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Spatial variation of temperature of surface soil layer adjacent to constructions: A theoretical framework for atmosphere-building-soil energy flow systems

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ABSTRACT

Lack of concern for spatial variation of urban soil temperature does not reflect the importance of soil temperature in ecosystem service. The method of construction-soil micro gradient transects (CSMGT) and *in situ* observations were applied in this study to understand the mechanism of higher soil temperatures in urban areas and the spatial variation of the temperature of surface soil layer adjacent to constructions. Based on experimental data, a new theoretical framework for atmosphere-building-soil energy flow systems was established to analyse the changing rate of the temperature of surface soil layer (R_S) adjacent to constructions. The results of redundancy analysis and hierarchical partitioning showed horizontal heat flux between building and soil (HHF_0) played a very important role in driving R_S along the CSMGT at night, whereas joint effects of multiple energy factors drove it during daytime or on the scale of an entire day. Moreover, a formula was fitted to express the temperature of surface soil layer (T_S) along the CSMGT. Each parameter (a, b and c) of the equation was significant relative to energy or meteorological factors ($P < 0.01$), and the distribution of the P value of parameter b matched the results of the redundancy analysis and hierarchical partitioning.

1. Introduction

Urban soil is an important carrier of urban ecosystems and plays a crucial role in urban areas. Soil thermal environments relate to a citizen's daily life and many ecosystem processes [1,2]. In recent decades, accelerated global urbanization has changed surface properties significantly in urban areas, and a great quantity of buildings and roads made of concrete and asphalt have taken the place of original vegetation [3], forming unique micro-meteorological conditions. On the one hand, these structures provide human beings with places to conduct daily activities and convenient transportation options, making a highly effective urban system. On the other hand, a series of negative effects result from these structures, such as the urban heat island effect [4].

Due to being covered and sealed by impervious materials (asphalt, concrete and stone) [5], the physical, chemical and biological properties of soil are gradually changed by influences of structures and anthropogenic activities. Compacted and hardened soil is distributed widely in urban areas and most of the soil is isolated from the atmosphere, this type of soil limits gas effusion and rainfall infiltration, thus changing natural habitats. Moreover, energy transfer processes are changed by structures and anthropogenic activities [5]. Many scholars have reported an upward trend of soil temperature in urban areas [6–11] because of the synergistic action of multiple factors, such as energy flows within and between various spheres [5,12]. Soil temperature links many ecosystem processes and structures directly, such as food webs, soil heterotrophic respiration, microbial decomposition, nutrient

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cycling, root respiration, and C and N mineralization [13–16]. Changes in soil thermal processes caused by structures and anthropogenic activities may lead to a degradation of soil ecological services. Thus, it is of great scientific significance to do researches on spatial variation of temperature of surface soil layer adjacent to constructions.

Gradient analysis is a traditional method used in ecological research. It has been applied in vegetation research [17] and in the analysis of urban landscape patterns [18]. In recent years, a wider scope regarding gradient analysis has been used, which has produced abundant results [19,20]. Therefore, gradient analysis can be appropriately applied to researches at an urban scale.

Numerous studies have focused on the relationship between air temperature and soil temperature [21,22], the process of how buildings lose heat to soil [13,23–25] and the response of the thermal performance of facades to external circumstances [26,27]. There have been few studies of the energy connections between the atmosphere, buildings and soil, and few studies that have considered exploring the spatial variation of soil temperature adjacent to buildings. Using gradient analysis, the aim of this research was to establish a preliminary theoretical framework for the atmosphere-building-soil energy flow system to study the horizontal spatial distribution of the temperature of surface soil layer (T_S) next to building facades in summer and to determine influencing factors. Additionally, an equation was fitted to express the relationship between the distance from a building and the T_S and influencing ecological and meteorological factors for the parameters of the equation were found out.

2. Method

2.1. Site condition

The research site is located in the Haidian District, Beijing City, China (40.008°N, 116.337°E). Summer is hot and humid in the region, with a sunshine duration of approximately 230 h per month. Several buildings, roads, and green spaces are distributed throughout the study area, which has loam soil (density of soil in study area is shown in Section S1 in the Supplemental Materials). The detailed situation for selected sample areas can be described as follows: most of the surface is evenly covered by grass (approximately 0.1 m in height), there are no large trees but some arbuscles were planted in the selected sample area, and sunshine is not blocked by any vegetation in this area.

2.2. Theoretical framework

This study was focuses on the energy connections between the atmosphere, buildings and soil, referred to as the atmosphere-building-soil energy flow system. Fig. 1 shows energy flows in the atmosphere-building-soil system. In this research, not all energy flows were considered, only those marked as red arrows in Fig. 1, including solar radiation (SR), net radiation (NR), ground radiation (GR), atmospheric counter radiation (ACR), vertical soil heat flux (VHF), horizontal heat flux between building and soil (HHF_0: 0 m from baseline) and horizontal heat flux in soil (HHF_{20}: 0.2 m from baseline, HHF_{30}: 0.3 m from baseline, and HHF_{60}: 0.6 m from baseline).

Sensible heat flux (H) and latent heat flux (LE) are very important energetic factors that influence soil temperature very much, but they had to be ignored in this study, due to lack of relevant equipment to investigate them. The assessment of excluding sensible and latent heat flux from the theoretical framework was shown in the Section S2 in the Supplemental Materials. The result indicated that it did not influence the final conclusion without H and LE.

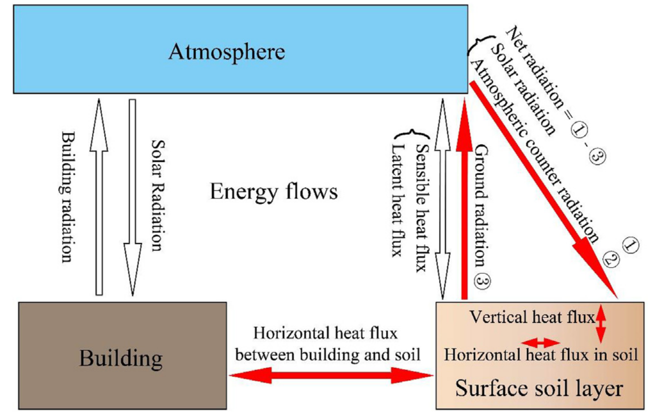

Fig. 1. Preliminary theoretical framework of atmosphere-building-soil energy flow systems.

2.3. Layout of the CSMGT

The scale of study changes with different research objects; hence, every study has to be conducted on an appropriate scale or it may lead to incorrect conclusions. Due to soil physical properties, soil temperature changes significantly at depths of 0.3–0.4 m on a diurnal scale [7,28]. Therefore, this research was conducted on a micro scale, with the gradient analysis scaled down the centimetre level. The construction-soil micro gradient transect (referred to as the CSMGT [29,30] henceforth) was considered appropriate for this research.

The green space next to one south facade was selected as the sample area for the experimental CSMGT. Observation points for soil temperature sensors were set as 0, 0.05, 0.1, 0.15, 0.2, 0.3, 0.4, 0.6, 0.9 and 1.5 m from the construction baseline respectively, where soil temperature were arranged (Fig. 2c). All observation points were in a straight line.

2.4. In situ observations

In situ observations are widely applied in ecological studies and often with reliable results [31–34]. We made *in situ* observations of T_S in this research. The entire observation period was divided into two phases. Phase I involved the analysis of changing rate of temperature of surface soil layer (R_S) along the CSMGT and its influencing energy factors; a statistical approach was applied to explain the energy mechanisms of R_S. Phase II involved fitting the data to an appropriate formula and determining which energy factors affect the parameters of the equation directly. The observation period and meteorological conditions are listed in Table 1.

Both phases included sunny days (with a total cloud cover less than 20%), partly sunny days (with a total cloud cover between 20% and 80%), cloudy days (with a total cloud cover greater than 80%) and rainy days.

T_S were observed with soil temperature sensors (unit: K, sensor accuracy: 0.2 K) and stored with data loggers. The arrangement of soil temperature sensor was shown in Section S3 in the Supplemental Materials. The sampling interval was 1 min, the logging interval was 10 min and data for each sensor were averaged for each hour (0-59th min). T_S at different observation points were recorded as T_0, T_5, T_{10}, T_{15}, T_{20}, T_{30}, T_{40}, T_{60}, T_{90} and T_{150}. Soil temperature differences between two adjacent observation points (ΔT) were recorded as ΔT_0, ΔT_5, ΔT_{10}, ΔT_{15}, ΔT_{20}, ΔT_{30}, ΔT_{40}, ΔT_{60} and ΔT_{90}.

Most meteorological data were gathered and logged with a