Article

CO₂ Payoff of Extensive Green Roofs with Different Vegetation Species

Takanori Kuronuma ¹, Hitoshi Watanabe ^{1,*}, Tatsuaki Ishihara ², Daitoku Kou ², Kazunari Touda ², Masaya Ando ¹ and Satoshi Shindo ¹

¹ Center for Environment, Health and Field Sciences, Chiba University, 6-2-1 Kashiwa-no-ha, Kashiwa, Chiba 277-0882, Japan; t.kuronuma@chiba-u.jp (T.K.); m-ando@chiba-u.jp (M.A.); shindo@faculty.chiba-u.jp (S.S.)

² Kyodo KY-Tec Corporation, 1-15-1, Ebisu-minami, Shibuya-ku, Tokyo 150-0022, Japan; ishikawa@ky-tec.co.jp (T.I.); kou@ky-tec.co.jp (D.K.); touda@ky-tec.co.jp (K.T.)

* Correspondence: hwatanabe@faculty.chiba-u.jp; Tel.: +81-47-137-8106

Received: 6 June 2018; Accepted: 27 June 2018; Published: 30 June 2018

Abstract: Green roofs are considered effective in the reduction of atmospheric CO₂ because of their ability to reduce energy consumption of buildings and sequester carbon in plants and substrates. However, green roof system components (substrate, water proofing membrane, etc.) may cause CO₂ emissions during their life cycle. Therefore, to assess the CO₂-payoff for extensive green roofs, we calculated CO₂ payback time it takes their CO₂ sequestration and reduction to offset the CO₂ emitted during its production process and maintenance practices. The amount of CO₂ emitted during the production of a modular green roof system was found to be 25.2 kg-CO₂·m⁻². The annual CO₂ emission from the maintenance of green roofs was 0.33 kg-CO₂·m⁻²·yr⁻¹. Annual CO₂ sequestration by three grass species with irrigation treatment was about 2.5 kg-CO₂·m⁻²·yr⁻¹, which was higher than that of *Sedum aizoon*. In the hypothetical green roofs, annual CO₂ reduction due to saved energy was between 1.703 and 1.889 kg-CO₂·m⁻²·yr⁻¹. From these results, we concluded that the CO₂ payback time of the extensive green roofs was between 5.8 and 15.9 years, which indicates that extensive green roofs contribute to CO₂ reduction within their lifespan.

Keywords: building energy savings; CO₂ emission; CO₂ payback time; CO₂ sequestration; extensive green roof; inventory analysis

1. Introduction

Global warming caused by the increase of greenhouse gases in the atmosphere has been identified as one of the most important environmental issues currently faced by human civilization. Carbon dioxide (CO₂) is known to be a primary anthropogenic greenhouse gas. In urban areas, according to the Intergovernmental Panel on Climate Change [1], climate change is projected to increase environmental risks for people, assets, economies and ecosystems, including risks from heat stress, storms and extreme precipitation, inland and coastal flooding, landslides, air pollution, drought, water scarcity, sea level rise and storm surges. Increasing urban greenspaces is one proposed method of mitigating these problems through urban planning [2–6].

Greenspace in urban areas reduces atmospheric CO₂ through sequestration, shading and evapotranspiration. Shading and evapotranspiration reduce atmospheric CO₂ indirectly by reducing the necessity for air conditioning [7–11], which decreases CO₂ emissions from electric power generation. CO₂ sequestration is the direct removal of CO₂ from the atmosphere through photosynthesis and the fixation of carbon in plant litter and root exudates. The capacity of urban greenspaces (urban

forests, parks, trees, etc.) to sequester CO₂ in plants and soils has already been quantified [12–16], demonstrating that an ecosystem can serve as a carbon sink over a sufficient time period.

However, urban areas are covered mainly by impervious surfaces (e.g., streets, parking lots and buildings), which makes it difficult to plant trees and increase urban greenspace. Accordingly, a green roof, which replaces an impervious surface with greenspace, is a key solution to this problem. The total area of green roofs in Japan actually increased about 29-fold between 2000 (135,222 m²) and 2013 (3,875,716 m²). Green roofs also contribute to atmospheric CO₂ reduction through their reduction energy consumption of buildings and sequestration of carbon in plants and substrates. The energy saving potential of green roofs has been widely investigated [17–23] and Sailor and Bass [24] developed a web tool—the Green Roof Energy Calculator—to readily estimate the annual energy savings for a building with a green roof. By contrast, although Getter et al. [25] and Whittinghill et al. [26] measured the capacity of green roofs to sequester carbon in plants and substrates, efforts to quantify carbon sequestration in green roofs have been limited.

A green roof can be classified as extensive or intensive. The extensive type is characterized by a shallow substrate (<20 cm deep) and requires little maintenance. In contrast, the substrate depth of an intensive green roofs is greater than 20 cm and can support the growth of woody plants. However, an intensive green roof requires careful maintenance and is costly. Because of these reasons, the extensive green roof is currently more common. In particular, modular extensive green roof systems are used exclusively in Japan. They are designed for ease of installation and alteration and generally consist of vegetation mats, substrate, substrate containers, water reservoir trays, water proofing membrane, edge dividers and an irrigation system.

These green roof system components have potential environmental impacts throughout their life cycles (raw material extraction, manufacture, distribution, use, repair and maintenance and disposal or recycling). Several studies have used the life cycle assessment (LCA) methodology to determine the environmental impacts of green roofs [27–29]. These studies compared the environmental load and benefits of green roofs and assessed their overall environmental impacts. In particular, a study by Bianchini and Hewage [30] indicated that the annual air pollution (NO₂, SO₂ and O₃) reduction from a green roof will offset the emissions associated with its production after 13 to 32 years. The study calculated the amount of air pollution created by the production of the polymers of a typical green roof system and compared their results with its pollution removal capacity [31]. However, there have been few studies on the CO₂ payoff of modular green roofs and the carbon balance of a modular green roof system—that is, whether it acts as a sink or a source—is therefore open to debate.

In studies estimating the emissions reduction potential of power plants utilizing renewable energy, CO₂ payoff is often defined as the CO₂ payback time [32–34]. This index is calculated as the ratio of the CO₂ emissions from the production of each power plant to the annual CO₂ reduction resulting from the generation of electricity from renewables.

In this study, therefore, we used LCA methodology to calculate the CO₂ emissions from the production process and maintenance practices of a modular green roof and investigated the annual CO₂ sequestration by several green roof plants (Figure 1). In addition, we estimated the amount of energy saved of buildings with green roofs using the Green Roof Energy Calculator. We used these parameters to assess the CO₂-payoff for modular green roofs by calculating their CO₂ payback time. We defined the CO₂ payback time of a green roof system as the time it takes total CO₂ reduction by the system to offset the CO₂ emitted during its production and maintenance.

CO ₂ emissions from a modular green roof	CO ₂ reductions of green roof
<u>Research boundary in this study</u> • Production process for the green roof system components • Maintenance practices (annually) → Calculations using a LCA software	• CO₂ sequestration (annually) → Experiments for four plants. • Building energy saving (annually) → Estimation using the Green Roof Energy Calculator [24]

Figure 1. A schematic drawing of the investigation scope in this study to estimate the CO₂ payback time of a modular green roof.

2. Materials and Methods

In order to estimate CO₂ emissions and energy savings from a modular green roof, we set a hypothetical average for green roofs in Japan to a greening area of 200 m² and a substrate depth of 5 cm. We conducted partial LCA for the hypothetical green roofs. The functional unit studied was 1 m² of the modular green roof with a service lifetime of 45 years on a flat concrete roof. We therefore converted our results for CO₂ emissions and reductions into values per m².

2.1. CO₂ Emission from a Modular Green Roof

2.1.1. Definition of Goal and Scope

In this section, we calculated the CO₂ emitted during the production and maintenance of a typical modular green roof.

We defined the system boundaries as the production processes for the system components (substrate, substrate containers, water reservoir trays, water proofing membrane, edge dividers, irrigation tubes, irrigation pipes and automatic watering device) and the maintenance practices (irrigation and fertilization) of a modular green roof system. The life cycle system included the extraction and refinement of raw materials and the consumption of natural resources. The production process for vegetation mats in a farm and transportation of the components were not taken into account because of a lack of relevant information.

2.1.2. Inventory Analysis

We collected data from companies and experts about the components and maintenance practices of a typical modular green roof system. We calculated the CO₂ emission factors for each component and maintenance practice using the MiLCA LCA software developed by the Japan Environmental Management Association for Industry. We used inter-industrial relation analysis to calculate the CO₂ emission factors of the irrigation tube and automatic watering device. This analytical method is a form of economic analysis based on the interdependencies between economic and environmental sectors. It enables us to estimate the environmental impacts of products throughout their costs. For all of the other components and maintenance practices, we used a bottom-up approach for building the inventory. We calculated the amount of CO₂ emitted by each component or maintenance practice by multiplying its CO₂ emission factor by the quantity of that component used in the hypothetical green roof.

We set the dimensions of a typical green roof at 12.5 m by 16 m (200 m²) and we calculated the use of each green roof system component in this size. A schematic drawing of a typical modular green roof system (with the irrigation pipes and automatic watering device excluded) is shown in Figure 2. The main raw materials used to produce each component and the quantity of each component used in the hypothetical green roof, are shown in Table 1.

Figure 2. A schematic drawing of a typical modular green roof system that was calculated the CO₂ emissions from the production process in this experiment (with the irrigation pipes and automatic watering device excluded).

Table 1. The main raw material and the quantity of each component used for the hypothetical green roof in production and maintenance practice.

System Components and Maintenance	Main Raw Material	Required (for 200 m ²)
Substrate	Perlite	1572 kg
Substrate container	Polypropylene	800 kg
Water reservoir tray	Polyvinyl chloride	174 kg
Water proofing membrane	Polyvinyl chloride	55 kg
Edge divider	Aluminum	75 kg
Irrigation pipe	Polyvinyl chloride	5 kg
Irrigation tube	Special polyethylene	208 m (142 \$)
Automatic watering device	-	1 machine (231 \$)
Irrigation	Water	161.6 t·year ⁻¹
Fertilizer	Compound fertilizer	8 Kg·year ⁻¹

The substrate contains more than 50% perlite, along with compost and zeolite. We calculated the CO₂ emission factors of each substrate component using MiLCA and weighed their individual content ratios (kg·kg⁻¹). We used the results to calculate a CO₂ emission factor for the substrate.

The substrate containers were made of polypropylene, with numerous small holes for drainage. The substrate containers were 50 cm long by 50 cm wide and 6.5 cm deep. Vegetation mats were planted in the containers after filling with substrate to a depth of 5 cm. Each container was connected to adjoining containers to prevent wind uplift.

Drainage from the containers was collected in the water reservoir trays, which were 50 cm long by 50 cm wide by 1.5 cm deep and made of polyvinyl chloride. Each reservoir tray was also connected to adjoining trays.

The irrigation pipes connected the automatic watering device to the irrigation tubes, which were aligned under every second substrate container (13 lines × 16 m). The irrigation pipe needed to be aligned with the edge of the green roof, so we set the length of the irrigation pipe to 15 m. Irrigation pipe consists mainly of polyvinyl chloride.

The water proofing membrane was also made of polyvinyl chloride and was 0.3 mm thick. This membrane was the final layer of the modular green roof system and served as water proofing and a root barrier. It was intended to protect the building from penetration by water and roots.

The edge dividers were made of aluminum and used for sealing the edge of the green roof (57 m). The edge dividers play a crucial role in locking the green roof components in place and preventing wind uplift.

According to the inter-industry relations analysis implemented in MiLCA, the prices of the irrigation tubes and automatic watering device for the hypothetical green roof were \$142 and \$231, respectively, at an exchange rate of 110 yen to the U.S. dollar.

The use of water and fertilizer during maintenance of the hypothetical green roof are shown in Table 1. According to an interview with a relevant company, a green roof is irrigated 101 times annually, with $8 \text{ L} \cdot \text{m}^{-2}$ of water used for each irrigation. Fertilizer is applied twice annually, with $20 \text{ g} \cdot \text{m}^{-2}$ used each time.

2.2. CO₂ Sequestration by Several Green Roof Plants

In order to quantify CO₂ sequestration in green roofs, we investigated the annual CO₂ sequestration by three grass species—*Cynodon dactylon* Pers., *Festuca arundinacea* Schreb. and *Zoysia matrella* L. “Himekourai-shiba”—and a flowering plant, *Sedum aizoon* L. Grasses and *Sedum* species are the most common green roof vegetation in Japan.

This experiment was conducted at the Center for Environment, Health and Field Sciences at Chiba University over one year. All plants in this experiment were propagated as cuttings in plug flats ($128 \text{ cells} \cdot \text{tray}^{-1}$) filled with seedling propagation soil (Metro Mix; Sun Gro Horticulture, Agawam, USA). After approximately one month, the plugs were planted in 0.2 L polyethylene pots (44 cm^2) filled to a depth of 5 cm with commercial artificial soil for green roofs (the same as the substrate mentioned above) and grown in a greenhouse for two months. They were then placed on the rooftop and acclimated for three weeks. For a more accurate simulation in this experiment, we should have used the same modular green roof system. However, we used polyethylene pots and irrigated by hand sowing because we had to test a number of experimental plants using a limited roof area.

At the start of the experiment, on October 20, 2014, we sampled all species from a total of 15 pots over a period of about 10 days. Green roofs composed of grasses are generally fitted with irrigation systems to prevent drought stress. In contrast, irrigation systems are less common in *Sedum* green roofs because *Sedum* uses the CAM photosynthetic pathway and is thus better adapted to drought conditions. The *S. aizoon* pots were therefore assigned randomly to irrigation and non-irrigation treatments after the first sampling. Plants in the irrigation treatment group were watered once a week from January to March, once every two days from April to June, every day from July to September and once every two days from October to December. The non-irrigation treatment group was never irrigated. The three grass species received only the irrigation treatment, in keeping with general cultivation practice. All treatments received about $20 \text{ g} \cdot \text{m}^{-2}$ ($0.1 \text{ g} \cdot \text{pot}^{-1}$) of controlled-release fertilizer (8N-8P-8K) on June 13 and August 13, 2015. As the end of the experiment, on 20 October 2015, we harvested 15 pots, including all species and treatments.

All plants were dried at 70°C for 72 h and then divided into plant and substrate matter. Plant and substrate carbon concentrations were measured using an organic elemental analyzer (2400 Series II CHNS/O System; PerkinElmer, Waltham, MA, USA). Carbon content was quantified by multiplying carbon concentration by the dry weight. Annual CO₂ sequestration was calculated by subtracting the total carbon content in October 2014 from the total carbon content in October 2015.

In order to calculate the leaf area index (LAI) of the four species in summer, 15 pots, including all species and treatments, were sampled on August 20, 2015 and divided into leaves and non-leaf parts. Leaves were scanned (LP-A500; EPSON, Nagano, Japan) and image analysis software was used to measure the leaf area (ImageJ [35]). The LAI was calculated as leaf area per 44 cm^2 (the area of each polyethylene pot).

Data were analyzed using IBM SPSS Statistics version 22.0 (IBM Japan, Tokyo, Japan). Differences in mean values were assessed with a Student's *t*-test.

2.3. Estimation of the Energy Savings Amount

We used the Green Roof Energy Calculator to estimate the energy saved by a building covered with the hypothetical green roof (200 m^2 greening area of rooftop, 5 cm substrate depth). This web tool was developed from the Energyplus-based green roof model [24] and requests the following information: state and city, surface area of the roof, building type (old or new, office or apartment), substrate depth (limited to $5 \text{ cm} < \text{depth} < 30 \text{ cm}$), leaf area index (limited to $0.5 < \text{LAI} < 5$), irrigation flag (yes or

no), percentage of roof covered by the green roof system and roofing type for the non-green roof area [black (albedo: 0.15) or white (albedo: 0.65)]. Because this tool requires LAI values, we ran separate simulations for the *C. dactylon*, *F. arundinacea*, *Z. matrella* and *S. aizoon* green roofs, as was done in the CO₂ sequestration experiment. The growing media characteristics for all green roof simulations were set as follows: thermal conductivity 0.35 W·mK⁻¹, density 1100 kg·m⁻³, specific heat 1200 J·kgK⁻¹, saturation volumetric moisture 0.3, residual volumetric moisture 0.01, initial volumetric moisture 0.1. See the article for further details of GREC [24].

The location was entered as Houston, Texas, because the meteorological conditions in that city resemble those in Tokyo, Japan. The percentage of roof covered by the green roof system was set at 50%, which set the surface area of the roof at 400 m². In Japan, about 90% of green roofs are located on new building, so the building type was set as “new office”. In order to embed the LAI values in summer into this model, the results in August 2015 was added. The irrigation flag was set as “yes” for all simulations, except for that of the non-irrigated *S. aizoon* roof. The roofing type for the non-green roof area was set as “black”.

The reduction in electricity and gas consumption was estimated in kWh and converted to CO₂ emissions reduction (kg-CO₂) using the CO₂ emission factor (0.505 kg-CO₂·kWh⁻¹) obtained from the Ministry of the Environment in Japan.

2.4. CO₂ Payback Time of Modular Green Roofs

In non-irrigated green roof systems (the non-irrigation treatment), CO₂ emitted during the production of the irrigation system (irrigation tubes, irrigation pipes and automatic watering device) and associated with the annual water supply was excluded from the calculation of the total CO₂ emissions from the modular green roof. The amount of annual CO₂ sequestration by the green roof plants may decrease with their age because carbon in plants and soils eventually reaches a carbon equilibrium, with sequestration offset by decomposition [36,37]. Therefore, we calculated the CO₂ payback time based on two different scenarios. In Scenario 1, we hypothesized that the CO₂ sequestration by green roof plants occurs only during the first year after construction. CO₂ payback time for this scenario was defined as

$$\text{CO}_2 \text{ payback time} = (\text{CO}_{2\text{e-p}} - \text{CO}_{2\text{r-s}}) / (\text{CO}_{2\text{r-e}} - \text{CO}_{2\text{e-m}}) \quad (1)$$

In Scenario 2, we hypothesized that the same amount of CO₂ sequestration by the green roof plants occurs every year. CO₂ payback time for this scenario was defined as

$$\text{CO}_2 \text{ payback time} = \text{CO}_{2\text{e-p}} / (\text{CO}_{2\text{r-s}} + \text{CO}_{2\text{r-e}} - \text{CO}_{2\text{e-m}}) \quad (2)$$

where CO_{2e-p} is the amount of CO₂ emitted during the production of the modular green roof system, CO_{2r-s} is the annual CO₂ reduction owing to CO₂ sequestration, CO_{2r-e} is the annual CO₂ reduction owing to energy savings and CO_{2e-m} is the annual CO₂ emission from maintenance of the hypothetical green roof.

3. Results and Discussion

3.1. CO₂ Emissions from a Modular Green Roof

The CO₂ emission factors and total CO₂ emissions from each component are shown in Table 2. The aluminum edge divider had the highest CO₂ emission factor out of all of the components analyzed using a bottom-up approach. The water reservoir tray, water proofing membrane and irrigation pipe had similar CO₂ emission factors because they are all made from the same raw material (Tables 1 and 2).

Aluminum is a lightweight construction material and is therefore suitable for use in green roofs, whose weights are subject to architectural constraints. However, Bribián et al. [38] found that primary

energy demand and global warming potential are higher for aluminum production than for the production of several other common building products. Using materials other than aluminum for edge dividers may therefore decrease the environmental load, including CO₂ emissions, associated with the production of green roof systems.

The amount of CO₂ emitted during the production of substrate was higher than that from any of the other components (Table 2). This was due mainly to the relatively large quantify of substrate used in green roof systems (Table 1). The automatic watering device exhibited the second lowest CO₂ emissions out of all of the components. However, this result is the amount of CO₂ emitted during the production of one machine and, unlike the results for the other components, is independent of the area of the green roof. It is therefore clear that the environmental load per m² of the automatic watering device increases as the green roof area decreases.

The CO₂ emission factors and total CO₂ emissions for each maintenance practice are shown in Table 3. The total annual CO₂ emissions from maintenance practices were 0.33 kg-CO₂·m⁻²·yr⁻¹. The CO₂ emissions from the maintenance of a non-irrigated green roof were generated by fertilizer alone, at 0.04 kg-CO₂·m⁻²·yr⁻¹.

Table 2. CO₂ emission factors and CO₂ emissions for each modular green roof system component in this experiment.

System Components	CO ₂ Emission Factor	CO ₂ Emission (kg-CO ₂ ·200 m ⁻²)	CO ₂ Emission (kg-CO ₂ ·m ⁻²)
Substrate	1.15 kg-CO ₂ ·kg ⁻¹	1809	9.04
Substrate container	1.89 kg-CO ₂ ·kg ⁻¹	1512	7.56
Water reservoir tray	3.70 kg-CO ₂ ·kg ⁻¹	644	3.22
Water proofing membrane	3.29 kg-CO ₂ ·kg ⁻¹	182	0.91
Edge divider	10.26 kg-CO ₂ ·kg ⁻¹	769	3.85
Irrigation pipe	3.56 kg-CO ₂ ·kg ⁻¹	16	0.08
Irrigation tube	0.55 kg-CO ₂ ·\$ ⁻¹	78	0.39
Automatic watering device	0.13 kg-CO ₂ ·\$ ⁻¹	30	0.15
Total	–	5040	25.2

Table 3. CO₂ emission factors and annual CO₂ emissions for each maintenance practice in the hypothetical modular green roof.

Maintenances	CO ₂ Emission Factor	CO ₂ Emission (kg-CO ₂ ·200 m ⁻² ·yr ⁻¹)	CO ₂ Emission (kg-CO ₂ ·m ⁻² ·yr ⁻¹)
Water	0.36 kg-CO ₂ ·t ⁻¹	58.8	0.29
Compound fertilizer	0.90 kg-CO ₂ ·kg ⁻¹	7.2	0.04
Total	–	66.0	0.33

Total CO₂ emissions from the production of a modular green roof were 25.2 kg-CO₂·m⁻² (Table 2). This result is similar to the results of previous research quantifying the amount of CO₂ emitted during the manufacturing phase of layered green roofs [27]. For a green roof without an irrigation system (i.e., a non-irrigated green roof), the total CO₂ emissions from production process were 24.6 kg-CO₂·m⁻².

3.2. CO₂ Sequestration by Several Green Roof Plant

The plant and substrate dry weight, carbon concentration and carbon content of the different plant species, as recorded on 20 October 2014 and 20 October 2015, are shown in Table 4. For all species and treatments, plant dry weight was significantly higher at the end of the experiment than at the start. There were no significant differences in plant carbon content between October 2014 and October 2015,

except for that of *S. aizoon* with irrigation treatment. *F. arundinacea* was the only species for which substrate dry weight at the end of the experiment was significantly different from that at the beginning. The substrate carbon concentration of all species and treatments increased during the experimental period and *C. dactylon* was the only species for which it did not increase significantly. In addition, the plant and substrate carbon contents for all species and treatments increased significantly during the experimental period. These results suggest that some carbon from the plant litter and root exudate was fixed in the substrates.

Table 4. Mean values (n = 15) for plant and substrate dry weight, carbon concentration, carbon content and total annual carbon sequestration by four green roof plants (*C. dactylon*, *F. arundinacea*, *Z. matrella* and *S. aizoon*).

Species and Treatments			Dry Weight (g·pot ⁻¹)		Carbon Concentration (%)		Carbon Content (g·C·pot ⁻¹)		Total Annual Carbon Sequestration (g·C·m ⁻² ·yr ⁻¹)
			Oct-14	Oct-15	Oct-14	Oct-15	Oct-14	Oct-15	
<i>C. dactylon</i>	irrigation	plant	0.4 ± 0.0 ^z	7.0 ± 0.4*	39.2 ± 0.3	40.7 ± 0.4	0.1 ± 0.0	2.9 ± 0.2*	690
		substrate	30.7 ± 0.7	32.4 ± 0.7	5.1 ± 0.3	5.9 ± 0.2	1.6 ± 0.1	1.9 ± 0.1*	
<i>F. arundinacea</i>	irrigation	plant	0.4 ± 0.0	7.2 ± 0.3*	38.5 ± 0.2	36.3 ± 0.5	0.1 ± 0.0	2.6 ± 0.1*	751
		substrate	30.0 ± 0.3	33.6 ± 0.6*	5.7 ± 0.1	7.6 ± 0.3*	1.7 ± 0.0	2.5 ± 0.1*	
<i>Z. matrella</i>	irrigation	plant	0.6 ± 0.0	6.6 ± 0.4*	42.7 ± 0.2	43.2 ± 0.5	0.2 ± 0.0	2.9 ± 0.2*	671
		substrate	30.8 ± 1.3	31.8 ± 2.5	6.2 ± 0.2	7.0 ± 0.2*	1.9 ± 0.1	2.2 ± 0.1*	
<i>S. aizoon</i>	irrigation	plant	0.6 ± 0.0	3.9 ± 0.2*	38.9 ± 0.5	41.5 ± 0.3*	0.2 ± 0.0	1.6 ± 0.1*	459
		substrate	30.7 ± 0.4	30.9 ± 0.5	5.5 ± 0.2	7.6 ± 0.2*	1.7 ± 0.0	2.3 ± 0.0*	
	non	plant	0.6 ± 0.0	3.1 ± 0.1*	38.9 ± 0.5	38.5 ± 0.2	0.2 ± 0.0	1.2 ± 0.0*	336
		substrate	30.7 ± 0.4	30.5 ± 0.3	5.5 ± 0.2	6.9 ± 0.3*	1.7 ± 0.0	2.1 ± 0.0*	

^z Represent means ± SE. * represent significant differences between the results of October 2014 and October 2015 (Student's *t*-test, *P* < 0.05).

The total annual carbon sequestration by *F. arundinacea* was higher than that of any other species and was similar to those of the other grasses (Table 4). *S. aizoon* exhibited higher total annual carbon sequestration with irrigation treatment than with non-irrigation treatment. The results for *S. aizoon* were similar to results from previous research investigating *Sedum* green roofs [25]. With the assumption that carbon sequestration resulted only from CO₂ uptake, total annual carbon sequestration was converted to annual CO₂ sequestration. *C. dactylon* sequestered 2.530 kg-CO₂·m⁻²·yr⁻¹, *F. arundinacea* sequestered 2.754 kg-CO₂·m⁻²·yr⁻¹, *Z. matrella* sequestered 2.459 kg-CO₂·m⁻²·yr⁻¹, *S. aizoon* with irrigation treatment sequestered 1.684 kg-CO₂·m⁻²·yr⁻¹ and *S. aizoon* with non-irrigation treatment sequestered 1.232 kg-CO₂·m⁻²·yr⁻¹. This experiment thus supports the CO₂ sequestration capacity of several green roof plants.

Kuronuma and Watanabe [39] suggested that competence for carbon sequestration of *Sedum* under wet and increased nutrient conditions are equivalent to those of other green roof plants (*Zoysia matrella* and *Ophiopogon japonicus*). However, it was disaccorded with the present results. This is probably because the present experiment conditions keeping with general cultivation practice was nutrient-poor for *Sedum* species. From this reason, it is suggested that carbon sequestration of *Sedum aizoon* was lower than those of the grasses. For the carbon sequestration of green roofs, therefore, more suitable design and maintenance practice of vegetation should be studied further.

The LAI of each specie and treatment, as recorded in August 2015, is shown in Table 5. *S. aizoon* with irrigation treatment exhibited the highest LAI out of all of the species and treatments and *C. dactylon* exhibited the lowest.

3.3. Estimation of the Energy Savings Amount

The annual energy savings from the hypothetical green roofs are shown in Table 5. Of the irrigated green roofs (with irrigation treatment), the annual energy saving from the *S. aizoon* green roof was the highest because the LAI of *S. aizoon* was higher than that of the three grass species. In contrast, although *S. aizoon* with non-irrigation treatment exhibited the median LAI of all species and treatments, its annual energy saving was the lowest because its irrigation flag was set as “no”. However, annual energy savings did not differ much between species and treatments and annual CO₂ reductions due to

energy savings were between 1.703 and 1.889 kg-CO₂·m⁻²·yr⁻¹ (Table 5), being similar to those in previous research [22].

Table 5. Mean values (n = 15) for leaf area index (LAI), energy saved annually and annual CO₂ reduction due to saved energy of modular green roofs with different species (*C. dactylon*, *F. arundinacea*, *Z. matrella* and *S. aizoon*) and treatments (irrigation and non-irrigation).

Species	Treatments	LAI (m ² ·m ⁻²)	Energy Saved Annually (kWh·200 m ⁻² ·yr ⁻¹)	Annual CO ₂ Reduction (kg-CO ₂ ·m ⁻² ·yr ⁻¹)
<i>C. dactylon</i>	irrigation	2.21 ± 0.16	696.4	1.758
<i>F. arundinacea</i>	irrigation	3.68 ± 0.21	747.1	1.886
<i>Z. matrella</i>	irrigation	2.45 ± 0.17	713.5	1.802
<i>S. aizoon</i>	irrigation	3.71 ± 0.15	748.2	1.889
	non	3.07 ± 0.19	674.3	1.703

3.4. CO₂ Payback Time of Modular Green Roofs

The CO₂ payback time calculated from the Scenario 1, which hypothesized the CO₂ sequestration by the green roof plants occurs only first year after construction, was in the range of 14.0 to 15.9 years (Table 6). On the other hand, Scenario 2 was hypothesized that the same amount of annual CO₂ sequestration by the green roof plants occur every year. Thus, the CO₂ payback time calculated from the Scenario 2 was in the range of 5.8 to 8.5 years and shorter than that calculated from the Scenario 1. For the *S. aizoon* green roofs, the amount of CO₂ emitted during the production of a non-irrigated green roof was lower than that from an irrigated green roof. Therefore, the CO₂ payback time calculated from Scenario 1 was longer for the irrigated green roof than for the non-irrigated green roof. However, the CO₂ payback time calculated from Scenario 2 was longer for a non-irrigated green roof than for an irrigated one because the increase through in CO₂ reduction from irrigation is greater than the amount of CO₂ emitted by the addition of an irrigation system and annual water supply (Tables 4 and 6). However, these results indicate that there were not significant differences among the CO₂ payback time of modular green roofs with different species and treatments in this experiment. Our results for the hypothetical green roofs indicate that CO₂ reduction from the combination of CO₂ sequestration and energy savings by a green roof can offset the CO₂ emitted during its production and maintenance after 5.8 to 15.9 years (Table 6). The lifespans of green roof components are generally thought to be between 40 and 50 years [28–30,40], so it is clear that the lifetime CO₂ reduction of modular green roofs offsets the CO₂ emitted during their production and maintenance. Accordingly, our results suggest that modular green roofs are an effective way to reduce atmospheric CO₂ and mitigate global warming. In addition, Tripanagnostopoulos et al. [34] clarified CO₂ payback time of solar photovoltaic systems which is between 1.3 and 4.1 years. Thus, CO₂ payback time will be one of the index which could compare the carbon balance of green roofs with that of rooftop solar photovoltaic systems [41].

In this study, we focused on the production processes and maintenance practices for green roofs. However, CO₂ sequestration in plants and substrates seems to be greatly influenced by their disposal phase. In addition, the period for which green roofs serve as carbon sinks may be shorter than those of other urban greenspaces (e.g., urban forests, parks and trees) because of the more frequent repair and demolition of buildings. Therefore, the disposal phase also needs to be discussed to ensure the sustainable design of green roofs although the CO₂ payback time calculated from energy savings alone was shorter than the system component's lifespan (17.6 years for *C. dactylon*, 16.2 years for *F. arundinacea*, 17.1 years for *Z. matrella*, 16.2 years for *S. aizoon* with irrigation treatment and 14.7 years for *S. aizoon* with non-irrigation treatment).

This study did not cover all green roof types (e.g., different green roof systems, system components, vegetation plants, substrate depth and locations) that could influence the CO₂ payback time results. Thus, the CO₂ emissions from a green roof and CO₂ reductions from secondly environmental benefits

should be studied further. Our results will serve as a baseline for future research on the CO₂ payoff of green roofs.

Table 6. CO₂ payback time of modular green roofs with different species (*C. dactylon*, *F. arundinacea*, *Z. matrella* and *S. aizoon*) and treatments (irrigation and non-irrigation).

Species	Treatments	CO ₂ Payback Time (years)	
		Scenario 1	Scenario 2
<i>C. dactylon</i>	irrigation	15.9	6.4
<i>F. arundinacea</i>	irrigation	14.4	5.8
<i>Z. matrella</i>	irrigation	15.5	6.4
<i>S. aizoon</i>	irrigation	15.1	7.8
	non	14.0	8.5
Means $\pm$ SE		11 $\pm$ 4.3	
Standard uncertainty		1.4	

Note: Scenario 1 was hypothesized that the CO₂ sequestration by the green roof plants occurs only in the first year following construction. Scenario 2 was hypothesized that the same amount of annual of CO₂ sequestration by the green roof plants occurs every year.

4. Conclusions

This study quantified the CO₂ emitted during the production and maintenance of a hypothetical modular green roof and estimated the CO₂ reduction from energy savings and CO₂ sequestration. The results of the study show that CO₂ emissions are offset through CO₂ sequestration and energy savings after 5.8 to 15.9 years, which indicates that extensive modular green roofs contribute to atmospheric CO₂ reduction and global warming mitigation within their lifespan. In addition, this study provided a method to assess the CO₂ payoff of green roofs. It is hoped that the findings presented in this paper will contribute to the development and design of green roofs more suitable for CO₂ reduction and global warming mitigation.

Author Contributions: All of the authors contributed to the work in the paper. T.K. designed the research and wrote the paper. H.W., M.A. and S.S. provided advice and suggestions. I.T., D.K. and K.T. collected the data. H.W. contributed to project supervision. All authors reviewed the manuscript.

Funding: This research was funded by [JSPS KAKENHI] grant numbers [15K07663].

Conflicts of Interest: The authors declare no conflict of interest.

References

- Intergovernmental Panel on Climate Change. *Climate Change 2014: Synthesis Report: Summary for Policymakers*; IPCC: Geneva, Switzerland, 2014. Available online: http://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf (accessed on 29 June 2018).
- Bowler, D.E.; Buyung-Ali, L.; Knight, T.M.; Pullin, A.S. Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landsc. Urban Plan.* **2010**, *97*, 147–155. [CrossRef]
- Gill, S.E.; Handley, J.F.; Ennos, A.R.; Pauleit, S. Adapting cities for climate change: The role of the green infrastructure. *Built Environ.* **2007**, *33*, 115–133. [CrossRef]
- James, P.; Tzoulas, K.; Adams, M.D.; Barber, A.; Box, J.; Breuste, J.; Elmqvist, T.; Frith, M.; Gordon, C.; Greening, K.L.; et al. Towards an integrated understanding of green space in the European built environment. *Urban For. Urban Green.* **2009**, *8*, 65–75. [CrossRef]
- Jo, H.K. Impacts of urban greenspace on offsetting carbon emissions for middle Korea. *J. Environ. Manag.* **2002**, *64*, 115–126. [CrossRef]
- Li, F.; Wang, R.; Paulussen, J.; Liu, X. Comprehensive concept planning of urban greening based on ecological principles: a case study in Beijing, China. *Landsc. Urban Plan.* **2005**, *72*, 325–336. [CrossRef]

7. Ca, V.T.; Asaeda, T.; Abu, E.M. Reductions in air conditioning energy caused by a nearby park. *Energy Build.* **1998**, *29*, 83–92. [[CrossRef](#)]
8. Georgi, N.J.; Zafiriadis, K. The impact of park trees on microclimate in urban areas. *Urban Ecosyst.* **2006**, *9*, 195–209. [[CrossRef](#)]
9. Kjelgren, R.; Montague, T. Urban tree transpiration over turf and asphalt surfaces. *Atmos. Environ.* **1998**, *32*, 35–41. [[CrossRef](#)]
10. Simpson, J.R. Improved estimates of tree-shade effects on residential energy use. *Energy Build.* **2002**, *34*, 1067–1076. [[CrossRef](#)]
11. Soares, A.L.; Rego, F.C.; McPherson, E.G.; Simpson, J.R.; Peper, P.J.; Xiao, Q. Benefits and costs of street trees in Lisbon, Portugal. *Urban For. Urban Green.* **2011**, *10*, 69–78. [[CrossRef](#)]
12. Golubiewski, N.E. Urbanization increases grassland carbon pools: Effects of landscaping in Colorado's front range. *Ecol. Appl.* **2006**, *16*, 555–571. [[CrossRef](#)]
13. Gratani, L.; Varone, L. Carbon sequestration by *Quercus ilex* L. and *Quercus pubescens* Willd. and their contribution to decreasing air temperature in Rome. *Urban Ecosyst.* **2006**, *9*, 27–37. [[CrossRef](#)]
14. Liu, C.; Li, X. Carbon storage and sequestration by urban forests in Shenyang, China. *Urban For. Urban Green.* **2012**, *11*, 121–128. [[CrossRef](#)]
15. Nowak, D.J.; Crane, D.E. Carbon storage and sequestration by urban trees in the USA. *Environ. Pollut.* **2002**, *116*, 381–389. [[CrossRef](#)]
16. Stoffberg, G.H.; Van Rooyen, M.W.; Van der Linde, M.J.; Groeneveld, H.T. Carbon sequestration estimates of indigenous street trees in the City of Tshwane, South Africa. *Urban For. Urban Green.* **2010**, *9*, 9–14. [[CrossRef](#)]
17. Castleton, H.F.; Stovin, V.; Beck, S.B.M.; Davison, J.B. Green roofs; building energy savings and the potential for retrofit. *Energy Build.* **2010**, *42*, 1582–1591. [[CrossRef](#)]
18. Gagliano, A.; Detommaso, M.; Nocera, F.; Berardi, U. The adoption of green roofs for the retrofitting of existing buildings in the Mediterranean climate. *Int. J. Sustain. Build. Technol. Urban Dev.* **2016**, *7*, 116–129. [[CrossRef](#)]
19. Gagliano, A.; Detommaso, M.; Nocera, F.; Patania, F.; Aneli, S. The retrofit of existing buildings through the exploitation of the green roofs—A simulation study. *Energy Procedia* **2014**, *62*, 52–61. [[CrossRef](#)]
20. Lazzarin, R.M.; Castellotti, F.; Busato, F. Experimental measurements and numerical modelling of a green roof. *Energy Build.* **2005**, *37*, 1260–1267. [[CrossRef](#)]
21. Niachou, A.; Papakonstantinou, K.; Santamouris, M.; Tsangrassoulis, A.; Mihalakakou, G. Analysis of the green roof thermal properties and investigation of its energy performance. *Energy Build.* **2001**, *33*, 719–729. [[CrossRef](#)]
22. Sailor, D.J. A green roof model for building energy simulation programs. *Energy Build.* **2008**, *40*, 1466–1478. [[CrossRef](#)]
23. Wong, N.H.; Cheong, D.K.W.; Yan, H.; Soh, J.; Ong, C.L.; Sia, A. The effects of rooftop garden on energy consumption of a commercial building in Singapore. *Energy Build.* **2003**, *35*, 353–364. [[CrossRef](#)]
24. Sailor, D.J.; Bass, B. Development and features of the Green Roof Energy Calculator. *J. Living Archit.* **2014**, *1*, 36–58. Available online: https://static1.squarespace.com/static/588221e420099e47b8fe06d8/t/589cbfb6e58c62750d518c8d/1486667704564/JLIV2014Volume1_Issue3-Sailor_etal.pdf (accessed on 29 June 2018).
25. Getter, K.L.; Rowe, D.B.; Robertson, G.P. Carbon sequestration potential of extensive green roofs. *Environ. Sci. Technol.* **2009**, *43*, 7564–7570. [[CrossRef](#)] [[PubMed](#)]
26. Whittinghill, L.J.; Rowe, D.B.; Schutzki, R.; Cregg, B.M. Quantifying carbon sequestration of various green roof and ornamental landscape systems. *Landsc. Urban Plan.* **2014**, *123*, 41–48. [[CrossRef](#)]
27. Chenani, S.B.; Lehvavirta, S.; Häkkinen, T. Life cycle assessment of layers of green roofs. *J. Clean. Product.* **2015**, *90*, 153–162. [[CrossRef](#)]
28. Kosareo, L.; Ries, R. Comparative environmental life cycle assessment of green roofs. *Build. Environ.* **2007**, *42*, 2606–2613. [[CrossRef](#)]
29. Saiz, S.; Kennedy, C.; Bass, B.; Pressnail, K. Comparative life cycle assessment of standard and green roofs. *Environ. Sci. Technol.* **2006**, *40*, 4312–4316. [[CrossRef](#)] [[PubMed](#)]
30. Bianchini, F.; Hewage, K. How “green” are the green roofs? Lifecycle analysis of green roof materials. *Build. Environ.* **2012**, *48*, 57–65. [[CrossRef](#)]
31. Yang, J.; Yu, Q.; Gong, P. Quantifying air pollution removal by green roofs in Chicago. *Atmos. Environ.* **2008**, *42*, 7266–7273. [[CrossRef](#)]

32. Sherwani, A.F.; Usmani, J.A.; Varun. Life cycle assessment of solar PV based electricity generation systems: A review. *Renew. Sustain. Energy Rev.* **2010**, *14*, 540–544. [[CrossRef](#)]
33. Tahara, K.; Kojima, T.; Inaba, A. Evaluation of CO₂ payback time of power plants by LCA. *Energy Convers. Manag.* **1997**, *38*, 615–620. [[CrossRef](#)]
34. Tripanagnostopoulos, Y.; Souliotis, M.; Battisti, R.; Corrado, A. Energy, cost and LCA results of PV and hybrid PV/T solar systems. *Prog. Photovolt. Res. Appl.* **2005**, *13*, 235–250. [[CrossRef](#)]
35. Schneider, C.A.; Rasband, W.S.; Eliceiri, K.W. NIH Image to ImageJ: 25 Years of Image Analysis. *Nat. Methods* **2012**, *9*, 671–675. [[CrossRef](#)] [[PubMed](#)]
36. Costa, P.M.; Wilson, C. An equivalence factor between CO₂ avoided emissions and sequestration—Description and applications in forestry. *Mitig. Adapt. Strategy Glob. Chang.* **2000**, *5*, 51–60. [[CrossRef](#)]
37. Matamala, R.; Jastrow, J.D.; Miller, R.M.; Garten, C.T. Temporal changes in C and N stocks of restored prairie: Implication for C sequestration strategies. *Ecol. Appl.* **2008**, *18*, 1470–1488. [[CrossRef](#)] [[PubMed](#)]
38. Bribián, I.Z.; Capilla, A.V.; Usón, A.A. Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. *Build. Environ.* **2011**, *46*, 1133–1140. [[CrossRef](#)]
39. Kuronuma, T.; Watanabe, H. Physiological and morphological traits and competence for carbon sequestration of several green roof plants under a controlled environmental system. *J. Am. Soc. Hortic. Sci.* **2016**, *141*, 583–590. [[CrossRef](#)]
40. Clark, C.; Adriaens, P.; Talbot, F.B. Green roof valuation: a probabilistic economic analysis of environmental benefits. *Environ. Sci. Technol.* **2007**, *42*, 2155–2161. [[CrossRef](#)]
41. Diomnd, K.; Webb, A. Sustainable roof selection: Environmental and contextual factors to be considered in choosing a vegetated roof or rooftop solar photovoltaic system. *Sustain. Cities Soc.* **2017**, *35*, 241–249. [[CrossRef](#)]

© 2018 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).