A Micro to Macro Evaluation of Evaporation Considering the Pore-Scale Mechanisms through Unsaturated Soil Profiles

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論　文　内　容　の　要　旨

Climate change has become a global concern over the past decades. From global warming to shifting weather patterns, the impacts of climate change are global in scope and unprecedented in scale. Drylands worldwide cover around 46.5% of the global land area and are home to around 38.6% of its population. Besides the hot and dry conditions, the global warming ramifications, such as the increased drought frequency, extensive water evaporation, and precipitation deficit, are causing a reduction in soil moisture availability, water scarcity, and land degradation in such regions. All these factors are exacerbating the desertification phenomenon where over the past several decades, it has extended to about 9.4% of drylands, affecting more than 500 million people, most of whom are in developing countries. Therefore, providing simple and economical technologies is essential to mitigate soil degradation and combat desertification.

Ground surface boundary fluxes and water movement through unsaturated soils are critical for many engineering and water management applications. Despite the proposed methods to predict and control such fluxes in the literature, solving unsaturated soils related issues requires developing more comprehensive and easily applied models. Generally, the upward evaporation flux from soil profiles is dominant in drylands. It is a complex multiphase pore-scale process involving coupled heat-mass transfer, liquid-gas phase change, and liquid-vapor transport through its pores. From bare soil profiles, evaporation is a function of the surface's atmospheric demand and the soil's ability to supply water, which depends on soil pore properties. Most existing research tackles the evaporation process from a phenomenological point of view. It is usually considered a boundary flux where the mechanisms occurring at the pore level are neglected due to the lack of suitable techniques. Moreover, previous evaporation estimation models usually consider complicated parameters to estimate the evaporation rate. However, for a complete description of the evaporation process and an accurate evaluation of its rate, the atmospheric demand should be solved in conjugation with the water supply and considering its mechanisms through unsaturated soils based on a simplified parameter.

This thesis investigates and evaluates the evaporation process from unsaturated soils by tackling the evolving micro-mechanisms occurring at the soil pore level and reflecting them on the macroscale behavior of evaporation. Moreover, it considers developing natural soil covers to control and suppress evaporation from bare soil profiles in drylands as a step toward combating desertification. Four objectives are drawn to satisfy the goals of the thesis. It starts with the parameterization of the soil pore structure through an experimental approach and investigates its influence on evaporation behavior. Secondly, experimental visualization of the formation and development of the unsaturated soil layer and its boundaries during evaporation and investigation of their role in the process. Thirdly, to formulate an empirical and theoretical framework for accurately estimating the evaporation rate based on the soil pore structure parametrization and the visualization of the unsaturated layer dynamics. Finally, optimization of a conceptual framework for a natural soil cover that suppresses evaporation and maximizes water retention in drylands by identifying the role of the relative soil properties between the natural ground and the applied soil cover. Consequently, the thesis is divided into seven chapters as follows:

Chapter 1 presents the scientific understanding of the climatic changes leading to desertification. It briefly discusses global warming ramifications and its threat to humanity and the ecosystem. It presents facts about drylands and discusses the necessity to combat desertification. It concludes with the vital role and needs to accurately evaluate the ground surface boundary fluxes, mainly the dominant evaporation flux, for many engineering applications. Finally, the proposed goals, objectives, and framework are reported.

Chapter 2 presents a comprehensive literature review of the current research scopes and objectives. It presents an inclusive view of the potential and actual evaporation fluxes and their micro and macroscale definitions. The most used models and methods to evaluate the evaporation rates in practice are discussed. The influencing factors of the actual evaporation behavior are delineated, while the importance of bridging the atmospheric demand and water supply through the soil profile is reviewed. Moreover, the latest methods used to suppress water evaporation from soil profiles are presented. This chapter concludes with the current research's original contributions and expected impacts on the field.

Chapter 3 focuses on understanding the macroscale behavior of the evaporation process and the influence of the soil pore structure on its behavior. The evaporation process and soil pore structure are investigated through experimental testing of homogeneous sandy soil profiles under constant atmospheric demand. Accordingly, a robust and comprehensive pore structure-based index is proposed to represent the pore structure variation while its significant influence on evaporation behavior is discussed.

Chapter 4 focuses on investigating the microscale behavior of the evaporation process by studying the evolving mechanisms occurring at the pore level during drying. Accordingly, a novel and effective technique is developed to visualize the unsaturated layer during evaporation. The image analysis-based technique considers capturing high-quality images, followed by a series of image analysis operations to enable the detection of the air-dry layer, film region, and their boundaries during Stages 2 and 3. Accordingly, new insights are discussed regarding the dynamics of the drying front, vaporization plane, and film region. Furthermore, the influence of the pore structure on the unsaturated layer dynamics is further elucidated.

The main focus of Chapter 5 is reflecting the evolving micro-mechanisms at the pore level to the macroscale behavior of the evaporation process. Consequently, a new actual evaporation rate estimation model is proposed based on the pore structure and water transfer mechanisms through the unsaturated soil profile. The pore-scale-based estimation model conjugately solves the atmospheric demand and the water supply during evaporation. The theory, assumptions, and empirical-theoretical derivation are thoroughly discussed, and its reliability, limitations, and the simplicity of its utilization are presented.

Following the need to develop innovative solutions to combat desertification in drylands, Chapter 6 proposes a new design concept for an environmental-friendly natural soil cover that suppresses water evaporation and maximizes water storage in bare soil profiles. The physics behind the two proposed criteria is thoroughly explained. Moreover, the efficiency and applicability of the design concept in selecting the suitable material and thickness of the natural soil cover are discussed.

Finally, Chapter 7 summarizes this thesis's main findings and conclusions and delineates future work.