soil systems

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Combined Application of Multiple Global Change Factors Negatively Influences Key Soil Processes across an Urban Gradient in Berlin, Germany

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Abstract: Urbanization is a growing phenomenon affecting soils worldwide. Urban centers have been highlighted as hotspots for global change factors due to heightened anthropogenic activity. However, few studies have investigated the multifaceted impacts of global change factors (GCFs) acting in concert with urban soils. Thus, the objective of this study was to add GCFs in different combinations (0, 1, 2, 5, and 8 simultaneously) in three high-urbanity and three low-urbanity soils in Berlin and to evaluate their effects on soil parameters and functions. We hypothesized four potential outcomes of soil process responses to GCF exposure, Site-Specific Resistance, General Susceptibility, Low-Urbanity Resistance, and High-Urbanity Resistance. We provide evidence for the negative impacts of individual and multiple GCF application on litter decomposition, water repellency, and water-stable aggregates. Additionally, we highlight the General Susceptibility of litter decomposition to GCF exposure regardless of urbanity, as well as the Low-Urbanity Resistance of water repellency and High-Urbanity Resistance of water-stable aggregates under increased exposure to GCFs. This study expands on evidence of the growing threat of global change factors in urban settings and highlights some potential consequences regarding soil function.

Keywords: global change; litter decomposition; urbanization; water repellency; water-stable aggregates

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1. Introduction

Increasing rates of urbanization represent a ubiquitous global phenomenon, with urban populations expected to rise by 2.5 billion by 2050, accounting for nearly 70% of the human population [1]. Urban areas represent heterogeneous landscapes comprising different land uses, ranging from parks to intensively developed residential and industrial areas [2]. Notably, it has been widely documented that urban centers represent hotspots not only for anthropogenic disturbance in general, but also for the accumulation of global change factors (GCFs), including antibiotics [3], heavy metals [4,5], increased temperatures [6–8], salinization [9–11], and microplastics, among others [12]. As a result of GCF accumulation, key processes such as nutrient cycling, hydrological dynamics, and biodiversity have been negatively impacted [13–15].

Urban soils are responsible for the maintenance of a variety of integral ecosystem services, including nutrient cycling, hydrological control, the maintenance of biodiversity, and the sequestration of pollutants such as heavy metals [16–18]. Globally, over 80% of industrial waste originates in cities, despite them only accounting for 2% of the total land surface [19]. Urban soils often act as a sink for a variety of these pollutants; however, the increased pressure on urban soil may compromise the ability of soils not only to buffer the impacts of pollution but also to maintain the other critical ecosystem services they currently provide [20]. Although the impact of global change factors [GCFs] and other anthropogenic disturbances has been studied extensively in agriculture and rural settings, far fewer studies examine similar dynamics in urban and peri-urban soils, revealing a notable shortage in our understanding of these integral systems [21].

Here, we report on a study exploring the role of multiple global change factors and their impact on key soil processes across a gradient of six urban soils from Berlin, Germany, between two major classes, low urbanity [LU] and high urbanity [HU], with three individual soils selected per class. Subsequently, we subjected each of these soils to random combinations of 2,5, and 8 GCFs. Additionally, we applied each GCF individually to each soil to parse potential differences in the magnitude of impact each factor caused. We tested for the effects of our treatments by assessing several soil processes and properties, including litter decomposition, water repellency, and water-stable aggregation. We hypothesized four potential outcomes resulting from our treatments, including I. Site-Specific Responses, II. General Susceptibility, III. Low-Urbanity Soil Resistance, and IV. High-Urbanity Soil Resistance.

Site-Specific Responses—where each soil produces differing responses to the factors based on a suite of soil parameters. This hypothesis is grounded in significant literature that has revealed the high rates of variation between microbial communities of different areas and land use types, which ultimately governs the biogeochemical processes and functions of a given site [22–24].

General Susceptibility—where both LU and HU sites are similarly impacted by global change factors regardless of their level of urban exposure. This hypothesis is based on the documented negative impacts of GCFs on microbial communities and soil processes in general, across a wide range of land use changes [25–27].

Low-Urbanity Soil Resistance—characterized by higher rates of measured processes in response to GCFs as opposed to those in the high-urbanity class. Some literature has pointed to urban areas as harboring reduced rates of key processes, including water infiltration and water-stable aggregation, and also a reduction in microbial diversity; thus, we hypothesized that these, amongst other factors, could reduce urban soil's ability to deal with the added effects of GCFs [28–31].

High-Urbanity Resistance—This hypothesis assumes that exposure to various components of urbanity and GCFs has selected for microbial communities adapted for resilience to such impacts. Prior studies have revealed such trends are possible in a variety of different ecosystems, when one or more GCFs will essentially select for microbes that can survive under heightened stress [32–34].

2. Material and Methods

2.1. Site Selection

Berlin is a major urban center and the largest city in Germany, classified as a moderately continental climate system with cold winters (average 0 °C) and moderately warm summers (average 25 °C). Over the years, Berlin has fostered substantial research regarding urban ecology, including the CityScapeLab research platform, which established dozens of plots throughout the city to investigate urban-related questions [35]. Within this set of heterogeneous zones are a total of 56 grassland sites. These locations range from highly urbanized areas to grasslands in forests surrounding the city of Berlin, together representing a general spectrum of urbanity. As part of the CityScapeLabs, a large database of environmental data was collected from each of these sites, including the level of soil sealing, soil chemistry, soil nutrients, heavy metal content, road and population density, and the floor area ratio [35]. Due to the unique design of the CityScape platform, as well as Berlin's geography, we selected it as an ideal urban area to examine our hypotheses. In order to select sites, we used this database, in addition to a PCA analyses of these data which grouped sites based on factors of urbanity including soil sealing, population density, distance from roads, and distance from the city center [29]. We selected three sites within the cluster we classed as "high urbanity" (NL_208, NL_220, NM_201) and three sites we termed "low urbanity" (OL_16, NM_03, BRB_3) to compare potential differences between heavily and minimally urbanized grassland sites (Figure 1). Additionally, we limited our choices specifically to grassland sites to reduce potential bias between other major ecosystem types.

Figure 1. Overview of the city of Berlin and the surrounding state of Brandenburg (in white) (map licensed via istock images). The average elevation of Berlin is 35 m, with a Longitude of 52.338824 and Latitude of 13.76116. The location of each of the six sites is shown, with low-urbanity (LU) sites represented by trees and high-urbanity (HU) sites represented by apartment blocks. Each site is colored uniquely, and the site ID color is consistent throughout all subsequent figures.

2.2. Experimental Design and GCF Selection

To examine the role of urbanization on the susceptibility of soils to the threats of GCFs, we selected a pool of ten commonly occurring GCFs, including the antibiotic oxytetracycline, drought, the fungicide carbendazim, copper, the herbicide diflufenican and insecticide imidacloprid, tire particles, nitrogen deposition, salinity, and a common surfactant, sodium dodecylbenzene-sulfate (Figure 2). In addition to a soil control, each soil was then subjected to each of our ten GCFs, in addition to random combinations of 2, 5, and 8 GCFs. With this design, we hoped to not only identify the magnitude of the impact of soil processes on each GCF but also on increased exposure to GCFs via multi-factor treatments. We selected this design and established our hypotheses based on prior studies that have established the impacts of multiple factors on soil processes, the potential interactions between said factors, and finally the exposure of urban systems to multiple GCFs (Figure 3).

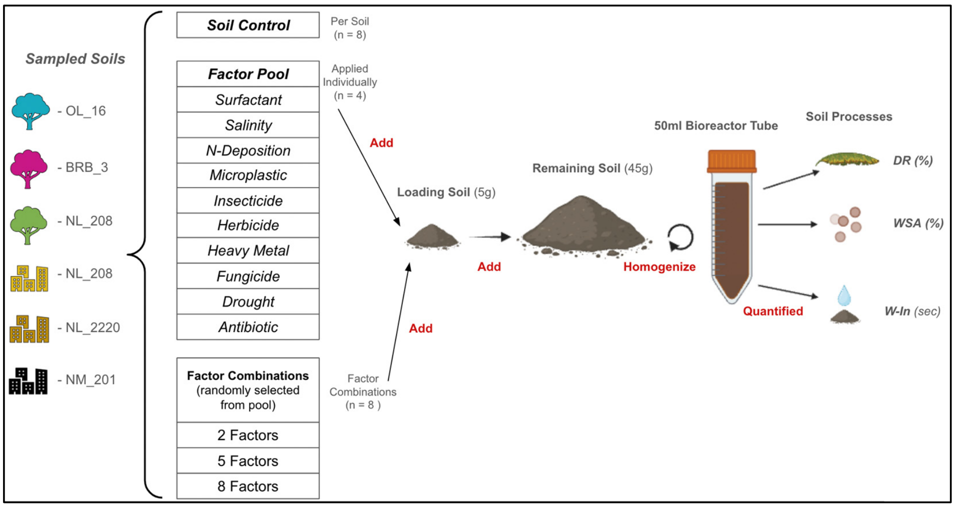


Figure 2. Overview of experimental setup. Each of our six sampled soils was subjected to a treatment regimen including a soil control (n = 8), a test of each individual GCF (n = 4 per GCF), and three GCF combination treatments, 2, 5, and 8 (n = 8 per combination treatment). GCF treatments were first applied to 5 g of loading soil before being added to the remaining 45 g of soil that made up the remainder of the 50 g experimental unit. The soil was then homogenized and added to a bioreactor tube. Tubes were randomized and incubated before the measurement of soil processes. Figure created at Biorender.com.

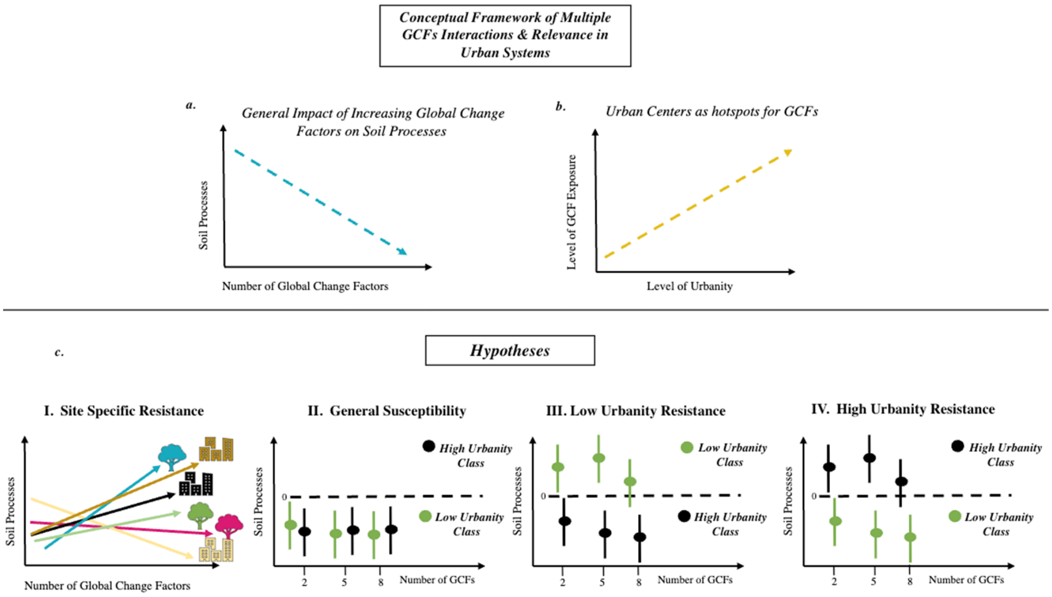


Figure 3. Overview of conceptual frameworks underpinning the study design and hypotheses—(**a**) The general negative trend in soil health and processes is a result of exposure to an increasing amount of global change factors [25,36]. (**b**) Trend exemplifying urban centers as hotspots of global change factors [37,38]. (**c**) Our primary hypotheses: With matching trees or apartment buildings corresponding to the color line representing each site for Hypothesis I. For hypotheses I., III, and IV., grouped high- and low-urbanity sites [EE1] are represented by either black or green shapes meant to symbolize means and standard error when observing mean differences in effect size. Hypotheses Summary—Site-specific responses reveal no major effect of urbanity on soil responses to increasing GCFs. II. General Susceptibility—both HU and LU soils are negatively impacted by GCFs regardless of their level of urban exposure. III. Low-Urbanity Resistance is exemplified by heightened soil processes for low-urbanity sites due to their decreased resistance to GCFs. IV. High-Urbanity Resistance—showing increased soil processes for sites that are exposed to more urban factors.

2.3. Soil Collection

We collected roughly 5 kg of soil from the top 10 cm of each designated site on 3 April 2022. One kg of soil was selected at each of the four cardinal points of the plot, in addition to at the center of the plot. These were then combined for a total of 5 kg of soil taken per site. Latex gloves were worn to prevent the potential contamination of samples. Samples were then returned to the lab and stored at 4 °C until the experiment's setup.

2.4. Experimental Setup

The soil was first homogenized by mixing and passing the soil through a 2 mm sieve, followed by the removal of large roots, rocks, and detritus by hand. The soil was then air-dried at room temperature (20 °C) before the application of the treatments. We then randomly selected GCFs for each combined treatment for application to each soil. We kept the randomly drawn GCFs constant for each of the soils, meaning there was only one set of random draws that we used for all six soils. Doses of each were selected via thresholds established by regulatory bodies and prior studies [25]. Factor solutions were added to 5 g of loading soil and allowed to dry overnight in a fume hood to reduce potential bias in liquid distribution between experimental units [25]. Loading soil and dry GCFs (salt, MPs) were then added to each respective unit and mixed for five minutes via a mixing machine (Heidolph—Reax 2, Schwabach, Germany) to ensure an equal distribution of factors within each 50 mL tube. Each experimental unit contained 50 g of soil. Samples were randomized and then placed in incubators (Memmert—PP110 Plus, Schwabach, Germany) at 20 °C, where they remained for the six-week incubation. Every week, samples were re-randomized, and then each tube's weight was compared to its initial weight and any water loss was replaced to maintain either 60% or 30% WHC respective to the standard or drought treatment.

2.5. Analysis of Soil Parameters

To analyze the impact of the treatments on litter decomposition rates, we made miniature tea bags with 30 µm nylon mesh (Sefar Nitex), which was cut into 2.5 by 3 cm rectangles that were sealed with an impulse sealer (Mercier Corporation, product no. 127174, New Taipei City, Taiwan). The bags were then filled with 300 mg of green tea (Lipton green tea, Sencha Exclusive Selection), sealed, autoclaved (121 °C for 20 min in a dry cycle), and dried at (60 °C). Decomposition rates were determined by calculating the amount of litter lost per bag divided by its original weight.

Air-dried soil samples were assessed for aggregate stability [39]. First, samples were passed through a 4 mm sieve, then 4.0 g of soil was rewetted by capillary action for 5 min. Soils were placed in a wet-sieving machine (Eijkelkamp, Giesbeek, The Netherlands) for 3 min (stroke = 1.3 cm, 34 times min^{-1}). The remaining fraction was then dried at 60 °C and weighed. Coarse matter, consisting of organic debris and sand larger than 0.25 mm, was quantified, and the percent of water-stable aggregates (WSAs) was then calculated via the following formula: % WSAs = [water-stable aggregates − coarse matter]/(4.0 g − coarse matter).

Soil pH was assessed by mixing 5.0 g of air-dried soil into a 50 mL falcon tube with 10 mM $CaCl_2$ at a ratio of 1:5. After mixing with a shaker for ten minutes, the samples were centrifuged, and three sub-samples were pipetted from the solution for a triplicate measurement per soil sample. The average value was then used for all further data analysis.

Soil EC was quantified via a 1:5 soil-to-water suspension that was placed in a 50 mL falcon tube and shaken for ten minutes. Samples were then centrifuged at 3000 rpm at room temperature before measurement with a conductivity meter.

Water repellency was quantified via the water drop penetration time method, by weighing 5 g of dry soil into 50 mL falcon tubes and then pipetting 50 µL of water onto the surface of the soil, with the time to penetrate the soil recorded. This was repeated three times per sample, with the average value of these technical replicates used for further statistical analysis [40].

2.6. Statistical Analysis and Graphics

Statistics were performed on R—version 4.1.1 [R Development Core Team 2024]. To assess the effects of single and multiple GCF treatments on our response variables, effect sizes, and their corresponding 95% confidence intervals were calculated via the nonparametric bootstrapping of data with 10,000 permutations. Linear models and robust ANOVAs were generated in R, and all plots were produced via the ggplot2 package [41].

Null models were calculated as described previously [25]. We used an additive model, generated by adding the effect sizes of each GCF factor, a multiplicative model where joint effects are quantified by multiplying the proportional change in each single GCF in comparison to the control. Finally, the dominative model was used, which assumes that joint effects can be calculated by the effect size of the most dominant (highest impact) GCF.

3. Results

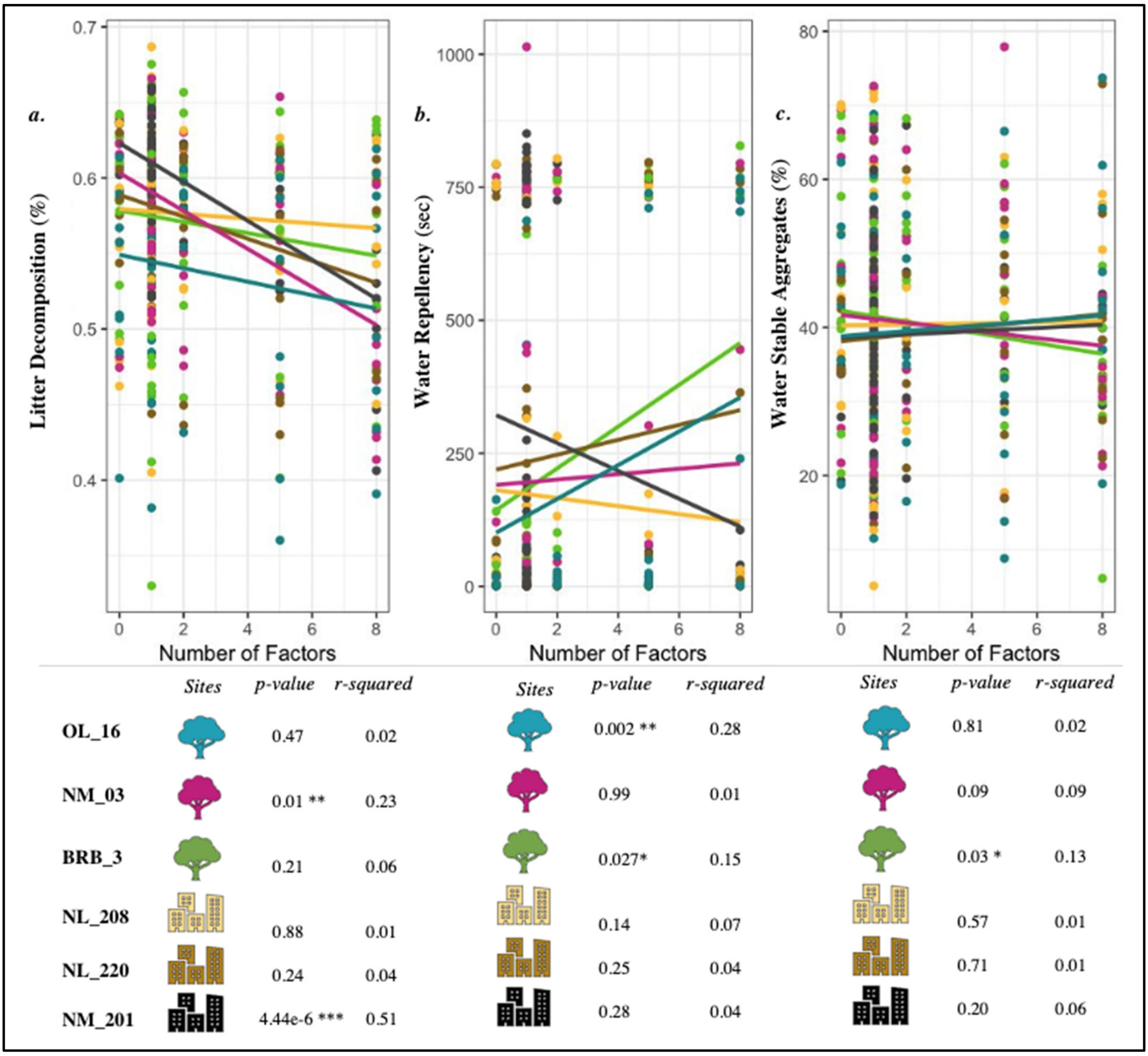
To link the results of our analyses to our original hypotheses, results for each response variable will be presented separately within a subsection. In regards to our original hypotheses, due to the variability of responses between different soils, the site-specific resilience hypothesis was supported for all measured response variables, with no variable responding uniformly across all six measured soils. Support for our other hypotheses is addressed in the subsequent section regarding the analysis of grouped LU and HU classes.

3.1. Site-Specific Resistance to Global Change Factors

When analyzing linear models exploring litter decomposition rate responses to increasing numbers of GCFs, we found a significant decrease in two of the six soils (NM_03 and NM_201; one low-urbanity and one high-urbanity soil), whereas there was no clear trend for the other four soils (Figure 4), thus supporting the notion that there were site-specific effects independent of urbanity. Further trends regarding the negative impacts of GCFs were evident when comparing differences in effect size between treatments of single GCFs and random combinations of two, five, and eight GCFs. In single-factor treatments, soils exhibited varying but predominantly positive responses to single GCF treatment, with four of six soils showing elevated decomposition rates under both fungicide and nitrogen deposition treatments. Furthermore, the microplastic treatment boosted decomposition rates in three of the six soils, while surfactant boosted rates in two. Antibiotic treatment and insecticide treatment each elevated a single soil's decomposition rates (Supplementary Figure S1). Negative impacts of single-factor GCF treatment were much less common, with one soil, NM_201, revealing decreased decomposition rates under herbicide, insecticide, and microplastic treatments, respectively. Soil OL_16's decomposition rate was also decreased under surfactant treatment. Single-factor treatments, when viewed collectively (combined single factors), exhibited increased rates of decomposition for three of six soils, while the other three did not differ from their controls. A single soil, NM_201, was overall negatively affected when viewing the combined effects of single factors.

Despite the predominantly positive impacts of single GCFs on litter decomposition between the six soils, GCF combination treatments had a markedly more negative effect. Under five GCF treatments, two of the six soils exhibited significant decreases in decomposition rates, and three soils revealed similar trends under the eight GCF treatments (Supplementary Figure S1).

To predict the joint effects of multiple GCF treatments based on single-factor data, we analyzed three null models. In regards to litter decomposition, the only model that revealed a significant fit was for soil NM_201 in regards to its eight-GCF treatment. This model showed significant support for the dominative model, specifically, the impact of the fungicide (Supplementary Figure S1). For the remainder of the models tested for all soils and treatment impacts on litter decomposition, no significant relationships were found for any model types, pointing towards potential synergistic effects between GCFs.



	Sites	*p-value*	*r-squared*	Sites	*p-value*	*r-squared*	Sites	*p-value*	*r-squared*
OL_16	🌳	0.47	0.02	🌳	0.002 **	0.28	🌳	0.81	0.02
NM_03	🌳	0.01 **	0.23	🌳	0.99	0.01	🌳	0.09	0.09
BRB_3	🌳	0.21	0.06	🌳	0.027*	0.15	🌳	0.03 *	0.13
NL_208	🏢	0.88	0.01	🏢	0.14	0.07	🏢	0.57	0.01
NL_220	🏢	0.24	0.04	🏢	0.25	0.04	🏢	0.71	0.01
NM_201	🏢	4.44e-6 ***	0.51	🏢	0.28	0.04	🏢	0.20	0.06

Figure 4. Effects of increasing number of GCFs (control, single GCFs, two, five, and eight GCFs per soil) on soil processes (**a**) litter decomposition (%), (**b**) water repellency (sec), and (**c**) water-stable aggregates (%). The color of data points corresponds to the site's urbanity level. Relationships between variables are exhibited via a linear regression fitted between GCF number and decomposition, water infiltration, and WSAs. The significance of the relationship and amount of variation explained is shown by the *p*-values and their corresponding r-squared values in the table beneath each linear model. Significance ranks are denoted with varying numbers of asterisks—* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Linear models examining the response of water repellency to an increasing number of GCFs exhibited significantly increased rates in two soils (OL_16 and BRB_3).

Water repellency responded both positively and negatively to single GCF treatments between soils. Insecticide and surfactant decreased repellency in one soil each, while antibiotic and salinity treatments decreased it in two soils each. More drastic responses could be seen in response to fungicide, nitrogen deposition, and copper, which reduced rates in three soils each, with the exception of copper, which reduced water repellency in four of the six soils (Supplementary Figure S2). Fewer soil water infiltration values responded positively to single GCFs, with herbicide, surfactant, and copper increasing rates in one soil each. Antibiotics, fungicides, and drought increased rates in the two soils (Supplementary Figure S2).

In regards to combined treatments, three soil values increased in the combined single-factor analysis, with only a single soil responding positively to the two-factor treatment. Two soils responded positively and two negatively to the eight-factor treatment (Supplementary Figure S2).

The null model analysis of joint GCF effects revealed one significant trend in site NL_208's eight-GCF treatments which pointed towards the importance of a dominative factor in its impact on water repellency in that specific soil (Supplementary Figure S2). No other significant relationships were identified between other models and soil relationships with water repellency.

Only a single soil (BRB_3) was shown via linear models to have decreased soil aggregation due to exposure to an increasing number of GCFs (Figure 4). Five of six soils responded negatively to single GCF treatments. Insecticide, antibiotic, and nitrogen treatments reduced WSA rates in one soil each, while salinity decreased rates in two of six soils. Furthermore, fungicide and drought each reduced WSAs in three soils and herbicide reduced rates in four of six soils (Supplementary Figure S3). Only NM_201 responded positively to single GCF treatments, including fungicide, insecticide, copper, microplastic, and drought (Supplementary Figure S3).

In combined treatments, four of six soils responded negatively to combined single GCF analysis, with a single soil further responding negatively to the two- and five-GCF treatments. Two soils responded negatively to the eight-GCF treatment, with a single soil responding positively to the eight-GCF treatment (Supplementary Figure S3).

Null models revealed several notable interactions between GCF treatments, including support for a multiplicative model in the soil NM_03 five-GCF treatment and dominative interaction in the NM_03 eight-GCF treatment. Furthermore, the OL16 eight_GCF treatment offered marginal support for both a multiplicative and additive interaction between GCFs. Finally, the NM_201 five-GCF treatment offered support for all three models, including additive, multiplicative, and dominative interactions (Supplementary Figure S3).

3.2. Support for General Susceptibility Hypothesis in Regards to Litter Decomposition Rate

When examining the combined response of LU and HU sites, the positive effects of some single factors were again apparent for both soil groups. LU soil decomposition rates were positively affected by fungicide, nitrogen deposition, and microplastics, while HU soil decomposition rates increased under antibiotic, microplastic, and nitrogen deposition treatments (Figure 5).

Combined single-factor treatments were marginally significant in terms of elevated decomposition rates for both LU and HU sites. When observing the impact of combined GCF treatments, HU sites experienced significantly reduced rates of decomposition under the five-GCF treatments and both LU and HU sites' rates of decomposition were negatively affected by the eight-GCF treatments (Figure 5). Null models were unable to identify significant patterns between GCF interactions.

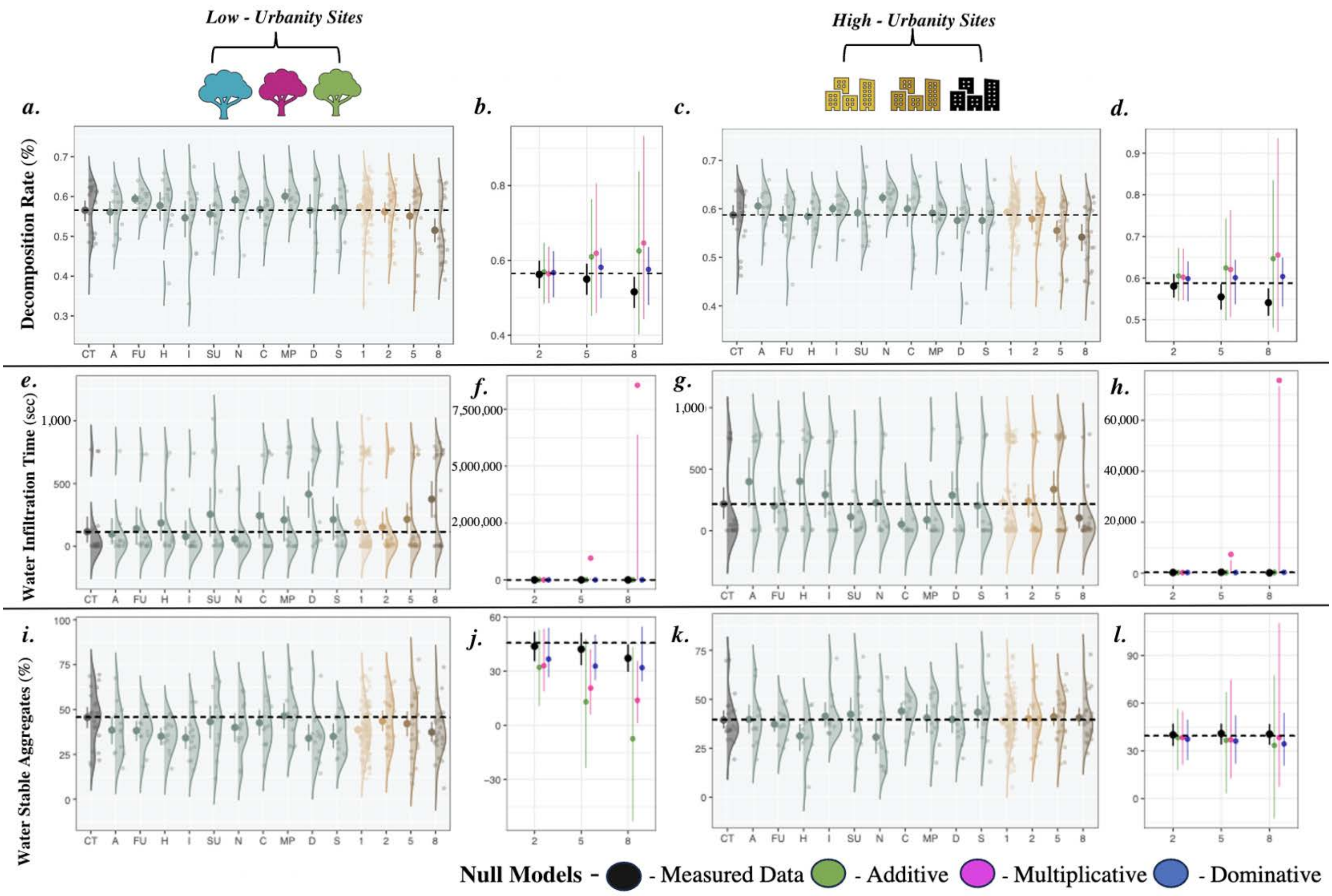


Figure 5. Impact of multiple global change factors on litter decomposition rates (%), water repellency (sec), and water-stable aggregates (%) in combined low-urbanity and high-urbanity sites. Single and multiple GCFs mean differences in effect size are shown for both low-urbanity and high-urbanity sites. Observed data are represented by black circles with a density distribution of the raw data in gray behind each treatment. Colors correspond to different treatments with single factors in green, and combined 1–8 factors occurring in a gradient from light yellow to dark brown. Panels (**a**,**c**,**e**,**g**,**i**,**k**) show the mean difference in effect sizes compared to the control: specifically, circles represent the bootstrapped effect size mean (effect magnitude), and vertical lines represent the corresponding 95% confidence interval (effect precision). The density plots depict bootstrapped data distribution. Single-factor effects were used to generate null models (**b**,**d**,**f**,**h**,**j**,**l**). Error bars of multiple-factor interactions were generated by bootstrapped values with 1000 iterations. Measured data are presented in black, followed by additive (green), multiplicative (pink), and dominative (blue models).

3.3. Support for Low-Urbanity Hypotheses in Regards to Water Repellency

In LU soils, only drought was shown to increase the water repellency rate. In combined treatments, both five- and eight-GCF treatments also increased rates of water repellency (Supplementary Figure S3). HU soils responded positively to single herbicide treatment but exhibited negative trends in surfactant, copper, and microplastic treatments. In five-GCF treatments, rates increased in HU soils but were shown to decrease in the eight-GCF treatment (Supplementary Figure S3). Similar to litter decomposition, no significant relationships were identified between the null models tested to explore GCF interactions and their subsequent impact on water infiltration.

3.4. Support for High-Urbanity Hypotheses in Regards to Water-Stable Aggregates

In LU soils, antibiotics, fungicides, herbicides, insecticides, drought, and salinity were all found to negatively influence rates of WSAs (Supplementary Figure S3). Furthermore, the LU soil WSAs decreased in the combined single-GCF treatment and eight-GCF treatment, with no response to the two-and five-GCF treatments (Supplementary Figure S3). HU soils viewed as a whole also revealed the negative effects of herbicides on WSAs, rates in addition to nitrogen deposition. No notable impacts were detected for combined GCF treatments (Supplementary Figure S3). The null model analysis revealed significant support for both additive and multiplicative models between GCFs in both the five- and eight-factor treatments (Supplementary Figure S3).

We provide support for three of our hypotheses, including the General Susceptibility of litter decomposition across urban soil class, LU Resistance in regards to water repellency rates, and HU Resistance for water-stable aggregation.

4. Discussion

GCFs when occurring individually can result in both positive and negative consequences for soil health and processes. Here, we discuss evidence for our site-based resistance hypothesis via the varied impacts of single GCFs on six soils representing an urban gradient, analyzed individually and as grouped LU and HU sites, for our three major response variables, litter decomposition, water repellency, and water-stable aggregation. Furthermore, we discuss support for our General Susceptibility hypothesis in regards to litter decomposition rates, the Low-Urbanity Resistance Hypothesis in regards to water repellency, and finally High-Urbanity Resistance in regards to water-stable aggregates.

4.1. Site-Specific Resistance to Global Change Factors

When analyzing the impacts of GCFs on individual sites, we found substantial support for Site-Specific Resistance in all three of our measured response variables. Site variability was also ubiquitous when observing the impacts of a single GCF application, with none of the measured factors causing uniform responses between all six soils. Soil variability in general is a widely researched topic, and many factors, including soil texture, organic carbon, nutrient levels, pH, microbial community, and others, have been shown to contribute to site-specific differences [2–44]. In prior studies using the same sites as this study, differences between the sites' microbial communities were revealed, including non-mycorrhizal fungi, bacteria, and protists [30]. Because both fungi and bacteria are critical players in nutrient processing, including litter decomposition as well as the formation and stability of water-stable aggregates [45–48], it is likely that differences between fungal and bacterial communities between sites dictated each site's ability to cope with GCFs, thus resulting in the variation in rates observed in litter decomposition and water-stable aggregation. Furthermore, impacts on soil structure, including rates of water-stable aggregates, have been shown to have consequences for water repellency rates, notably in urban soils, which could result from the loss of specific microbial groups between sites [29,48]. In summary, site variability in microbial communities offers the most robust explanation of the site-based resistance observed in the soil processes quantified in our study.

4.2. Support for General Susceptibility Hypothesis in Regards to Litter Decomposition

Despite the predominantly positive effects of GCFs on litter decomposition rates when applied singly, the opposite trend is apparent when combined treatments of GCFs are considered. When viewing the collective LU and HU classes, both were negatively impacted when exposed to an increasing number of GCFs. This negative trend has been documented in soil systems exposed to a variety of GCFs that can damage the microbial community by reducing their abundance and or activity, thus altering their intimate link to ecosystem processes, including decomposition [25,36,49]. However, to our knowledge, this is the first study to document such trends in both urban and peri-urban soils, since most studies have focused on the impacts of urbanity but without consideration of the role of GCFs [50–52]. This result highlights a key vulnerability in soils regardless of their exposure to urbanity, which likely points to a core group of microbes whose ability is notably reduced when exposed to several GCFs.

4.3. Low- and High-Urbanity Resistance to Global Change Factors

When observing both water repellency and water-stable aggregation, differing trends were evident between the HU and LU classes. In regards to water repellency, decreased levels were associated with HU sites. Decreased water repellency concerning urban soils has been previously documented, predominantly due to the prevalence of soil sealing in urban zones, although water repellency has also been shown to be heavily dependent on soil type [29,53]. Additionally, support for the convergence of microbial communities in urban centers has been shown to reduce the biodiversity of some microbial taxa; potentially, groups helping to maintain soil structure in urban environments could be subsequently weakened by GCF treatment, with ensuing consequences for processes such as water repellency [54]. Finally, soil organic matter, a major factor influencing water repellency, has been shown to vary widely between sites in urban areas, and due to our relatively low sample size of inner-city plots, our results could have been influenced by variation in soil organic matter [55].

Alternatively, water-stable aggregates exhibited negative trends in the collective analysis of LU and HU soils. This trend runs counter to another study examining WSAs via Berlin's CityScape project, which revealed reduced WSAs with increasing urbanity; however, this study also noted that individual sites exhibited high rates of variation, which could have influenced our results, based on our relatively small numbers of sites per urban class [29]. Additionally, because our LU soils were less likely to be influenced by urban-based pollutants, it is probable that microbial organisms were less susceptible to exposure to GCFs, which has been documented previously in regards to both heavy metals and levels of urbanity [55]. This lack of exposure could thus potentially elucidate why the LU soils' rates of WSAs were reduced under heightened exposure to multiple GCFs.

5. Conclusions

GCFs have been shown to present multifaceted consequences to both high-urbanity and low-urbanity soils, with more negative effects tending to manifest when soils are exposed to multiple stressors. We highlight the negative impacts on water repellency in heavily urbanized soil when exposed to multiple GCFs, and the threats this could pose. Furthermore, litter decomposition was also found to be negatively affected in both low- and high-urbanity soils, emphasizing the role of GCFs interference with key soil processes. Ideally, this study will serve as a stark reminder of the increasing threat of GCFs globally but also within the urban realm.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/soilsystems8030096/s1. Raw Data: Data can be downloaded as a csv file. Analyses and Figure Generation R-script: downloadable R file. Supplementary Table S1: Global change factors—concentrations and references. Supplementary Figure S1: Impact of GCFs on ind. soils' decomposition rates—null modeling. Supplementary Figure S2: Impact of GCFs on ind. soils' water repellency—null modeling. Supplementary Figure S3: Impact of GCFs on ind. soils' water-stable aggregates—null modeling. Consolidated Supp Fig File: pdf file with all associated tables, figures, and legends.

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