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Urbanization can accelerate climate change by increasing soil N_2O emission while reducing CH_4 uptake

Running title: Urbanization effect on soil non-CO_2 GHG flux

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Abstract

Urban land use change has the potential to affect local to global biogeochemical carbon (C) and nitrogen (N) cycles and associated greenhouse gas (GHG) fluxes. We conducted a meta-analysis to 1) assess the effects of urbanization-induced land-use conversion on soil nitrous oxide (N_2O) and methane (CH_4) fluxes, 2) quantify direct N_2O emission factors (EF_d) of fertilized urban soils used e.g., as lawns or forests, and 3) identify the key drivers leading to flux changes associated with urbanization. On average, urbanization increases soil N_2O emissions by 153%, to 3.0 kg N ha^{-1} yr^{-1}, while rates of soil CH_4 uptake are reduced by 50%, to 2.0 kg C ha^{-1} yr^{-1}. The global mean annual N_2O EF_d of fertilized lawns and urban forests is 1.4%, suggesting that urban soils can be regional hotspots of N_2O emissions. On a global basis, conversion of land to urban greenspaces has increased soil N_2O emission by 0.46 Tg N_2O-N yr^{-1} and decreased soil CH_4 uptake by 0.58 Tg CH_4-C yr^{-1}. Urbanization driven changes in soil N_2O emission and CH_4 uptake are associated with changes in soil properties (bulk density, pH, total N content and C/N ratio), increased temperature, and management practices, especially fertilizer use. Overall, our meta-analysis shows that urbanization increases soil N_2O emissions and reduces the role of soils as a sink for atmospheric CH_4. These effects can be mitigated by avoiding soil compaction, reducing fertilization of lawns, and by restoring native ecosystems in urban landscapes.

KEY WORDS: urbanization; nitrous oxide; methane; climate change; greenspace; lawn; urban forest; emission factor

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1 INTRODUCTION

Increasing populations and the search for social and economic opportunities are driving people to move from rural to urban areas (Montgomery, 2008; Wang et al., 2021a; Zhang et al., 2022a). Approximately 4% of the global land area is urbanized and half of the world's population lives in urban areas (United Nations, 2018; Zhang et al., 2021). The trend towards urbanization is driving conversion of natural (e.g., grassland and forest) and managed (e.g., arable land and grazed pasture) ecosystems into urban landscapes dominated by residential areas with interspersed greenspaces (e.g., lawns and urban forests) (IPCC, 2013; van Delden et al., 2018; Liu et al., 2019, 2020). These conversions affect ecosystem functions and services including biodiversity support, food security, and climate regulation by carbon sequestration (Zhou et al., 2004; Seto et al., 2012; Wang et al., 2021a; Yu et al., 2022; Zhang et al., 2022a).

Urbanization and associated increases in energy consumption are drivers of global climate change (e.g., Kaye et al., 2006; Grimm et al., 2008; Hopkins et al., 2016; Pan et al., 2020). Urban building, transport and industrial activities produce significant amounts of greenhouse gas (GHG) emissions (Hoornweg et al., 2011; Sari and Bayram, 2014; Ward et al., 2015). Cities also have significant greenspaces for recreation or improvement of air quality and urban climate (Gregg et al., 2003; Law and Patton, 2017; Nowak et al., 2018; Liu et al., 2021; Yu et al., 2022). These urban green areas can act sources and/or sinks for GHGs, including carbon dioxide (CO_2), which can be sequestered in urban forest ecosystems (Escobedo et al., 2011), as well as the non-CO_2 GHG methane (CH_4) and nitrous oxide (N_2O), which have global warming potentials 28 and 273 times higher than CO_2 over a 100-year horizon, respectively (IPCC, 2021). CH_4 and N_2O fluxes at the soil-atmosphere interface are the result of simultaneously occurring microbial aerobic or anaerobic production and consumption processes, which

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are regulated by a complex suite of environmental factors such as soil moisture and temperature as well as nutrient availability (Conrad, 1996; Butterbach-Bahl et al., 2013; van Delden et al., 2018; Ni and Groffman, 2018). Urbanization significantly alters these factors due to heat island effects, increased atmospheric N deposition as a result of industrial and traffic emissions, and soil compaction and redistribution in the course of urban landscaping. This alteration affects C and N biogeochemical cycles in urban soils and associated production and consumption of CH_4 and N_2O (Kaye et al., 2006; Groffman et al., 2009; Ni and Groffman, 2018; Xu et al., 2022). Previous studies have reported low or full inhibition of soil atmospheric CH_4 uptake in urban forests and lawns in China and the USA due to increases in soil bulk density, which constrains diffusion of atmospheric CH_4 to sites of microbial CH_4 uptake by methanotrophs, or increases in soil N availability, which may directly inhibit CH_4 uptake (Kaye et al., 2004; Groffman and Pouyat, 2009; Zhang et al., 2014). Zhang et al. (2021) found that with increasing intensity of urbanization soil CH_4 uptake decreased, while the methanotrophic community was not affected.

With regard to soil N_2O emissions from urban greenspaces, contradictory results have been reported. While some studies have reported low N_2O emissions from urban soils (e.g., Groffman et al., 2009), other studies have reported high fluxes, especially if soils were fertilized (e.g., lawns or golf courses) (Kaye et al., 2004; van Delden et al., 2018; Xu et al., 2022). Dutt and Tanwar (2020) conducted a meta-analysis to evaluate the effect of fertilzer application on lawn N_2O emissions, and found that lawn N_2O emissions from fertilized plots were 41% (or 0.29 g N m^{-2} yr^{-1}) higher than those from non-fertilized controls. A literature review by Braun and Bremer (2018) found that annual N_2O emissions from fertilized urban lawns ranged from 1.0 to 7.6 kg N ha^{-1} yr^{-1}, comparable to N_2O fluxes from intensively fertilized agricultural soils. A study

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conducted in Fort Collins, Colorado USA showed that even though fertilized urban lawns occupied only 6.4% of the land area, they contributed 30% of regional soil to atmosphere N_2O emissions (Kaye et al., 2004). Fertilization rates of lawns can exceed 200 kg N ha^{-1} yr^{-1} (Braun and Bremer, 2018), and as soil N_2O emissions can increase nonlinearly in response to fertilization (Shcherbak et al., 2014), the currently used N_2O emission factor (EF_d) for fertilized soils of 1% (IPCC, 2006) may not accurately estimate the regional source strength of soils in urban areas (Kaye et al., 2006). There is a clear need to test and develop N_2O EF_d for fertilized urban soils.

In this study, we performed a global synthesis of studies of soil CH_4 and N_2O fluxes from urban greenspaces. Our objectives were (1) to provide an overall assessment of how urbanization-induced land-use conversion affects soil CH_4 and N_2O fluxes, (2) to calculate a general global N_2O EF_d for fertilized soils of urban greenspaces, and (3) to explore how climate conditions, soil properties or land-use modulates the response of soil non-CO_2 GHGs fluxes to urbanization.

2 MATERIALS AND METHODS

2.1 Literature search and data extraction

In order to study the effects of urbanization on non-CO_2 GHG (CH_4 and N_2O) fluxes in soils of urban greenspaces, we carried out a detailed review of the peer-reviewed literature published before April 2022, using ISI-Web of Science and Google Scholar. Specific search terms were: urbanization; urban greenspace; turfgrass; lawn; urban forest; N_2O; nitrous oxide; CH_4; methane; GHG; greenhouse gas. Articles were retained for use in our meta-analysis if: (a) the study was field-based (i.e., excluding e.g., pot and laboratory experiments or model simulations); (b) the observation period covered at least a growing season (which usually refers to the main growing period, i.e., during the summer and/or wet season); (c) CH_4 and/or N_2O fluxes were reported for soils of

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urban greenspaces (lawns or urban forests) as well as for comparable land-uses in a non-urban setting; (d) the reported experiment included treatments of different N type or rate of fertilizer application in the urban greenspaces. The raw data were either extracted directly from tables and texts or retrieved digitally from graphs using GetData Graph Digitizer (version 2.25.0.32, http://www.getdata-graph-digitizer.com/).

We identified a total of 32 peer-reviewed publications reporting on 197 side-by-side comparisons of urban lawns and forests with natural (grassland and forest) or non-urban managed (arable land and grazed pasture) ecosystems, as well as 119 observational studies of soil N_2O emissions in urban greenspaces (Dataset S1). The majority of these observations were made in North America, with a few studies in Europe, Australia or Asia. The 197 paired observations were further grouped into three categories: urbanization effects on (1) soil N_2O emission (n = 78), (2) soil CH_4 uptake (n = 72) and (3) sum of non-CO_2 GHG (CH_4+N_2O) flux (n = 47). The 119 experimental observations were used to investigate N fertilization effects on soil N_2O emission from urban forests and lawns.

For soil CH_4 fluxes, all observations covered at least an entire year, allowing us to directly retrieve or calculate annual cumulative uptake rates (in kg C ha^{-1} yr^{-1}). For soil N_2O fluxes, not all studies report on measurements covering an entire observational year (n = 12 out of 28 studies). For cases reporting only growing season soil N_2O fluxes (these studies were mainly located on the temperate zone), we gap-filled the data by assuming that non-growing time fluxes account for on average 28% of the total annual budget as was found by Zhan et al. (2021) for a temperate urban site in China. Cumulative non-CO_2 GHG fluxes, i.e., the sum of soil CH_4 and N_2O fluxes, were only calculated for studies which simultaneously measured both GHG fluxes (n = 6 out of 15 studies). For this calculation we used the conversion factors of 28 and 273 for the

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global warming potential of CH_4 and N_2O, respectively, for a 100-year time horizon (IPCC, 2021), and expressed the non-CO_2 GHG flux as CO_2 equivalents (in kg CO_2-eq ha^{-1} yr^{-1}). In addition, other key information including location of experimental site, rate and type of N fertilizer application, soil texture, soil bulk density (BD), soil pH, soil organic C (SOC), total N (TN) and C/N ratio was extracted and included in our database (Dataset S1).

2.2 Data and statistical analysis

An effect size of the natural logarithm of the response ratio (ln RR) was employed to assess the effect of urbanization-induced land-use conversion on soil N_2O emission, soil CH_4 uptake and soil physicochemical properties (e.g., SOC, TN, C/N ratio, BD, pH and clay content) (Hedges et al., 1999):

$$\ln \mathrm{RR} = \ln\left(\frac{\overline{\mathrm{X}_\mathrm{t}}}{\overline{\mathrm{X}_\mathrm{c}}}\right) = \ln(\overline{\mathrm{X}_\mathrm{t}}) - \ln(\overline{\mathrm{X}_\mathrm{c}})$$

where $\overline{X_t}$ and $\overline{X_c}$ are the mean values of the selected annual N_2O emissions, CH_4 uptake rates or soil property parameters for urban and non-urban land-use, respectively. The meta-analysis results were reported as percentage changes (i.e., %change= (exp (ln RR) - 1) × 100%). Positive percentage changes indicate an increase, and negative values denote a decrease in the variable as an effect of urbanization.

The values of non-CO_2 GHG (CH_4+N_2O) fluxes can be both positive and negative, which makes the abovementioned ln RR equation problematic. As suggested by previous studies (e.g., van Groenigen et al., 2011; Xia et al., 2017), therefore, the response of a variable (RR′) was assessed by the formula:

$$\mathrm{RR}' = \overline{\mathrm{X}}_\mathrm{t} - \overline{\mathrm{X}}_\mathrm{c}$$

For these analyses, effect sizes were weighted by the inverse of the pooled variance (var) of each individual observation, calculated by the following equation (Hedges et al., 1999):

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$$var = \frac{s_t^2}{n_t\bar{X}_t^2} + \frac{s_c^2}{n_c\bar{X}_c^2}$$

where s_t and s_c are the standard deviations (SD) of $\bar{X}_t$ and $\overline{X_c}$, respectively; n_t and n_c are the number of replicates per treatment for $\bar{X}_t$ and $\overline{X_c}$, respectively. For studies in which the standard error (SE) rather than SD was reported, we recalculated the SD by:

$$SD = SE \times \sqrt{n}$$

where n is the number of replicates. When the SD or SE data were not reported, we estimated the SD values based on the average coefficient of variation for the known data (De Stefano and Jacobson, 2018).

To assess N fertilization effects on soil N_2O emissions in urban greenspaces, we performed a pair-wise meta-analysis using EF_d as the effect size, which was calculated by the equation (Wang et al., 2020):

$$EF_d(\%) = \frac{E_f - E_0}{N} \times 100$$

where N refers to the rate of N fertilizer application (in kg N ha^{-1} yr^{-1}), and E_f and E_0 represent annual cumulative N_2O emissions (in kg N ha^{-1} yr^{-1}) for fertilized urban soils and non-fertilized controls, respectively. For sites where no background N_2O emissions from a non-fertilized control (E_0) were reported, we estimated background emissions from studies conducted in the same region under comparable climate and soil conditions. More than half of the EF_d data lacked information on the pooled variance, so the meta-analysis of EF_d was unweighted (Chen et al., 2013; Qasim et al., 2021).

Means of effect sizes and their 95% confidence intervals (CIs) were calculated using a bootstrapping procedure with 999 iterations generated by MetaWin 2.1 (Rosenberg et al., 2000). If 95% CI values of the ln RR for a variable did not overlap with zero, the effect size was considered to be significant at $P < 0.05$. According to Wang et al. (2021b), the frequency distribution of response ratios (i.e., ln RR) for each variable

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were plotted by a Gaussian function, which was generally normally distributed (Figure S1).

In this meta-analysis, several categorical variables were used to evaluate their effects on land-use conversion-induced changes in soil CH_4 and N_2O fluxes as well as non-CO_2 GHG (CH_4+N_2O) fluxes, including land-use change type and climate conditions (mean annual temperature (MAT) and precipitation (MAP), Table S1). The subgroup classification of these variables was conducted in terms of aiming for maximal in-group homogenization and exploration of site-specific variation (Jeffery et al., 2011). For MAT and MAP, therefore, subgroups were split at MAT > 13°C and MAP >1060 mm. In addition, the effects of N application rate, N type and soil properties (e.g., soil texture, pH, BD, SOC, TN and C/N ratio) on the N_2O EF_d were also examined (Table S1). Between-group heterogeneity (Q_b) tests were used to examine the significance of each sub-group category (Table S2). A model selection analysis in the R package "*glmulti*" was used to identify the most important predictors of the response of soil N_2O emission and CH_4 uptake to urbanization as well as the N_2O EF_d of urban soils (Calcagno and de Mazancourt, 2010). The relative importance of a particular predictor was expressed as the sum of Akaike weights for all multiple linear models that included this predictor, and a cutoff of 0.8 was set to differentiate between important and non-essential predictors (Terrer et al., 2016). We also used non-linear or linear regression analysis to analyze the relationships between environmental factors and soil N_2O emission, CH_4 uptake or N_2O EF_d under urbanization. The regression analysis was conducted with SPSS version 23.0 (SPSS China, Beijing, China) and the graphs were drawn with the Origin software (Origin 2018 for Windows).

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3 RESULTS

3.1 Effects of urbanization-induced land-use conversion on soil non-CO_2 GHG (CH_4 and N_2O) fluxes

Overall, urbanization-induced land-use conversion (hereafter referred to as urbanization) significantly increased soil N_2O emissions by 153% (CIs: 107% to 214%). The increase was 102% (CIs: 19% to 339%) if arable land and grazed pasture (hereafter referred to as managed ecosystems) are changed into fertilized lawns, 225%-1259% if natural grassland and forest (hereafter referred to as natural ecosystems) are converted to fertilized lawns, and 126% if natural forest is converted to fertilized urban forests (Figure 1a). In contrast, the increase tended to be relatively lower (ranging from 111% to 266%) if natural ecosystems are converted to non-fertilized urban lawns and forests. On average, annual soil N_2O emissions increased from 1.2 ± 0.2 (mean ± SE) kg N ha^{-1} yr^{-1} (median: 0.5 kg N ha^{-1} yr^{-1}) in non-urban environments to 3.0 ± 0.4 kg N ha^{-1} yr^{-1} (median: 1.8 kg N ha^{-1} yr^{-1}) in urban greenspaces (Figure 2a).

The response of soil N_2O emission to urbanization varied with climate conditions (Figures. 1 and S3). For example, the positive effects of urbanization on soil N_2O emission tended to be higher at sites with a MAT >13 °C or if the MAP exceeded 1060 mm, but their trends were not statistically significant.

Our analysis shows that urbanization also affects soil properties such as BD (+10.4%), TN (+34.9%), pH (+ 9.7%), SOC (-19.2%), C/N ratio (-21.6%) and clay content (-26.7%) (Figure S2). Regression analysis indicated that the ln RR of soil N_2O emission was positively correlated with the ln RR of SOC and clay content (Figure S3). These findings were further supported by assessing the performance of multiple linear models using Akaike weights, showing that MAT, clay content and C/N ratio were key environmental factors explaining the variance of soil N_2O emissions in response to

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urbanization (Figure 3a).

On average, urbanization significantly decreased soil CH_4 uptake by 50% (CIs: 45% to 55%) (Figure 1b). However, the effects of urbanization on soil CH_4 uptake depended greatly on the type of land-use change. Urbanization significantly reduced soil CH_4 uptake by 48%-98% for changing natural ecosystems into urban greenspaces regardless of N fertilization, but showed the tendency of increased CH_4 uptake (39%, CIs: -4% to 106%) if managed ecosystems are converted to lawns (Figure 1b). The mean annual CH_4 uptake by soils of urban greenspaces was 2.0 ± 0.2 kg C ha^{-1} yr^{-1} (median: 2.1 kg C ha^{-1} yr^{-1}), lower than uptake by non-urban soils (mean: 4.3 ± 0.3 kg C ha^{-1} yr^{-1}; median: 4.4 kg C ha^{-1} yr^{-1}) (Figure 2b).

Similar to soil N_2O emission, the response of soil CH_4 uptake to urbanization was affected by soil properties. The ln RR of soil CH_4 uptake was negatively correlated with the ln RR of BD, TN and pH, and there was a quadratic relationship with clay content (Figure S3). Our multiple linear model selection analysis confirmed the importance of land-use type and TN on the response of soil CH_4 uptake to urbanization (Figure 3b).

Across all studies reporting simultaneous measurements of soil N_2O and CH_4 fluxes, urbanization significantly increased the fluxes of non-CO_2 GHG (CH_4+N_2O) by 674 kg CO_2-eq ha^{-1} yr^{-1} (CIs: 497 to 842 kg CO_2-eq ha^{-1} yr^{-1}) (Figure 1c). Increases for changing natural ecosystems into urban forests and lawns were with 661-1000 kg CO_2-eq ha^{-1} yr^{-1}, higher than the effect of converting managed ecosystems to lawns (381 kg CO_2-eq ha^{-1} yr^{-1}, CIs: 82 to 767 kg CO_2-eq ha^{-1} yr^{-1}).

3.2 Direct N_2O emission factors (EF_d) for fertilized soils in urban greenspaces

The mean annual N_2O emission from fertilized urban soils was 3.5 ± 0.4 kg N ha^{-1} yr^{-1}, significantly higher than emissions from non-fertilized soils (2.0 ± 0.4 kg N ha^{-1} yr^{-1}) (Figure 4). Annual N_2O emissions from urban soils increased linearly with

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increasing N fertilization, but this correlation was weak, as the determination coefficient R^2 was only 0.04 (Figure S4).

Overall, the global mean annual N_2O EF_d of fertilized urban soils was 1.4% (CIs: 1.1% to 1.8%), but this varied with the type of urban greenspace (Figure 5a). On average, the annual N_2O EF_d was 3.7% (CIs: 2.6% to 4.9%) for fertilized urban forests. For fertilized urban lawns, the annual N_2O EF_d decreased in the following order: athletic lawn (5.4%) > golf course (2.3%) > residential lawn (1.2%) > institutional lawn (1.0%) > other lawns (public park and ornamental landscape) (0.8%), with an overall mean value of 1.3%. Further analyses showed that the annual N_2O EF_d was not affected by climate or type of N fertilization (Figure 5). However, a higher N_2O EF_d was calculated for soils in urban greenspaces with BD >1.3 g cm^{-3} (Figures. 5g and S5).

Our model selection analysis revealed that soil BD and pH were the most important variables explaining variations of the N_2O EF_d (Figure 3c).

4 DISCUSSION

4.1 Effects of urbanization on soil N_2O and CH_4 fluxes and its drivers

Urbanization is driving local to global alterations of biogeochemical cycles and these changes also affect soil GHG emissions (Kaye et al., 2006; Grimm et al., 2008). While the effect of urbanization on regional CO_2 fluxes is well documented, showing that urban areas are strong net sources (while terrestrial ecosystems, specifically natural and forested landscapes may function as carbon sinks) (e.g., Seto et al., 2012; Chien and Krumins, 2022), little information is available on effects of urbanization on soil non-CO_2 GHG (CH_4 and N_2O) fluxes. In this study, our synthesis shows that non-CO_2 GHG emissions from soils of urban greenspaces are significantly higher than emissions from non-urban soils. This difference was due to increases in soil N_2O emission (+153%), while uptake of atmospheric CH_4 by soils was decreased by about 50% in urban

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greenspaces (Figures. 1 and 2). Urban land conversion had a positive effect on N_2O emissions even if the conversion does not involve fertilizer. However, relatively higher rates of soil CH_4 uptake were observed if managed ecosystems were converted to urban lawns (+39%).

Previous studies have shown that natural forest and grassland soils are a major sink for atmospheric CH_4 via microbial consumption by methanotrophic bacteria (e.g., Kirschke et al., 2013; Ni and Groffman, 2018). Generally, farming practices such as tillage, N fertilization or grazing decrease soil methanotrophic populations and activities, and thus, soil CH_4 uptake (e.g., Ding et al., 2004; Chen et al., 2011). Conversion of such agricultural soils into lawns reduces soil disturbance, which may explain why uptake of atmospheric CH_4 was increased by conversion to lawns (van Delden et al., 2018).

In our study, the estimated N_2O EF_d for urban forests (3.7%) was higher than the mean EF_d of 1.43% for global fertilized forest soils (Liu et al., 2017); while the mean N_2O EF_d for urban lawns (1.3%) was in the middle of the reported range for fertilized grassland soils (0.30%-2.49%) at regional and global scales (Freibauer and Kaltschmitt, 2003; Aguilera et al., 2013; van der Weerden et al., 2016; Liu et al., 2017). The overall mean N_2O EF_d (1.4%) for soils in urban greenspaces was higher than the estimated EF_d of 1.2% for tropical and subtropical agricultural systems (Albanito et al., 2017), or the IPCC default value of 1% for global croplands (IPCC, 2006). All these comparisons indicate that urban soils are regional hotspots for N_2O emissions.

While there are no reliable published global estimates of the area occupied by urban greenspaces, several studies have suggested that urban ecosystems currently comprise at least 2% of the global terrestrial land area (Kaye et al., 2004; Potere and Schneider, 2007; Hall et al., 2008). Also, multiple studies have shown that for urban greenspaces approximately 50% of lawns and 10% of forests are fertilized (Law et al., 2004; Fraser

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et al., 2013; Polsky et al., 2014; Groffman et al., 2016; Locke et al., 2018, 2019). Therefore, we roughly estimate that the total area of individual greenspaces is 149 Mha for fertilized lawns, 30 Mha for fertilized urban forests and 119 Mha for non-fertilized lawns and forests (Table 1). To estimate the global effect of urbanization on soil non-GHG emissions, we multiplied the differences in soil N_2O emission and CH_4 uptake due to urbanization-induced land-use conversion (both expressed as area-scaled metrics) by the corresponding total greenspace areas. We estimate that conversion from non-urban landscapes to urban greenspaces increases N_2O emission by 0.46 (CIs: 0.30-0.64) Tg N_2O-N yr^{-1} and decreases CH_4 uptake by 0.58 (CIs: 0.38-0.80) Tg CH_4-C yr^{-1}, which is equivalent to 6.3% of global anthropogenic N_2O emissions (i.e., 7.3 Tg N_2O-N yr^{-1}) and 2.6% of global soil CH_4 uptake (i.e., 22.5 Tg CH_4-C yr^{-1}) (IPCC, 2021). Overall, the urban land conversion-induced increase in soil non-CO_2 GHG emissions is 218 (CIs: 158-286) Tg CO_2-eq yr^{-1}, which is equivalent to 3.5% of global agriculture non-CO_2 GHG emissions (i.e., 6.2 Pg CO_2-eq yr^{-1}) (IPCC, 2021).

It is well known that soil N_2O and CH_4 fluxes are strongly affected by many abiotic, biotic and anthropogenic factors, including climate conditions, soil properties and management practices (e.g., Groffman and Pouyat, 2009; Butterbach-Bahl et al., 2013). With regard to climate conditions, the best-documented feature of urbanization is the urban heat island effect, which elevates air temperatures in urban environments by 1-3 °C compared to rural sites (Santamouris, 2015). At increased soil temperatures, if soil moisture does not become limiting, decomposition of organic matter and nutrient mineralization is stimulated, which contribute to the increase in N_2O emission from urban soils (Bijoor et al., 2008; Zhan et al., 2021). Likewise, the urban heat island effect may also promote soil methanogenic and methanotrophic activities (i.e., the rates of CH_4 production and oxidation) (Butterbach-Bahl and Papen, 2002; Zhang et al., 2021).

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Besides increased temperatures, urban areas also often receive higher precipitation, since higher concentrations of condensation nuclei and surface roughness in urban environments have been found to stimulate precipitation (Gregg et al., 2003; Liu and Niyogi, 2019; Sun et al., 2021). This change in precipitation affects soil moisture, soil aeration and redox potential, and may support the development of soil anaerobiosis which promotes the activity of methanogens and stimulates microbial denitrification processes (Hartmann et al., 2011; van Delden et al., 2018). These changes decrease net uptake of CH_4 and increase N_2O emissions. Consistent with this reasoning, our results show that N_2O emissions from urban soils tended to be higher at sites with MAP > 1060 mm, while the response of soil CH_4 uptake tended to decrease with increasing precipitation (Figure 1).

In addition to climate conditions, greater atmospheric N deposition (due to fossil fuel combustion and industrial processes) as well as anthropogenic management (e.g., N fertilization and irrigation) in urban greenspaces can result in increased abundances and activity of ammonia oxidizer and denitrifier populations, and higher soil inorganic N concentrations and soil TN content (as shown in this and previous (Dutt and Tanwar, 2020) studies). These changes in soil nutrient concentrations and the soil microbiome in urban soils support greater rates of nitrification and denitrification and subsequent N_2O emissions (Rao et al., 2014; Xu et al., 2022; Zhang et al., 2022b). Higher rates of N cycling in urban soils usually leads to a reduction in CH_4 uptake by suppressing methanotroph populations and activities (Kravchenko et al., 2002; Costa and Groffman, 2013; Bodelier, 2011; Tate, 2015; Wu et al., 2022).

Soil properties can also be altered by human disturbances associated with urbanization, such as removal, compaction, burial or construction activities (Byrne, 2007). Our meta-analysis shows that urbanization significantly increases soil BD, TN and pH and

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decreases soil C/N ratio, SOC and clay content (Figure S2). The urbanization-induced changes in these soil parameters likely contribute to the observed changes in soil CH_4 and N_2O fluxes. The higher BD associated with urban soil compaction reduces porosity and gas diffusivity, decreasing the flow of CH_4 from the atmosphere to oxidizing populations. Increases in BD can increase N_2O production by increasing the fraction of anaerobic volume in soils (De Neve and Hofman, 2000; Byrne, 2007; Pulido-Moncada et al., 2022). This effect is supported by our regression analysis showing that the ln RR of soil CH_4 uptake was negatively correlated with the ln RR of BD (Figure S3).

The higher TN and lower C/N ratio in urban soils likely support higher rates of N transformation (particularly mineralization and nitrification) and associated N_2O production, while hampering methanotrophic activities and CH_4 uptake (Zhu and Carreiro, 2004; Zhang et al., 2021). This is supported by the negative correlation between the ln RR of CH_4 uptake and the ln RR of soil TN (Figure S3). In addition, the alteration of soil pH associated with urbanization may affect soil N_2O and CH_4 fluxes. For example, increasing soil pH has been observed to accelerate soil N_2O emissions, due to stimulation of nitrification and N_2O production by nitrifiers (Baggs et al., 2010; Wang et al., 2021b). On the other hand, increases in soil pH may negatively affect CH_4 uptake or even result in net emissions of CH_4 from arable and forest soils due to effects on soil inorganic N and labile C availability (Butterbach-Bahl and Papen, 2002; Wang et al., 2021b). However, our study also shows that urbanization is associated with decreases in SOC and soil clay content. This is most likely due to the addition of materials from a variety of sources (e.g., the presence of dust and materials from the buildings, external soils and other materials with low differentiation of clay), the change of arrangement or sequence of horizons in urban soil profile during the urbanization processes, or the lower coefficient of clay formation values in the urban soils

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(Doichinova et al., 2006; Sun et al., 2013; Herrmann et al., 2018). This indicates that the availability of C substrates and the tendency of soils to become anaerobic is lower in urban soils as compared to soils in rural areas. These changes would tend to decrease soil N_2O emissions and increase CH_4 uptake (Li et al., 2005; Yao et al., 2019). The net effect of the interacting soil factors controlling N_2O and CH_4 fluxes appears to be changes in environmental conditions and soil physicochemical properties that stimulate urban soil N_2O emissions, while reducing soil CH_4 uptake in urban environments (Figure 6).

4.2 Uncertainties and implications for future studies

There are several important uncertainties in our analysis. First, some bias may arise from uneven distribution of experimental sites, with a dominance of studies in North America and other areas in the temperate zone, and an unbalanced selection of ecosystem types. Specifically, there were no studies available for South America and Africa. Given the rapid urban sprawl in all parts of the world, particularly in emerging countries like China and India, more studies in these regions are needed to better understand the importance of urbanization on soil non-CO_2 GHG fluxes in a global context. Second, too few studies had multiple years of data. The majority of studies in our database lasted for 1 or 2 years, and the few observations available reporting on flux measurements of >2 years showed high interannual variations (Ni and Groffman, 2018; van Delden et al., 2018). There is a clear need for future field measurements spanning multiple years, particularly for underrepresented regions or climate zones (e.g., in tropical regions of South America) in order to more accurately quantify changes in non-CO_2 GHG fluxes under urbanization. Lastly, the complex interactions among various biotic and abiotic factors (i.e., climate conditions, soil properties and anthropogenic management activities) involved in the consumption, production and net

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flux of CH_4 and N_2O from urban soils results in unavoidable uncertainties. Future studies should focus on processes of CH_4 and N_2O formation and consumption in urban soils to allow for comparative evaluation of biogeochemical changes associated with urban land use change.

Given ongoing trends in urbanization, the importance of urban soils as sources of non-CO_2 GHG at regional scales will increase. This highlights the urgent need for accurate mapping of dynamic land use change due to urbanization and to incorporate urbanization effects on soil GHG fluxes into Earth system models to allow better evaluation of the relationships between urbanization and climate. These assessments will also help to identify effective and efficient mitigation and adaptation strategies (e.g., avoiding urban soil compaction, reducing N input in urban environments and improving urban afforestation) to achieve sustainable and resilient urban development.

5 CONCLUSIONS

Our meta-analysis provides a first comprehensive assessment of the response of soil N_2O emission and CH_4 uptake to urbanization. Overall, our results show that urbanization can accelerate global climate change by increasing soil N_2O emissions while reducing rates of CH_4 uptake in soils in urban greenspaces. The global mean annual N_2O EF_d for urban forests and lawns are at least 50% higher than the current IPCC default value, highlighting that urban soils can be significant hotspots for regional N_2O emissions. With a rapid proliferation of urban land use and cover worldwide, greater non-CO_2 GHG emissions from urban soils can be anticipated. However, the magnitude of these urbanization effects is largely dependent on environmental conditions, soil properties and land-use type. Overall, our study may help to better understand effects of urbanization on soil GHG fluxes as an underestimated driver of climate change, to stimulate more research in this field, and to consider urban soil

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management as an overlooked tool for sustainable development.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are publicly available at Dryad via https://doi.org/10.5061/dryad.v9s4mw714.

REFERENCES

Aguilera, E., Lassaletta, L., Sanz-Cobena, A., Garnier, J., & Vallejo, A. (2013). The potential of organic fertilizers and water management to reduce N_2O emissions in Mediterranean climate cropping systems. A review. Agriculture Ecosystems & Environment, 164, 32-52. https://doi.org/10.1016/j.agee.2012.09.006

Albanito, F., Lebender, U., Cornulier, T., Sapkota, T. B., Brentrup, F., Stirling, C., & Hillier, J. (2017). Direct nitrous oxide emissions from tropical and sub-tropical agricultural systems- A review and modelling of emission factors. *Scientific Reports, 7*. https://doi.org/10.1038/srep44235

Baggs, E. M., Smales, C. L., & Bateman, E. J. (2010). Changing pH shifts the microbial sourceas well as the magnitude of N_2O emission from soil. *Biology and Fertility of Soils, 46*(8), 793-805. https://doi.org/10.1007/s00374-010-0484-6

Accepted Article

13652486, ja, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/gcb.16652 by Test, Wiley Online Library on [28/02/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Accepted Article

Bijoor, N. S., Czimczik, C. I., Pataki, D. E., & Billings, S. A. (2008). Effects of temperature and fertilization on nitrogen cycling and community composition of an urban lawn. *Global Change Biology, 14*(9), 2119-2131. https://doi.org/10.1111/j.1365-2486.2008.01617.x

Bodelier, P. L. E. (2011). Interactions between nitrogenous fertilizers and methane cycling in wetland and upland soils. *Current Opinion in Environmental Sustainability, 3*(5), 379-388. https://doi.org/10.1016/j.cosust.2011.06.002

Braun, R. C., & Bremer, D. J. (2018). Nitrous oxide emissions in turfgrass systems: a review. *Agronomy Journal, 110*(6), 2222-2232. https://doi.org/10.2134/agronj2018.02.0133

Butterbach-Bahl, K., & Papen, H. (2002). Four years continuous record of CH_4-exchange between the atmosphere and untreated and limed soil of a N-saturated spruce and beech forest ecosystem in Germany. *Plant and Soil, 240*(1), 77-90. https://doi.org/10.1023/A:1015856617553

Butterbachbahl, K., Baggs, E. M., Dannenmann, M., Kiese, R., & Zechmeisterboltenstern, S. (2013). Nitrous oxide emissions from soils: how well do we understand the processes and their controls? *Philosophical Transactions of The Royal Society B Biological ences, 368*(1621), 20130122. https://doi.org/10.1098/rstb.2013.0122

Byrne, L. B. (2007). Habitat structure: A fundamental concept and framework for urban soil ecology. *Urban Ecosystems, 10*(3), 255-274. https://doi.org/10.1007/s11252-007-0027-6

13652486, ja, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/gcb.16652 by Test, Wiley Online Library on [28/02/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Calcagno, V., & de Mazancourt, C. (2010). glmulti: An R Package for Easy Automated Model Selection with (Generalized) Linear Models. *Journal of Statistical Software, 34*(12), 1-29.

Chen, H., Li, X., Hu, F., & Shi, W. (2013). Soil nitrous oxide emissions following crop residue addition: a meta-analysis. *Global Change Biology, 19*(10), 2956-2964. https://doi.org/10.1111/gcb.12274

Chen, W., Wolf, B., Zheng, X., Yao, Z., Butterbach-Bahl, K., Bruggemann, N.,... Han, X. (2011). Annual methane uptake by temperate semiarid steppes as regulated by stocking rates, aboveground plant biomass and topsoil air permeability. *Global Change Biology, 17*(9), 2803-2816. https://doi.org/10.1111/j.1365-2486.2011.02444.x

Chien, S.C., & Krumins, J. A. (2022). Natural versus urban global soil organic carbon stocks: A meta-analysis. *Science of the Total Environment, 807*, 150999. https://doi.org/10.1016/j.scitotenv.2021.150999

Conrad, R. (1996). Soil microorganisms as controllers of atmospheric trace gases (H_2, CO, CH_4, OCS, N_2O, and NO). *Microbiological Reviews, 60*(4), 609-640. https://doi.org/10.1128/mr.60.4.609-640.1996

Costa, K. H., & Groffman, P. M. (2013). Factors regulating net methane flux in urban forests and grasslands. *Soil Science Society of America Journal, 77*(3), 850-855. https://doi.org/10.2136/sssaj2012.0268n

De Neve, S., & Hofman, G. (2000). Influence of soil compaction on carbon and nitrogen mineralization of soil organic matter and crop residues. *Biology and*

Accepted Article

13652486, ja, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/gcb.16652 by Test, Wiley Online Library on [28/02/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

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Fertility of Soils, 30(5), 544-549. https://doi.org/10.1007/s003740050034

De Stefano, A., & Jacobson, M. G. (2018). Soil carbon sequestration in agroforestry systems: a meta-analysis. *Agroforestry Systems, 92*(2), 285-299. https://doi.org/10.1007/s10457-017-0147-9

Ding, W. X., Cai, Z. C., & Tsuruta, H. (2004). Cultivation, nitrogen fertilization, and set-aside effects on methane uptake in a drained marsh soil in Northeast China. *Global Change Biology, 10*(10), 1801-1809. https://doi.org/10.1111/j.1365-2486.2004.00843.x

Doichinova, V., Zhiyanski, M., & Hursthouse, A. (2006). Impact of urbanisation on soil characteristics. *Environmental Chemistry Letters, 3*(4), 160-163. doi:10.1007/s10311-005-0024-z

Dutt, N., & Tanwar, T. (2020). Nitrous oxide emissions from turfgrass lawns as a result of fertilizer application: a meta-analysis of available literature. *Current Science, 118*(8), 1219-1226. doi:10.18520/cs/v118/i8/1219-1226

Escobedo, F. J., Kroeger, T., & Wagner, J. E. (2011). Urban forests and pollution mitigation: Analyzing ecosystem services and disservices. *Environmental Pollution, 159*(8), 2078-2087. https://doi.org/10.1016/j.envpol.2011.01.010

Fraser, J. C., Bazuin, J. T., Band, L. E., & Grove, J. M. (2013). Covenants, cohesion, and community: The effects of neighborhood governance on lawn fertilization. *Landscape and Urban Planning, 115*, 30-38. https://doi.org/10.1016/j.landurbplan.2013.02.013

Freibauer, A., & Kaltschmitt, M. (2003). Controls and models for estimating direct

13652486, ja, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/gcb.16652 by Test, Wiley Online Library on [28/02/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

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Accepted Article

nitrous oxide emissions from temperate and sub-boreal agricultural mineral soils in Europe. *Biogeochemistry, 63*(1), 93-115. https://doi.org/10.1023/a:1023398108860

Gregg, J. W., Jones, C. G., & Dawson, T. E. (2003). Urbanization effects on tree growth in the vicinity of New York City. *Nature, 424*(6945), 183-187. https://doi.org/10.1038/nature01728

Grimm, N. B., Faeth, S. H., Golubiewski, N. E., Redman, C. L., Wu, J. G., Bai, X. M., & Briggs, J. M. (2008). Global change and the ecology of cities. *Science, 319*(5864), 756-760. https://doi.org/10.1126/science.1150195

Groffman, P. M., Grove, J. M., Polsky, C., Bettez, N. D., Morse, J. L., Cavender-Bares, J.,... Locke, D. H. (2016). Satisfaction, water and fertilizer use in the American residential macrosystem. *Environmental Research Letters, 11*(3). https://doi.org/10.1088/1748-9326/11/3/034004

Groffman, P. M., & Pouyat, R. V. (2009). Methane uptake in urban forests and lawns. *Environmental Science & Technology, 43*(14), 5229-5235. https://doi.org/10.1021/es803720h

Groffman, P. M., Williams, C. O., Pouyat, R. V., Band, L. E., & Yesilonis, I. D. (2009). Nitrate leaching and nitrous oxide flux in urban forests and grasslands. *Journal of Environmental Quality, 38*(5), 1848-1860. https://doi.org/10.2134/jeq2008.0521

Hall, S. J., Huber, D., & Grimm, N. B. (2008). Soil N_2O and NO emissions from an arid, urban ecosystem. *Journal of Geophysical Research-Biogeosciences,*

Accepted Article

113(G1). https://doi.org/10.1029/2007jg000523

Hartmann, A. A., Buchmann, N., & Niklaus, P. A. (2011). A study of soil methane sink regulation in two grasslands exposed to drought and N fertilization. *Plant and Soil, 342*(1), 265-275. https://doi.org/10.1007/s11104-010-0690-x

Hedges, L. V., Gurevitch, J., & Curtis, P. S. (1999). The meta-analysis of response ratios in experimental ecology. *Ecology, 80*(4), 1150-1156. https://doi.org/10.1890/0012-9658(1999)080[1150:TMAORR]2.0.CO;2

Herrmann, D. L., Schifman, L. A., & Shuster, W. D. (2018). Widespread loss of intermediate soil horizons in urban landscapes. *Proceedings of the National Academy of Sciences, 115*(26), 6751-6755. doi:10.1073/pnas.1800305115

Hoornweg, D., Sugar, L., & Gomez, C. L. T. (2011). Cities and greenhouse gas emissions: moving forward. *Environment and Urbanization, 23*(1), 207-227. https://doi.org/10.1177/0956247810392270

Hopkins, F. M., Kort, E. A., Bush, S. E., Ehleringer, J. R., Lai, C. T., Blake, D. R., & Randerson, J. T. (2016). Spatial patterns and source attribution of urban methane in the Los Angeles Basin. *Journal of Geophysical Research-Atmospheres, 121*(5), 2490-2507. https://doi.org/10.1002/2015JD024429

IPCC. (2006). *IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme*. In: Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (Eds). IGES, Japan.

IPCC. (2013). *Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on*

13652486, ja, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/gcb.16652 by Test, Wiley Online Library on [28/02/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Climate Change (pp. 659–740). Cambridge University Press. https://doi.org/10.1017/CBO97 81107 415324.004.

IPCC. (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 673-816). Cambridge University Press. https://doi.org/10.1017/9781009157896.007

Jeffery, S., Verheijen, F. G. A., van der Velde, M., & Bastos, A. C. (2011). A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, Ecosystems & Environment, 144*(1), 175-187. https://doi.org/10.1016/j.agee.2011.08.015

Kaye, J. P., Burke, I. C., Mosier, A. R., & Pablo Guerschman, J. (2004). Methane and nitrous oxide fluxes from urban soils to the atmosphere. *Ecological Applications, 14*(4), 975-981. https://doi.org/10.1890/03-5115

Kaye, J. P., Groffman, P., Grimm, N., Baker, L., & Pouyat, R. (2006). A distinct urban biogeochemistry? *Trends in Ecology & Evolution, 21*(4), 192-199. https://doi.org/10.1016/j.tree.2005.12.006

Kirschke, S., Bousquet, P., Ciais, P., Saunois, M., Canadell, J. G., Dlugokencky, E. J., ... Zeng, G. (2013). Three decades of global methane sources and sinks. *Nature Geoscience, 6*(10), 813-823. https://doi.org/10.1038/NGEO1955

Kravchenko, I., Boeckx, P., Galchenko, V., & Van Cleemput, O. (2002). Short- and medium-term effects of NH_4^+ on CH_4 and N_2O fluxes in arable soils with a different texture. *Soil Biology and Biochemistry, 34*(5), 669-678.

Accepted Article

13652486, ja, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/gcb.16652 by Test, Wiley Online Library on [28/02/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

https://doi.org/10.1016/S0038-0717(01)00232-2

Law, N., Band, L., & Grove, M. (2004). Nitrogen input from residential lawn care practices in suburban watersheds in Baltimore county, MD. *Journal of Environmental Planning and Management, 47*(5), 737-755. https://doi.org/10.1080/0964056042000274452

Law, Q. D., & Patton, A. J. (2017). Biogeochemical cycling of carbon and nitrogen in cool-season turfgrass systems. *Urban Forestry & Urban Greening, 26*, 158-162. https://doi.org/10.1016/j.ufug.2017.06.001

Li, C., Frolking, S., & Butterbach-Bahl, K. (2005). Carbon sequestration in arable soils is likely to increase nitrous oxide emissions, offsetting reductions in climate radiative forcing. *Climatic Change, 72*(3), 321-338. https://doi.org/10.1007/s10584-005-6791-5

Liu, J., & Niyogi, D. (2019). Meta-analysis of urbanization impact on rainfall modification. *Scientific Reports, 9*(1), 7301. https://doi.org/10.1038/s41598-019-42494-2

Liu, S., Lin, F., Wu, S., Ji, C., Sun, Y., Jin, Y., … Zou, J. (2017). A meta-analysis of fertilizer-induced soil NO and combined NO+N_2O emissions. *Global Change Biology, 23*(6), 2520-2532. https://doi.org/10.1111/gcb.13485

Liu, X., Huang, Y., Xu, X., Li, X., Li, X., Ciais, P., … Zeng, Z. (2020). High-spatiotemporal-resolution mapping of global urban change from 1985 to 2015. *Nature Sustainability, 3*(7), 564-570. https://doi.org/10.1038/s41893-020-0521-x

Accepted Article

13652486, ja, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/gcb.16652 by Test, Wiley Online Library on [28/02/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Accepted Article

Liu, X., Pei, F., Wen, Y., Li, X., Wang, S., Wu, C., … Liu, Z. (2019). Global urban expansion offsets climate-driven increases in terrestrial net primary productivity. *Nature Communications, 10*(1), 5558. https://doi.org/10.1038/s41467-019-13462-1

Liu, Z., Cheng, W., Jim, C. Y., Morakinyo, T. E., Shi, Y., & Ng, E. (2021). Heat mitigation benefits of urban green and blue infrastructures: A systematic review of modeling techniques, validation and scenario simulation in ENVI-met V4. *Building and Environment, 200*, 107939. https://doi.org/10.1016/j.buildenv.2021.107939

Locke, D. H., Avolio, M., Trammell, T. L. E., Roy Chowdhury, R., Morgan Grove, J., Rogan, J., … Wheeler, M. M. (2018). A multi-city comparison of front and backyard differences in plant species diversity and nitrogen cycling in residential landscapes. *Landscape And Urban Planning, 178*, 102-111. https://doi.org/10.1016/j.landurbplan.2018.05.030

Locke, D. H., Polsky, C., Grove, J. M., Groffman, P. M., Nelson, K. C., Larson, K. L., … O'Neil-Dunne, J. (2019). Residential household yard care practices along urban-exurban gradients in six climatically-diverse US metropolitan areas. *Plos One, 14*(11). https://doi.org/10.1371/journal.pone.0222630

Montgomery, M. R. (2008). The urban transformation of the developing world. *Science, 319*(5864), 761-764. https://doi.org/10.1126/science.1153012

Ni, X., & Groffman, P. M. (2018). Declines in methane uptake in forest soils. *Proceedings of the National Academy of Sciences, 115*(34), 8587-8590.

13652486, ja, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/gcb.16652 by Test, Wiley Online Library on [28/02/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

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https://doi.org/10.1073/pnas.1807377115

Nowak, D. J., & Greenfield, E. J. (2018). Declining urban and community tree cover in the United States. *Urban Forestry & Urban Greening, 32*, 32-55. https://doi.org/10.1016/j.ufug.2018.03.006

Pan, H., Page, J., Zhang, L., Cong, C., Ferreira, C., Jonsson, E., … Kalantari, Z. (2020). Understanding interactions between urban development policies and GHG emissions: A case study in Stockholm Region. *AMBIO, 49*(7), 1313-1327. https://doi.org/10.1007/s13280-019-01290-y

Polsky, C., Grove, J. M., Knudson, C., Groffman, P. M., Bettez, N., Cavender-Bares, J., … Steele, M. K. (2014). Assessing the homogenization of urban land management with an application to US residential lawn care. *Proceedings of the National Academy of Sciences, 111*(12), 4432-4437. https://doi.org/10.1073/pnas.1323995111

Potere, D., & Schneider, A. (2007). A critical look at representations of urban areas in global maps. *GeoJournal, 69*(1-2), 55-80. https://doi.org/10.1007/s10708-007-9102-z

Pulido-Moncada, M., Petersen, S. O., & Munkholm, L. J. (2022). Soil compaction raises nitrous oxide emissions in managed agroecosystems. A review. *Agronomy for Sustainable Development, 42*(3), 38. https://doi.org/10.1007/s13593-022-00773-9

Qasim, W., Xia, L., Lin, S., Wan, L., Zhao, Y., & Butterbach-Bahl, K. (2021). Global greenhouse vegetable production systems are hotspots of soil N_2O emissions and nitrogen leaching: A meta-analysis. *Environmental Pollution, 272*, 116372. https://doi.org/10.1016/j.envpol.2020.116372

Rao, P., Hutyra, L. R., Raciti, S. M., & Templer, P. H. (2014). Atmospheric nitrogen inputs and losses along an urbanization gradient from Boston to Harvard Forest, MA. *Biogeochemistry, 121*(1), 229-245. https://doi.org/10.1007/s10533-013-9861-1

Rosenberg, M., Adams, D., & Gurevitch, J. (2000). *MetaWin: Statistical software for meta- analysis*. In M. Sunderland (Ed.). Sinauer Associates.

Santamouris, M. (2015). Analyzing the heat island magnitude and characteristics in one hundred Asian and Australian cities and regions. *Science of the Total Environment, 512-513*, 582-598. https://doi.org/10.1016/j.scitotenv.2015.01.060

Sari, D., & Bayram, A. (2014). Quantification of emissions from domestic heating in residential areas of Izmir, Turkey and assessment of the impact on local/regional air-quality. *Science of the Total Environment, 488*, 431-438. https://doi.org/10.1016/j.scitotenv.2013.11.033

Seto, K. C., Reenberg, A., Boone, C. G., Fragkias, M., Haase, D., Langanke, T., … Simon, D. (2012). Urban land teleconnections and sustainability. *Proceedings of the National Academy of Sciences, 109*(20), 7687-7692. https://doi.org/10.1073/pnas.1117622109

Shcherbak, I., Millar, N., & Robertson, G. P. (2014). Global metaanalysis of the nonlinear response of soil nitrous oxide (N_2O) emissions to fertilizer nitrogen.

Accepted Article

13652486, ja, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/gcb.16652 by Test, Wiley Online Library on [28/02/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Proceedings of the National Academy of Sciences, 111(25), 9199-9204. https://doi.org/10.1073/pnas.1322434111

Sun, T., Sun, R., Khan, M. S., & Chen, L. (2021). Urbanization increased annual precipitation in temperate climate zone: A case in Beijing-Tianjin-Hebei region of North China. *Ecological Indicators, 126*, 107621. https://doi.org/10.1016/j.ecolind.2021.107621

Sun, X., Wu, S., Wang, H., Zhao, Y., Zhang, G., Man, Y., & Wong, M. (2013). Dealing with spatial outliers and mapping uncertainty for evaluating the effects of urbanization on soil: A case study of soil pH and particle fractions in Hong Kong. *Geoderma, 195-196*, 220-233. doi: 10.1016/j.geoderma.2012.11.017

Tate, K. R. (2015). Soil methane oxidation and land-use change – from process to mitigation. *Soil Biology and Biochemistry, 80*, 260-272. https://doi.org/10.1016/j.soilbio.2014.10.010

Terrer, C., Vicca, S., Hungate Bruce, A., Phillips Richard, P., & Prentice, I. C. (2016). Mycorrhizal association as a primary control of the CO_2 fertilization effect. *Science, 353*(6294), 72-74. https://doi.org/10.1126/science.aaf4610

United Nations (2018). *Economics and social affairs. In: World Population Prospects: the 2018 Revision. Highlights and Advance Tables.* United Nations Population Division, United Nations (NY).

van Delden, L., Rowlings, D. W., Scheer, C., De Rosa, D., & Grace, P. R. (2018). Effect of urbanization on soil methane and nitrous oxide fluxes in subtropical Australia. *Global Change Biology, 24*(12), 5695-5707. https://doi.org/10.1111/gcb.14444

Accepted Article

13652486, ja, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/gcb.16652 by Test, Wiley Online Library on [28/02/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Accepted Article

van der Weerden, T. J., Cox, N., Luo, J., Di, H. J., Podolyan, A., Phillips, R. L., . . . Rys, G. (2016). Refining the New Zealand nitrous oxide emission factor for urea fertiliser and farm dairy effluent. *Agriculture, Ecosystems & Environment, 222*, 133-137. https://doi.org/10.1016/j.agee.2016.02.007

van Groenigen, K. J., Osenberg, C. W., & Hungate, B. A. (2011). Increased soil emissions of potent greenhouse gases under increased atmospheric CO_2. *Nature, 475*(7355), 214-U121. https://doi.org/10.1038/nature10176

Wang, S., Bai, X., Zhang, X., Reis, S., Chen, D., Xu, J., & Gu, B. (2021). Urbanization can benefit agricultural production with large-scale farming in China. *Nature Food, 2*(3), 183-191. https://doi.org/10.1038/s43016-021-00228-6

Wang, Y., Yao, Z., Zhan, Y., Zheng, X., Zhou, M., Yan, G., … Butterbach-Bahl, K. (2021). Potential benefits of liming to acid soils on climate change mitigation and food security. *Global Change Biology, 27*(12), 2807-2821. https://doi.org/10.1111/gcb.15607

Wang, Y., Yao, Z. S., Pan, Z., Wang, R., Yan, G. X., Liu, C., . . . Butterbach-Bahl, K. (2020). Tea-planted soils as global hotspots for N_2O emissions from croplands. *Environmental Research Letters, 15*(10). https://doi.org/10.1088/1748-9326/aba5b2

Ward, H. C., Kotthaus, S., Grimmond, C. S. B., Bjorkegren, A., Wilkinson, M., Morrison, W. T. J., … Iamarino, M. (2015). Effects of urban density on carbon dioxide exchanges: Observations of dense urban, suburban and woodland areas of southern England. *Environmental Pollution, 198*, 186-200.

13652486, ja, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/gcb.16652 by Test, Wiley Online Library on [28/02/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

https://doi.org/10.1016/j.envpol.2014.12.031

Wu, J., Cheng, X., Xing, W., & Liu, G. (2022). Soil-atmosphere exchange of CH_4 in response to nitrogen addition in diverse upland and wetland ecosystems: A meta-analysis. *Soil Biology and Biochemistry, 164*, 108467. https://doi.org/10.1016/j.soilbio.2021.108467

Xia, L., Lam, S. K., Yan, X., & Chen, D. (2017). How does recycling of livestock manure in agroecosystems affect crop productivity, reactive nitrogen losses, and soil carbon balance? *Environmental Science & Technology, 51*(13), 7450-7457. https://doi.org/10.1021/acs.est.6b06470

Xu, X., He, C., Zhong, C., Zhang, Q., Yuan, X., Hu, X., … Zhang, L. (2022). Soil N_2O emission in *Cinnamomum camphora* plantations along an urbanization gradient altered by changes in litter input and microbial community composition. *Environmental Pollution, 299*, 118876. https://doi.org/10.1016/j.envpol.2022.118876

Yao, Z., Ma, L., Zhang, H., Zheng, X., Wang, K., Zhu, B., … Butterbach-Bahl, K. (2019). Characteristics of annual greenhouse gas flux and NO release from alpine meadow and forest on the eastern Tibetan Plateau. *Agricultural And Forest Meteorology, 272-273*, 166-175. https://doi.org/10.1016/j.agrformet.2019.04.007

Yu, S., Wu, Z., Xu, G., Li, C., Wu, Z., Li, Z., ... Lin, Y. (2022). Inconsistent Patterns of Soil Fauna Biodiversity and Soil Physicochemical Characteristic Along an Urbanization Gradient. *Frontiers in Ecology and Evolution, 9*.

Accepted Article

13652486, ja, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/gcb.16652 by Test, Wiley Online Library on [28/02/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

https://doi.org/10.3389/fevo.2021.824004

Zhan, Y., Xie, J., Yao, Z., Wang, R., He, X., Wang, Y., & Zheng, X. (2021). Characteristics of annual N_2O and NO fluxes from Chinese urban turfgrasses. *Environmental Pollution, 290*, 118017. https://doi.org/10.1016/j.envpol.2021.118017

Zhang, M., Weng, S., Gao, H., Liu, L., Li, J., & Zhou, X. (2021). Urbanization degree rather than methanotrophic abundance decreases soil CH_4 uptake. *Geoderma, 404*, 115368. https://doi.org/10.1016/j.geoderma.2021.115368

Zhang, W., Wang, K., Luo, Y., Fang, Y., Yan, J., Zhang, T., ... Mo, J. (2014). Methane uptake in forest soils along an urban-to-rural gradient in Pearl River Delta, South China. *Scientific Reports, 4*(1), 5120. https://doi.org/10.1038/srep05120

Zhang, X., Brandt, M., Tong, X., Ciais, P., Yue, Y., Xiao, X., … Fensholt, R. (2022). A large but transient carbon sink from urbanization and rural depopulation in China. *Nature Sustainability, 5*(4), 321-328. https://doi.org/10.1038/s41893-021-00843-y

Zhang, Y., Zhang, F., Abalos, D., Luo, Y., Hui, D., Hungate, B. A., . . . Chen, J. (2022). Stimulation of ammonia oxidizer and denitrifier abundances by nitrogen loading: Poor predictability for increased soil N_2O emission. *Global Change Biology, 28*(6), 2158-2168. https://doi.org/10.1111/gcb.16042

Zhou, L., Dickinson Robert, E., Tian, Y., Fang, J., Li, Q., Kaufmann Robert, K., ... Myneni Ranga, B. (2004). Evidence for a significant urbanization effect on climate in China. *Proceedings of the National Academy of Sciences, 101*(26),

Accepted Article

13652486, ja, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/gcb.16652 by Test, Wiley Online Library on [28/02/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

9540-9544. https://doi.org/10.1073/pnas.0400357101

Zhu, W., & Carreiro, M. M. (2004). Temporal and spatial variations in nitrogen transformations in deciduous forest ecosystems along an urban–rural gradient. *Soil Biology and Biochemistry, 36*(2), 267-278. https://doi.org/10.1016/j.soilbio.2003.09.013

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13652486, ja, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/gcb.16652 by Test, Wiley Online Library on [28/02/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

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TABLE 1 Global-scale estimates of urbanization-induced changes in soil nitrous oxide (Δ N_2O) emission and methane (ΔCH_4) uptake as well as the non-carbon dioxide (CO_2) greenhouse (Δnon-CO_2 GHG) emission on basis of the total area of fertilized and non-fertilized urban greenspaces.

Greenspace type	Area [a] (Million ha)	The difference in soil N_2O and CH_4 fluxes due to urbanization-induced land-use conversion [b]		Urbanization-induced changes at global scale [c]		
		Soil N_2O emission (kg N ha^{-1} yr^{-1})	Soil CH_4 uptake (kg C ha^{-1} yr^{-1})	ΔN_2O emission (Tg N_2O-N yr^{-1})	ΔCH_4 uptake (Tg CH_4-C yr^{-1})	Δnon-CO_2 GHG (Tg CO_2-eq yr^{-1})
Fertilized lawn	149	1.0 (0.5~1.6)	-2.0 (-3.2~-0.9)	0.15 (0.07~0.24)	−0.30 (−0.48~−0.13)	75 (48~108)
Fertilized urban forest	30	5.4 (3.9~6.5)	-0.6	0.16 (0.12~0.20)	−0.02	69 (52~87)
Non-fertilized soil	119	1.3 (0.9~1.7)	-2.2 (-2.5~-1.9)	0.15 (0.11~0.20)	−0.26 (−0.30~−0.23)	74 (58~94)
Total	298			0.46 (0.30~0.64)	−0.58 (−0.80~−0.38)	218 (158~286)

[a] The area of each urban greenspace type was calculated by combining information on the urban greenspace proportion of global land area (i.e., ca. 2% of global land area, Kaye et al., 2004; Potere and Schneider, 2007; Hall et al., 2008) with information on the distribution of fertilized and non-fertilized urban lawns and forests (i.e., ca. 50% of fertilized lawns, 10% of fertilized urban forests and 40% of non-fertilized soils, Law et al., 2004; Fraser et al., 2013; Polsky et al., 2014; Groffman et al., 2016; Locke et al., 2018, 2019).

[b] The difference in soil N_2O emission and CH_4 uptake due to urban land conversions was calculated on basis of our dataset S1.

[c] Δnon-CO_2 GHG emission was estimated by $\Delta N_2O + \Delta CH_4$ and applying IPCC global warming potential factors for CH_4 (28) and N_2O (273), respectively, over a 100-year time horizon (IPCC, 2021).

Negative sign (−) indicates a reduction of soil CH_4 uptake due to urbanization. Numbers in brackets represent 95% confidence intervals.

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FIGURE CAPTIONS:

FIGURE 1 Response of soil nitrous oxide (N_2O) emission (a), methane (CH_4) uptake (b) and non-carbon dioxide (CO_2) greenhouse gas (GHG, i.e., CH_4+N_2O) fluxes (c) to urbanization-induced land-use conversion. Managed ecosystem refers to arable land and grazed pasture. The data in brackets indicates the number of paired observations in each sub-group. Error bars represent 95% confidence intervals (CIs). Variables were significant at $P < 0.05$, if 95% CIs did not overlap with zero. MAT = mean annual temperature, MAP = mean annual precipitation.

FIGURE 2 Box-plots of annual nitrous oxide (N_2O) emission (a) and methane (CH_4) uptake (b) as well as non-carbon dioxide (CO_2) greenhouse gas (GHG, i.e., CH_4+N_2O) fluxes (c) from urban greenspaces and non-urban soils. Solid and dashed lines inside the boxes represent medians and means, respectively. Box boundaries represent 75th and 25th percentiles, whisker caps represent 95th and 5th percentiles, and circles represent data points. Curves represent the normal distribution of data. Different letters (a or b) indicate significant differences between urban and non-urban soils ($P < 0.05$).

FIGURE 3 Model-averaged importance of predictors of the response of soil nitrous oxide (N_2O) emission (a) and methane (CH_4) uptake (b) to urbanization-induced land-use conversion, as well as the annual direct N_2O emission factor (EF_d) for soils of urban greenspaces (c). The relative importance is based on the sum of Akaike weights derived from the model selection using corrected Akaike's Information Criteria. The cutoff set at 0.8 (dashed line) differentiates between essential (> 0.8) and non-essential (< 0.8)

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model predictors. MAT = mean annual temperature, MAP = mean annual precipitation, BD = bulk density, SOC = soil organic C, TN = total N.

FIGURE 4 Box-plots of annual nitrous oxide (N_2O) emissions from fertilized urban soils and non-fertilized controls. Solid and dashed lines inside the boxes represent medians and means, respectively. Box boundaries represent 75th and 25th percentiles, whisker caps represent 95th and 5th percentiles, and circles represent data points. Curves represent the normal distribution of data. Different letters (a or b) indicate significant differences between fertilized and non-fertilized soils ($P < 0.05$).

FIGURE 5 Effects of type of greenspace (a), mean annual temperature (MAT) (b), mean annual precipitation (MAP) (c), N fertilization rate (d), N fertilizer type (e), soil texture (f), bulk density (BD) (g), soil pH (h), soil organic C (SOC) (i), total N (TN) (j) and C/N ratio (k) on annual direct emission factors (EF_d) of nitrous oxide (N_2O) in urban soils. The values in brackets indicate the number of observations in each sub-group. Error bars represent 95% confidence intervals. “Other lawns” refer to public park and ornamental landscapes. “Other synthetic” refers to synthetic N fertilizer other than urea and slow-release fertilizer, e.g., calcium nitrate and ammonium nitrate. Acid, neutral and alkaline mean pH ≤ 6.5, 6.6 ≤ pH < 7.3 and pH > 7.3, respectively.

FIGURE 6 Conceptual diagram illustrating urbanization effects on soil nitrous oxide (N_2O) emission and methane (CH_4) uptake as well as the associated soil processes. Non-CO_2 GHG emissions = non-carbon dioxide (CO_2) greenhouse gases (GHG, i.e., CH_4+N_2O). EF_d = direct N_2O emission factor.

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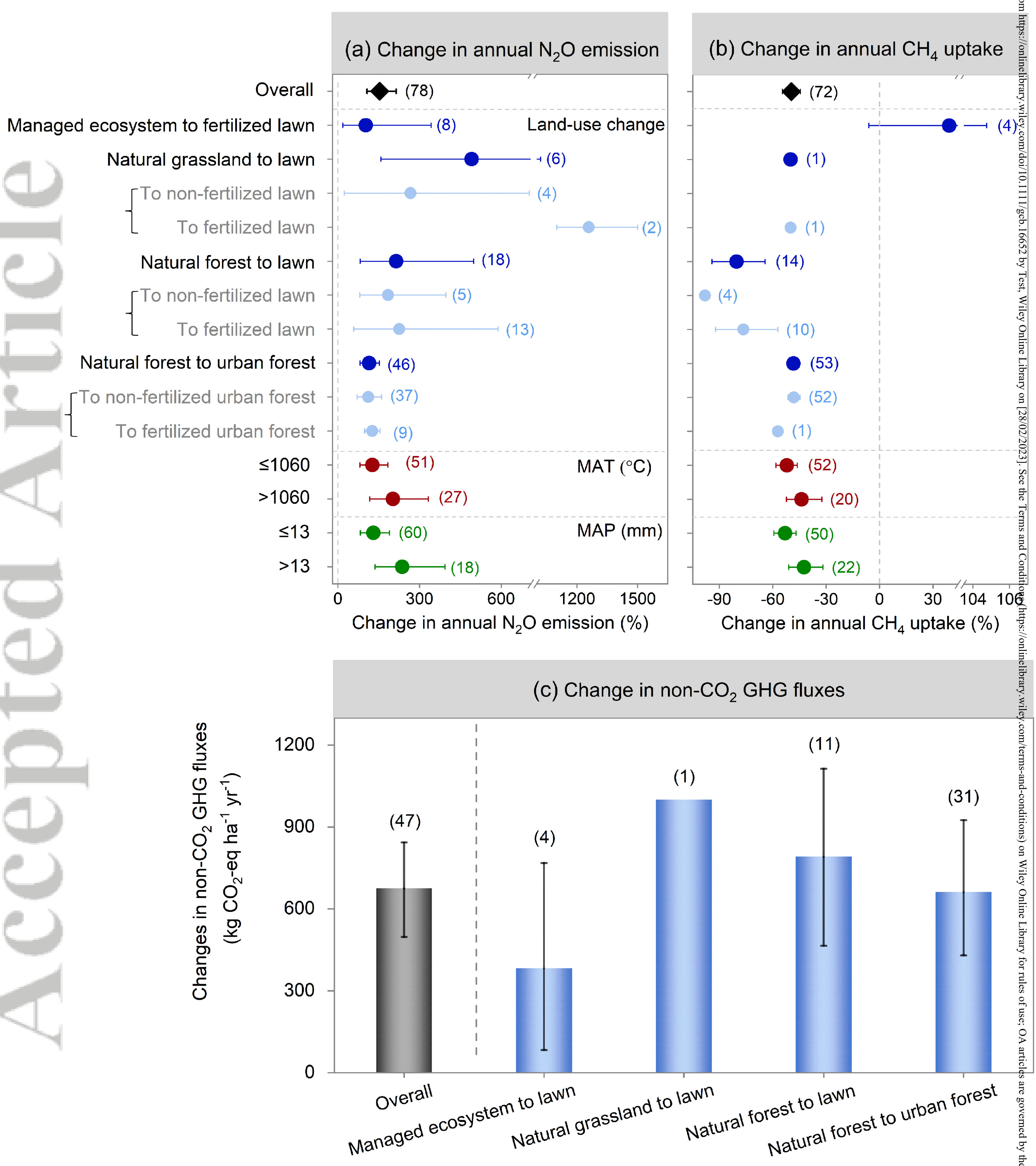

GCB_16652_FIGURE1.png

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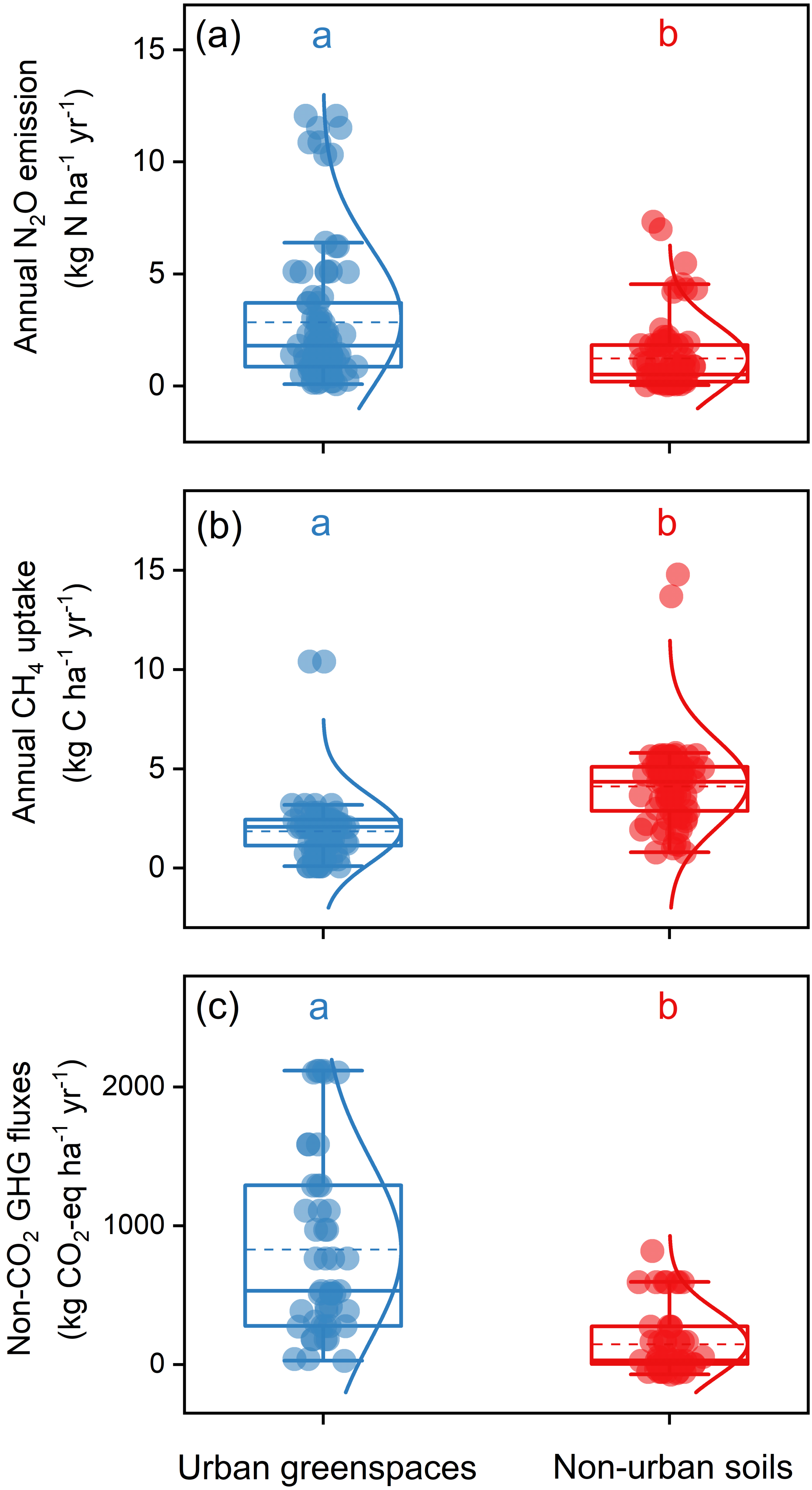

GCB_16652_FIGURE2.png

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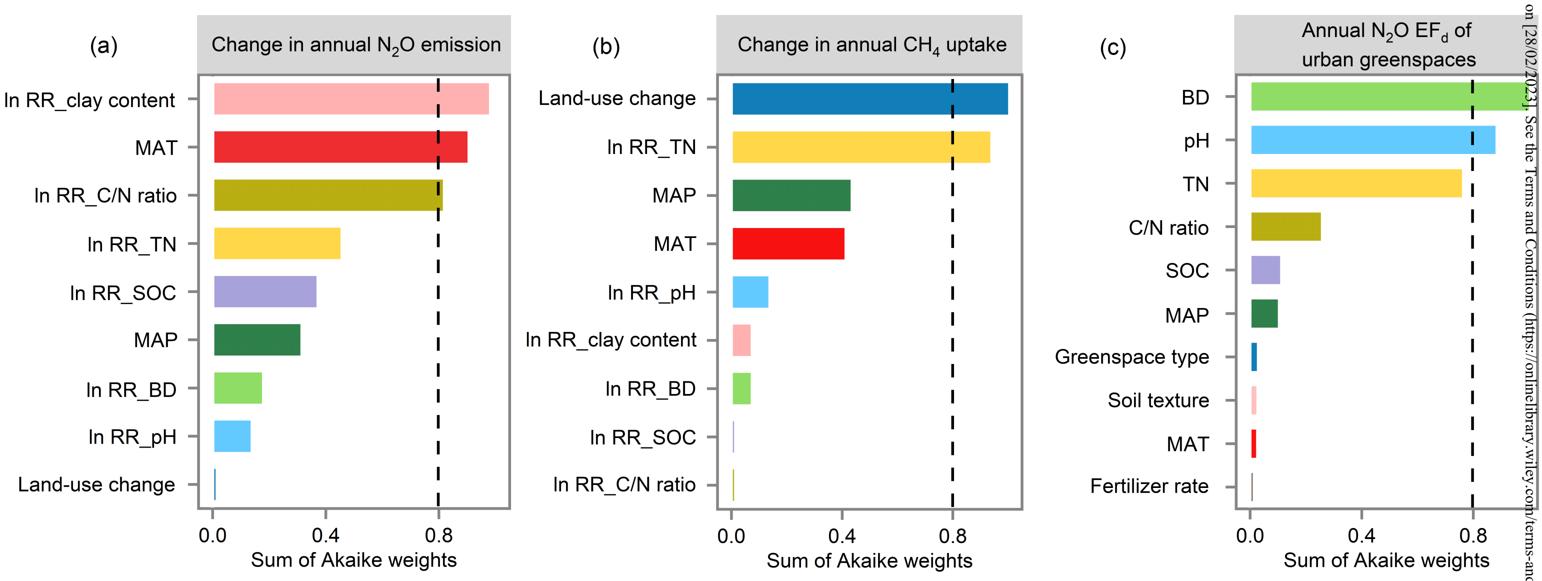

GCB_16652_FIGURE3.png

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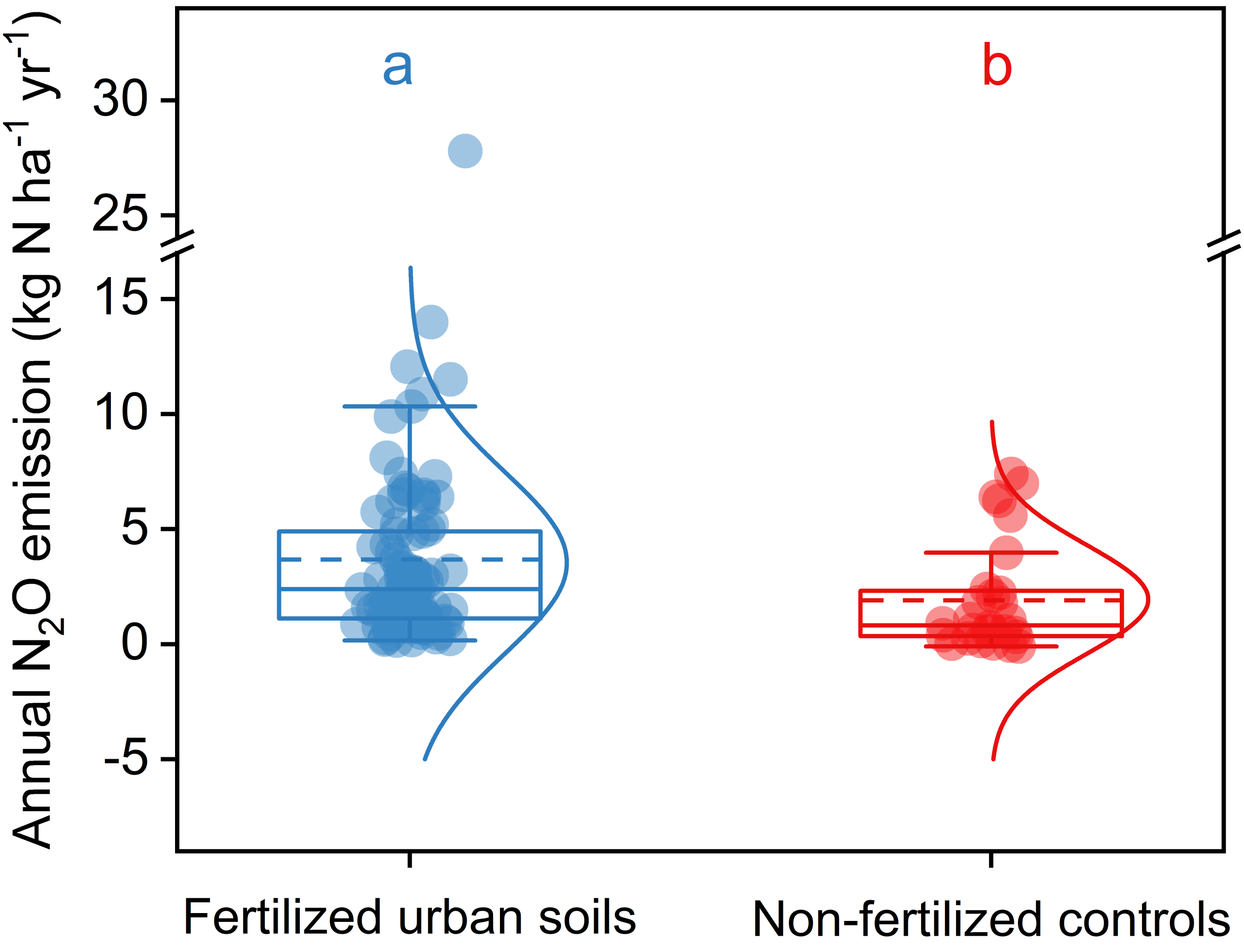

GCB_16652_FIGURE4.png

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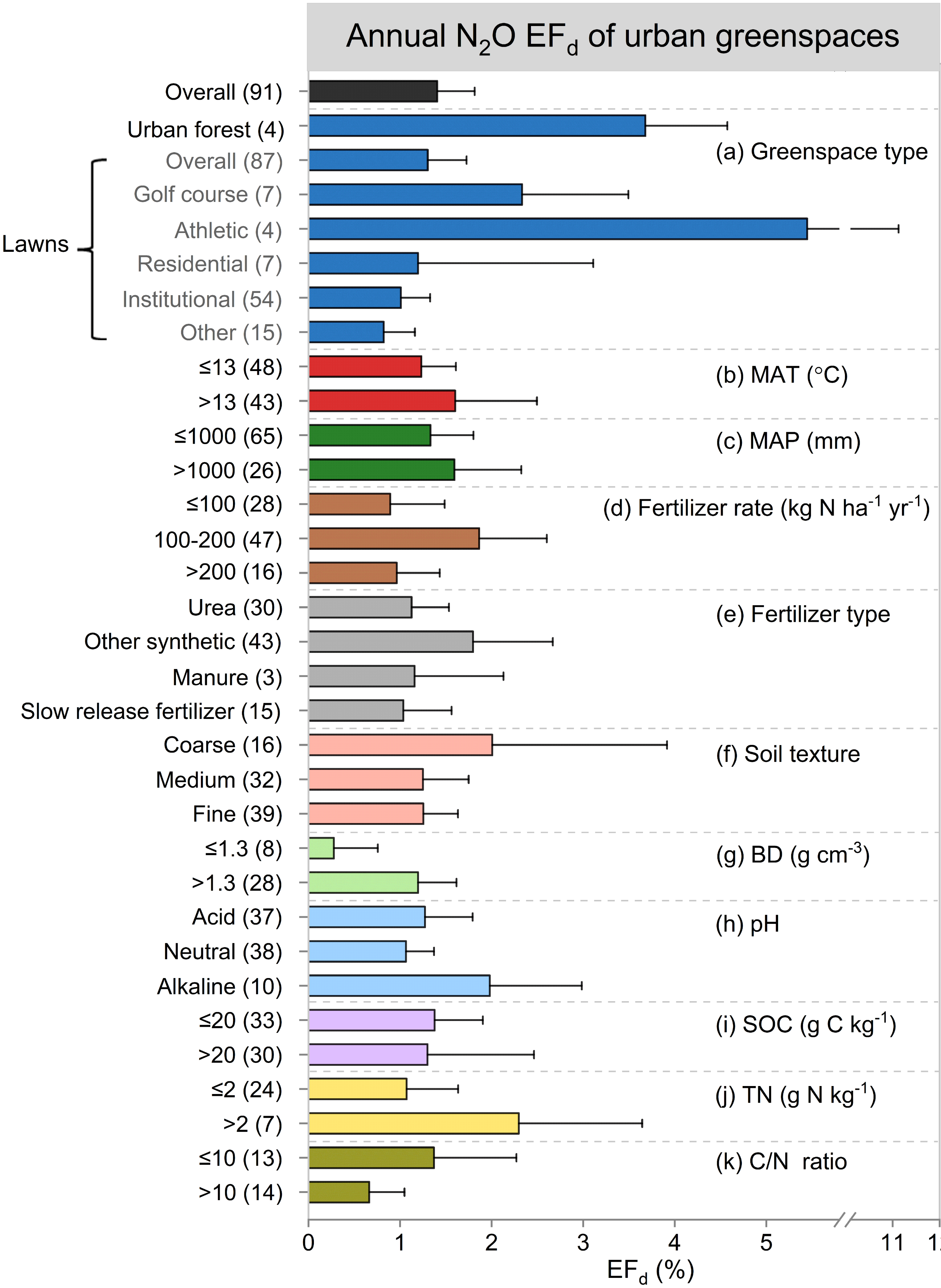

GCB_16652_FIGURE5.png

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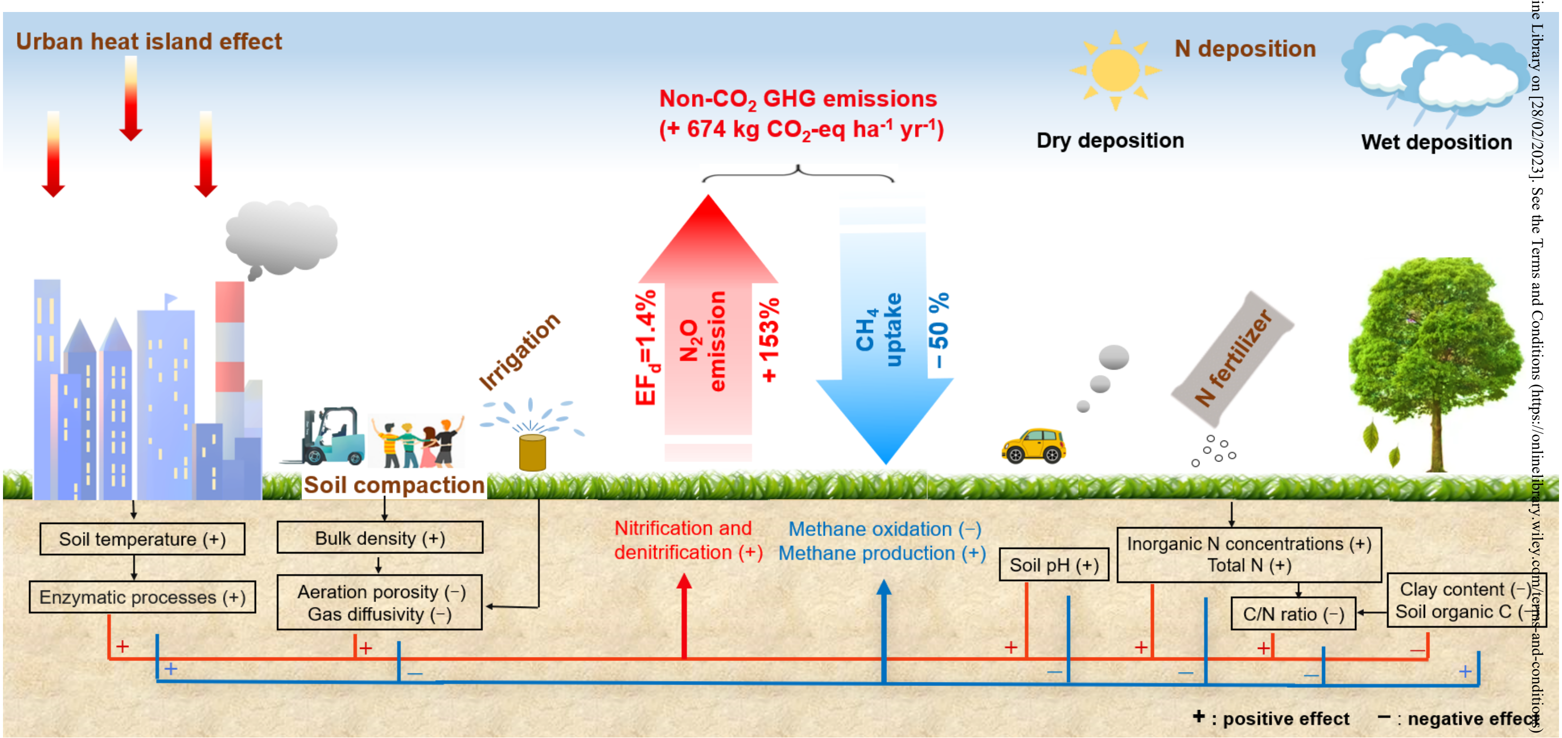

GCB_16652_FIGURE6.png

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