mathrm{plant}_i}$ (g C m^{-2}) is the substrate carbon sequestration and plant carbon sequestration of *i* green roof, respectively. $\mathrm{SOC}_{\mathrm{substrate}_{i-B}}$ (g kg^{-1}) and $\mathrm{SOC}_{\mathrm{substrate}_{i-E}}$ (g kg^{-1}) is the substrate organic carbon of *i* green roof at the end and at the beginning of this experiment. $D_{\mathrm{substrate}_i}$ (g cm^{-3}) is the substrate's bulk density of *i* green roof. $H_{\mathrm{greenroof}_i}$ (*m*) is the substrate depth of *i* green roof. POC_{ij-E}(g kg^{-1}) andPOC_{ij-B}(g kg^{-1}) is plant organic carbon of *j* plant at green roof *No. i* at the end and at the beginning of this experiment.DW_{ij} (kg) is the plant's dry weight of *j* plant in green roof*No. i*. A_{ij}(m^2) is the plant area of *i* green roof.

The urban ecosystem of green roof for carbon sequestration can be calculated by following equation:

$$C = \sum_j^n \left(C_i \times A_{ij} \times \mathrm{N}_k\right) = \left[\frac{1}{n}\sum_j^n C_i\right] \times S \times G\% \tag{3}$$

Where, C is the total carbon sequestration of urban ecosystem service (kg C); C_i is the carbon sequestration of green roof NO. *i* per year (kg C m^{-2} year^{-1}); A_{ij} is the area of green roof No. *i* in the *j* of district of city; N_k is the service time of green roof NO. *i* (years); $\frac{1}{n}\sum_j^n C_i$ is the average carbon sequestration of total green roof in the city (kg C m^{-2} yeasr^{-1}); S is the total area of city (m^2); G% is the area percentage of total green roof area in the city (%). Because there is about 38-km^2 roof area at central of Chengdu City and about 89.3% of roofs have no greening features, it is available for engineering application of green roofs if appropriate (Li 2012).

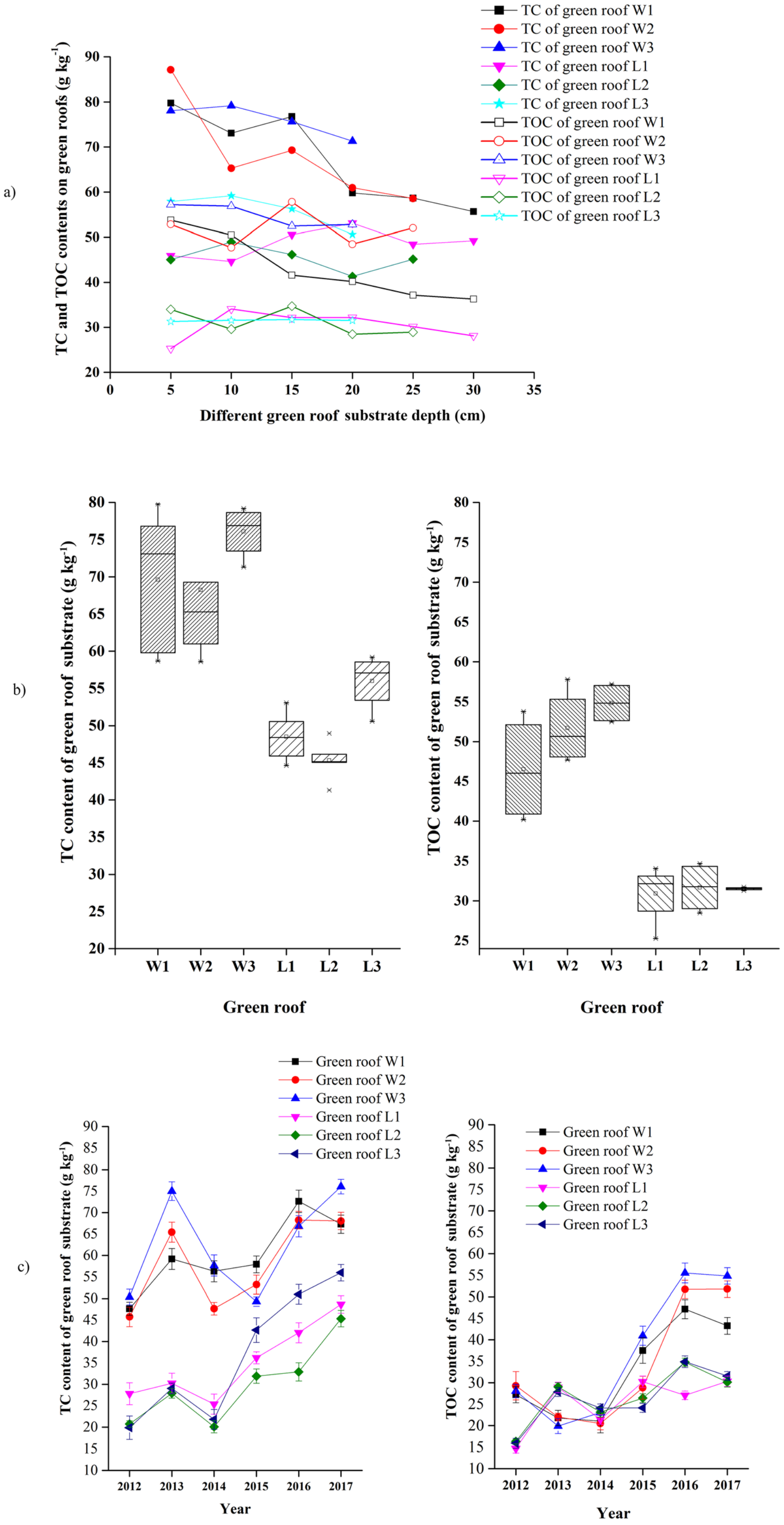
Results

TOC and TC content of substrate in green roof

Figure 2 describes the TOC and TC contents of WBMS and LNS in green roofs. Figure 2 a shows annual content of TOC and TC at every 5 cm depth of green roof substrates. For the WBMS, TC content of W1, W2, and W3 manifests a decreasing tendency with deeper substrate tendency while TC value (55.7 g kg^{-1}) of W1 was lowest at 30 cm. TOC content of W1 and W3 had a similar trend with corresponding TC content. TC content of W2 was no significant change with deeper substrate depth. The content in WBMS was large discrepancies between TC and TOC. Especially, the average content in WBMS presented as average TC of W1, W2, and W3 was higher than corresponding TOC respectively. For the LNS, TC and TOC content were not significant with deeper substrate depth.

Figure 2 b shows the TOC and TC content ranges of WBMS and LNS substrates in green roofs. The average TC content of L1, L2, L3, W1, W2, and W3 was 48.6, 45.3, 56.0, 67.3, 68.2, and 76.1 g kg^{-1}, respectively. The average TOC content of L1, L2, L3, W1, W2, and W3 was 30.3,

Fig. 2 TC and TOC content in green roofs substrates. **a** TC and TOC contents in different depth from roof substrates from six green roofs; **b** TC and TOC contents ranges of green roof substrates from six green roofs; **c** TC and TOC contents change of green roof substrates of LNS and WBMS in different years



31.1, 31.5, 43.2, 51.8, and 54.8 g kg^{-1} respectively. In addition, percentage of TOC to TC was 70% in LNS and 62% in WBMS. The TC content of the WBMS was 1.41 times higher than that in the LNS.

Figure 2 c presents the TC and TOC contents in WBMS and LNS during five years. Both the WBMS and LNS appeared to be on the rise during the process of green roofs. Results suggest both the WBMS and LNS of TC were at the peak in 2017, respectively, except W1 and W2 (72.6 and 68.2 g kg^{-1}) at 2016. TOC content of WBMS gradually increased after the decrease slightly at 2013 while TOC content of LNS was at a higher value in 2013.

Plant TOC content and green roof biomass

A brief summary of the green roof plant TOC contents and plant biomass in July 2012 is shown in Table 3 and the corresponding situations in July 2017 are shown in Table 4. Dry weight of *N. auriculata*, *L. Vicaryi*, and *L. spicata* increased by 280.6 g, 769.3 g, and 43.3 g in green roof group 1 respectively, and increased by 205.9 g, 846.7 g, and 70.6 g in green roof group 2 respectively. Results indicate that *N. auriculata* and *L. spicata* grew better in LNS, while *L. vicaryi* grew better in WBMS. In addition, TOC content of each plant in aboveground was higher than belowground in both July 2012 and 2017. The TOC contents of green roof group 1 and green roof group 2 in 2012 were closed to the TOC values in 2017.

Weed and litter are indispensable parts of green roof ecosystem. Figure 3 demonstrates the TOC content of green roof litter and weed from green roof group 1 and green roof group 2. The average TOC content of weed in 2017 was higher than in 2012 from both green roof group 1 and green roof group 2. In 2012, the average weed TOC content in green roof group 1 (485.8 g kg^{-1}) was close to average weed TOC content in green roof group 2 (478.7 g kg^{-1}). In 2017, the average TOC content was close between the litter (523.2 g kg^{-1}) and weed (521.8 g kg^{-1}) in green roof group 1.

Performance of carbon sequestration and carbon storage on green roofs

Green roof carbon (GFC) values were summarized including plant carbon (PC), substrate carbon (SC), weed carbon (WC), and litter carbon (LC). Carbon sequestration and carbon storage from July 2012 to July 2017 is shown in Fig. 4. For these two green roofs, the five-year carbon storage was 65.6 kg C m^{-2} of green roof group 1, 72.6 C m^{-2} of green roof 2, respectively. The carbon sequestration performance followed the order of 64.0 kg C m^{-2} (green roof group 2) > 57.1 kg C m^{-2} (green roof group 1). In green roof group 1, plant storage accounted for 84.4%, weeds storage accounted for 4.1%, and substrate storage accounted for 14.6%, respectively. Similarly, in green roof group 2, plant, weeds, and substrate contributed 78.1%, 3.5%, and 21.9% of the total carbon storage, respectively. The carbon storage of substrate, plant, and total green roof in green roof group 2 was 1.7 times, 1.0 times, and 1.1 times greater than the corresponding carbon storage in green roof group 1, respectively. Results indicate that the total GFC storage in green roof group 2 was greater than in green roof group 1. Meantime, it concludes that green roof plant had made great contributions to carbon storage of green roofs.

Discussion

Achievement on carbon storage and sequestration from green roof substrates

In general, the carbon storage ability of WBMS was higher than of LNS in each year (in Fig. 5). Specifically, the average carbon storage ability of LNS was 4.9, 8.9, 7.1, 8.5, 9.9, and

Table 3 Biomass and mean total organic carbon (TOC) of green roof plant in July 2012 and July 2017

Green roofs	Year	Plant	Biomass (g)		TOC (g kg^{-1})	
			Wet weight	Dry weight	Aboveground	Belowground
Green roof group 1	2012	*L. spicata*	26.6	7	349.7	380.5
		N. auriculata	51.4	13.3	356.8	470.6
		L. vicaryi	83.4	28.5	409.3	361.9
	2017	*L. spicata*	141.5	50.30	612.4	625.2
		N. auriculata	340.6	293.90	619.5	642.5
		L. vicaryi	1253.6	797.80	626.5	644.3
Green roof group 2	2012	*L. spicata*	38.2	9.9	502.0	490.4
		N. auriculata	75.1	22.3	543.9	503.7
		L. vicaryi	65.1	30.6	555.4	508.4
	2017	*L. spicata*	91.2	80.56	578.4	586.4
		N. auriculata	382.4	228.20	582.1	607.3
		L. vicaryi	1053.3	877.30	575.2	617.4

Fig. 3 TOC contents of weed and litter of green roofs

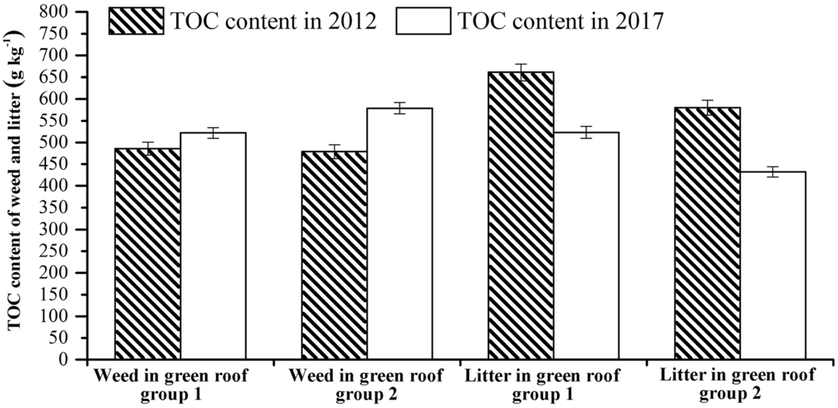
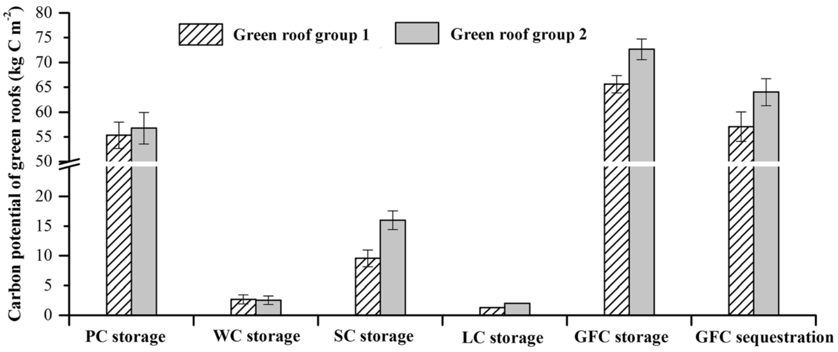


Fig. 3 TOC contents of weed and litter of green roofs.

9.6 kg C m^{-2} in 2012, 2013, 2014, 2015, 2016, and 2017 respectively. There is a relationship between carbon storage and the number of years ($Y_{\text{storage}} = 0.79X + 5.36$, $R^2 = 0.79$). For WBMS, the average carbon storage was 7.5, 9.3, 8.8, 11.5, 16.5, and 16.0 kg C m^{-2} ($Y_{\text{storage}} = 1.91X + 4.92$, $R^2 = 0.87$). The carbon storage of average WBMS was 11.6 kg C m^{-2} while the carbon storage of average LNS was 7.9 kg C m^{-2}. Carbon storage followed the order of W1 (13.4 kg C m^{-2}) > W2 (10.3 kg C m^{-2}) > L1 (9.2 kg C m^{-2}) > W3 (9.1 kg C m^{-2}) > L2 (8.1 kg C m^{-2}) > L3 (6.3 kg C m^{-2}). This result of carbon storage by WBMS was lower than by MSSS (13.1 kg C m^{-2} (Luo et al. 2014)). The carbon storage would present the carbon density of the green roof substrates (WBMS and LNS) in the middle-high level in a world scale, which is still lower than the world average (12.1 kg C m^{-2})(Houghton et al. 2001). However, to date, there have been not many publications about the effect of WBMS as substrates on carbon sequestration and storage by the green roof.

Figure 5 c manifests the substrate carbon sequestration (LNS and WBMS) from 2012 to 2017. Annual mean carbon sequestration performance of the WBMS (2.3 kg C m^{-2} year^{-1}) was 1.8 times higher than LNS. In addition, the carbon sequestration ability was in the order of WBMS > LNS over time. During 2013 to 2014, the mean carbon sequestration of LNS and WBMS was − 1.87 and − 0.59 kg C m^{-2} respectively, which as the carbon source. Analogously, the average carbon sequestration of both LNS and WBMS during 2016 to 2017 performance as the carbon source. The mean carbon sequestration of WBMS (12.8 kg C m^{-2} year^{-1}) was evidently higher than the MSSS (7.03 kg C m^{-2} year^{-1}) in our previous report (Luo et al. 2014). As well as the deeper the depth of substrates, the stronger was the carbon sequestration ability of WBMS. These results can be explained by Durhman (Durhman et al. 2007), who pointed that deeper substrates promote greater survival and growth. Plant growth highly depend on substrate depth which deeper substrates can help plants to gain higher biomass for survive (Benvenuti and Bacci 2010; Eksi et al. 2017). Many researchers found similar results in substrate depth. One report noticed carbon contents are higher in 15–30 cm layer on the bottom than in 0–15 cm layer on the top in rice land (Ratnayake et al. 2017). The growth of green roof was more successfully obtain at a deeper substrate thickness, which deeper substrate improved fewer temperature fluctuations, the protection from digging by animals, and moisture retention (Nagase and Dunnett 2013). Ondoño tested two substrates with two depths (5 and 10 cm) and found that the aboveground biomass at 10 cm was also higher than at 5 cm (Ondoño et al. 2016a). Several previous studies have evaluated the carbon sequestration ability of green roof substrates (Getter et al. 2009b). In addition, the potential of carbon sequestration from reclaimed lands can gain a maximum of

Fig. 4 Carbon storage and sequestration of green roofs in 2017



(PC - plant carbon; WC - weeds carbon; LC - litter carbon; SC - substrate carbon; GFC - green roof carbon)

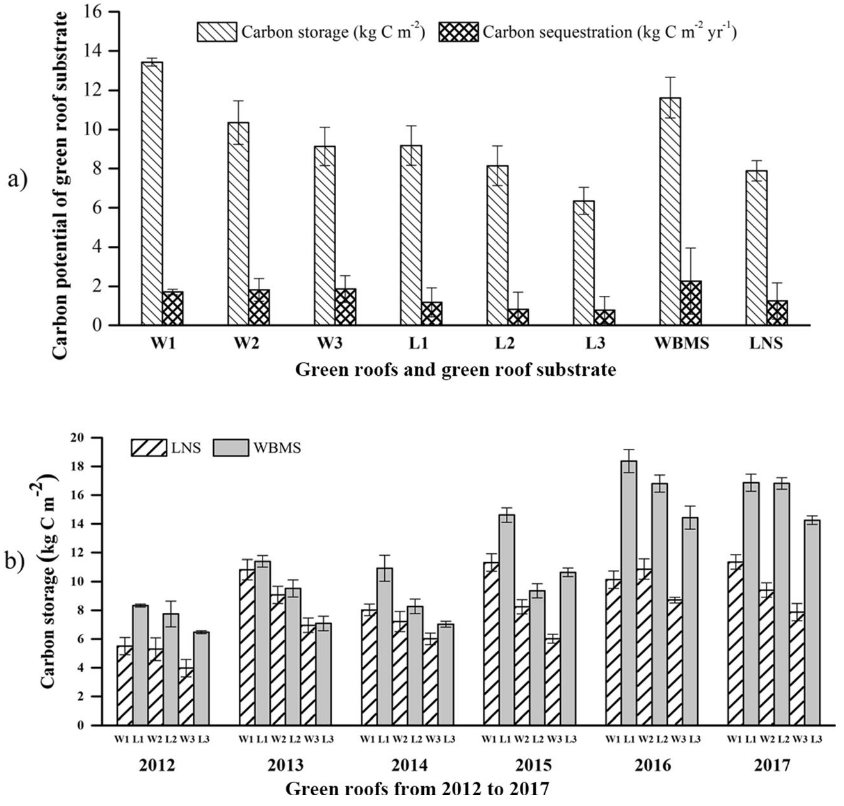


Fig. 5 Carbon storage and sequestration performance in green substrate

5.80 kg C m^{-2} when flooded land is come from dry land by vegetable-rice cropping (Deng et al. 2016).

The change of carbon storage and carbon sequestration ability is shown in Fig. 5b and Fig. 5c. Substrate carbon storage gradually increased from 2012 to 2017 (Fig. 5b). It has demonstrated differences between carbon storage and sequestration ability of two kinds of substrates (WBMS and LNS). A reason can explain this trend is plants affect the distribution of soil carbon. Under natural conditions, plant types and the biomass determine the amount of plant residues in the soil (Eswaran et al. 1993). The different the way into the substrate, the different the amount of organic matter with plants types or the biomass. Moreover, small changes in substrate pH, MC, and depth can also significantly affect carbon emissions by affecting microbial activity to make the decomposition rate of organic carbon different (Wang et al. 1993). In summary, it can be concluded that the carbon sequestration ability of WBMS is better than LNS in this study. This result may due to the substrate (Table 1) with low dry bulk density, high hydraulic and greater porosity are ideal conditions for plant growth (Mickovski et al. 2013).

Achievement on carbon sequestration and storage of green roof plants

Figure 6 shows the plant carbon sequestration and storage annual variation in green roofs in this study. Figure 6 a manifests the plant carbon storage in green roof group 2 and green roof group 1. The growth of the three plants (*N. auriculata, L. vicaryi*, and *L. spicata*) is generally on the rise from 2012 to 2017 in both green roof group 2 and green roof group 1. This trend shows the carbon storage of plants closely related to biomass (Hieu et al. 2017; Lautenbach et al. 2017). The average carbon storage (9.9 kg C m^{-2}) of *N. auriculata* at green roof group 1 was 1.3 times more than that in green roof group 2 (7.5 kg C m^{-2}). The average carbon storage of *L. vicaryi* (15.6 kg C m^{-2}) and *L. spicata* (4.8 kg C m^{-2}) at green roof group 2 was 1.1 times and 1.2 times higher than that at green roof group 1. This difference determined by specific research areas and specific biological characteristics of plants (Tilman et al. 2001; Means et al. 2016). On the one hand, different plants in the soil directly change the type of ecosystem, thus change the net primary productivity of the ecosystem and the input of the corresponding soil organic carbon (Myneni et al. 1997; Schwartz 1998; Vliet and Schwartz 2002). On the other hand, it potentially changes the physical and chemical properties of the substrates and altering the respiration of soil (Rustad 2001; Wan and Luo 2003; Zhou et al. 2013).

The carbon sequestration of *N. auriculata, L. vicaryi*, and *L. spicata* is shown in Fig. 6b. To sum up, the trend of carbon storage and sequestration remained consistent in the two substrates. The carbon sequestration of the three plants reached its highest value in 2012–

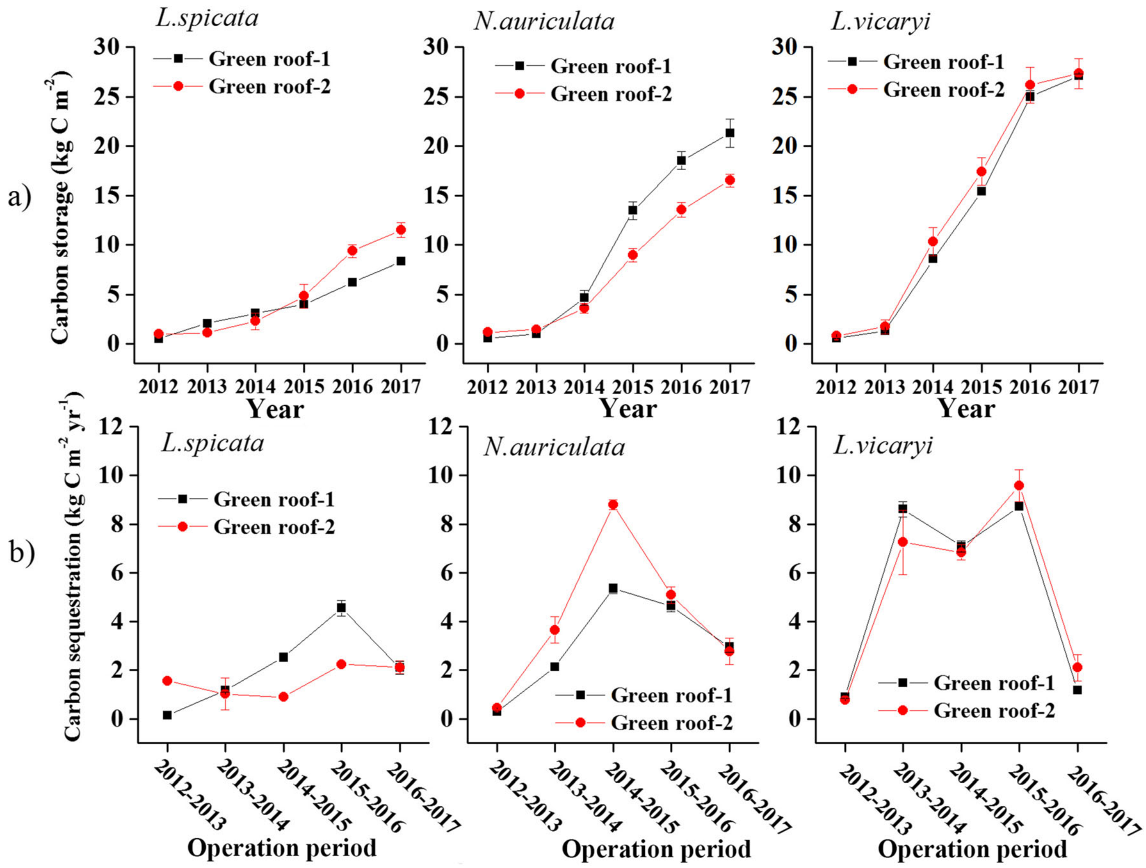


Fig. 6 Carbon storage and sequestration in green plants

2015 while a significant reduction from 2016 to 2017. The research explored in the field of carbon sequestration to date (Getter et al. 2009b) shows different potential of carbon sequestration is associated to the green roof substrate depth and composition, and the plant species (Ondoño et al. 2016a). Carbon sequestration investigation of substrate and plants is interactive (Wei et al. 2010; Macivor et al. 2013) because of plants growth influenced by many environmental factors (Kozar et al. 2002; Cienciala et al. 2016) such as climate, light conditions, substrate conditions, and human activity (Luo et al. 2014; Klimešová et al. 2016; Tao et al. 2017). Changes of climatic characteristics are predicted to induce biomasses changes (Silveira and Thiébaut 2017). Many researchers found out carbon sequestration and the related biomass are influenced by temperature and climate (Beedlow et al. 2004; Heimann and Reichstein 2008; Wamelink et al. 2009). Depth of substrates is an important factor liming the plant growth. There are consistent results that plant growth improves as the increase of substrate depth (Boivin 2001; Durhman et al. 2007; Thuring et al. 2010).

The average carbon sequestration of *N. auriculata, L. vicaryi*, and *L. spicata* was 3.6, 5.3, and 1.8 kg C m^{-2} year^{-1}, respectively. This study result is higher than by Chen that green roofs saved an average of 92.55 g m^{-2} in biomass from 39.47 to 138.41 g C m^{-2} (Chen et al. 2015). Getter conduct an experiment to quantify the carbon storage potential of extensive green roofs in Maryland, ranging from 1st to 6th years in ages. Results showed the average of biomass was 168 g C m^{-2} with a carbon sequestration rate of 100 g C m^{-2} over the 2 years (Getter et al. 2009b). The plants in green roof are most commonly composed by shrubs or small tree species (Chen 2015). The carbon sequestration by the biomass under *L. ovatus* was 1.32 kg C m^{-2} (Ondoño et al. 2016a), which was close to the result about *L. spicata* in this study. The green roof painted with shrubs (69.1 kg C m^{-2}), herbaceous perennials (68.8 kg C m^{-2}), and grasses (67.7 kg C m^{-2}) had higher carbon fixation compared with this study (Whittinghill et al. 2014). Analogously, perennial grasses in sequestering atmospheric CO_2 play a key role (Li et al. 2017). The carbon sequestration by plants in green roof, therefore, is accounted as a middle-high level compared to other researches. In sum, the important finding in this study among three native plants manifests that *L. vicaryi* had the strongest ability of carbon sequestration, adaptive capacity, and carbon storage, than that of *N. auriculata* and *L. spicata*. Therefore, carbon emission from green roofs can be effectively mitigated by recycling waste building-material as green roof substrate during five-year operation.

Ecosystem service by carbon sequestration performance of green roofs

Green roof carbon sequestration of substrate, plant, weeds, and litter together on the six green roofs was assessed overall the performance ability of carbon sequestration. Results show that the highest configuration of green roof by the carbon sequestration level could be determined as combining the WBMS and the *L. vicaryi* planted. In this study, the carbon storage of green roofs was in a middle level through a world scale, and the carbon sequestration was located in a high level compared to other green roofs but a middle level in comparison to other ecosystems through a world scale. Previous researchers investigated the different regions and ecosystems in the world. The greatest potential of carbon sequestration was gained by the CsS mixture, reaching 1.06 kg TC m^{-2} of green roof substrate (Ondoño et al. 2016b). Total phytolith C sequestration in global terrestrial biomes is 156.7 ± 91.6 Tg C $year^{-1}$ (Craft et al. 2017). Therefore, it concludes that carbon sequestration in this study was in an upper level compared with green roofs to date.

The assumed calculation conditions on carbon sequestration of green roofs in Chengdu City for the ecosystem service in this study are (1) the average substrate depth of green roofs is 25 cm deep. (2) The average greening area of roof is 50%, and (3) suggested scaling-up of green roof configuration is the WBMS and *L. vicaryi* with carbon sequestration of 12.8 kg C m^{-2} $year^{-1}$ from this study.

The calculated results of carbon sequestration are 2.16×10^8 kg C $year^{-1}$ in Chengdu City, which is equal to 7.95×10^8 kg C $year^{-1}$of reduced CO_2 emissions and is also equal to remove more than 39,304 midsized trucks or SUV off the road for a year. Further, this benefit would be about 2.24×10^6 m^3 waste building material (equal 2.46×10^6 Tons) for the recycling waste building material in the Chengdu City. Therefore, these calculated results should be modified to correction based on real green roof application engineering and local climate, and is evidently significant potential for sequestering carbon in urban ecosystem service of Chengdu City.

As so far, there is only less report on the carbon sequestration or carbon saving by green roof in urban ecosystem service. Another result is 7.03 kg C m^{-2} $year^{-1}$ by reusing green roof configuration combined plant of *L. vicaryi* and substrate of sewage sludge in our previous report (Luo et al. 2014). The carbon sequestration on sedum is 1.187 kg C m^{-2} $year^{-1}$ on extensive green roof (Getter et al. 2009b). It is reported that the soil or substrate of carbon sequestration is 3.11 kg C m^{-2} of native prairie mix, 3.27 kg C m^{-2} of grasses and Herbaceous perennials, and 9.82 kg C m^{-2} of vegetable and herb garden, respectively (Whittinghill et al. 2014). A comparative case study was reported from three pioneering Scandinavian companies that produce building materials with secondary material (certainly degree, as waste building material compare to this study) input to asses potential of carbon savings under three strategies (Nußholz et al. 2019). Carbon sequestration, also as carbon saving potential, depends on which of waste material possibly coming from the secondary materials can replace the primary material production accounting on the harmful processes by indirect consequences at different industry level. In future, green roof processes and markets possibly based on life cycle assessment (LCA) must be carefully determined at green roof product and urban industry level to guarantee actual carbon savings or carbon sequestration for urban ecosystem service, especially if the support of chosen urban regulations is from policy initiatives.

Conclusions

The hypothesis in this study is whether carbon emission from green roofs can be effectively mitigated by recycling waste building material as green roof substrate. The results of this hypothesis are effectively mitigate carbon emission on green roofs by using WBMS in five years. After 5 years' performance of green roof operations for urban ecosystem service, the two substrate (WBMS and LNS) with 20 cm, 25 cm, and 30 cm depth on the two green roofs (divided into six equal volume part: green roof L1, L2, L3, W1, W2, and W3) were potential candidates as green roof substrates with a strong ability for carbon sequestration. Carbon storage of green roof group 1 was 65.6 kg C m^{-2} and green roof group 2 was 72.6 C m^{-2}. As green roof substrate, annual mean carbon sequestration performance of the WBMS was 1.8 times higher than the LNS. The carbon sequestration of green roof group 2 using WBMS substrate and three native plant was higher than green roof group 1 using LNS substrate and three native plant. The results of the three native plants in this study manifest that *L. vicaryi* had the strongest ability for carbon storage, carbon sequestration, and adaptive capacity. The overall average carbon sequestration in green roof group 2 (12.8 kg C m^{-2} $year^{-1}$) was 1.1 times than corresponding in green roof group 1 (11.4 kg C m^{-2} $year^{-1}$). The most adaptable green roof configuration can be determined to consider both the WBMS and *L. vicaryi*. Therefore, carbon sequestration of WBMS with waste building material reutilization can be considered to assess the improvement of urban ecosystem service by green roofs for green building. The limitation of this study is not to monitor the microbial in green roof substrate and the photosynthesis of green roof plant, and is not to investigate the environmental impact on the WBMS. Future work may focus on the GF carbon model, water interface, long-term monitoring, environmental impact, water quality and quantity, synthesized effect on GF ecosystem, low impact development (LID), management and simulation, and combination on intelligent urban system, based on LCA. Green roofs are promising application engineering as a carbon sequestration service for urban ecosystem service to mitigate the climate change.

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