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Environmental quality assessment of soil as a component of green spaces in parks of the megalopolis

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Abstract. Intensive land degradation occurs under conditions of accelerated urbanization; it is strongly associated with the loss of soil natural capital, primarily animals, plant cover, and biological diversity in general. The creation and functioning of parks, in particular green spaces, in the urbanized areas is an effective mechanism for optimizing the ecological situation within the cities and preventing desertification. The soils of parks are an integral component of green infrastructure; they determine the conditions for the growth and development of both individual plants and green spaces as a whole. The soil buffering capacity actively participates in the mechanisms of implementation of the development and stabilization of soil fertility potentials. The buffering capacity determines the proportion of the soil potential that controls the processes of immobilization (deposition) and mobilization (release, loss) of a particular element of fertility: first of all, mineral nutrients for plant growth, productive moisture, thermal energy in soil, gas composition of soil air, and acidity. We collected soil samples beneath the crowns of trees growing in the territory of the Taras Shevchenko Central Culture and Leisure Park, as one of the largest parks in the city of Dnipro (Ukraine). The soil samples were collected in order to assess the soil acid-base (pH) buffering capacity (pHBC) and determine the direction of microbiological processes in urban soils of the park area afforested with stands from such introduced tree species as green ash (*Fraxinus pennsylvanica*), black locust (*Robinia pseudoacacia*), northern red oak (*Quercus rubra*), tree of heaven (*Ailanthus altissima*), Kentucky coffee tree (*Gymnocladus dioica*), and box elder (*Acer negundo*). The acid-base buffering capacity of the urban soil was determined using the Arrhenius method and estimated according to the buffering area within the acid-base range, calculated using the Simpson formula. Direction of microbial processes in the soil was determined according to the indexes of mineralization-immobilization, pedotrophicity, and oligotrophicity. The output was processed using statistical methods (arithmetic mean and standard deviation were calculated; the difference in the means was found according to the Tukey's comparison test; interdependencies were determined by linear correlation). We have found significant, strong positive correlations between the pH level of urban soils in the rhizosphere area of the introduced species of park dendroflora and the buffering area within the acid and acid-base (total) range of external influence, as well as a strong negative correlation between pH and buffering area in the alkaline range of external influence. We identified weak mineralization signs according to the ratio of functional groups of microbiota in the studied sites forested with *Fraxinus pennsylvanica* and *Acer negundo*.

Keywords: urban green space; biotic potential of urban soil; soil buffering capacity; pHBC; trends in microbial processes.

Introduction

Globally, the process of urban expansion has accelerated in the last 60 years, as over 50 percent of the world population currently resides in urban areas (Cubino et al., 2015; Vasquez & Wood, 2022). As is commonly known, urbanization is caused by population growth, increasing proportion of urban population, and it is also driven by economic, political and geographical factors (Divakara et al., 2022). According to the estimates of Morel et al. (2017), almost 70% of the world's population will live in cities by 2050. In the paper cited, since the 1950s, the area of land affected by human activities has increased by 78% of the area of cities in Europe, resulting in a loss of 10,000 km^2 of agricultural land for 10 years. About 2.3% of the European area is now sealed, representing 200 m^2 per citizen, and up to 250 ha of natural soils are converted daily into an urbanized surface. As noted by Khokhryakova (2020), the built-up area in Ukraine is 2,552.9 thousand ha, the population living in cities amounts to 70%. Consequently, by the impact of intensive development of new territories for an urbanized environment and agriculture, large natural habitats are changed with simultaneous declining of natural capital, in particular soils, meadow and forest ecosystems, etc. (Macías et al., 2020). This process results in desertification – land degradation with the loss of vegetation cover and biological diversity as a whole, affecting all regions around the world (Briassoulis, 2019; Vieira et al., 2023).

The creation and functioning of parks, in particular park green spaces, in large settlements (cities) is one of the effective mechanisms for optimizing the ecological situation in urbanized areas and preventing desertification (Liu et al., 2023); such green spaces are called "green walls" of the urban ecosystem (Solecki & Welch, 1995). The development of a network of green spaces is a trend, most promising in the improvement of environment in cities (Kunakh et al., 2022; Shamray & Didur, 2022). Being a specific kind of urban space, parks are of great recreational importance (Cornelis & Hermy, 2004; Kunakh et al., 2022). At the same time, being large structures of vegetation, parks perform a microclimatic, sanitary and hygienic functions, and have landscape, architectural, and aesthetic significances (Annerstedt et al., 2012; Bertram & Rehdanz, 2015; Van Doesum et al., 2021; Kunakh et al., 2022); they are green spaces with an important ecological function (Lin et al., 2014), improving the quality and comfort of the environment for urban residents who are disconnected from nature in their daily lives (Rosso et al., 2022). As a result of increasing the area of cities and megacities, specific soil-like bodies have occurred in most of the cities' terrains, that are called urban soils and differ from natural soils in structure, properties, and functions (Khokhryakova, 2016; Pidkova, 2020; Xiao et al., 2020; Mónok et al., 2021): soil disturbance caused by movement of soil horizons from natural places of their development; the soil structure deformation and loss of the sequence of soil horizons; low organic matter; decrease in the population number and activity of soil microorganisms and invertebrates as a consequence of organic matter deficiency; presence of inclusions of construction and household waste in the topsoil layers; changes in the acid-base balance with a trend towards alkalinization; high levels of contamination with heavy metals, petroleum products, components of industrial emissions; changes in soil physical and mechanical properties (reduced water-holding capacity, increased density, rockiness), and so on.

Soils, being an integral unit of park areas within the urban systems, are known to determine the conditions for the growth and development of green spaces in megacities (Morel et al., 2015; Didur et al., 2019); they can implement, principally, such environmental functions as the ability to provide plants with nutrients, water, and their root systems – with a sufficient amounts of air, heat and a physical and chemical environment that is favorable for the normal plant growth and development (fertility), as well as the ability to sorb pollutants in soil and prevent them from penetrating the groundwater (sorptional function and buffering capacity relative to heavy metals). The environmentally negative implications for soils within an urbanized territory include a destruction of soil profile, compacted root layer, and limiting the volume of the root system development in plants, low fertility (depletion of nutrients, humus, trace elements), contamination with heavy metals and other toxicants (Probst et al., 2023), abnormal changes in soil acidity and alkalinity, and reduced diversity of soil microorganisms and invertebrates (Didur et al., 2017). All these factors together reduce the productivity and sustainability of green spaces in park areas. Therefore, there is an urgent need to create conditions for restoring, reproducing and optimizing both the ecological properties of the soil and tree stands as a whole in megacities, especially their park areas.

Soil buffering capacity can serve as a possible tool for environmental assessment of soil quality (Bartmiński et al., 2012; Didur et al., 2019) and the direction of soil microbial processes (Mónok et al., 2021). In a broad sense, the soil buffering capacity characterizes the energy potential of soil, which determines the mobilization (release) and immobilization (deposition) of a particular element of fertility (Truskavetskyi, 2003). More often, buffering is understood as the ability of the soil to resist changes in pH under the influence of various factors. This is the so-called acid-base buffering, pH-buffering (Truskavetskyi, 2003; Kissel et al., 2012). Mónok et al. (2021) emphasized that assessment of soil quality using the microbiological analysis is crucial because soil microorganisms play a key role in numerous soil functions, such as nutrient circulation, organic matter decomposition, and biodiversity regulation. Previous studies (Zhao & Li, 2013; Rai et al., 2018) showed that microbial biomass and the activity of various enzymes are sensitive to anthropogenic changes in the soil. Probst et al. (2023) noted that microbial interactions are one of the key factors in soil functionality and can vary depending on environmental conditions, such as nutrient availability and soil pH.

Therefore, identification and assessment of soil buffering capacity, as one of the potentials of soil fertility, in recreational areas in the territories of megacities on the example of urban parks and identification of the soil biological potential are of scientific and practical interest. The objective of the study was to determine the range of acid-base buffering capacity and the direction of microbiological processes in urban soil in the areas with various plantings of introduced tree species within the park area in the territory of the city of Dnipro.

Materials and methods

The material for the study was sampled from the central part of the city of Dnipro (Ukraine) in the territory of the Taras Shevchenko Central Park of Culture and Leisure, a large urban park (48°27'40"N 35°04'21" E) located on the right bank of the Dnipro River. The city of Dnipro is a large city and industrial center located in the center of Dnipropetrovsk Oblast. The area of Dnipro is 410 km^2, and its height above sea level is in the range of 51–188 m (Lovynska et al., 2023). The region of the study corresponded to the steppe physical-geographic zone, which covers 40% of the total territory of Ukraine (Brygadyrenko, 2015); it corresponds to the temperate continental climate zone of Central Europe and is characterized by warm, often hot summers (Khromykh et al., 2018) and cold, wet winters. The average annual precipitation in the region is about 475 mm, and the average annual air temperature is +8 °C. The average growing season lasts 210 days (Lovynska et al., 2023).

The Taras Shevchenko Central Culture and Leisure Park is one of the major garden and park complexes of the city, which belongs to the objects of the nature reserve fund and is a park-monument of landscape art of national significance. Its total area (together with Monastyrskyi Island) accounts for 45 ha. The park consists of bank and island parts. It includes about 8 thousand trees and more than 2 thousand shrubs. The composition of the tree and shrub complexes is represented by more than 70 plant species. The soil cover of the park belongs to the category of anthropogenic deeply transformed soils (urbozems). The park's soils are potentially suitable for the growth of woody and shrubby vegetation. The park includes well-established lawns, and flower beds fulfill their functional purpose.

To determine the soil pH buffering capacity (pHBC) in the park area, we collected soil samples from a depth of 0–20 cm in the sites beneath the crowns of such introduced deciduous and ornamental woody plants as green ash *Fraxinus pennsylvanica* Marshall, black locust *Robinia pseudoacacia* L., northern red oak *Quercus rubra* L., tree-of-heaven *Ailanthus altissima* (Mill.) Swingle, Kentucky coffee tree *Gymnocladus dioica* (L.) K. Koch, and box elder *Acer negundo* L. Latin names of plant species are given according to the Catalogue of Life Checklist.

We determined the soil pHBC according to changes in pH value after adding increasing quantities of acid or base to a given mass of soil (Nelson & Su, 2010). To calculate the soil pHBC, the Arrhenius method (titration curve method) was used (Truskavetskyi, 2003; Raczuk & Deska, 2012). According to the method, a series of standardized incremental amounts of either acidic (hydrochloric acid, HCl 0.1 mol/dm^3) or alkaline component (sodium hydroxide, NaOH 0.1 mol/dm^3) were added to the air-dried soil samples (Huang et al., 2009). The total amount of solution that interacted with the soil, i.e. the acidic component and water, or alkali and water, was constant (the ratio was 1 : 2.5, respectively). The same procedures were performed with pure calcined sand as a bufferless substrate. The pH level of the solutions was measured after 1 hour resuspension of the samples.

Based on the measurements of the actual pH value, a chart was developed, where the abscissa was concentration of the acid (or alkaline) component, and the ordinate was the corresponding pH values. The obtained graphical curves allowed us to estimate the pHBC of the studied soils by the buffering area in the area of acid and alkaline ranges of external influence, which was defined as the area between the titration curve of the soil sample and the bufferless standard, and expressed in conventional square centimeters. For calculation of the buffering areas, the numerical integration method and the Simpson formula were used (Chapra, 2012; Krylyk et al., 2019). We measured the pH values in bufferless substrate (calcined sand) and soil samples using an electronic digital laboratory ion meter I-160MI, in five repetitions for each pH.

Analysis of the soil microbiocenosis was performed using a differential diagnostic nutrient media by serial dilutions of the soil suspension. The number of microorganisms of the main ecological-trophic groups was determined by inoculating the soil suspensions onto appropriate nutrient media. We enumerated the ammonizers on meat-peptone agar, and actinomycetes and microorganisms that assimilate mineral forms of nitrogen (amylolytic microorganisms) – on starch-ammonia agar, oligotrophic microorganisms – on starvation agar, and pedotrophic microorganisms – on soil agar. The microorganism count was expressed as the number of colony forming units (CFU) per g of completely dried soil sample, taking into account the soil moisture coefficient and dilution of the soil suspension. The ratio of individual functional groups of microorganisms (amylolytic, ammonifying, oligotrophic) was determined according to Andreiuk et al. (2001). We determined the orientation of microbiological processes occurring in the urban soils using the indices of mineralization-immobilization, pedotrophicity, and oligotrophisity. The mineralization-immobilization index is the ratio of amylolytic microorganisms that use ammonia (mineral) nitrogen to ammonifying microorganisms that assimilate organic nitrogen (soil protein substances); the index of pedotrophicity is the ratio of pedotrophic microorganisms involved in the conversion of the water-soluble fraction of soil nutrients to ammonifying microorganisms that assimilate organic nitrogen; the index of oligotrophisity is the ratio of oligotrophic microorganisms that complete the mineralization of organic soil compounds to amylolytic microorganisms that assimilate mineral nitrogen (Patyka & Symochko, 2013). Statistical processing of the experimental results was based on analysis of variance (ANOVA). The obtained data were expressed as the mean ± standard deviation (x ± SD), and the differences between the means were tested with the Tukey's HSD. All differences were considered to be statistically significant at $P < 0.05$.

Results

The samples of the studied soils were represented by a humic loamy topsoil, and initially (before adding acidic or alkaline components) had a conditionally neutral (site 2, site 5), neutral (site 4), and slightly alkaline reaction of the soil solution (site 1, site 3, site 6) (Table 1).

Table 1
Measurements of actual pH level in the urbanzem
sampled beneath the crowns of introduced tree species
(Taras Shevchenko Central Culture and Leisure Park) (x ± SD, n = 7)

Site 1 (*Fraxinus pennsylvanica*)	Site 2 (*Robinia pseudoacacia*)	Site 3 (*Quercus rubra*)	Site 4 (*Ailanthus altissima*)	Site 5 (*Gymnocladus dioica*)	Site 6 (*Acer negundo*)
7.24 ± 0.06^a	6.89 ± 0.07^b	7.49 ± 0.09^c	6.92 ± 0.07^b	6.83 ± 0.04^b	7.71 ± 0.07^d

Note: different letters in the line mean significant differences ($p < 0.05$) for different sample sites by Tukey's.

After determining soil pHBC of the samples of the park urban soil (humic topsoil), we found the minimum buffering area in the acid range of external exposure for sample site 2, site 5, and the maximum value for site 6 (Table 2). The same trend was observed for the total buffering area, which integrally accounts for the influence of both acid and alkaline factors.

The dataset of buffering areas within the alkaline range had a higher statistical homogeneity than the dataset of the acid and acid-base (total) range of external influence. Therefore, the samples of urban soil collected from site 1, site 3, and site 6 had a minimal buffering area and did not differ statistically from each other, forming a homogeneous group. Samples of urban soil collected from site 2, site 4, and site 5 had a statistically larger buffer area compared with site 1, site 3, and site 6, and also formed a pooled statistically homogeneous group (Table 2).

Table 2
Statistical assessment of indicators of soil pHBC (humic topsoil)
under the influence of tree stands of introduced species in the territory
of the Taras Shevchenko Central Culture and Leisure Park (x ± SD, n = 5)

Sampling site with marker – tree species	Buffer area (cm^2) in the range of external influence		
	acidic	alkaline	acid-base (total)
Site 1 (*Fraxinus pennsylvanica*)	24.14 ± 0.34^a	12.52 ± 0.55^a	36.66 ± 0.64^a
Site 2 (*Robinia pseudoacacia*)	18.23 ± 0.38^b	16.72 ± 0.65^b	34.95 ± 0.75^b
Site 3 (*Quercus rubra*)	27.84 ± 0.32^c	13.78 ± 0.64^a	41.62 ± 0.75^c
Site 4 (*Ailanthus altissima*)	22.55 ± 0.20^d	17.12 ± 0.68^b	39.67 ± 0.81^d
Site 5 (*Gymnocladus dioica*)	18.08 ± 0.19^b	16.76 ± 0.65^b	34.84 ± 0.51^b
Site 6 (*Acer negundo*)	38.25 ± 0.31^e	13.76 ± 0.90^a	52.01 ± 0.85^e

Note: different letters in the column mean significant differences ($P < 0.05$) for different sample sites by Tukey's.

The data processing revealed the relationship between the level of actual pH and buffer areas (Fig. 1). The closest positive correlations were found between pH and buffering area in the acid (0.93, $P = 0.0001$) and acid-base (total) ranges of external influence (0.83, $P = 0.0001$), respecttively. A negative correlation was seen between pH and buffering area in the alkaline range of external influence (–0.76, $P = 0.0001$).

The mineralization-immobilization index and the index of pedotrophicity of the soil samples collected from sites 2, 3, and 4 were less than 1 and varied between 0.50–0.51 and 0.63–0.78, respectively. For sites 1, 5, and 6, these indices exceed the value of 1 (Table 3). The index of oligotrophicity for all the studied soil samples of the park urban soil ranged 0.06 (site 6) to 0.85 and 0.92 (site 3, site 4).

The mineralization-immobilization coefficients of sites 1, 5, and 6 were slightly higher than 1 and indicated a relatively high level of mineralization processes carried out by soil microorganisms compared with sites 2, 3, and 4, where the mineralization capacity of microbial cenosis was almost two and three times lower. A similar trend was observed for the index of pedotrophicity, which characterized the ability of microbial communities to uptake organic and inorganic nutrients from the soil. The index of oligotrophicity in all studied sites (site 1 – site 6) did not exceed 1 and, according to this criterion, degradation processes in the soil were inhibited. In general, relatively low values of the mineralization-immobilization coefficients, as well as the indices of pedotrophicity and oligotrophicity indicated a balance between synthesis, destruction, and mineralization processes in the organic matter of the soil sampled in the rhizosphere area of the introduced dendroflora species in the conditions of the park.

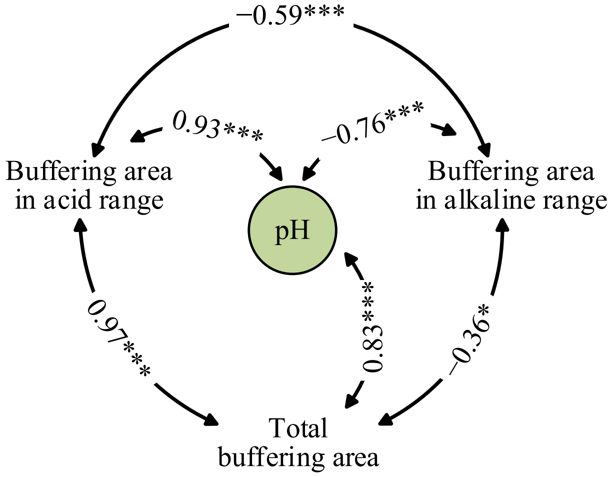

Fig. 1. Relationship (Pearson correlation coefficient) between actual acidity values of the park urban soil and their buffering characteristics; P-value: * – 0.05–0.01, *** – 0.001–0.0001

Table 3
Microbiological coefficients of intensity of soil-biological processes in the rhizosphere area of the introduced dendroflora species (by microbial functional groups)

Sampling site with marker – tree species	The index of mineralization-immobilization	The index of pedotrophicity	The index of oligotrophicity
Site 1 (*Fraxinus pennsylvanica*)	1.46	0.96	0.21
Site 2 (*Robinia pseudoacacia*)	0.51	0.78	0.48
Site 3 (*Quercus rubra*)	0.50	0.66	0.85
Site 4 (*Ailanthus altissima*)	0.51	0.63	0.92
Site 5 (*Gymnocladus dioica*)	1.04	1.27	0.63
Site 6 (*Acer negundo*)	1.93	1.90	0.06

A strong positive linear correlation was found between the mineralization-immobilization index and the index of pedotrophicity ($r = 0.88$, $P = 0.02$); the mineralization-immobilization index and the index of oligotrophicity revealed a strong negative correlation ($r = –0.88$, $P = 0.02$). The correlation between the index of pedotrophicity and the index of oligotrophicity was strongly negative, but not statistically significant ($r = –0.74$, $P = 0.09$).

Discussion

The soil is a biogenic link of nature, saturated with numerous and diverse biota (Frazaoa et al., 2019; Yakovenko & Zhukov, 2021). Important characteristics of soil quality are its biotic potential determined by the diversity of microorganisms in soil, their biological activity, the ratio of ecological and trophic groups of microorganisms in the rhizosphere, orientation of microbial processes (Andreiuk et al., 2001), as well as soil pHBC (Truskavetskyi, 2003; Bartmiński et al., 2012; Didur et al., 2019).

The report (Didur et al., 2019) highlighted positive contribution of earthworm castings to pHBC of the urban soil in park areas within the sites forested with Norway maple (*Acer platanoides* L.). The authors emphasized that the efficiency of restoration of urban park soil during its enrichment with earthworm castings increased in the conditions of a megalopolis, with simultaneous improvement of the soil ecological quality. Other scientists argued that soil buffering properties are among the important indicators of soil resistance to degradation, including anthropogenic land degradation. During their own study on urban soil, these authors have revealed that the value of soil pHBC within the acidic and alkaline ranges fluctuated in a wide range (from 27% to 98%, i.e. from low to very high level) and from 31% to 81% (i.e., from moderate to very high level), respectively. They also have developed computer models (using SURFER software) that allowed monitoring the state of urban soils in time and space, and assessing the degree of their degradation under the influence of increasing technogenic loads. Our research has revealed the sites (site 2, site 5) with a relatively low level of soil pHBC, as well as the sites (site 3, site 6) with a relatively high level of soil pHBC (Table 2).

By determining the soil pHBC, Bartmiński et al. (2012) assessed the resistance of urban soils to degradation caused by intense anthropogenic pressure. They have found that the reference soil profiles were more resilient to acidification that the studied soils in the city of Lublin (Poland). The authors associated soil degradation occuring within the agglomeration with the impacts of anthropogenic factors (in particular, acidification). In our study, the park soils sampled under the tree stands exhibited higher soil pHBC against acidification than against alkalinization (Table 2). This is obviously due to the fact that chemical composition of urbanzem is dominated by such exchange cations as Ca^{2+} and Mg^{2+} in its absorption complex inherited from the calcic chernozem as a zonal soil (Yakovenko et al., 2023).

"Soil pH is considered to be the "master variable" of soil chemistry due to its profound impact on countless chemical reactions involving essential plant nutrients, phytotoxic elements, and pollutants" (Penn & Camberato, 2019). Wei et al. (2022) showed a close relationship between the pH levels and the soil pHBC values. Our results have confirmed the pattern observed by the abovementioned authors. According to our experimental results, there was a statistically significant positive strong correlation ($r = 0.83$) between the actual acidity level and the soil pHBC.

Microbiota is an important element of urban phytocenoses; its composition was considered in the context of soil fertility (Ellanska & Yunosheva, 2021). The quantitative and qualitative composition of the soil microbiota is known to reflect the degree of anthropogenic load; it is therefore widely used as a diagnostic indicator in the process of assessing ecological state of soil (Andreiuk et al., 2001) and ecosystems as a whole (Bobryk et al., 2016). Since microorganisms respond rapidly to changes in the environmental conditions, identification of the ratio between ecological and trophic groups of rhizosphere microorganisms made it possible to find out the direction of microbiological processes occurring in the rhizosphere of urban soils under plantings of introduced dendroflora in the territory of the studied park. We found that relatively low levels of the indices of mineralization-immobilization, pedotrophicity and oligotrophicity reflected a certain balance between synthesis, destruction, and mineralization processes in organic matter of the soil in the rhizosphere area of the introduced dendroflora species grown in the urban area; we have found weak mineralization signs as a result of impairment of the natural biological cycle in the stands of introduced tree species in the territory of the park in a large city.

Conclusions

The study of soil pHBC in the urban soil samples collected beneath the stands of introduced tree species in the territory of the Taras Shevchenko Central Park of Culture and Leisure (under conditions of a large city on the example of the city of Dnipro) revealed that such soils had the total soil pHBC that can increase by 1.42 times (from the minimum value), depending on the soil properties and the composition of introduced tree species. In the area of rhizosphere influence, soils in sites with *Quercus rubra* and *Acer negundo* showed higher values of soil pHBC, and, therefore, greater resistance to degradation. We revealed significant strong positive correlations between the pH level of urban soils in the rhizosphere zone of the introduced park dendroflora and the buffering area within the acid and acid-base range of external influence, as well as a strong negative correlation between pH level and buffering area in the alkaline range of external influence. According to the ratio of functional groups of microbiota in the studied sites in the rhizosphere area of *Fraxinus pennsylvanica* (site 1) and *Acer negundo* (site 6), we observed weak mineralization signs. Such parameters as the level of soil pHBC and the mineralization-immobilization index can be used to assess the quality of the soil and its ecological state.

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