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SUMMARY OF DOCTORAL THESIS

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Title: Canopy temperature and energy balance of irrigated wheat in the hot-arid environment of Sudan
（スーダンの高温乾燥環境における灌漑コムギのキャノピー温度とエネルギー収支）

The impact of climate change on agriculture is critical and demands urgent attention. In Sudan, the agricultural sector is highly vulnerable to climate change, posing threats to food security and national economy. The consequences of climate change, specifically rising temperature, could significantly impact agricultural production in Sudan, affecting crop yields, water availability, and land use. Wheat is one of the major crops in Sudan and is strongly affected by climate change. Sudan produces wheat under irrigation in a hot and dry environment that has been considered one of the hottest wheat-producing areas in the world. Due to its adaptation to cooler environments, wheat is highly susceptible to high temperatures, leading to substantial anticipated effects on yields and the potential for significant reductions in production under future climate. To understand the response of wheat to heat stress, a comprehensive exploration of micrometeorological factors influencing canopy temperature is essential. However, existing knowledge about wheat microclimates in hot and dry environments remains limited. To bridge this gap, the purpose of this thesis was therefore to advance our understanding of microclimates in irrigated wheat cultivation in Sudan. The main objectives were to investigate cultivar differences in the canopy temperature and to characterize the energy balance in the hot-arid environment.

First, the response of two high-yield, heat-tolerant wheat cultivars, Imam and Bohaine, to a hot and dry environment was evaluated. Micrometeorological observations were carried out in two adjacent fields under irrigated conditions in the Gezira Scheme, Sudan. The hourly micrometeorological data were collected at 2-meter and canopy levels in the 2020-2021 growing season to specifically investigate canopy temperature depression (CTD) and its influencing factors. The micrometeorological observations revealed that there was a notable difference between canopy surface temperature and canopy-level air temperature. The former consistently displayed lower owing to the evaporative cooling effect, while the latter factored in both convective and radiant heat exchange reflecting the distinctive thermal exchanges above the canopy. Also, the micrometeorological observations reflected significant differences in CTD between the two wheat cultivars. Imam with a semi-prostrate growth habit had a much higher CTD than Bohaine with a fully erect growth habit, indicating that it has a better cooling ability and can be less vulnerable to heat stress. This cooling effect was observed not only during the daytime but was extended to the nighttime during all critical growth periods (vegetative, heading, and grain-filling). Besides, the study revealed that air temperature gradient and vapor pressure gradient were negatively correlated, and this correlation was greater during the nighttime due to the low wind speed. This indicates that wind speed has a crucial impact in altering the microclimate surrounding the wheat canopy due to the turbulent flux of heat and water vapor. Furthermore, the difference in canopy temperature between the two cultivars could be attributed to the significant difference in NDVI, which is used as a proxy for the leaf area index and aboveground biomass. This indicates that different cultivars possess varying mechanisms of adaptation to high temperatures, demonstrating a greater ability to modify the microclimate.

Next, the response of irrigated wheat to a hot-arid environment and the effect of irrigation on the microclimate were clarified. Net radiation (Rn), soil heat flux (G), soil moisture, and temperature and humidity at 2-meter height and canopy level were measured in a wheat field in Dongola, northern Sudan in two crop growing seasons (2021-2022 and 2022-2023). The Bowen ratio method was used to calculate the latent heat flux (LE) and sensible heat flux (H). The study discovered that irrigation has a significant impact on the microclimate, as air temperature in the field was lower than that at a nearby meteorological station. The wheat canopy showed a localized cooling effect generated by well-irrigated cropland, with varying degrees of cooling observed across different growth stages. The most significant cooling effect observed was a difference of over 5 °C during the late vegetative to early reproductive stages. This difference increased after the crop reached full canopy cover because LE was the dominant component of the energy balance over H and G. These findings highlight the crucial role of irrigation in mitigating the adverse effects of heat stress and improving crop performance in arid regions. The significant information provided in this study can fill the gap in understanding microclimate modification which can be used in the adaptation measures for enhancing wheat crop yield. In addition, the relationship between G and soil conditions was examined. The study revealed that G had a lower intensity during the main growth period from the late vegetative to early reproductive stages. However, during the early vegetative and late reproductive stages, G was higher. These findings not only contribute to a better understanding of the energy partitioning in the soil-plant-atmosphere continuum but also underscore the seasonal variations in soil heat flux.

This thesis presents insights that enhance our understanding of microclimate and energy balance in wheat cultivation, specifically in hot-arid environments. Firstly, using a micrometeorological approach, the study uncovered substantial differences in canopy temperature between two wheat cultivars, underscoring the importance of incorporating growth habits in such data analyses. Secondly, the study delved into irrigated wheat in a hot-arid environment and identified unique temperature modifications, particularly during the critical growth stages. Thirdly, the study highlighted the potential of the well-watered wheat canopy to produce localized cooling effects, which varied across different growth stages. Furthermore, the study identified the significant role of sensible heat advection in the energy balance, revealing the intricate relationships between the latent heat flux, net radiation, and surrounding environmental conditions. These findings not only deepen our understanding of crop-micrometeorological interactions in wheat cultivation but also offer valuable insights for developing climate-resilient agricultural practices that are tailored to hot-arid environments.

In conclusion, the implications of this thesis can be summarized as: the integration of cultivar-specific micrometeorological responses into crop models has a transformative impact. This inclusion enhances the accuracy of the models and makes more reliable simulations for crop development, growth, and yield under diverse environmental conditions. Tailoring the micrometeorological approach to specific cultivars increases precision by capturing unique morphological traits pivotal in crop-micrometeorological interactions. Furthermore, identifying cultivar-specific traits that harmonize with given microclimates provides critical insights into plant breeding, as breeding strategies that focus on traits such as canopy architecture and leaf area size align with optimizing micrometeorological conditions. This knowledge enables the targeted selection of traits associated with resilience to varying climatic challenges, paving the way for the development of wheat cultivars that can withstand diverse environmental conditions. Therefore, the application of micrometeorological insights in both crop modeling and plant breeding signifies a significant stride toward advancing climate-resilient and productive agricultural practices in the hot-arid environment of Sudan.