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SUMMARY OF DOCTORAL THESIS

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Title: **Soil Moisture Dynamics in the Cold, Arid Climate of Mongolia**

モンゴルの寒冷・乾燥気候における土壌水分動態

Soil moisture plays a central role in the global water cycle and climate system by controlling the partitioning of water and energy between the land-surface and the atmosphere. Soil moisture acts as a memory of anomalies in the water cycle, in turn, it has a delayed and durable influence on the overlying atmosphere through land–surface fluxes of heat and moisture and plays as a bridge between meteorological drought (deficits in precipitation) and agricultural drought (failures of plant growth). A number of drought indices have been proposed and applied to quantify drought conditions, although, presently very few studies have used ground-observed soil moisture as an indicator of agricultural drought in the world. A large drying trend has been observed in a soil moisture index over land areas in the Northern Hemisphere since the middle 1950s, including Mongolia, affecting the pastureland that is used for livestock. It has been found that soil moisture deficits limit the growth of pasture in Mongolia. Hence, accurate extensive assessment and modeling of soil moisture dynamics in this pastureland is required for reliable and timely monitoring of agricultural drought. This thesis represented recent advances in the observation and modeling of soil moisture dynamics and in analyses of its relationships with climate and vegetation activity in the cold, arid climate of Mongolia with a focus on three vegetation zones; forest steppe, steppe, and desert steppe. This study is the first comprehensive analysis on soil moisture dynamics in Mongolia and moreover, it was revealed the memory processes of soil moisture and vegetation in the cold, arid climate.

Firstly, the seasonal and spatial changes of soil moisture and its climatology and modeling were demonstrated. In this analysis, a unique long-term, updated soil moisture and meteorological datasets for 26 stations during 1986–2005 were used. The results showed that the soil moisture varies seasonally, depending not only on the balance of precipitation and evapotranspiration but also on winter soil-freezing and spring snowmelt. In general, there was a latitudinal gradient in soil moisture content, with the southwestern soils drier than the northeastern soils. The seasonal change in soil moisture was small and the seasonal pattern was similar throughout Mongolia. We documented three distinct seasonal phases; the spring drying, summer recharge, and autumn drying and their relationships to plant phenological phenomena of *Stipa* spp. that represents the dominant species in the Mongolian steppe. Over Mongolia, the available soil moisture was about 30% of the soil field capacity, while in the desert steppe; soil moisture was close to the wilting point throughout the year. A simple water balance model was developed for application in the cold, arid regions such as Mongolia, by considering soil freezing and snow melting. The model simulated the observed seasonal and interannual soil moisture variations reasonably well ($r = 0.75$, $p < 0.05$). This model will provide a useful tool for a reliable and timely monitoring of agricultural drought for decision-making and herding management in Mongolia.

Secondly, multi-decadal trends and memory of soil moisture were assessed in three

vegetation zones using the modeled daily soil moisture during 1961–2006. On an interannual basis, the modeled soil moisture was more strongly correlated with the observed soil moisture ($r = 0.91$, $p < 0.05$) than the widely used Palmer Drought Severity Index ($r = 0.65$, $p < 0.05$). All three vegetation zones showed a decreasing trend in soil moisture and shortening in the summer recharge phase due to decreased precipitation and increased potential evapotranspiration. Although only in the forest steppe revealed significant ($p < 0.05$) drying trend due to significantly decreased precipitation. Soil moisture memory analysis showed that the decay temporal scales of soil moisture anomalies were 6–7 months in the autumn and winter, which is larger than that in spring and summer of 1.8–3 months in the forest steppe. This indicates that soil moisture acts as an efficient memory of precipitation anomalies via the soil freezing and as an initial soil moisture condition for the subsequent summer land-surface.

Thirdly, the relationship between root-zone soil moisture and vegetation activity in the Mongolian steppe was analyzed based on remotely sensed NDVI data for seasonal and interannual periods during 1982–2005. Vegetation activity was more strongly correlated with soil moisture than with precipitation, suggesting that soil moisture plays an important and immediate role in controlling vegetation activity. A comparison between years with high and low vegetation revealed that that a significant difference in precipitation led to a half-monthly time-lagged significant difference in soil moisture, finally a difference in vegetation, with time lags of about one month. Interannual fluctuations in vegetation were strongly dependent on soil moisture of the current year ($r^2 = 0.53$) and even more strongly dependent on a combination of the current year soil moisture and vegetation of the preceding year ($r^2 = 0.55$). This result suggests that vegetation anomalies are likely stored as underground structures in the root system. To the best of our knowledge, this is the first study in Mongolia to point to the combination of soil moisture and root memories as predicting parameter for vegetation activity.

Fourthly, new observational evidence of a half year-long moisture memory mechanism mediated by the land surface that is manifested in the cold, arid climate of Mongolia was found. The analysis result showed that significant carryover of summer rainfall anomalies to subsequent years, mediated by the soil moisture–vegetation system. Namely, changes in precipitation led to time-lagged, directly correlated changes in soil moisture and plant production. During the following winter, anomalies in soil moisture were maintained in the frozen soil and biomass anomalies may have been stored as underground structures in the root system. Even though these land-surface anomalies are maintained through to the spring, they were shown only to have had a weak effect on early summer precipitation. Instead, the soil moisture anomalies tended to be disturbed by large-scale atmospheric variations during the summer, producing subsequent anomalies in precipitation, temperature, and evapotranspiration. The cold–season climate with low evapotranspiration and strong soil freezing acts to prolong the decay time scale of autumn soil moisture anomalies to 7.6 months in the steppe, which is the longest in Mongolia and among the longest in the world. In future applications, the concepts of soil moisture and vegetation memories presented in the present study would provide a useful basis for an early warning system of reduced pasture production during drought.