論 文 の 内 容 の 要 旨

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論文題目　Integrated modeling of a coupled human-environment system in a desertified region of Inner Mongolia, China
（中国北東部における砂漠化防止と持続的土地利用のための生態—社会経済統合モデルの開発）

A major research lesson over the past decades has been that sustainable environmental management cannot be achieved by focusing only on either the human or the environmental system. Understanding dynamic interactions between both systems is imperative. Emphasis has therefore progressively shifted to integrated approaches based on the concept of coupled human-environment (H-E) systems.

In desertified regions, land degradation and human livelihoods are closely interrelated; this relationship can be altered by policy intervention. However, most desertification estimates have been solely made either by ecological or by socioeconomic factors but rarely by both. In particular, since desertification is a global problem but is also strongly localized phenomena, local heterogeneity of both people and landscape is a critical factor to jointly address. Thus, accounting for complex H-E systems in drylands becomes necessary for accomplishing sustainable land management.

Researchers and policy-makers agree that the modeling approach is fundamental for understanding H-E systems. Recently, an agent-based model (ABM) has gained considerable attention. ABM is a computerized bottom-up simulation of entire patterns emerging from the interactions between numerous autonomous decision-makers and a dynamic environment. Although traditional models capturing combined ecological and socioeconomic systems were based on mathematical bioeconomics, they could not handle many important characteristics of H-E systems, e.g., space, interactions, and heterogeneity. ABM has the potential to overcome the shortcomings of traditional models and thus has become a major tool for understanding complex systems. However, ABM is still in its developing phase. In particular, multiple interaction mechanisms such as feedback, learning, and adaptation in a real heterogeneous system are poorly represented.

From an H-E system's perspective, this thesis aims to empirically elucidate ecological and socioeconomic characteristics in a desertified region and develop a spatial agent-based land-use model representing a heterogeneous dryland system with multiple interaction mechanisms. The model's operational capability as a decision-support tool for future land management was tested using scenario assessments. The study area was located in Naiman County, Inner Mongolia

Autonomous Region of China. It is situated in the southern part of the Horqin Sandy Land, one of the most desertified and poorest regions in Inner Mongolia. I considered the H-E systems of this area as three interrelated systems: landscape, household, and policy. First, I conducted three empirical studies on the landscape system for demonstrating the dynamics of land-degradation and land-restoration and spatial heterogeneity (Chapter 2). Second, I conducted two empirical studies on the household system to elucidate households' heterogeneity and land-use decision-making (Chapter 3). Third, I conducted an empirical study on the policy system to clarify the local mechanisms of a key environmental policy, called Sloping Land Conversion Program (SLCP), and designed hypothetical scenarios that could improve the current SLCP (Chapter 4). Finally, I integrated the results of these empirical studies using agent-based modeling and constructed the spatial land-use model, named Inner Mongolia Land-Use Dynamic Simulator (IM-LUDAS) (Chapter 5). Further, using IM-LUDAS and the designed scenarios, I assessed the effects of current and hypothetical SLCP on the land-use change and dynamics of households' livelihoods, land degradation, and land restoration.

Chapter 2 Landscape system

Land degradation in this area is mainly due to cultivation and grazing. Since pasture degradation has been intensively studied by earlier research, I conducted empirical research on cropland degradation.

The landscape of this area is characterized by sand-dune topography, a factor determining land conditions and use. I examined the changes in crop, weed, and soil properties in three typical cropland types having cultivation periods of up to 20 years: maize cropland on non-irrigated lowlands, maize cropland on irrigated flat sandy lands, and bean-centered cropland on non-irrigated sand dunes. The crop biomass and soil properties were more degraded in non-irrigated lowlands and non-irrigated dunes than in irrigated flatland. The weed communities in non-irrigated croplands became established in drier conditions, whereas wetland weeds were more abundant on irrigated flatland. The changes in property did not always occur simultaneously and differed statistically for different croplands.

I conducted vegetation and soil surveys along a topographic gradient (interdune lowland, lower, middle, and upper part of sand dune) in the following four types of restoration site, having restoration periods of up to 35 years, and in two control sites: grazing-exclusion sites; shrub, pine, and poplar plantations; fixed and shifting sand dunes. Vegetation and soil conditions were restored simultaneously. Tree plantations facilitated land restoration more rapidly than grazing exclusions and shrub plantations until the first 25 years; however, both tree plantations and grazing exclusion sites reached a stable state at the end of 35 years. Land restoration progressed more at lower positions than at higher positions; this indicated that the establishment and dispersal of invader plant species beginning at interdune lowlands would promote restoration.

I developed a method to spatially extract topographic and land-use types, survey units of ecological studies, for demonstrating spatial landscape heterogeneity and for enabling field-scale ecological models to function in IM-LUDAS. The method used a combination of object-oriented analysis, digital photogrammetry, and GIS analyses using images from Advanced Land Observation Satellite. First, object-oriented classification was performed to discriminate land-use types that were hardly differentiated from others using only spectral information. Second, a digital surface model (DSM) was extracted by digital photogrammetry; the landform types were classified on basis of DSM using GIS analyses. The land-use types were then extracted by overlaying two classification maps. I applied the method to a test site in the study area, and the overall accuracy of object-oriented and landform classification was high, i.e., 87% and 88%, respectively.

The clarifications of unique degradation and restoration patterns corresponding to spatially-explicit landscape heterogeneity enables the formation of uneven policies such as detailed zoning and also makes IM-LUDAS sensitive to uneven-policy scenarios.

Chapter 3 Household system

First, I examined regional socioeconomic heterogeneity to find representative villages where household surveys would be carried out. I interviewed village representatives about the socioeconomic conditions and classified all villages into three types: livestock-farming-oriented, crop-farming-oriented, and off-farming-oriented. Because off-farming-oriented villages did not largely depend on land resources or undergo land degradation, other types seemed to need prioritized support. Next, I conducted household surveys in five villages selected as representatives of the prioritized village types. From the collected households' socioeconomic data, their livelihoods were classified into three types: livestock-farming-oriented, crop-farming-oriented, and off-farming-oriented. These were similar to the village classification types; this implied that the main economic activities would be the primary indicator to characterize socioeconomic heterogeneity, regardless of scales, in this area.

From spatially-explicit landholding data of households, collected in household surveys, I built the land-use decision-making model for each livelihood type using multinomial logistic regression. The result showed that the topography and proximity to used land significantly affected the land-use patterns of each livelihood type. However, these effects on land uses were positive or negative, depending on the livelihood types.

The identification of different livelihood types with distinct land-use patterns clarified the socioeconomic heterogeneity of households in this region. This identification also facilitated adaptive decision making to be embedded in IM-LUDAS; this decision making mechanism enabled households to change their livelihood types by changing their socioeconomic conditions.

Chapter 4 Policy system

Three hierarchical actor levels were involved in SLCP: township government, village committees (self-governing bodies), and households. I interviewed the senior officials of the township government, village, and household representatives to understand the SLCP local mechanisms. The results showed that the target villages of SLCP were determined by voluntary village applications and government screening. This process spontaneously considered regional heterogeneity; i.e., SLCP was not uniformly executed across the township. Households hardly participated in the implementation process as autonomous actors. In researched villages, although the SLCP participation was not compulsory, all the villagers were given uniform land quotas for SLCP and they actually attended it. Moreover, even though households were given the option to choose implementation plots, they were encouraged to choose flatland because flatland was suitable for cultivation as it could be irrigated; thus, the planted trees could be easily preserved. The government aimed to increase the plantation area, and the households were required to preserve the planted trees in order to receive the SLCP subsidy. Therefore, a major shortcoming of the present SLCP was the lack of proper prioritization in identifying target plots and beneficiaries, which raises doubts in the program's cost-effectiveness. Further, even if target villages, households, and plots were appropriately selected, certain proactive measures would be essential for the prevention of desertification because the planting of trees was a reactive measure. The Chinese government expects the SLCP to facilitate the households' labor reallocation, particularly from agriculture to non-agriculture, which would contribute to stable livelihoods after the implementation of SLCP. This SLCP effect could be considered as a proactive measure against desertification; however, it is still not clear whether SLCP has the potential to achieve this effect.

In addition to a baseline scenario designed on the basis of the current SLCP, I designed two hypothetical SLCP scenarios with reference to the two abovementioned challenges on the current SLCP: rational SLCP scenario, introducing rational criteria for selecting implementation plots, i.e., only targeting the cropland abandoned by households below average income in this region because of unacceptably low yield; intensive SLCP scenario, introducing intensive criteria for selecting implementation plots, i.e., targeting all croplands used by households below average income in this region. The former scenario aimed to assess whether the cost-effectiveness of the SLCP could be improved in terms of both ecological and economic benefits, whereas the latter aimed to assess whether households' labor reallocation could be induced by SLCP.

Chapter 5 Agent-based modeling of a coupled human-environment system

I constructed IM-LUDAS using empirical studies results. The model's spatial extent was confined to the boundaries of the five selected villages (Chapter 3); the landscape data of these villages were created by the developed method (Chapter 2). Landscape agents (congruent land pixels), having ecological attributes and sub-models of crop yield, land degradation, and land restoration (Chapter 2), and household agents, having socioeconomic attributes and land-use decision sub-model (Chapter 3), constitute the IM-LUDAS. Default settings of IM-LUDAS are based on the current SLCP (Chapter 4). The agent's attributes, functions, and interaction mechanisms are related to external policy settings, so that the mutual ecological and socioeconomic impacts of SLCP can be assessed. Because IM-LUDAS represents landscape heterogeneity and household population, the effects of various implementation mechanisms, e.g., designed scenarios (Chapter 4), on the program's cost-effectiveness can be quantitatively tested. Moreover, the effectiveness of the SLCP in changing the households' labor allocation can be assessed using the embedded adaptive decision-making mechanism.

Using IM-LUDAS, I assessed the current and hypothetical SLCP impacts according to three designed scenarios. As expected, the ecological benefit was higher and expected budget was lower in the rational SLCP scenario than in the baseline scenario. However, poverty alleviation effects were not observed probably because the resultant total implementation area was very small; this means that the paid subsidy was too low to contribute to poverty alleviation. The intensive SLCP scenario did not induce the reallocation of the households' labor, whereas their land-use structure and income level largely changed. This is probably owing to other unchanged critical attributes such as ethnicity and education levels. The livelihood types are determined by their multiple attributes including those mentioned above. This result implies that the use of only SLCP is not enough to induce livelihood change; other policies, e.g., educational programs, should be implemented.

This thesis empirically elucidated the heterogeneous landscape and its dynamics as well as heterogeneous households and their decision-making in a desertified region. Moreover, their complex interactions, including adaptive decision-making, were represented by agent-based land-use modeling. IM-LUDAS is one of the first models that can assess the mutual impacts of external factors on the change in land-use along with the dynamics of households' livelihoods, land degradation, and land restoration with reference to landscape heterogeneity and human population. The scenario assessments generated rational and new insights for future policies, indicating its usefulness as a decision-support tool. Although many features of relevant H-E systems in this region are not included in the model yet, its agent-based structure has a built-in flexibility for upgrading and modification. As a virtual computational laboratory, IM-LUDAS can contribute to scientific experiments on various complex phenomena in desertified regions and can support negotiation among multiple stakeholders for future land management in this area.