

Mitigation of Annual Nitrous Oxide Emissions by Groundcovers in Apple Orchard Soil

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Abstract: This study evaluated the effects of herbaceous groundcovers—white clover (WC) and Kentucky bluegrass (KG)—on annual nitrous oxide (N₂O) emissions compared with a bare-soil control (CT). Annual N₂O emissions were 1.68±0.24 kg N₂O–N ha^{−1} in CT, whereas WC and KG showed substantially lower emissions of 0.89±0.23 and 0.92±0.22 kg N₂O–N ha^{−1}, corresponding to significant reductions of 47% and 45%, respectively. Daily N₂O fluxes exhibited significant positive correlations with soil temperature across all treatments, while no significant relationship was observed with water-filled pore space (WFPS). Although these findings indicate that soil temperature is a key factor influencing short-term N₂O variability, further analyses of soil mineral nitrogen and microbial properties are needed to clarify the underlying mechanisms of N₂O production and mitigation. Overall, the introduction of groundcovers markedly reduced annual N₂O emissions compared with bare soil, demonstrating their potential as an effective low-carbon management practice for perennial orchard systems.

Keywords: Groundcovers, Kentucky bluegrass, Orchard soil, Soil temperature, White clover

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Introduction

Korea has actively engaged in global efforts to reduce greenhouse gas emissions by establishing its 2030 national mitigation targets in 2015 and declaring carbon neutrality by 2050 in 2020. Nitrous oxide (N₂O) is a major greenhouse gas emitted from agricultural systems and has a global warming potential 273 times greater than that of carbon dioxide (CO₂), based on the IPCC 2021 report. In croplands, N₂O is primarily produced through microbial nitrification and denitrification processes following the input of nitrogen fertilizers and organic matter [1]. Therefore, appropriate management of nitrogen inputs and soil organic matter is essential for reducing N₂O emissions and contributing to carbon neutrality.

According to the Intergovernmental Panel on Climate Change (IPCC), maintaining plant cover and reducing bare soil in agricultural fields can enhance photo-

synthesis, increase soil carbon storage, and lower dependence on synthetic nitrogen fertilizers, ultimately mitigating greenhouse gas emissions. Herbaceous groundcovers not only help suppress weeds and reduce soil erosion but may also contribute, to some extent, to creating soil conditions that could potentially reduce N₂O emissions by improving soil physical properties and nutrient availability [2].

Orchards, due to their perennial nature and reduced tillage, offer favorable conditions for maintaining groundcovers year-round, and their generally low nitrogen inputs may lead to different N₂O emission responses compared with upland or paddy fields. Furthermore, N₂O emissions can be strongly influenced by environmental factors such as soil moisture, temperature, and climatic variability, as well as by the type of groundcover species and management practices [3]. However, the extent to which N₂O emissions in orchard soils respond to soil temperature and water-filled pore space (WFPS)—remains poorly understood, indicating the need for further investigation under orchard conditions.

To address this gap, this study evaluates the annual N₂O mitigation potential of two widely used orchard groundcovers—white clover and Kentucky bluegrass—through year-round flux monitoring in a commercial apple orchard. Additionally, this study examines how N₂O emissions respond to variations in soil temperature and WFPS under each groundcover type, providing mechanistic insight into the environmental controls of N₂O emissions in temperate orchard soils.

Results and Discussion

Soil chemical properties under different groundcover treatments

Soil chemical properties determined after more than one year of groundcover cultivation are summarized in Table 1. Organic matter (OM) content was highest in the Kentucky bluegrass (KG) treatment (31.9 g kg⁻¹), followed by white clover (WC, 26.7 g kg⁻¹) and the bare-soil control (CT, 25.4 g kg⁻¹). Total nitrogen (T-N) exhibited a similar trend, with concentrations of 2.08 g kg⁻¹ in KG, 1.76 g kg⁻¹ in WC, and 1.69 g kg⁻¹ in CT. Soil pH was slightly higher in CT (7.0) than in WC and KG (both 6.4), a pattern consistent with the higher exchangeable Ca²⁺ and Mg²⁺ concentrations observed in CT.

Available phosphorus (Av. P₂O₅) was notably higher in CT (686.9 mg kg⁻¹) than in the groundcover treatments (495.2 mg kg⁻¹ in WC and 533.7 mg kg⁻¹ in KG). This reduction in available P may reflect active phosphorus uptake by herbaceous groundcover species, which commonly reduces soil inorganic P relative to bare soil [4]. Overall, although differences among treatments were evident, the magnitude of change was moderate, likely reflecting the relatively short duration of groundcover establishment.

Weather and soil factors associated with N₂O emission dynamics

Daily rainfall and mean air temperature recorded at the experimental site in Jangsu-eup, Jangsu-gun, are shown in Fig. 1A. Total annual rainfall was 2,329.0 mm, approximately 170% of the recent 10-year national average (1,362.9 mm). The mean air temperature during the study period was 12.3°C, which was 0.6°C lower than the long-term average (12.9°C) and 2.5°C lower than the 2024 annual mean (14.8°C). Rainfall was heavily concentrated between late June and mid-September. Given that annual

Table 1. Soil chemical properties after one year of groundcover cultivation in the apple orchard

Treatments	pH (1:5, H ₂ O)	EC ¹⁾ (1:5, dS m ⁻¹)	OM (g kg ⁻¹)	T-N (g kg ⁻¹)	Av. P ₂ O ₅ (mg kg ⁻¹)	Exch. cations (cmol _c kg ⁻¹)		
						K ⁺	Ca ²⁺	Mg ²⁺
CT	7.0	0.28	25.4	1.69	686.9	0.44	6.37	2.23
WC	6.4	0.46	26.7	1.76	495.2	0.17	6.33	1.58
KG	6.4	0.29	31.9	2.08	563.0	0.33	6.71	1.88

¹⁾ EC, electrical conductivity; OM, organic matter; T-N, total nitrogen; Av. P₂O₅, available phosphorus; Exch., exchangeable.

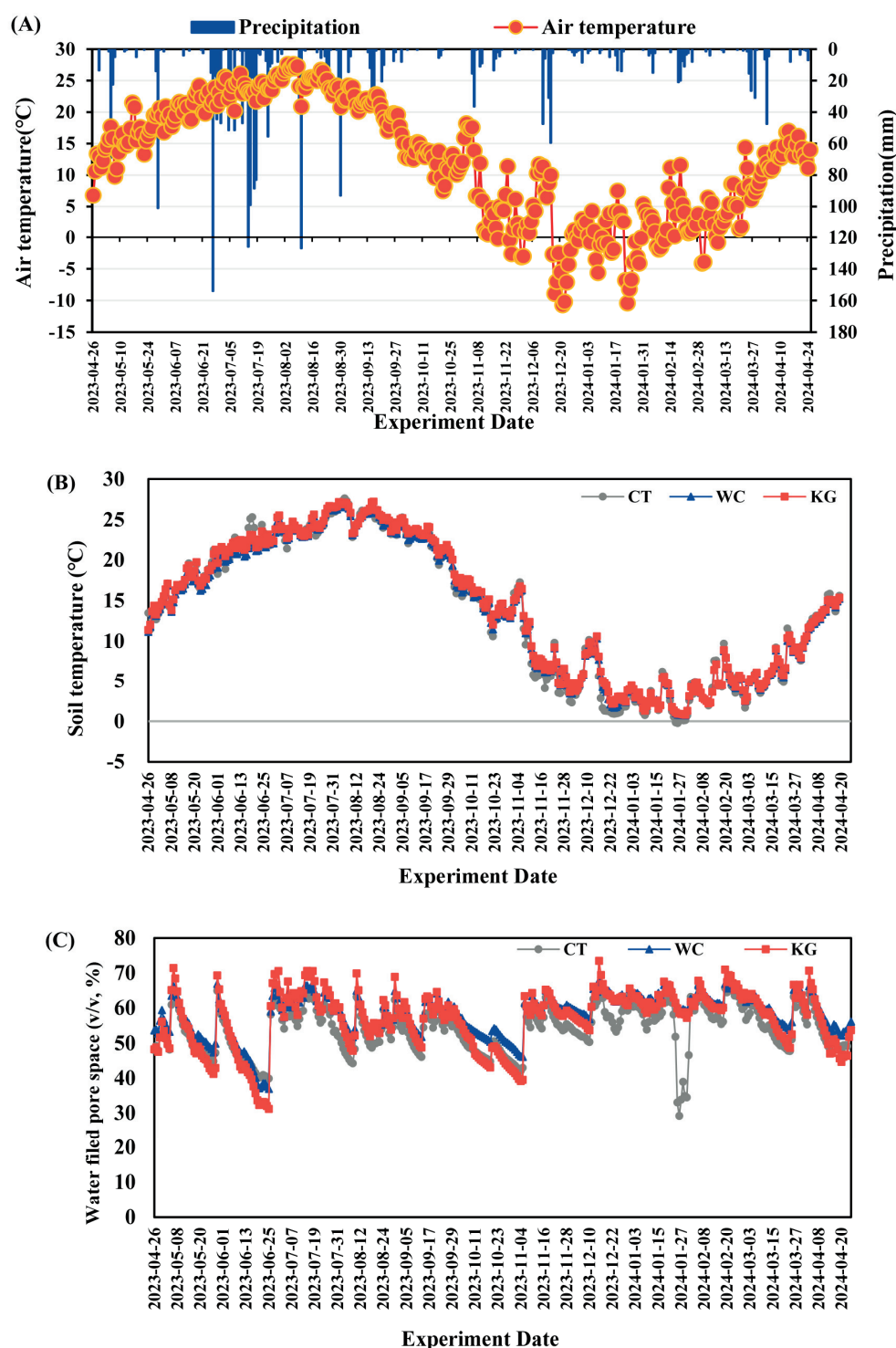


Fig. 1. Daily precipitation, air temperature, soil temperature, and water-filled pore space (WFPS) measured at the experimental site during the study period (April 2023–April 2024). Panel (A) shows daily precipitation and mean air temperature, (B) shows soil temperature under different groundcover treatments (CT, WC, KG), and (C) presents corresponding WFPS dynamics.

rainfall was substantially above normal levels, interpretations of N_2O emission patterns should account for the unusually wet conditions.

Soil temperature closely followed the pattern of air temperature (Fig. 1B). Rainfall events had a direct effect on soil water-filled pore space (WFPS), which increased immediately after precipitation (Fig. 1C). Both soil moisture and soil temperature are

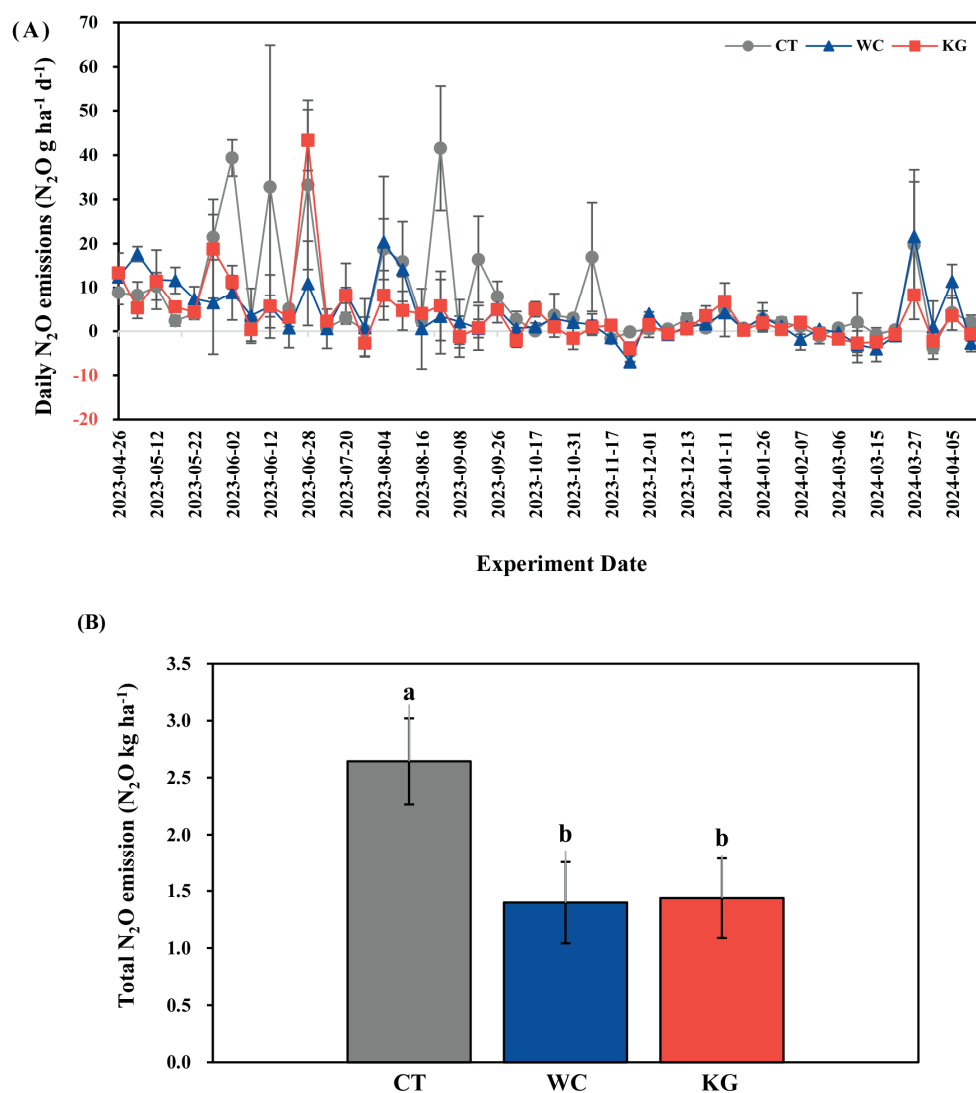


Fig. 2. Daily nitrous oxide (N₂O) emissions and total annual emissions under different groundcover treatments. Panel (A) shows daily N₂O fluxes (N₂O–N, g ha⁻¹ d⁻¹) with standard errors (n = 3), and Panel (B) Cumulative annual N₂O emissions for CT, WC, and KG treatments, with lettering (a, b) indicating statistically significant differences according to DMRT (p < 0.05)

well-known regulators of N₂O emissions [5]. In this study, WFPS increased sharply during heavy rainfall from late June to mid-September, coinciding with elevated N₂O emissions (Fig. 2A). These observations are consistent with previous findings that N₂O production is stimulated when WFPS approaches approximately 60% [6]. In contrast, N₂O emissions were negligible during winter due to suppressed microbial activity under low air and soil temperatures [7]. Collectively, these results indicate that soil temperature and moisture were the primary environmental drivers of N₂O emission dynamics in the orchard.

Characteristics of N₂O emissions

Groundcover treatments substantially reduced N₂O emissions relative to the bare-soil control (Fig. 2b). Total annual emissions were 1.68 ± 0.24 kg N₂O–N ha⁻¹ in CT, compared with 0.89 ± 0.23 kg N₂O–N ha⁻¹ in WC and 0.92 ± 0.22 kg N₂O–N ha⁻¹ in KG. This corresponds to reductions of 47% in WC and 45% in KG. When expressed in CO₂-equivalent units, annual emissions were 722.0 ± 102.8 kg CO₂eq ha⁻¹ in CT, compared with 383.0 ± 98.9 kg CO₂eq ha⁻¹ in WC and 397.7 ± 95.0 kg CO₂eq ha⁻¹ in KG. According to DMRT (p < 0.05), both WC and KG exhibited significantly lower annual emissions than CT, although the two groundcover treatments did not differ significantly from each other.

Higher N₂O emissions in CT were likely attributable to the absence of plant nitrogen uptake, which may have allowed greater accumulation of mineral nitrogen—specifically ammonium (NH₄⁺) and nitrate (NO₃⁻)—available for microbial nitrification and denitrification [8]. Although WC is a leguminous species capable of biological nitrogen fixation, increased plant nitrogen demand in both WC and KG during the growing season may have reduced the pool of readily available mineral nitrogen in the soil [9]. Soil chemical analyses (Table 1) indicated that available phosphorus (Av. P₂O₅) was lower in the groundcover treatments than in CT, reflecting active P uptake by herbaceous plants. This reduction in available P may indicate enhanced nutrient acquisition processes that also increase the utilization of inorganic nitrogen [10], thereby limiting substrates for N₂O production [11]. However, because mineral N was not directly measured, these interpretations should be considered tentative. Enhanced root growth and greater organic matter inputs under groundcovers can also improve soil structure, increase aggregate stability, and modify soil water and aeration dynamics, reducing the formation of anaerobic microsites and thus mitigating denitrification-based N₂O production [12]. Meanwhile, some studies have reported that winter cover crops markedly increase soil organic carbon stocks and total nitrogen, yet N₂O emissions increased under certain conditions [13]. These findings suggest that the effects of cover crops on N₂O emissions can vary depending on soil properties, carbon inputs, and management practices. A previous study has also reported mitigation of N₂O emissions following the adoption of cover crops, with reductions often reaching several tens of percent depending on crop species and management practices [14].

Correlation between N₂O emissions and environmental factors

Correlation coefficients between daily N₂O fluxes and soil temperature or WFPS are summarized in Table 2. Across all treatments, soil temperature showed weak but positive correlations with N₂O fluxes, whereas correlations with WFPS were negligible. The CT plots exhibited slightly higher coefficients than WC and KG, suggesting greater sensitivity of bare soil to environmental fluctuations. However, none of the correlations were strong, indicating that temperature and moisture alone did not sufficiently explain temporal variability in N₂O emissions.

Scatterplots with fitted regression lines (Fig. 3) further illustrate these relationships. The CT treatment displayed a noticeable increase in N₂O emissions at higher soil temperatures, although variability remained high. In contrast, WC and KG showed lower slopes and reduced scatter, implying diminished temperature sensitivity when groundcovers were present. Across all treatments, WFPS exerted minimal influence on N₂O emissions, consistent with flat regression slopes and low R² values. These findings suggest that groundcovers may buffer soil microclimatic conditions, reducing the responsiveness of N₂O emissions to environ-

Table 2. Pearson correlation coefficients between daily N₂O fluxes and soil temperature or WFPS under control (CT), white clover (WC), and Kentucky bluegrass (KG) treatments; the table includes correlation values (r) for each variable pair, allowing comparison of the strength and direction of relationships across treatments(p<0.05).

Treatment	Statistical coefficient	Soil Temperature (a)	Soil WFPS (b)
CT	Standardized (β)	0.426	0.130
	Pearson correlation (r)	0.407**	0.070ns
	Contribution (%)	76.6	23.4
	Multiple regression eq.	y = -0.000 + 0.426a + 0.130b	
WC	Standardized (β)	0.368	0.143
	Pearson correlation (r)	0.314**	0.007ns
	Contribution (%)	71.9	28.1
	Multiple regression eq.	y = 0.000 + 0.368a + 0.143b	
KG	Standardized (β)	0.358	0.232
	Pearson correlation (r)	0.294**	0.134ns
	Contribution (%)	60.6	39.4
	Multiple regression eq.	y = 0.000 + 0.358a + 0.232b	

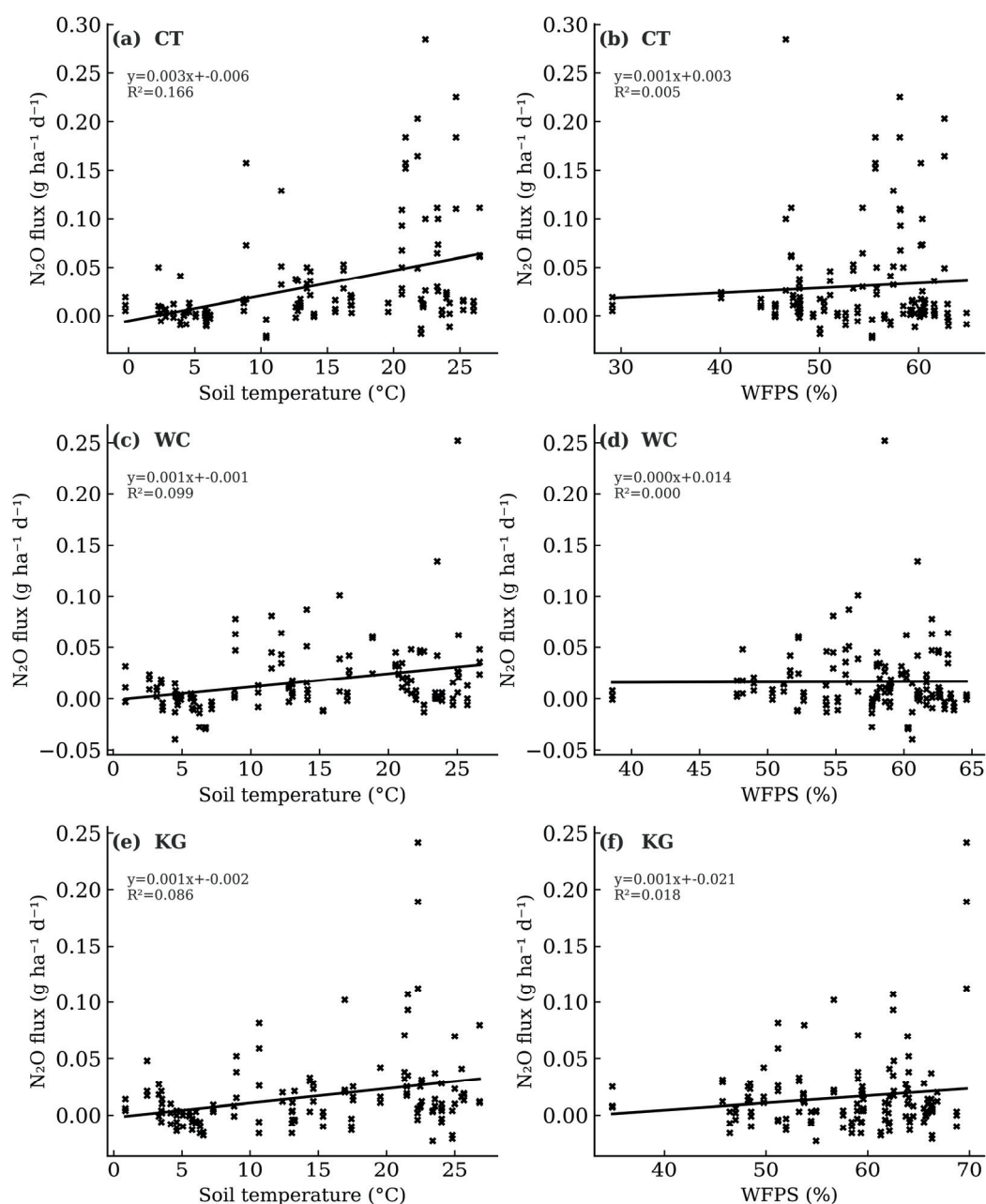


Fig. 3. Correlations between daily N_2O emissions and soil temperature (left column) or WFPS (right column) under three groundcover treatments. Panels (a)–(b) show the control (CT), (c)–(d) show white clover (WC), and (e)–(f) show Kentucky bluegrass (KG). Each panel includes a linear regression model and corresponding R^2 value to illustrate the strength of the relationship.

mental drivers.

Conclusions

This study demonstrated that herbaceous groundcovers substantially reduced N_2O emissions in an apple orchard, lowering annual fluxes by 45–47% compared with the bare-soil control. Although N_2O emissions increased during the rainy season, the magnitude of this increase was considerably smaller under groundcover cultivation, indicating that groundcovers function as an effective low-carbon management practice. Groundcovers also moderated the sensitivity of N_2O emissions to environmental

fluctuations. Compared with the control, both white clover and Kentucky bluegrass showed weaker correlations between daily N_2O fluxes and soil temperature or WFPS, suggesting that groundcovers help buffer short-term variation in soil microclimate and associated microbial processes.

This study has limitations, including the absence of mineral nitrogen measurements, the unusually high rainfall during the study year, and the lack of microbial and soil biochemical data, all of which constrain mechanistic interpretation. Nonetheless, the results highlight the potential of groundcovers to mitigate N_2O emissions and underscore the need for multi-year, multi-site studies to evaluate their broader applicability.

Materials and Methods

Experimental site and treatment setup

This study was conducted at an apple orchard located within the Jangsu Agricultural Technology Center in Jangsu-gun, Jeonbuk, Korea ($35^{\circ}37'15.0''\text{N}$, $127^{\circ}30'32.8''\text{E}$). The orchard has been under continuous cultivation for more than 20 years. The apple cultivar used in this experiment was 'Hongro' (*Malus domestica* Borkh.), and 7–8-year-old trees were planted at 4×2 m spacing under semi-dense management. 'Hongro' was selected because it is one of the major cultivars in Jeonbuk Province, accounting for 13.4% of the regional apple cultivation area and ranking second after the Fuji group, thereby providing both regional and national representativeness [15].

Three treatments were established: a bare-soil control (CT), white clover (WC; *Trifolium repens* L.), and Kentucky bluegrass (KG; *Poa pratensis* L.). In September 2022, WC and KG were sown in the inter-row spaces at rates of 3 kg ha^{-1} and 20 kg ha^{-1} , respectively, while CT plots were maintained as bare soil through periodic weeding. Because Korean apple orchards are often located on sloping terrain where erosion risk is high, groundcovers are commonly managed in inter-row alleys; therefore, all treatments were installed within the inter-row spaces. To minimize inherent soil variability, all plots (CT, WC, KG) were established within the same inter-row space, where soil type and past management—including fertilizer application, pesticide spraying, and mowing—were uniform. In addition, 2-m buffer zones were installed between adjacent plots within the same inter-row to prevent interference among treatments.

Fertilizer application and monitoring of environmental variables

Fertilizer was applied once annually based on soil test recommendations from the "Heuktoram" fertilization guideline provided by the National Institute of Agricultural Sciences. Composite fertilizer was applied on March 3, 2023, and March 6, 2024. Application rates were $51\text{--}37\text{--}42 \text{ kg ha}^{-1}$ for $\text{N}\text{--}\text{P}_2\text{O}_5\text{--}\text{K}_2\text{O}$, and the same amounts were applied to all treatments.

To compare soil chemical properties among treatments, soil samples from the 0–15 cm layer were collected in February 2024, more than one year after treatment establishment and immediately before fertilizer application for the new growing season, thereby avoiding any direct influence of fertilization on the measurements.

For chemical analysis, soil samples were air-dried and passed through a 2-mm sieve, following the Soil Chemical Analysis Method described by Rural Development Administration (2023). Soil pH was measured after mixing soil and distilled water at a 1:5 (w/v) ratio, stirring for 30 min, and analyzing with a pH meter (Orion Star, Thermo, Singapore). Electrical conductivity (EC) was measured using the same extract, filtered through #42 filter paper, with an EC meter (Orion Star, Thermo, Singapore), and multiplied by 5. Total carbon and nitrogen contents were analyzed using a CN analyzer (Vario Max CN, Elementar, Germany). Available phosphorus (Av. P_2O_5) was analyzed using the Lancaster method at 720 nm with a spectrophotometer (AU/CARY 300, Varian Australia). Available silicon was measured at 700 nm using the same spectrophotometer. Exchangeable cations were extracted with 1 M NH_4OAc (pH 7.0), filtered, and analyzed with an inductively coupled plasma spectrometer (Potima 7300 DV, Perkin Elmer, USA).

Daily air temperature and rainfall during the experimental period were obtained from the Agricultural Weather Information System (AgWeather 365) operated by the Rural Development Administration. Soil temperature and moisture were recorded using sensors (ZL6, METER Group, Inc., USA) installed at a 10-cm depth in the inter-row spaces. Measurements were taken hourly and converted to daily averages. Soil moisture data were used to calculate water-filled pore space (WFPS) [16]. WFPS was calculated using a bulk density of 1.20 Mg m^{-3} and a porosity of 54.7%, derived from the 2018 national orchard soil survey (320 sites). Because bulk density shows strong short-range spatial variability in soils and direct measurements at a small number of sampling points are prone to operator-induced errors [17], nationally representative values were adopted to ensure consistency and reduce potential measurement uncertainty. To evaluate the robustness of the WFPS calculation, a simple sensitivity analysis was conducted by recalculating WFPS with bulk density and porosity adjusted by $\pm 10\%$. The resulting variation in WFPS estimates ($\pm 5\text{--}7\%$) indicated that the use of national reference values is unlikely to influence the interpretation of treatment effects.

N₂O measurement and analysis

N₂O emissions were measured using the closed-chamber method. The chamber fabrication and installation for nitrous oxide measurements were based on the Rural Development Administration (RDA) / National Institute of Agricultural Sciences (NIAS) (2023) guidebook for nitrous oxide measurement in agricultural fields. For each treatment, three static chambers were installed as independent replicates. The experiment was conducted as follows to reflect the specific conditions of the orchard. Chambers were made of acrylic, an inert material for N₂O, and had a cylindrical shape with a bottom diameter of 25 cm, a lower height of 10 cm, and an upper height of 35 cm. Because chambers were installed in the inter-row space where machinery passes, the lower section was inserted firmly into the soil (Fig. 4). To reflect the effect of fertilizer application, the chambers were installed 30 cm from the tree canopy edge. Gas samples were collected once per week between 10:00 and 12:00, the period when daily greenhouse gas emissions are typically stable [18]. After closing the chamber lid, an initial gas sample was collected immediately, followed by a second sample 30 minutes later [19]. Gas concentrations were analyzed using gas chromatography (7890B, Agilent Technologies, USA) equipped with an electron capture detector for N₂O.

Daily N₂O flux was calculated using Eq. (1), and cumulative annual emissions were estimated using Eq. (2).

$$F = \rho \times V/A \times \Delta c/\Delta t \times 273/T \quad (1)$$

F is N₂O flux ($\text{mg m}^{-2} \text{ h}^{-1}$), ρ is gas density (mg L^{-1}), V is chamber air volume (m^3), A is chamber base area (m^2), $\Delta c/\Delta t$ is rate of increase in gas concentration inside the chamber ($\mu\text{L L}^{-1} \text{ h}^{-1}$), T is chamber air temperature (K), expressed as $273 + ^\circ\text{C}$.



Fig. 4. Installation of closed static chambers in the inter-row space of the apple orchard for N₂O flux measurements. Chambers were made of acrylic and consisted of a 25-cm inner diameter, a lower height of 10 cm, and an upper height of 35 cm.

$$\text{Annual N}_2\text{O flux} = \sum_i^n (F_i \times D_i) \quad (2)$$

F_i is daily flux on day i ($\text{g m}^{-2} \text{ d}^{-1}$), D_i is interval (days) between sampling dates, n is number of sampling intervals.

Direct greenhouse gas emissions from cropland were converted to CO_2 -equivalent using Eq. (3), applying a global warming potential (GWP) of 273 for N_2O [2].

$$\text{Direct GWP (kg CO}_2\text{ - eq. ha}^{-1}\text{)} = 273 \times \text{N}_2\text{O} \quad (3)$$

Statistical analysis

Annual N_2O emissions from each treatment were analyzed using IBM SPSS Statistics 26. A one-way analysis of variance (ANOVA) was conducted for the three replicated measurements ($p < 0.05$). Significant differences among treatments were identified using Duncan's Multiple Range Test (DMRT) [20].

Pearson correlation analyses were performed to examine the relationships between daily N_2O fluxes and two environmental variables: soil temperature and water-filled pore space (WFPS). Correlation coefficients (r) were calculated separately for each groundcover treatment (CT, WC, and KG). Linear regression models were additionally fitted to quantify the sensitivity of N_2O emissions to variations in soil temperature and WFPS.

Data Availability: All data are available in the main text or in the Supplementary Information.

Author Contributions: H.R. Park: data curation, writing—original draft, visualization, supervision; J.M. Lee: data curation, writing—review; H.S. Lee, M.J. Lee, Y.J. Jeong, Y.S. Shin: data curation; T.K. Oh: conceptualization, writing—review & editing.

Notes: The authors declare no conflict of interest

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Additional Information:

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