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Annual greenhouse gas fluxes from a thin-layer rooftop lawn

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Green roofs are a key solution for increasing green spaces in urban areas covered with impervious surfaces. In recent years, there has been growing interest in the ability of green spaces to reduce greenhouse gas (GHG) emissions and enhance carbon sequestration. To investigate whether green roofs contribute to GHG reduction, it is essential to quantify both carbon sequestration and GHG fluxes. However, few studies have investigated GHG fluxes from green roofs over the long term. To address this gap, this study measured and quantified the annual GHG (carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O)) fluxes from a thin-layer rooftop lawn using clear acrylic automatic open/close chambers. In addition, we calculated CO_2 sequestration based on the difference between total carbon contents in rooftop lawns (soil and turf) at the beginning and end of the experiment. The annual CO_2, CH_4, and N_2O fluxes were calculated to be –1762 g-CO_2• m^{-2}• $year^{-1}$, 92.33 mg-CH_4• m^{-2}• $year^{-1}$, and 0.53 mg-N_2O•m^{-2}• $year^{-1}$ respectively, and CO_2 sequestration by plants and soil was estimated to be –2,626 g-CO_2•m^{-2}•$year^{-1}$ during the first year after construction. The CH_4 and N_2O fluxes from the rooftop lawn were significantly lower than those reported in other studies conducted on ground-level lawns. Based on these results, annual GHG emission (total of CO_2, CH_4, and N_2O) from the rooftop lawn were calculated to be –1759 to –2,623 g-CO_2e (CO_2 equivalents). m^{-2}• $year^{-1}$, indicating that the rooftop lawn acts as GHG sink.

KEYWORDS

green roof, turf, carbon neutral, soil flux, carbon sequestration

1 Introduction

Greenhouse gas (GHG) reduction is an urgent issue across all sectors to mitigate climate change. The Intergovernmental Panel on Climate Change (IPCC)'s Sixth Assessment Report (IPCC, 2023) identifies urban green infrastructure and improved grassland management as technically viable and cost-effective mitigation strategies. In urban areas covered with impervious surfaces, green roofs are a key solution for increasing green spaces.

Green roofs offer several environmental benefits, including cooling and insulating buildings (Morakinyo et al., 2017; He et al., 2020), mitigating the urban heat-island effect (Feng et al., 2022; Mutani and Todeschi, 2020; Park et al., 2022), managing stormwater (Kim et al., 2021; Zhang et al., 2021; Pumo et al., 2023), and reducing air pollution (Arbid et al., 2021; Kostadinović et al., 2023). Regarding carbon sequestration, several reports have demonstrated that green roofs can accumulate carbon dioxide (CO_2) in plants and soils (Getter et al., 2009; Whittinghill et al., 2014). In Japan, studies have shown that rooftop lawns can sequester 110 g-C.m^{-2}• $year^{-1}$ for at least 15 years (Kuronuma et al., 2014; 2018a), which is comparable to the carbon sequestration rates in grassland (93.5 g-C•m^{-2}• $year^{-1}$),

FIGURE 1
State of gas sampling from the thin-layer rooftop lawn on August 22, 2022. An automatic open/close chamber was set in the center of all turfs to measure the fluxes of CO_2, CH_4, and N_2O from the surface of the rooftop lawn.

determined by a meta-analysis of 63 studies (Phillips et al., 2023). In contrast, to investigate whether green roofs contribute to GHG reduction, it is essential to quantify both carbon sequestration and GHG fluxes from green roofs.

GHG such as methane (CH_4) and nitrous oxide (N_2O) fluxes are caused by biochemical reactions in the soil, and their occurrence has been reported in grasslands and the other green spaces (Dutt and Tanswar, 2020; Law et al., 2021). Teemusk et al. (2019) and Halim et al. (2022) reported CH_4 and N_2O fluxes from green roofs and clarified substrate characteristics influencing the GHG fluxes. However, no reports on the annual GHG emissions (fluxes) from green roofs are found. These findings will be extremely important in calculating the GHG budgets of green roofs.

Therefore, to present basic information in the calculation of GHG budgets of green roofs, this study quantified the annual GHG (CH_4 and N_2O) fluxes from a thin-layer rooftop lawn. In addition, this study focused only on gas exchange in green roofs and compared GHG fluxes and carbon fixation to discuss whether green roofs contribute to GHG reductions.

2 Methods

2.1 Experimental sites and green roof system

This study was conducted on an unobstructed rooftop in Tochigi, Japan. New 1 m^2 thin-layer containers (soil thickness: 35 mm) filled with a medium primarily composed of perlite were set up, with three replicates. Zoysia (*Zoysia matrella* (L.) Merr.) sods were planted in these containers. Three months later, on November 25, 2021, gas sampling began. Hourly temperature data for this site during the experimental period are shown in Supplementary Figure S1. Fertilizer (N:P:K = 10:10:10) applications of 20 g/m^2 were conducted on April 14 and July 19, 2022. An automated bottom irrigation system supplied water to the containers. The turfgrass was clipped when exceeding a height of 5 cm, and the clippings were collected. The properties of the experimental medium, identified in previous studies (Kuronuma et al., 2012; Kuronuma et al., 2014), are listed in Supplementary Table S1.

2.2 GHG fluxes measurements

Gas sampling was conducted from November 25, 2021, to November 10, 2022, at approximately fortnightly intervals, at 10:00 and 22:00 each time. On July 21, August 4, and August 22, 2022, sampling was conducted at 8:00 and 22:00 to prevent turf damage due to high temperatures in the closed chamber. The sampling frequency was set to be equal to or higher than the frequency of previous studies that have investigated long-term GHG fluxes from green roofs (Teemusk et al., 2019) and grass lands (Law et al., 2021). Sampling times were established throughout the preliminary study.

In each rooftop lawn (n = 3), gas samples were collected at 1, 7, 13, 19, and 25 min after a clear acrylic chamber was placed over the center of the turfs (Figure 1). Regardless of weather conditions on the designated sampling days, the automatic open/close chamber collected gases at the aforementioned interval times and sealed these in a vial (Kuronuma et al., 2023).

CO_2, CH_4, and N_2O concentrations in the gas samples were analyzed using a gas chromatograph equipped with flame ionization, thermal conductivity, and ^{63}Ni electron capture detectors (GC-2014, Shimadzu, Kyoto, Japan). The fluxes of the three gases in each sampling and the emissions during the experimental period were calculated according to the closed chamber guidelines (Minamikawa et al., 2015) as follows:

$$Flux_{GHGs} = \frac{\Delta C}{\Delta t} \times \frac{V}{A} \times \rho \times \frac{273}{273 + T}$$

where $\Delta C/\Delta t$ is the concentration change over time (ppm-CO_2/h, ppm-CH_4/h, or ppb- N_2O/h), V is chamber volume (0.00408 m^3), A is chamber area (0.0295 m^2), ρ is gas density (1.977 kg/m^3 for CO_2, 0.717 kg/m^3 for CH_4, and 1.977 kg/m^3 for N_2O at 0°C), and T is the mean air temperature inside the chamber (°C). Cumulative GHG emissions over a 1-year period were calculated using a trapezoidal integration method. (i.e., linear interpolation was conducted for each GHG flux result (sampling time) and total GHG emissions were calculated based on numerical integration between sampling times) (Minamikawa et al., 2015). Trapezoidal integration method is the most commonly used in literature to calculate cumulative GHG fluxes (Matson et al., 1996; Levy et al., 2017).

To eliminate the influence of the sampling times, cumulative CO_2 emissions were determined from the difference between the cumulative values of the light and dark periods. For convenience, to calculate cumulative CO_2 emissions during light period, we assumed that the light period continues until sampling during the subsequent light period. Similarly, for the dark periods, calculations were performed assuming that the dark period would continue until sampling during the subsequent dark period.

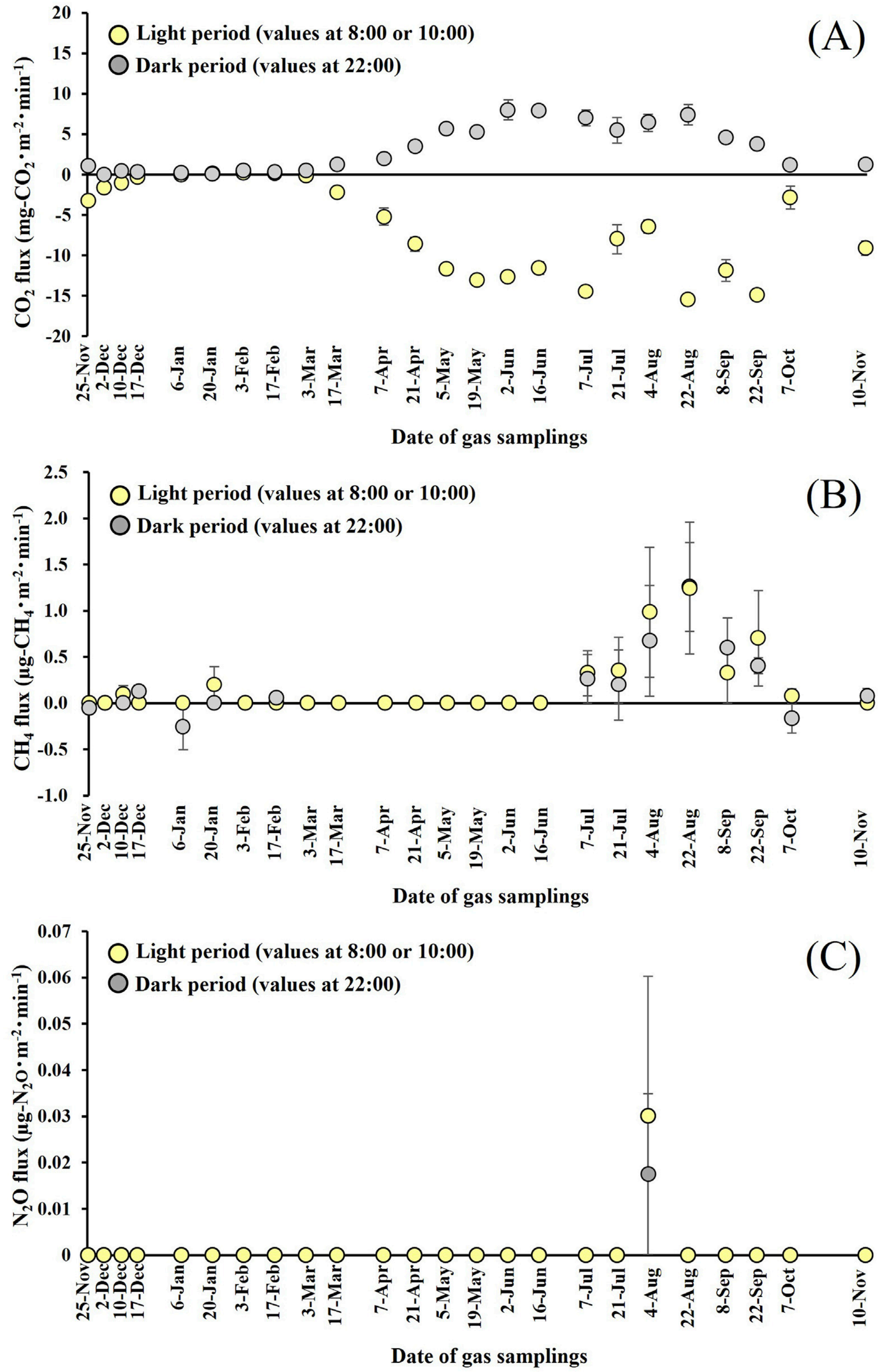

FIGURE 2
CO_2 **(A)**, CH_4 **(B)**, and N_2O **(C)** fluxes during each gas sampling over 1 year in the thin-layer rooftop lawn.

TABLE 1 Dry weights, carbon concentrations, and carbon contents of turf and soil at the beginning (November 1st, 2021) and end (November 10th, 2022) of the experimental period.

Type	Period	Dry weight ($g/20\ cm^2$)	Carbon	
			Concentration (%)	Content (g/m^2)
Turf	Nov-21	3.54 ± 0.21 [a]	43.4 ± 0.4 n.s	659 ± 51 [a]
	Nov-22	5.12 ± 0.38	41.8 ± 0.8	1,065 ± 73
Soil	Nov-21	22.9 ± 1.1 n.s	7.7 ± 0.5 [a]	871 ± 79 [a]
	Nov-22	24.4 ± 1.3	9.8 ± 0.5	1,181 ± 77

[a]indicates significant differences between the results obtained in November 2021 and November 2022 (Student's t-test, $P < 0.05$). n. s Indicates no significant differences between the results obtained in November 2021 and November 2022 (Student's t-test, $P > 0.05$).

2.3 Carbon sequestration by plant and soil

Unlike other GHGs, CO_2 fluxes are strongly influenced by photosynthesis. Thus, cumulative CO_2 emission calculated by GHG flux (above-mentioned method) is likely to be over- or underestimated. Thus, we also calculated the cumulative emissions of CO_2 based on the difference between the total carbon contents in rooftop lawns (soil and turf) at the beginning (November 1st, 2021) and end (November 10th, 2022) of the experiment. Using an HSC-5 soil sampler (Fujiwara Scientific Co. Ltd., Tokyo, Japan), we collected 20 cm^2 samples of soil and turf from three sites per rooftop lawn unit (n = 9). These samples were dried and separated into turf and soil and weighed. The total carbon concentrations in the samples were determined using a 2,400 Series II CHNS/O analyzer (PerkinElmer, USA), on the basis of which, we calculated the carbon contents per rooftop lawn area by multiplying the dry weight by the carbon concentrations.

2.4 GHG budget assessment

To quantify the annual GHG emission from a thin-layer rooftop lawn as CO_2 equivalents (CO_2e), the global warming potential (GWP) of CH_4 and N_2O were set at 28 and 265 times greater than that of CO_2, respectively (IPCC, 2023). Total GHG emissions from rooftop lawns were calculated by integrating these results. For determining the cumulative emissions of CO_2, we used the result quantified based on two calculation methods (CO_2 flux and carbon sequestration) to present more objective information.

3 Results

3.1 Annual GHG fluxes from the rooftop lawn

CO_2, CH_4, and N_2O fluxes during the experimental period are shown in Figure 2. Error bars indicated standard errors (n = 3). Since May 17, CO_2 absorption (photosynthesis) during the light period and CO_2 emission (respiration) during the dark period were detected (Figure 2A), signaling that the Zoysia turf had broken dormancy and was growing healthily. The mean values of CO_2 flux during the light and dark period were calculated at −6.35 and 3.08 $mg\text{-}CO_2 \cdot m^{-2} \cdot min^{-1}$, respectively. Cumulative CO_2 emissions in light and dark period were calculated at −3,416 $g\text{-}CO_2 \cdot m^{-2} \cdot year^{-1}$ and 1654 $g\text{-}CO_2 \cdot m^{-2} \cdot year^{-1}$, respectively. Consequently, the annual CO_2 balance during the experiment was −1762 $g\text{-}CO_2 \cdot m^{-2} \cdot year^{-1}$.

For CH_4, positive fluxes were observed during high temperature periods (between July 7 to September 22), while no notable fluxes were observed from the beginning of the experiment to June 16 (Figure 2B). No significant differences or trends were identified in the flux between light and dark periods. The mean value of CH_4 flux during the experiment period was 0.156 $\mu g\text{-}CH_4 \cdot m^{-2} \cdot min^{-1}$ which is intermediate between those from perennial ryegrass and bermudagrass in the previous study (Law et al., 2021). The annual CH_4 emission from the thin-layer rooftop lawn was 92.33 $mg\text{-}CH_4 \cdot m^{-2} \cdot year^{-1}$ (2.59 $g\text{-}CO_2e \cdot m^{-2} \cdot year^{-1}$).

N_2O fluxes were only observed on August 4 during the experimental period (Figure 2C). Additionally, the standard

TABLE 2 Cumulative CO_2, CH_4, and N_2O emissions and annual GHG emissions from rooftop lawns.

Quantification method	CO_2 emission	CH_4 emission	N_2O emission	Annual GHG emission from rooftop lawn
	(G-CO_2e•m^{-2}•$year^{-1}$)			
CO_2 flux	1,762	2.59	0.14	1,759
Carbon sequestration	−2,626			−2,623

errors were very large because significant flux was detected only in certain samples (Figure 2C). No significant N_2O emissions were observed immediately after fertilization. The annual N_2O emission from the thin-layer rooftop lawn was 0.53 mg-N_2O.m^{-2}. $year^{-1}$ (0.14 g-CO_2e.m^{-2}. $year^{-1}$).

3.2 Carbon sequestration and total GHG emission from the rooftop lawn

Total carbon contents in rooftop lawns (soil and turf) at the beginning and end of the experiment are shown Table 1. Over a 1-year period, we observed significant increments in the dry weight of turf and in the total carbon concentrations of soil, contributing to an increase in total carbon in rooftop lawn (soil and turf) of 716.1 g-C/m^2 from the beginning to the end of the experiment, thereby indicating that rooftop lawns sequestrated −2,626 g-CO_2•m^{-2}•$year^{-1}$.

From these results, the annual GHG emission from the thin-layer rooftop lawn was calculated at −1759 to −2,623 g-CO_2• m^{-2}• $year^{-1}$ (Table 2). These results varied greatly depending on the method used to calculate CO_2 emission (CO_2 flux or carbon sequestration). The cause of this is unknown, but continued research is needed to derive more robust data.

4 Discussion

4.1 GHG budget in rooftop lawn

In this study, we found that the sequestration of CO_2 by rooftop lawns far exceeded the emissions of CH_4 and N_2O (Table 2). High sequestration of CO_2 by rooftop lawn during the first year after construction are similarly observed in our previous study [*Z. matrella*: 670 g-C•m^{-2}•$year^{-1}$ (Kuronuma and Watanabe, 2017)]. Likewise, Getter et al. (2009) have reported that the plants and soils of Sedum green roofs sequestrated 375 g-C•m^{-2}•$year^{-1}$ during the first 2 years after construction. In addition, even if the carbon sequestration capacity of rooftop lawns is 110 g-C• m^{-2}• $year^{-1}$ (403 g-CO_2e•m^{-2}• $year^{-1}$) for 15 years (Kuronuma et al., 2014; 2018a), CO_2 absorption far exceeds GHG emissions since the GHG (CH_4 and N_2O) flux was calculated at only 2.73 g-CO_2e•m^{-2}• $year^{-1}$. Therefore, this study suggests that rooftop lawns could serve as a GHG sink.

In contrast, previous studies have estimated that increasing soil organic matter reduces carbon sequestration and increases soil GHG fluxes (Bandaranayake et al., 2003; Zhang et al., 2013; Gu et al., 2015). Thus, the quantification of GHG emissions from rooftop lawns at different ages is a topic for future research. Additionally, there have been reports of environmental impacts associated with the use of thin-layer substrates, fertilizers, and other materials (Kuronuma et al., 2018b; Scolaro and Ghisi, 2022). A more comprehensive analysis that includes these environmental impacts will be required in the future to ensure that the overall environmental benefits of rooftop lawns are accurately assessed. The use of materials with lower environmental impact will be important to increase the GHG absorption capacity of rooftop lawns.

4.2 GHG fluxes in rooftop lawn

The CH_4 and N_2O fluxes in this experiment were approximately one-half and one-eighth, respectively, of the values reported in similar previous studies using Andosols (Kuronuma et al., 2023). Additionally, results from other studies of ground-level (not rooftop) lawns indicated that the CH_4 and N_2O fluxes observed in our experiment were very low (Dutt and Tanwar, 2020; Brandani et al., 2021; Law et al., 2021). This is likely due to the use of a perlite, which has low total carbon and nitrogen concentrations (Supplementary Table S1), as the main component of the medium. The extremely thin soil thickness in the rooftop lawn compared to ground-levels lawns may also be a reason for the lower GHG emissions. Moreover, microbial biomass C and microbial activity, measured by fluorescein diacetate (FDA) assay, were lower in the medium (main component: perlite) that in the organic layer (Kuronuma et al., 2018a). These findings suggest that green roofs, which require the use of light artificial soils (e.g., perlite), are likely to have lower GHG emissions than ground-level lawn.

In this study, N_2O fluxes were only observed on August 4 and no significant N_2O emissions were observed immediately after fertilization (Figure 2C). Teemusk et al. (2019) had reported N_2O fluxes in green roofs were very low, correlation with meteorological parameters was insignificant. To detect trace amounts of N_2O emissions, lengthening the interval between gas samplings (e.g., 0 min, 30 min, 60 min, and 90 min) might be an effective approach. For the CH_4 fluxes, the findings of some studies have indicated that urban turfgrass can function as a CH_4 sink throughout the year (van Delden et al., 2018; Teemusk et al., 2019). However, in the present study, we observed positive CH_4 fluxes during summer, which we suspect could be attributable to a high soil water content as a consequence of frequent irrigation. In any case, it is difficult to make precise reference in this study to the relationship between CH_4 and N_2O fluxes and various environmental conditions, *etc.* Accordingly, further investigations are essential to gain insights into these areas. In this study, we adopted a closed chamber method having issues such as the limited number of observation points and the inability to quantify the flux in all directions. In the future, we plan to investigate different gas flux measurement methods in order to improve the output.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

SM: Investigation, Supervision, Funding acquisition, Conceptualization, Formal Analysis, Writing – original draft, Methodology. TM: Funding acquisition, Investigation, Conceptualization, Writing – review and editing, Resources, Supervision, Methodology, Formal Analysis. MM: Investigation, Writing – review and editing, Formal Analysis. TK: Formal Analysis, Supervision, Investigation, Methodology, Writing – original draft, Conceptualization. HW: Supervision, Writing – review and editing, Resources.

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Conflict of interest

Authors SM, TM, and MM were employed by Honda R&D Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declare that no Generative AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenve.2025.1634737/full#supplementary-material

References

Arbid, Y., Richard, C., and Sleiman, M. (2021). Towards an experimental approach for measuring the removal of urban air pollutants by green roofs. *Build. Environ.* 205, 108286. doi:10.1016/j.buildenv.2021.108286

Bandaranayake, W., Qian, Y. L., Parton, W. J., Ojima, D. S., and Follett, R. F. (2003). Estimation of soil organic carbon changes in turfgrass systems using the CENTURY model. *Agron. J.* 95, 558–563. doi:10.2134/agronj2003.5580

Brandani, G., Baldi, A., Caturegli, L., Gaetani, M., Grossi, N., Magni, S., et al. (2021). Carbon dioxide and methane emissions by urban turfgrasses under different nitrogen rates: a comparison between tall fescue (*Festuca arundinacea* schreb.) and hybrid bermudagrass (*Cynodon dactylon* [L.] pers. Var. *dactylon* × *cynodon Treansvaalensis* burtt-davy). *Appl. Ecol. Environ. Res.* 19, 1–12. doi:10.15666/aeer/1901_001012

Dutt, N., and Tanwar, T. (2020). Nitrous oxide emissions from turfgrass lawns as a result of fertilizer application: a meta-analysis of available literature. *Curr. Sci.* 118, 1219–1226. doi:10.18520/cs/v118/i8/1219-1226

Feng, Y., Wang, J., Zhou, W., Li, X., and Yu, X. (2022). Evaluating the cooling performance of green roofs under extreme heat conditions. *Front. Environ. Sci.* 10, 874614. doi:10.3389/fenvs.2022.874614

Getter, K. L., Rowe, D. B., Robertson, G. P., Cregg, B. M., and Andresen, J. A. (2009). Carbon sequestration potential of extensive green roofs. *Environ. Sci. Technol.* 43, 7564–7570. doi:10.1021/es901539x

Gu, C., Crane, J., II, Hornberger, G., and Carrico, A. (2015). The effects of household management practices on the global warming potential of urban lawns. *J. Environ. Manag.* 151, 233–242. doi:10.1016/j.jenvman.2015.01.008

Halim, M. A., Vantellingen, J., Gorgolewski, A. S., Rose, W. K., Drake, J. A., Margolis, L., et al. (2022). Greenhouse gases and green roofs: carbon dioxide and methane fluxes in relation to substrate characteristics. *Urban Ecosyst.* 25, 487–498. doi:10.1007/s11252-021-01166-8

He, Y., Yu, H., Ozaki, A., and Dong, N. (2020). Thermal and energy performance of green roof and cool roof: a comparison study in shanghai area. *J. Clean. Prod.* 267, 122205. doi:10.1016/j.jclepro.2020.122205

IPCC (2023). *Synthesis report of the IPCC sixth assessment report (AR6)*. Geneva, Switzerland: IPCC. Available online at: https://www.ipcc.ch/report/sixth-assessment-report-cycle/(Accessed February 30, 2025).

Kim, S. Y., Na, W., Jun, C., Seo, H., and Kim, Y. (2021). Hydrological performance of green roof systems: a numerical investigation. *Front. Environ. Sci.* 9, 806697. doi:10.3389/fenvs.2021.806697

Kostadinović, D., Jovanović, M., Bakić, V., and Stepanić, N. (2023). Mitigation of urban particulate pollution using lightweight green roof system. *Energy Build.* 293, 113203. doi:10.1016/j.enbuild.2023.113203

Kuronuma, T., Hashimoto, S., Chimura, R., Yokokawa, H., Sakamoto, K., and Watanabe, H. (2012). Annual change and temporal change of fertilizer component in rooftop garden thin substratum light soil. *J. Jpn. Soc. Reveg. Technol.* 38, 51–55. doi:10.7211/jjsrt.38.51

Kuronuma, T., Hashimoto, S., Ishihara, T., Yoshioka, T., and Watanabe, H. (2014). Temporal change about media and quantification of the carbon dioxide fixation in the rooftop lawn. *J. Jpn. Soc. Reveg. Technol.* 40, 20–24. doi:10.7211/jjsrt.40.20

Kuronuma, T., Masuda, S., Mito, T., and Watanabe, H. (2023). Inclusive greenhouse gas budget assessment in turfs: from turf production to disposal of grass clippings. *J. Environ. Manag.* 346, 118919. doi:10.1016/j.jenvman.2023.118919

Kuronuma, T., and Watanabe, H. (2017). Relevance of carbon sequestration to the physiological and morphological traits of several green roof plants during the first year after construction. *Am. J. Plant Sci.* 08, 14–27. doi:10.4236/ajps.2017.81002

Kuronuma, T., Watanabe, H., Ishihara, T., Kou, D., Toushima, K., Ando, M., et al. (2018b). CO_2 payoff of extensive green roofs with different vegetation species. *Sustainability* 10, 2256. doi:10.3390/su10072256

Law, Q. D., Trappe, J. M., Braun, R. C., and Patton, A. J. (2021). Greenhouse gas fluxes from turfgrass systems: species, growth rate, clipping management, and environmental effects. *J. Environ. Qual.* 50, 547–557. doi:10.1002/jeq2.20222

Levy, P. E., Cowan, N., Van Oijen, M., Famulari, D., Drewer, J., and Skiba, U. (2017). Estimation of cumulative fluxes of nitrous oxide: uncertainty in temporal upscaling and emission factors. *Eur. J. Soil Sci.* 68, 400–411. doi:10.1111/ejss.12432

Matson, P. A., Billow, C., Hall, S., and Zachariassen, J. (1996). Fertilization practices and soil variations control nitrogen oxide emissions from tropical sugar cane. *J. Geophys. Res. Atmos.* 101, 18533–18545. doi:10.1029/96JD01536

Minamikawa, K., Tokida, T., Sudo, S., Padre, A., and Yagi, K. (2015). *Guidelines for measuring CH4 and N2O emissions from rice paddies by a manually operated closed chamber method*. Tsukuba, Japan: National institute for agro-environmental sciences. Available online at: https://www.naro.affrc.go.jp/archive/niaes/techdoc/mirsa_guidelines.pdf (Accessed February 30, 2025).

Morakinyo, T. E., Dahanayake, K. W. D. K. C., Ng, E., and Chow, C. L. (2017). Temperature and cooling demand reduction by green-roof types in different climates and urban densities: a co-simulation parametric study. *Energy Build.* 145, 226–237. doi:10.1016/j.enbuild.2017.03.066

Mutani, G., and Todeschi, V. (2020). The effects of green roofs on outdoor thermal comfort, urban heat island mitigation and energy savings. *Atmosphere* 11, 123. doi:10.3390/atmos11020123

Park, J., Shin, Y., Kim, S., Lee, S. W., and An, K. (2022). Efficient plant types and coverage rates for optimal green roof to reduce urban heat island effect. *Sustainability* 14, 2146. doi:10.3390/su14042146

Phillips, C. L., Wang, R., Mattox, C., Trammell, T. L., Young, J., and Kowalewski, A. (2023). High soil carbon sequestration rates persist several decades in turfgrass systems: a meta-analysis. *Sci. Total Environ.* 858, 159974. doi:10.1016/j.scitotenv.2022.159974

Pumo, D., Francipane, A., Alongi, F., and Noto, L. V. (2023). The potential of multilayer green roofs for stormwater management in urban area under semi-arid mediterranean climate conditions. *J. Environ. Manag.* 326, 116643. doi:10.1016/j.jenvman.2022.116643

Scolaro, T. P., and Ghisi, E. (2022). Life cycle assessment of green roofs: a literature review of layers materials and purposes. *Sci. Total Environ.* 829, 154650. doi:10.1016/j.scitotenv.2022.154650

Takanori, K., Qianyu, R., Tastuaki, I., Daitoku, K., Kazunari, T., Masaya, A., et al. (2018a). Changes of carbon amount, soil microbial activities and nitrogen amount in rooftop lawns over the years. *J. Jpn. Soc. Reveg. Technol.* 44, 75–80. doi:10.7211/jjsrt.44.75

Teemusk, A., Kull, A., Kanal, A., and Mander, Ü. (2019). Environmental factors affecting greenhouse gas fluxes of green roofs in temperate zone. *Sci. Total Environ.* 694, 133699. doi:10.1016/j.scitotenv.2019.133699

van Delden, L., Rowlings, D. W., Scheer, C., De Rosa, D., and Grace, P. R. (2018). Effect of urbanization on soil methane and nitrous oxide fluxes in subtropical Australia. *Glob. Change Biol.* 24, 5695–5707. doi:10.1111/gcb.14444

Whittinghill, L. J., Rowe, D. B., Schutzki, R., and Cregg, B. M. (2014). Quantifying carbon sequestration of various green roof and ornamental landscape systems. *Landsc. Urban Plan.* 123, 41–48. doi:10.1016/j.landurbplan.2013.11.015

Zhang, S., Lin, Z., Zhang, S., and Ge, D. (2021). Stormwater retention and detention performance of green roofs with different substrates: observational data and hydrological simulations. *J. Environ. Manag.* 291, 112682. doi:10.1016/j.jenvman.2021.112682

Zhang, Y., Qian, Y., Bremer, D. J., and Kaye, J. P. (2013). Simulation of nitrous oxide emissions and estimation of global warming potential in turfgrass systems using the DAYCENT model. *J. Environ. Qual.* 42, 1100–1108. doi:10.2134/jeq2012.0486