Modelling land-use and land-cover change and related environmental impacts in Northern Mongolia

Dissertation

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Christian Schweitzer
geboren am 08.12.1977 in Frankenberg (Eder)

Gutachter: 1. Prof. Dr. Ralf Seppelt

2. Prof. Dr. Wolfgang Cramer

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‘*The only progress that knowledge allows is in enabling us to describe more and more in detail the world we see and its evolution. What matters in a world-view is to grasp the meaning and purpose of everything, and that we cannot do.*’

Albert Schweitzer

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Summary

In the arid and semi-arid areas of Central Asia some countries are already facing acute water scarcity leading to concerns about future water resources. To a large extent, water shortage is linked to changes in land use and land cover. Consequently, there is an urgent need for regionally adapted sustainable management strategies to minimize the negative impacts on humans and the environment.

In the Kharaa river basin in Northern Mongolia, significant land-use and land-cover changes have taken place in the last decades affecting the ecosystems and their functions. In addition, most of the activities in the region either decrease water availability or increase water demand or both, resulting in urgent scientific and political management tasks. Since 2006 Mongolian and German scientists have been developing new approaches for an Integrated Water Resources Management (IWRM). IWRM is a process which aims at the sustainable use and management of water, land and related natural resources in order to satisfy economic and social needs and further ensure the protection and enrichment of the ecosystem for future generations. Several disciplines, such as environmental modelling, are providing methods and tools which support the design and implementation of an IWRM. The methods comprise integrated models, which are able to analyse the complex links between different components of the human-environmental system as well as their interdependencies.

The aim of this thesis was to develop and apply an integrated model of the land system that is capable to measure and analyse historical, current and future land-use and land-cover changes in order to contribute to the development of future management options. In total, three case studies have been conducted, which are shortly summarized in the next paragraph. In all case studies the modelling framework SITE (Simulation of Terrestrial Environments) was used which provides generic functions as well as methods for the development, testing and application of spatial explicit land-use models. In SITE, the regional land-use model SITE-Mongolia was integrated, which links decision and rule-based concepts with the process-based simulation of the biophysical environment and other important components. This thesis first provides a detailed description of the underlying modelling approach including technical aspects and later progresses into the presentation and discussion of the case studies.

Motivated by current agricultural land-use policies that aim at massive expansion and intensification of the agricultural sector, a simulation experiment was performed to assess the availability of water for irrigation purposes. For this, SITE-Mongolia was coupled with a hydrological model. Results indicate that an expansion of agricultural water use will severely deplete water resources which in future may lead to increasing conflicts with other water users. The second case study addresses wildfires which are of major concern threatening grassland and forest ecosystems. A wildfire component was developed which is capable of simulating wildfire risk, wildfire spreading and intensity – the last is considered as an important factor to

assess impacts on the carbon cycle. Modelling results indicate that the approach is able to simulate wildfire behaviour at a scientifically acceptable accuracy level. Further, the integration, gains from a better estimation of the availability of forest biomass and an improved allocation of land. In addition, it was possible to study important feedbacks regarding the future use of land. In a collaboration between German and Mongolian scientists, environmental scenarios have been designed which aimed at investigating potential future trends with a focus on water use by different sectors. The study exemplified that a difference in boundary conditions can either release or increase the pressure on water and other resources. Simulation of agricultural intensification showed that under increasing fertilizer consumption the availability of water becomes the limiting factor for plant growth in Northern Mongolia, which under frequent occurrence of dry years would lead to considerable losses in yield.

In conclusion, the case studies indicate an urgent need for the development of courses of actions to guarantee the balance between protection and maintenance of ecosystems and the fulfilment of human needs. This has to be achieved under the consideration of the extreme climate conditions. Current developments in the agricultural sector and the increasing endangerment of forests, which play a vital role in regulating water balance, are especially important. The new modelling concept presented in this thesis provides a possibility to analyse important drivers of land-use change in North Mongolia in order to achieve a better understanding of the impacts on social- and environmental factors.

Zusammenfassung

In den ariden und semi-ariden Gebieten Zentralasiens sind einige Staaten bereits von akuter Wasserknappheit betroffen und es herrscht zunehmend Sorge um zukünftige Wasserressourcen. In vielen Fällen ist ein vermindertes Wasserdargebot auf Veränderungen der Landnutzung und Landbedeckung zurückzuführen. Hieraus ergibt sich die Notwendigkeit regional angepasste und nachhaltige Managementstrategien zu entwickeln, um in Zukunft negative Folgen für Mensch und Natur minimieren zu können.

Im Einzuggebiet des Kharaa Flusses in der Nordmongolei haben in den letzten Jahrzehnten signifikante Veränderungen in der Landnutzung und Landbedeckung stattgefunden, welche sich zunehmend negativ auf die Ökosysteme und deren Funktionen auswirken. Zudem verursacht ein Großteil der menschlichen Aktivitäten eine Minderung der Wasserverfügbarkeit, beziehungsweise einen Anstieg des Wasserbedarfs, woraus sich ein dringlicher wissenschaftlicher als auch politischer Handlungsbedarf ergibt. Seit 2006 sind mongolische und deutsche Wissenschaftler damit beschäftigt, neue Ansätze für ein integriertes Wasserressourcen-Management (IWRM) zu entwickeln. IWRM ist ein Prozess, welcher auf die nachhaltige Nutzung und das Management von Wasser- und Landressourcen ausgerichtet ist. Ziel ist es, für zukünftige Generationen die Erfüllung ökonomischer und sozialer Bedürfnisse sicherzustellen, sowie gleichermaßen Ökosysteme und deren Funktionen zu schützen. Verschiedenste Disziplinen, wie auch die Umweltmodellierung, stellen hierfür Methoden und Werkzeuge bereit, die die Konzeption und Umsetzung eines IWRMs unterstützen. Zu diesen Methoden zählen auch integrierte Modelle, welche in der Lage sind, die komplexen Zusammenhänge der verschiedenen Komponenten des Mensch-Umwelt-Systems und deren Wechselwirkungen zu analysieren.

Ziel dieser Dissertation war die Entwicklung und Anwendung eines integrierten Landnutzungsmodells, welches die Möglichkeit bietet, historische, aktuelle sowie zukünftige Veränderungen der Landnutzung und Landbedeckung abzuschätzen und zu analysieren und damit einen Beitrag zur Entwicklung von zukünftigen Managementoptionen zu leisten. Insgesamt wurden drei Fallstudien durchgeführt, welche in dem nachfolgenden Abschnitt kurz erläutert werden. Für alle Studien wurde die Modellierungssoftware SITE (SImulation of Terrestrial Environments) verwendet, welche generische Funktionen sowie Methoden bereitstellt, um räumlich explizite Landnutzungsmodelle zu entwickeln, zu testen und anzuwenden. In SITE wurde das regionale Landnutzungsmodell „SITE-Mongolia“ integriert, welches entscheidungs- und regelbasierte Konzepte mit der prozess-basierten Simulationen der biophysikalischen Umwelt sowie anderen wichtigen Komponenten verknüpft. Neben der Erläuterung des zugrundeliegenden Modellierungsansatzes, inklusive einiger technischer Aspekte, werden in dieser Arbeit die Ergebnisse der Fallstudien präsentiert und diskutiert.

Motiviert durch die aktuelle Landwirtschaftspolitik in der Mongolei, welche auf eine Ausweitung und Intensivierung des Agrarsektors abzielt, befasst sich die erste Studie mit der Simu-

lation der Wasserverfügbarkeit für Bewässerungszwecke. Hierfür wurde das Landnutzungsmodell mit einem hydrologischen Modell gekoppelt. Die Ergebnisse zeigen, dass durch eine Ausdehnung der Bewässerungslandwirtschaft Wasserknappheit entstehen kann und somit Konflikte mit anderen Wassernutzern in Zukunft verstärkt auftreten können. Die zweite Studie befasst sich mit Feuerereignissen welche zunehmend eine Bedrohung für die Steppe und Waldökosysteme darstellen. Es wurde eine Modellkomponente entwickelt, welche in der Lage ist, das Feuerrisiko, die Feuerausbreitung sowie deren Intensität abzubilden – Letztere stellt einen wichtigen Faktor für die Analyse von Auswirkungen auf den Kohlenstoffkreislauf dar. Modellierungsergebnisse zeigen, dass die entwickelte Methode in der Lage ist, Feuerereignisse mit einer wissenschaftlich akzeptablen Genauigkeit abzubilden. Mit dem neuen Ansatz konnte eine genauere Darstellung der Verfügbarkeit von Waldbiomasse und eine verbesserte Allokation von Landressourcen erreicht sowie wichtige Rückkopplungseffekte auf die künftige Landnutzung studiert werden. In einem weiteren Fallbeispiel wurden in Zusammenarbeit mit deutschen und mongolischen Wissenschaftlern Umweltszenarien erarbeitet, um mögliche zukünftige Entwicklungen aufzuzeigen, insbesondere potentielle Entwicklungen der zukünftigen Wassernutzung in unterschiedlichen ökonomischen Sektoren. Beispielhaft wurde gezeigt, dass die Rahmenbedingungen in bestimmten Fällen zu einer Entlastung in anderen zu einer Verstärkung des Drucks auf die bereits knappen Wasserressourcen beitragen. Weitere Simulationen zeigen, dass bei steigenden Düngergaben vor allem die Verfügbarkeit von Wasser den limitierenden Faktor des Pflanzenwachstums in der Nordmongolei darstellt, was in den häufigen Trockenjahren zu erheblichen Mindererträgen führen kann.

Zusammenfassend zeigen die oben beschrieben Fallstudien, dass es dringend notwendig ist, Handlungsoptionen zu entwickeln, um die Balance zwischen Schutz und Erhalt der Ökosysteme und der Sicherstellung von menschlichen Bedürfnissen zu gewährleisten. Dies sollte unter Berücksichtigung der extremen Klimabedingungen geschehen. Insbesondere die aktuellen Entwicklungen in der Landwirtschaft als auch die zunehmende Gefährdung der Wälder, welche im Einzugsgebiet eine zentrale Rolle bei der Regulierung des Wasserhaushalts spielen, sind hier von entscheidender Bedeutung. Der hier vorgestellte und neu entwickelte Modellansatz machte es möglich, wichtige Antriebe des Landnutzungswandels in der Nordmongolei zu analysieren, um dadurch ein besseres Verständnis für die Auswirkungen auf die Sozial- und Umweltfaktoren zu erlangen.

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List of abbreviations

ABMs	Agent-based models
ALGAC	Mongolian Administration of Land affairs, Geodesy and Cartography
AP	Application domain
API	Application Programming Interface
AUC	Area under the ROC-curve
CA	Cellular automaton / cellular automata
DEM	Digital Elevation Model
ET	Evapotranspiration
FMC	Fuel Moisture Content
GCM	General Circulation Models
GEO4	Forth assessment of the Global Environmental Outlook
GIS	Geographic Information System
GUI	Graphical User Interface
IMH	Institute of Meteorology and Hydrology, Mongolia
IRBM	Integrated River Basin Management
IWRM	Integrated Water Resources Management
LCS	Land change science
LUCC	Land-use and land-cover change
LULC	Land use and land cover
MaF	Markets First
MODIS	Moderate Resolution Imaging Spectrometer
NSO	National Statistical Office of Mongolia
ODD	Overview, Design concepts, and Details
OFR	Overall fire risk
RBO	River Basin Organisation
ROC	Receiver Operating Characteristic
SA	Sensitivity analysis
SD	System domain
SITE	Simulation of Terrestrial Environments
SOM	Soil organic matter
SuF	Sustainability First

Chapter 1

Introduction

1.1 Background

Land-use and land-cover change (LUCC) is considered as a main driving force of global environmental change (Lambin et al., 2000). Also known as ‘land change’, it describes the transformation process of the natural terrestrial surface by human modifications, thus affecting the ability of the biosphere to sustain life (GLP, 2005). LUCC has significant impacts on the functioning of the socio-environmental systems, comprising the largest environmental challenges we face today such as global climate change, biodiversity loss and pollution of water, air and soils (Ellis & Pontius, 2010).

Humans have altered the land surface since thousands of years. Early activities were aimed at securing essential resources. Land was burnt to enhance the availability of wild game, or managed using early forms of shifting cultivation (Ellis & Pontius, 2010). However, over time the nature and intensity of human activities changed, especially with the evolution of agriculture. Gradually cropland displaced other natural land-cover types, such as forests, savannas and steppes, displacement being mostly driven by the demand for food and fibre. Globally, the agricultural expansion has shifted between regions and in time, as a non-continuous process, followed the different development stages in civilization, economy and population (Lambin et al., 2003). Latest global studies on historical land-use change illustrate that cropland area has increased in the last 300 years (1700 – 2000) from 2.1 % to 10.6 %. In the same period, land under pasture has increased from 2.3 % to 24.3 % mainly due to deforestation and transformation of grasslands and savannas (Klein Goldewijk et al., 2010). Nevertheless, the most dramatic changes on land surface have occurred in the last century. In the last 50 years, the global population increased from two and a half to more then six billon.

During the same period, economic activities increased tenfold (GLP, 2005). In consequence, humans are largely active in modifying the land surface associated with changing consumption patterns and increasing demand for living space, agricultural production, water, fuel and other materials (Nelson et al., 2010). Today, almost 11 % or 15 million km² of the terrestrial surface is covered by cropland. Grazing land covers 26 % or 34 million km², while forests cover 30 % which corresponds to approximately 40 million km² (FAO, 2009a). Globally, significant land use change processes include change in forest cover due to (tropical) deforestation (FRA, 2010) and changes in agricultural areas and their management (Geist & Lambin, 2002). Changes in urban and settlement area are of minor importance with respect to spatial extent. However, the global area distribution shows clearly that currently one third of the globe is under agricultural land (crop- and pastureland) that thereby has become one of the largest biomes on earth (Klein Goldewijk & Ramankutty, 2001).

The Kharaa river basin, situated in Northern Mongolia, is part of the largest agricultural areas in Mongolia. In the region - cropland, pastures, wetlands and forests are under high anthropogenic pressure that is further amplified by climate change. The study conducted in this thesis applied a computer-based simulation model of land-use and land-cover change to address relevant impacts on affected ecosystems, with a focus on related resources - especially water. Due to the linkages between terrestrial ecosystems and other earth components (e.g. hydrosphere, atmosphere), research requires interdisciplinary approaches. In the last decades, the concepts of water resources management (IWRM) have become increasingly important for integrated research projects with a thematic focus on water issues. With the emergence of the Global Water Partnership (GWP) that was founded in 1996 by the Swedish International Development Agency (Sida), the World Bank and the United Nations Development Program (UNDP) the integrated view on processes associated with water was strengthened. The GWP defines IWRM as '…a process which promotes the co-ordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems' (GWP, 2000). Thus, IWRM aims at developing and implementing comprehensive approaches by the use of appropriate methods, tools, monitoring and management concepts.

The study presented here is part of an IWRM process in terms of assessing the links (direct or indirect) between land and water. Mongolia is perceived as a huge and sparsely populated country. While this perception is relevant for many of the remote areas, the majority of the population and most of their land-use activities are concentrated on a small fraction of the territory. Especially in these regions, shifts in land cover and land use have been observed in the last decades, which to a large extent is a reason for gradual increase in degradation of grasslands, forests, agro- and aquatic ecosystems. With an area of 1.56 million km² and a total population of 2.7 million Mongolia has a per capita land area of 0.6 km² - nearly the largest worldwide. 80 % of the territory is covered by grasslands, 11 % by forests and around 2 % is used as cropland or reserved for haymaking (World Bank, 2003). Due to the extreme continental climate conditions, water availability per capita is below the world's average (Batimaa et al., 2011). Various drivers, e.g. political, social, economical and environmental significantly contribute to increasing the pressure on the limited water resources of the country. Today 80 % of the water in Mongolia is consumed by industry (mainly mining) and agriculture. The rest is used for domestic purposes, of which the urban population, which accounts for 60 % of the total population, consumes large parts. In contrast, the amount of water consumed by the rural population is very low. Due to many reasons, e.g. high effort needed to acquire clean drinking water, daily average consumption is only equal to 8 to 10 litres per capita (Batimaa et al., 2011).

For pastoral livelihood in most semi-arid landscapes, central aspects are the availability of water, grazing land and mobility (Sternberg, 2008). In Northern Mongolia, these boundary conditions have changed to varying degrees. Climate studies indicate that current and future climate change, characterized by higher climate variability will increase water scarcity leading to water stress in the future (Batimaa et al., 2005). Most of the land-use activities today (e.g. agriculture, mining, forestry, grazing) in combination with other pressures (e.g. climate change, increasing water demand) are associated with negative impacts on water quality and quantity. The form of land management as it is practiced currently originated as a result of political and economic transition process occurring during the early 1990s (transition from socialism to market economy). During this time and the subsequent period the land sector lacked formal and informal regulation, adequate laws and law enforcement (Fernandez-Gimenez & Batbuyan, 2004). In the agricultural sector under the effect of privatisation livestock numbers reached 40 million in 2007, an increase of 64.5 % since 1990 (NSO, 1999; NSO, 2007). In addition, movements and mobility of herders have decreased (Fernandez-Gimenez, 2006) resulting in overuse of the pastures and degradation of the steppe and soils (Chuluun & Ojima, 2002). The forests of Northern Mongolia, origin of large amounts of freshwater, are besides the increasing occurrence of wildfires largely threatened by livestock causing trampling and bite damages, thereby significantly affecting natural forest re-growth (Tsogtbaatar, 2004).

Contrasting the intensification of the livestock sector, formerly state-managed agro-farms were no longer profitable for private farmers and had to be given up. From the 1990s until today, most farmers could not afford to buy expensive irrigation equipment, advanced machinery or apply agro-chemicals including fertilizers. In consequence, the cropland area cultivated and yield levels decreased considerably (Hickmann, 2006; World Bank, 2003). However, presently a re-intensification of agricultural land is on the national agenda, aiming towards increasing agricultural production and crop productivity, and ultimately independence from food imports via cheap farmer loans and subsidies for irrigation equipment, machinery, fertilisers and the use of better adapted crop-varieties (Bayar, 2008).

1.2 Research motivation and objectives

The study carried out in this thesis was motivated by the increasing anthropogenic pressure on agro-, grassland and forest ecosystems in Northern Mongolia. In the last two decades, large shifts have been observed in (i) the land use intensity, (ii) the composition of land cover types and (iii) in land management. Proximate and underlying causes have changed and were oriented differently, mainly pointed to and determined by market economy, trade and financial aspects. Additionally the use and management of land was accompanied by the incomplete environmental legislation and/or insufficient law enforcement. This, in combination with other factors (e.g. climate variability, increasing population, increasing water scarcity, higher water demand and water pollution) have gradually weakened the ability of the ecosystem to provide essential resources, such as enough and clean water, forage, food and fuel wood which are fundamental goods and services required to sustain Mongolian livelihood.

The development and application of adapted and sustainable management approaches are seen as a step towards the harmonization of the interdependencies existing in the human-environmental system. The major research objective was therefore the development of a computer-based land-use model to analyse and simulate current and future land-use and land-cover dynamics, with a focus on the linkages of terrestrial and hydrological processes. The model was developed using several components that reflect different parts of the socio-environmental system, which is considered as a basic requirement of such integrated models (Voinov & Cerco, 2010). As a framework for model development, testing and calibration, we used the modelling platform SITE (SImulation of Terrestrial Environments) (Mimler, 2007; Mimler & Priess, 2008; Schweitzer et al., 2011).

The three specific aims of the thesis can be summarized as:

(i) the identification of relevant drivers of land-use change,

(ii) the development and implementation of the land-use model and

(iii) the application of the model to analyse and quantify important aspects of terrestrial dynamics and their impacts on the socio-environment and ecosystems in Northern Mongolia.

1.3 Structure of the thesis

This thesis consists of eight chapters. Chapter 1 and 2 include background information. Chapter 3 and 4 comprise the methods of this study. Chapter 5, 6 and 7 include case study applications.

In **Chapter 2,** the reader is introduced to the research project in which the study is embedded. In the second section, the geography of the study region is presented. Finally, relevant environmental drivers, pressures and impacts are highlighted.

Chapter 3 presents the SITE-framework, which was used as the software tool to develop the land-use model. While providing an overview of the design and technical issues the chapter also presents how the software can be applied to implement case studies.

Chapter 4 presents in detail the land-use model SITE-Mongolia. A general model description is followed by a description of the model's scheduling and functions and purposes of submodels and linked third-party applications. The second part of this chapter deals with the sensitivity analysis, model calibration and testing.

Chapter 5 includes a case study in which the SITE-Mongolia model was applied to account for impacts of land-use intensification in the agricultural sector. For this study, a hydrological model was linked to SITE-Mongolia to enable estimation of water availability on the subcatchment scale.

Chapter 6 includes an analysis performed to study the impacts of wildfires. It includes the description of the implementation and application of a wildfire model that was included to account for wildfire spread and behaviour - a requirement to study feedbacks on biomass availability and land allocation.

Chapter 7 presents a scenario analysis. Different drivers have been studied with respect to their influence on future land- and water-use dynamics.

Finally, **Chapter 8** includes the synthesis.

This thesis is based on three publications which have been included as separate chapters. Edited versions of the original manuscripts form the basis of Chapters 3, 5 and 6 (the complete citation can be found as a footnote). Due to the use of published manuscripts, minor redundancies in the description of the study area or modelling tools occur.

Chapter 2

Study area

2.1 Introduction

The studies performed for this thesis were conducted within the framework of the project 'Integrated Water Resources Management in Central Asia, Model region Mongolia' (MoMo) (www.iwrm-momo.de), which is part of the 'Research for Sustainability' programme initiated and funded by the Federal Ministry for Education and Research (BMBF). MoMo is part of a group of BMBF IWRM projects focusing on the development and improvement of adapted research approaches and implementation strategies in developing and emerging countries. The main IWRM goals are: (i) improvement of local access to clean drinking water, sanitation and wastewater treatment, (ii) strengthening of the integration of German business on international markets of water supply and distribution, (iii) strengthening of bi- and multilateral corporation, (iv) trans-disciplinary and international co-operation among science, industry and administrative levels of water supply and treatment, (v) strengthening Germany as a location of business, education and science. As a joint cooperation between Mongolian and German research institutes, administrations and small and medium size business, a main objective of MoMo, besides the ones mentioned above, is the development of a profound data- and knowledge base together with state-of-the-art monitoring and implementation strategies. Lessons learned from the IWRM procedure should serve as a starting and discussion point for Mongolian authorities, or responsible institutions, e.g. the Mongolian River Basin Organization (RBO), to transfer the IWRM concepts to other basins in Mongolia.

The area of interest in MoMo is the Kharaa river basin located in Northern Mongolia. The study area was selected mainly due to the multitude of ongoing land-use activities which are considered to be typical under Mongolian climatic and socio-economic conditions. In the Kharaa catchment, MoMo covers and links the fields of hydrology of surface- and groundwater, land use, nutrient dynamics, river ecology, drinking water extraction and supply, wastewater treatment and sanitation. Scientific cooperation, capacity development and knowledge transfer are implemented in all thematic fields. The first project phase was conducted from 2006 to 2009 aiming at problem identification and development of tools, methods and monitoring concepts. The outcomes are reported in an 'IWRM – handbook' (MoMo, 2009). The second phase (2010 - 2013) has a broader focus towards implementation aspects.

2.2 Regional characterization

The Kharaa river basin is located in the forest-steppe region of Northern Mongolia, approximately 30 km north of the capital Ulaanbaatar. The basin has a total area of 14,534 km², situated between the latitudes 47°53' and 49°38' N and the longitudes 105°19' and 107°22' E (Figure 2-1). Elevation increases from north to south and from west to east, with a mean elevation of 1,200 m a.s.l. The lowest point, with 650 m, is located in the river valley north of the city of Darkhan. The highest elevation is located in the mountainous headwater region, towards the southeast, ascending to 2,560 m. The headwater region belongs to the buffer zone of the strictly protected area of the Khentii mountain range. The city of Darkhan, located in the northern part of the catchment and Ulaanbaatar are connected via the Trans-Mongolian Railway and through a paved road. This axis is considered as one of the most important trading directions in Mongolia, as it connects Mongolia with Russia and China. This is a particular reason why the area is attractive for merchandise trade and numerous human activities, e.g. agriculture, industry, mining and intensive grazing - a large contrast compared to other areas of the country, mostly undisturbed and less populated.

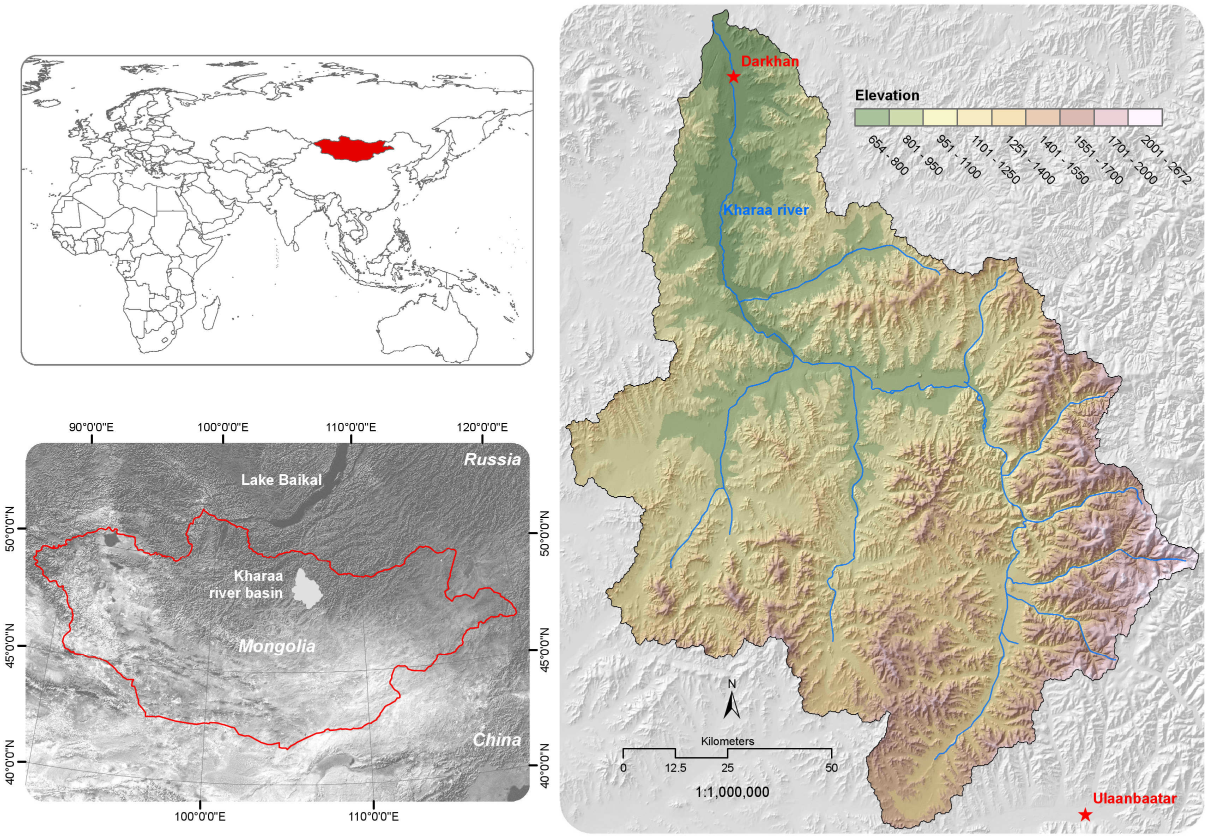


Figure 2-1. Location of the Kharaa river basin (left) and overview of the topography as well as very simplified hydrography (right).

2.2.1 Administrative units and population

In Mongolia administrative units are structured in several municipality levels. The top-level units are the provinces or ‘aimags’. The 21 aimags of Mongolia are sub-divided into ‘soums’ which corresponds to the district level. Each soum (in total 329) is further sub-divided into ‘bags’, which is the village level. All levels have an administrative centre except ‘bags’. The Kharaa river basin covers part of the area of three aimags: Darkhan Uul, Selenge and Tov. Darkhan Uul includes the city of Darkhan, which has 74,000 inhabitants and is the third largest city in Mongolia. From 1989 to 2006, the population in the Kharaa region has increased by 11 %. Total population is approximately 139,000 (NSO, 2007). Average population density (people per km²) is 9.5.

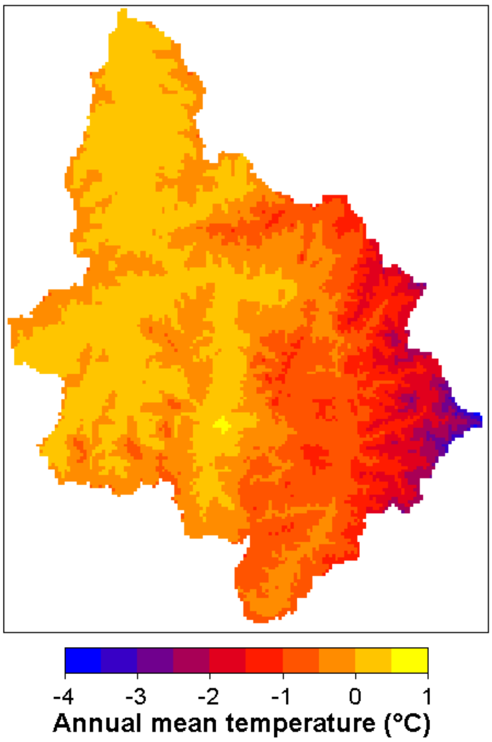
2.2.2 Climate and hydrology

The climate in the Kharaa river basin is semi-arid and continental, characterized by large seasonal temperature variability. According to Köppen & Geiger (Köppen & Geiger, 1936), by the use of their effective classification approach, the study area covers the climate zones ‘Dwc’ and ‘Bsk’. The former one, suitable for the northern part, refers to the snow climate, or boreal zone characterized by dry and cold winters and mild summers. The latter one, covering the southern part, refers to the cold semi-arid steppe climate zone with hot summers and cold winters (Kottek et al., 2006). Selected climate characteristics from the weather station Baruunkharaa, located nearly in the centre of the catchment, are presented in Table 2-1. Spatially interpolated temperature and precipitation pattern are given in Figure 2-2. Daily interpolated climate records from 1986 to 2006 indicate that summers are short, with a corresponding short growing season, and characterized by temperatures rising up to 40 °C. On the contrary, winters can be extreme cold, long and dry, with temperatures that drop below -45 °C. Mean annual air temperature in the basin is -0.4 °C and in the mountainous regions -4 °C (Figure 2-2). Average annual rainfall is 330 mm of which the majority (90 %) occurs between June and September. Due to the high summer temperatures, evapotranspiration (ET) rates are very high. Therefore, approximately 85 – 95 % of the rainfall is lost via ET (MoMo, 2009). Single rainfall events are recorded with amounts of 80 mm and related high rainfall intensities. Such singularities are a reason for flash floods and large surface erosion of susceptible soils. Countrywide between 1996 and 1999 in total 18 severe floods were recorded in which 54 people lost their lives (Davaa et al., 2006). Other extreme events with severe effects on the livelihood are droughts and so called ‘dzuds’ which is an extreme winter condition with a temperature drop below -50 °C and deep snow covering the forage.

Table 2-1. Climate and climate related parameters at Baruunkharaa (48°55'N, 106°04'E), (1987 - 2006).*

Parameter	Unit	Value
Elevation	[m]	807
Average annual temperature	[°C]	0.3
Average temperature January	[°C]	-24
Average temperature July	[°C]	19.4
Late frost	[date]	May, 6th
Early frost	[date]	September, 27th
Average annual rainfall	[mm]	290
Maximum monthly precipitation	[mm]	150
Length of growing period	[days]	80-120

* climate data provided by the Institute of Meteorology and Hydrology (IMH), Mongolia.



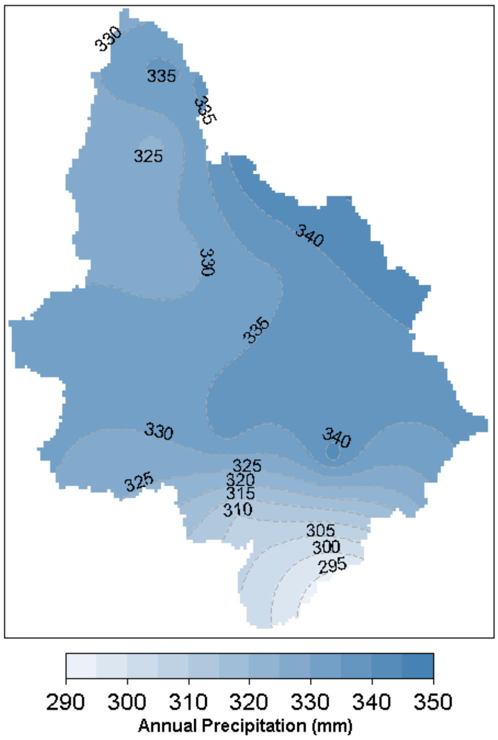


Figure 2-2. Spatially interpolated climate data. Mean annual temperature (left) and mean annual precipitation (right). Both maps are based on daily climate observations from the period 1986 – 2006. Data sets were derived from 12 climate stations located in and around the basin (from Wimmer et al., 2009).

The main stream of the Kharaa has a length of approximately 370 km (MoMo, 2009). The total length including all tributaries is difficult to assess due to meandering, seasonality of flow conditions and periodical disappearance of some rivers. Depending on the data used, total length varies between 2000 km (topographic maps) and 3000 km (satellite images). The Kharaa is a tributary of the Orkhon river that flows towards northeast and joins the Selenge river which drains into the Lake Baikal, one of the largest freshwater lakes on earth. The long-term annual mean discharge (1990 – 2008) of the Kharaa river at the basin outlet (Buren Tolgoi, 49°37' N, 105°52' E) is 12.1 m^3/s^{-1} (MoMo, 2009). Runoff has its peaks during the rainfall period in summer and in spring due to the snow and ice melt. In Northern Mongolia, hydrology is largely influenced by thawing and freezing processes, affecting rivers which in winter are regularly covered by a thick ice layer and further by the occurrence of permafrost soils. Number of days with snow cover are 100 to 150 (Dagvadorj et al., 2009) and average snow high is 2 - 5 cm. Sublimation of snow is considered as an important aspect affecting the hydrological regime. Wimmer et al. (2009) simulated snow sublimation in the Kharaa basin for the period 1986 to 2006 and identified that annual sublimation ranges between 13 to 35 mm, which corresponds to nearly 80 % of the total annual snowfall.

Observations show that climate has already changed in the last decades. Temperatures have risen in Mongolia in the last 70 year by 2.14 ℃. However, the trend is not consistent through the seasons. Winter temperatures have increased by 3.6 ℃, spring by 1.8 ℃, autumn by 1.3 ℃ and summer by 0.5 ℃ (Batimaa et al., 2011). Changes in precipitation have also been observed. Autumn and winter precipitation has increased by 4 to 9 % and spring and summer precipitation has decreased by 7 to 10 % (Batimaa et al., 2011). It can be concluded, that a shift towards increasing temperature and seasonality of precipitation has been observed already.

2.2.3 Land cover and land use

In the Kharaa river basin the main land-cover types are grasslands (60 %), forests (26 %) and croplands (11 %) (Figure 2-3). Vegetation forms a characteristic zoning along the elevation gradient. The riverbanks are typically covered by poplar and willow. Temperate grasses and sedges cover the more hilly grassland areas, characterized by gentle slopes. The forested area, situated in the elevated parts of the catchment, consists of natural boreal coniferous and secondary mixed forest. The former is dominated by larch, pine, spruce and fir. Mixed forest consists of coniferous species and large fractions of birch. Especially in the middle reaches of the catchment, a clear difference is evident between vegetation cover on north and south exposed slopes. Forests so far occur mostly on northern slopes. If forests cover south slopes, they are sparser due to water limitation caused by higher solar radiation.

Regarding the spatial extent, most important land-use activities are livestock grazing and farming (wheat, potatoes, and recently also horticulture). Next in importance are open pit mining (mainly gold) and forest use (legal and supposedly illegal timber extraction), followed by settlement sprawl close to the main centres. Each of these major land-use activities is subject to a number of (partly overlapping) driving forces, resulting in considerable land-use dynamics. In 1990, the peaceful Democratic Revolution started the initiative towards the new constitution that was ratified in 1992, establishing a democratic republic with the effect that in nearly every social and economic sector considerable changes occurred. This transition had large effects on land-use and land-cover change. In the following paragraphs, the most important land-use activities are presented.

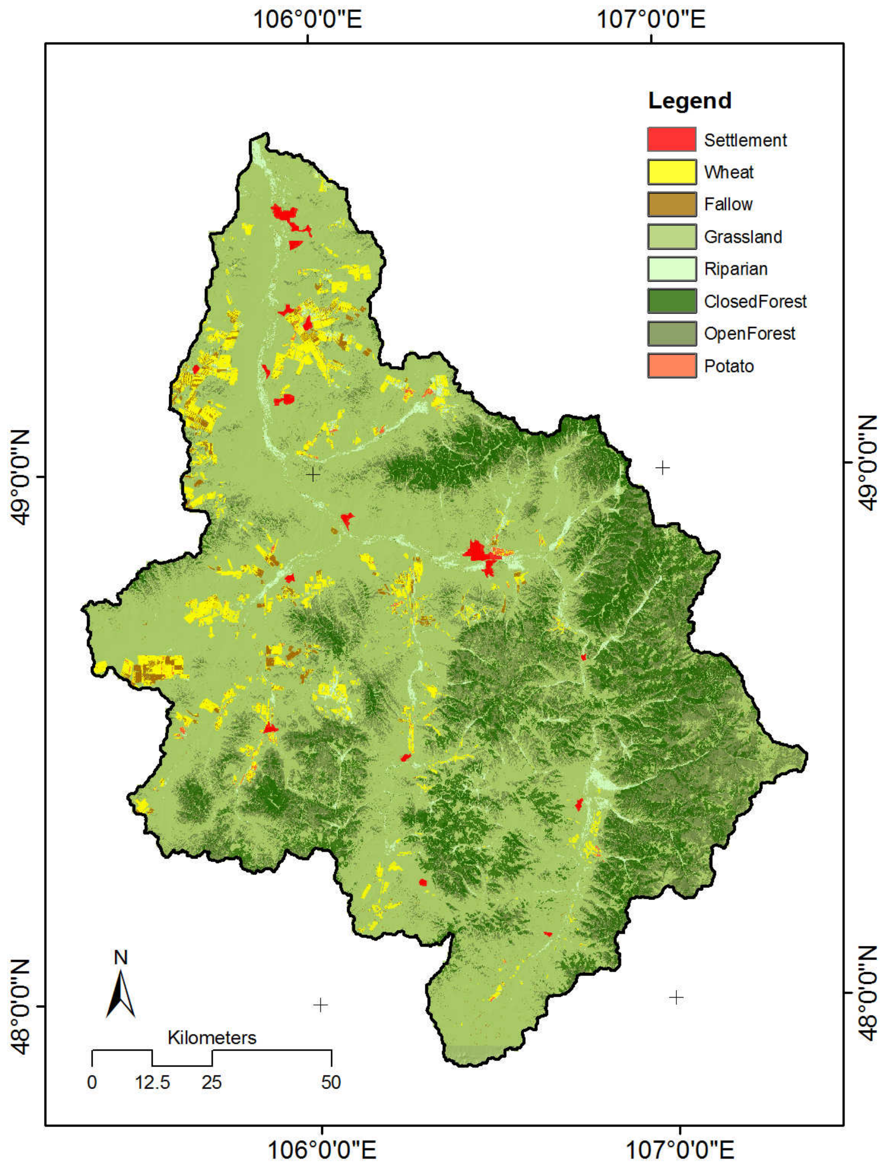


Figure 2-3. Land cover map of the Kharaa river basin for the year 2006.

Livestock grazing

Mongolia, known as a country dominated by pastoral nomadism, is to a large extent covered by one of the last and relatively undisturbed steppe ecosystem that once covered large parts of Central Asia (Hilbig, 1995). However, the traditional way of livestock husbandry (mainly sheep, goat cattle, horse and camel), which enabled the sustainable use of the Mongolian steppe for many centuries, has largely changed over the last decades both in its character and its intensity. Historic grazing activities were well organized by a combination of formal regulations enforced by ruling sovereigns and through informal customs, described by herders as 'unwritten laws' (Fernandez-Gimenez, 2006). During socialist times, herders were organised in herding collectives. Pasture management cope to balance carrying capacity avoiding overuse and compensate drought and severe winter conditions by adequate fodder reserves (Ojima & Chuluun, 2008). Herdsmen movements were managed strictly top-down by the provincial and national government regulating the allocation of pastures, size of herds and type of livestock, migration distance and frequency. With the different economic and political boundary conditions after 1992, the main characteristics that underlie the pastoral livelihood in Mongolia have not changed much. Mobile and flexible grazing strategies are required trying to handle the harsh climate conditions and the large variability in primary production (Fernandez-Gimenez, 2006). The privatization of the livestock sector had the effect that herders mobility was reduced due to the lack of formal and informal regulations, no access to trucks, the collapse of exports and trade, the reduction of incomes and poverty, furthermore the decline in public services, living standards and food security (Fernandez-Gimenez, 2006; Ojima & Chuluun, 2008). The reduced mobility promoted a more intensive use of pastures. In the last 20 years, privatization has led to a continuous increase in the number of livestock heads that increases grazing intensity and therewith leads to the degradation of soils and pastures (Chuluun & Ojima, 2002; Fernandez-Gimenez & Batbuyan, 2004). In the Kharaa catchment total number of livestock increased from 295,000 (212,000 sheep / 10,800 goats) in 1989 up to 592.000 (194,000 sheep / 175,000 goats) in 2006.

Cropland cultivation

In the late 1950s industrialized agriculture started in Mongolia. Under the Soviet regime, gradually a collective crop faming system was established, initiated by the 'land reclamation' programme. Population growth rates of 2.5 to 3 % in the 1960s and 1970s reveal that agricultural expansion and intensification was partly driven by the expected future demand for food (Stadelbauer, 1984). In order to remain independent from imports, grassland areas suitable for crop production were converted to cropland, mostly close to settlements and rivers. An intensification of the dairy sector, which would have been a comprehensible step, was not a major target (Stadelbauer, 1984). Intensively managed agriculture collapsed in 1990 and was from then on characterized by low in- and outputs and increasing cropland abandonment (Bayarsaihana & Coelli, 2003; Hickmann, 2006). From 1990 to 1998, the area under wheat decreased more than 50 % in Mongolia (Hickmann, 2006). Deficits in all kinds of supply were very common (e.g. equipment, chemicals, fertilizers, fuel, machinery, seeds), mainly due to financial limitations faced by the farmers. With the 'collapse' of the centrally organized, partly irrigated agriculture, crop cultivation in Mongolia was and still is strongly dependent on timely and sufficient rainfall in the short vegetation period from May to August. Early germination is crucial for production success in combination with sufficient plant available water in the soil. Agricultural practice in Mongolia therefore involves fallow periods, among other reasons to maximise residual moisture from late summer rains of the previous year. If delay in rainfall occurs, crop yields are threatened because yield levels and rainfall or soil moisture are highly correlated (see Chapter 7).

In the Kharaa river basin average cultivated crop area is approximately 59,000 ha of which approximately 6,000 ha are considered to be suitable for irrigation purposes. Fallow land (which includes the unused fields within the crop rotation cycle plus land that was formerly used for agriculture and has not been re-converted to grassland) covers on average 93,000 ha. Note, that the transition from socialist to market-oriented agriculture caused a considerable decrease in land-use intensity and spatial extent of agriculture. The described trend is strongly reversed by current policies, which are aiming at (re-) converting additional land for agriculture until 2010 (Badrakh, 2008; Bayar, 2008), with most of the land being located in the northern part of Mongolia (Kharaa and neighbouring catchments). This initiative is supported by credits from Russia and the Asian Development Bank, which plans to provide cheap farmer loans and subsidies for irrigation equipment, machinery, fertilisers and the use of better-adapted crop-varieties (see Chapter 5).

Forest and forest-use

Population increase has led to an increase in demand for forest products in Mongolia. Today the forestry sector lacks efficient management strategies and law enforcement. In the 1970s, much attention was paid to forest management, controlling forest use and protecting forest resources from negative anthropogenic impacts (Tsogtbaatar, 2002). However, today illegal use of wood is common to fulfil private and also commercial demands. For both, the volume of timber, which is currently being extracted, cannot be maintained on the long term (Tsogtbaatar, 2004). Especially forests that are accessible via roads are threatened (World Bank, 2006). Furthermore, forest ecosystems are threatened by livestock, wildfires and in recent years increasingly by pests and diseases. Annually around 100 large forest fires occur in Mongolia (Goldammer, 2007). Due to this reason, total aboveground forest-biomass decreases dramatically. The increasing numbers of livestock have been indentified as the major reason for deforestation in Mongolia having negative effects on natural forest re-growth caused by trampling and bite damages (Tsogtbaatar, 2004). In the Kharaa river basin, demand for forest products has constantly increased due to the increasing population and partly due to a poor law enforcement. In addition, nowadays most of the forested areas are affected by wildfires (see Chapter 6). Especially in the headwater regions, a gradual change from natural forest to secondary forest consisting of birch trees and shrubs can be observed.

Mining and industry

In Mongolia more than 500 natural and mineral deposits are known, providing mainly copper, gold and coal of which around 200 were exploited (ADB, 2005). Accordingly, the mining industry is of major importance contributing to the economic development of the country. Nevertheless, mining is combined with remarkable land modifications and environmental pollution. Most of the deposits, especially gold are extracted from surface sediments rather than from deep galleries. Gold placer open pit mining is practiced by removing vegetation, topsoil and up to 10 m of the alluvium of the riverbanks (Stubblefield et al., 2005). Furthermore, large quantities of water are required to separate e.g. gold from ore adding the toxic extractants mercury or cyanide. In the Kharaa river basin, mining plays a central role considering water quality issues and water use. Within the catchment, a large number of belowground and open pit (gold-) mining concessions have been issued during recent years. The total area, which is currently covered by mining licenses, is about 130 km². However, it is unclear how many licensed mines (and how many illegal ones) are currently active. Consequently, the amount of water withdrawal is unknown. It is worth mentioning that one of the largest and most productive goldmine - the Boroo mine (active until 2010) - is located in the Kharaa river basin. As in many other countries, the agricultural expansion and intensification in the socialist period went hand in hand with the development and improvement of infrastructure (e.g. roads, electricity, water, etc.) and the expansion of settlements (urbanization) and manufacturing industry. In the Kharaa region, mainly in the city of Darkhan an increasing number of heavy industries and other factories are located.

Settlement and housing

The fraction of built up land is much lower in Mongolia when compared to industrialized countries. Low household incomes of herders, harsh living conditions of the rural population in general, and other factors, drive an increasing fraction of the rural population to resettle in and around towns and small cities (mostly soum or aimag centers). From 1989 – 2002 the population in Darkhan city increased by 20 %, in the capital Ulaanbaatar it grew by 41 % (World Bank, 2004). In some of the soum and aimag centers, the existing infrastructure is unable to cope with the increasing number of citizens. Uncontrolled spread of informal ‘ger’ (yurt) settlements is common, mostly with inadequate supply of water, energy and other services.

2.3 Observed and expected problems, pressures and impacts

In the Kharaa river basin, several environmental problems are evident. However, many of the concerns expressed by scientists or by local citizens are qualitative. To be able to verify the processes, quantitative assessments and long-term monitoring of environmental variables are necessary. This section summarizes environmental concerns that emerge from the above described processes and drivers of change.

Due to the boundary conditions, i.e. fragile ecosystems, changing lifestyles and economic situation, Mongolia is considered to be very sensitive to climate change (Dagvadorj et al., 2009). Numerous studies have conducted research on the potential effects of climate change in Mongolia (Batimaa et al., 2005; Cruz et al., 2007; Sato et al., 2007; Wimmer et al., 2009).

Menzel et al. (2008) for example studied the effects of future climate change in Mongolia and in the Kharaa river basin by the application of a regional and a global hydrological model driven by climate data from General Circulation Models (GCM) using different sets of emission scenarios (IPCC A1B, B1). For the period 2071 to 2100 they illustrate a strong increase in mean annual temperature, affecting both the winter and summer season. Rainfall patterns show a more diverse and uncertain behaviour, indicated by large variations among the different scenarios and GCM combinations. However, expected higher temperature and change in rainfall seasonality will lead to rising actual ET rates, which are expected to have negative effects on river runoff leading to a decline in water availability.

The gradual decrease in freshwater availability is expected to be amplified by the pressures resulting from the entirety of land-use activities. The (re-)intensification of agricultural land, which is on the national agenda since 2008 (Bayar, 2008), aiming towards increasing agricultural production and crop productivity, and ultimately independence from food imports (mainly for wheat and potatoes) is only one example. While the precision of irrigation-water estimates is still limited, (e.g. because farmers use a variety of irrigation technologies and the size of the currently irrigated area is only roughly known; see Chapter 5), water shortages or water-use conflicts within the agricultural sector or with other water users may occur.

Modern livestock husbandry is driven and constrained by a number of economic, political, life style and environmental factors, including access to infrastructure, domestic and international markets and prices. The altered migration pattern, the availability of watering points and feedstock encourages the herdsmen to increase livestock numbers (Fernandez-Gimenez, 2006). In combination with the decreased amount of steppe areas being grazed, these dynamics partly result in overgrazing and land degradation. Based on Mongolian estimates and own qualitative observations, the carrying capacity for livestock is already reached or surpassed in large regions, especially in areas around settlements. Besides increasing drinking water requirements of the animals, trampling damage is also omnipresent in the vicinity of rivers and watering points, which in conjunction with overgrazing is decreasing vegetation cover, damaging river banks and floodplain vegetation and causing soil and nutrient depositions and loads, which negatively affect water quality (MoMo, 2009).

Current land-use activities in the forested areas are very critical issues in Mongolia, as they are often impact the freshwater source, a fact that also applies to the Kharaa region. According to Tsogtbaatar (2002) Mongolian forests play a '…critical role in preventing soil erosion and land degradation, in regulating the water regime in mountain areas, maintaining permafrost distribution, and in providing habitats for wildlife and preserving biodiversity'. However, inefficient management strategies and the lack of law enforcement seem to be the major flaws. The rate of successful reforestation is far too low and protection efforts often fail (Tsogtbaatar, 2004). Moreover, forests are frequently threatened by wildfires and in recent years increasingly by pests and diseases. Reduced forest areas may severely alter water discharge pattern, contribute to increased risks of both flooding, and water scarcity.

In the mining sector a poor monitoring and enforcement of the amounts of water withdrawn is dominant. Considering that nearly each mine is relying on its own uncontrolled groundwater supply, the amount of water withdrawal is substantial, but currently impossible to quantify. Further uncertainty about actual water use is caused by the fact that government calculations - on which water fees are based - assume the use of 1 - 4 m^3 of water per m^3 of ore. Whereas discussions with Mongolian and German experts during a stakeholder workshop in 2008 revealed that geological conditions and technology in use suggest the use of approximately 7 - 10 m^3 of water per m^3 ore (pers. comm. J. Priess and I. Dombrowsky, UFZ, Germany). In addition, the amounts of toxic waste (often deposited on unprepared and leaky ground) containing heavy metals and/or mercury and/or cyanide, are unknown. A further growth of the mining sector will have negative effects on water quality with potentially large negative impacts on human health (Steckling et al., 2011) and river ecology (Krätz, 2009). In addition, poor water quality of the tributaries may negatively affect the ecosystem of the Lake Baikal (Stubblefield et al., 2005).

The ongoing urbanisation is leading to considerably higher private water consumption. The measurements and interviews performed in MoMo reveal that rural population living in the countryside or ger settlements consume as little as 7 - 9 litres of water per capita per day, extracted from surface and groundwater sources, while village households supplied by water kiosks or water trucks consume on average 22 litres per capita per day (MoMo, 2009). Households connected to the central water supply on the other hand use more than 400 litres per capita per day including 40 % of water losses (MoMo, 2009). Furthermore, the industries located in the basin (Darkhan, Zuunkharaa and Baruunkharaa) use a presumably large amount of groundwater for processing, cooling and other purposes, contributing to the depletion of scarce water resources.

It can be summarized that all of the land uses and processes mentioned above have significant influence on regional hydrology, either decreasing water availability or increasing water demands or both, resulting in urgent scientific, political and management tasks.

Chapter 3

SITE - a generic framework for land-use modelling [1]

This chapter presents the generic modelling system SITE (SImulation of Terrestrial Environments) a software package to develop and apply models simulating regional land-use dynamics. The modelling system includes (i) a framework managing the model generics and (ii) code templates for the development of rule-based land-use and land-cover change (LUCC) models. SITE comprises built-in methods for e.g. map-comparison, model optimisation and environmental scenarios.

3.1 Introduction

Modelling land-use, land-cover and environmental change is a field of increasing importance and a broad range of models have been developed for this discipline (Haase & Schwarz, 2009; Schaldach & Priess, 2008). For numerous modelling approaches the development or adaptation of the appropriate software is a crucial step for successfully answering research questions, a step strongly constrained by financial resources and time available for model development. In order to overcome this problem, researchers often tend to modify existing or create new software, which may be functional, but often not very intuitive in terms of applicability and transferability. For users with little or no programming skills the application of such models is difficult and a reason for little or no interest in those approaches. To address this

[1] Edited version based on:
Schweitzer, C., Priess, J.A., Das S., 2011. A generic framework for land-use modelling. Environmental Modelling and Software, 26(8), 1052-1055.

problem, modelling frameworks try to bridge this gap by providing convenient user interfaces that communicate with the complex software generics. A 'framework', as it is used in our context, is defined as generic software that can be reused for custom applications, with the advantage that the software can be developed several times faster than without the framework (Fayad et al., 1999). In this manuscript we present the key features of the SITE framework and show an implementation example for a rule-based land-use model, in which land allocation is based on a multi-criteria analysis and regional preferences and constraints.

3.2 Modelling system

From the beginning, a core objective of the SITE developers was to facilitate maintenance and reuse of components within the entire software package, as the tool was intended to be applicable in more than one case study (Mimler & Priess, 2008). SITE consists of two main parts (i) the system domain (SD), which includes optimized methods, procedures and essential tools for the modelling process, implemented in C++ and (ii) the application domain (AD), which is a Python interface designed for the implementation of modelling routines and decision rules to address land-use modelling issues (Figure 3-1).

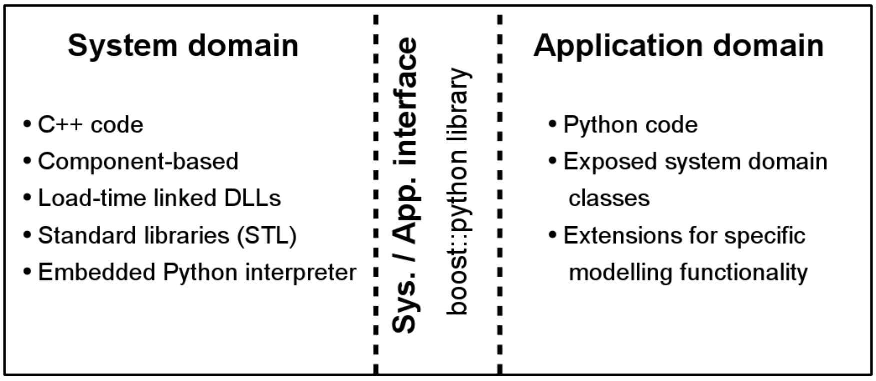


Figure 3-1. Software details of the system and application domain. The system domain includes generic software components that handle and execute models, while case-study specific code is located in the application domain (from Mimler, 2007).

SITE currently uses the concept of cellular automata (CA) models, which are defined as spatially and temporary discrete systems consisting of cells arranged in a lattice of *n* (>1) dimensions. The cells represent a discrete moment in time and change their current state due to a set of rules, mostly deterministically formulated in a local transition function taking into account the current state of neighbouring cells (Schiff, 2010). Theoretically it is possible to represent land-use decisions in SITE with spatial non-CA models such as multi-agent systems (Berger et al., 2006) or CLUE-type regression equations (Veldkamp & Fresco, 1996); although in the latter case much of the flexibility of rule-based approaches would be lost.

SITE has been applied for three case studies addressing different land-use related research questions. The first application investigated the land use dynamics of tropical rainforest margins in Sulawesi, Indonesia (Priess et al., 2007a). The second and third case studies, which are under advanced stages of development, analyse the impacts of LUCC on water resources and impacts of wildfire in Mongolia (Priess et al., 2011; Schweitzer & Priess, 2010) and the potential of bioenergy crops and food-fuel conflicts in South-India (Das et al., 2010) respectively. Figure 3-2 presents a generalized view of the SITE components used in previous studies. A detailed description of the software implementation is given in Mimler (2007) and Mimler and Priess (2008).

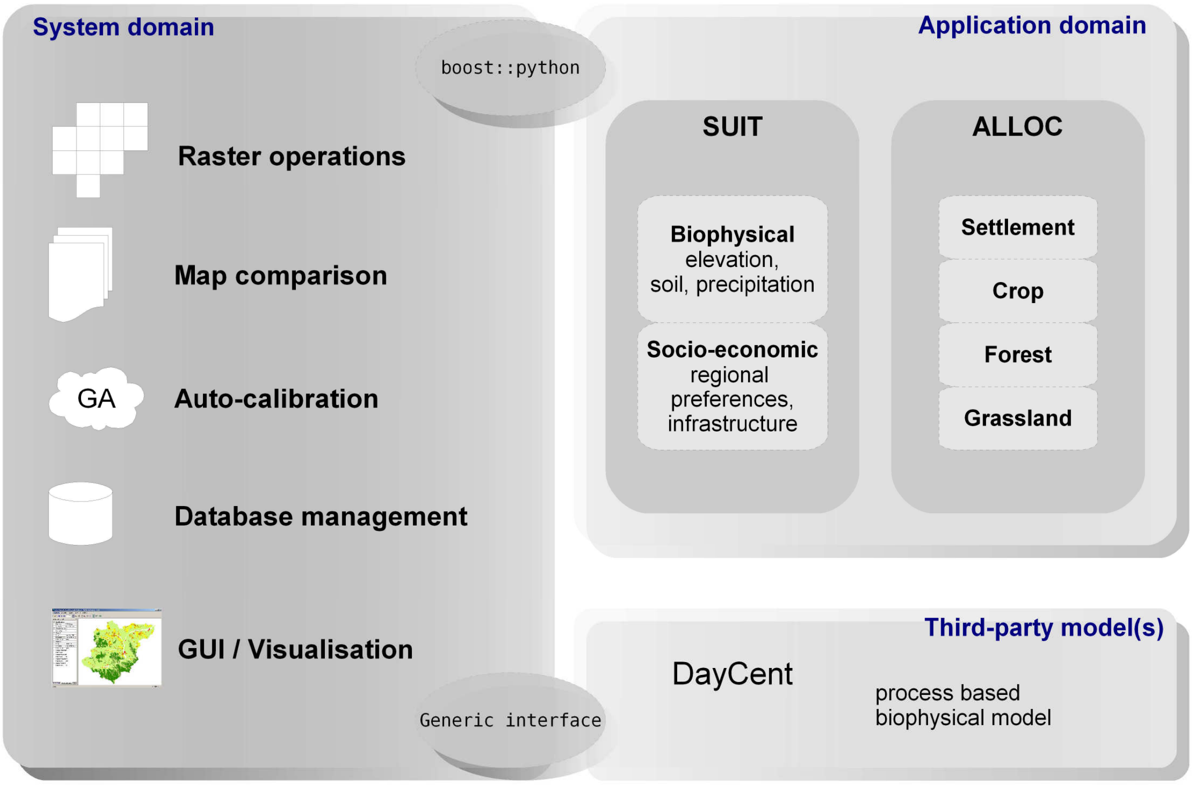


Figure 3-2. Main components of the SITE modelling system. The system domain represents the core engine of the framework, providing necessary modelling functionalities. Within the application domain user-specific decision rules are developed. A generic interface provides the possibility to link third-party models. Note that the external model DayCent is not a standard component of the SITE software.

3.2.1 System domain

The SD comprises the generic aspects in SITE and handles the grid system, cell-attributes, cell- / cluster-iterators and other components. The latter integrates methods for model testing and calibration using map comparison algorithms, distance and neighbourhood operations and clustering procedures. SITE includes a graphical user interface (GUI), which supports the execution of land-use models and visualisation of simulation results. A 3-D view offers the possibility to freely assign (and combine) x/y- and z-axis with cell attributes (e.g. ‘crop x’ and ‘distance to market’). Additionally, a command line is available for consecutive runs, e.g. during sensitivity analysis or model calibration.

The coupling of third party models is enhanced by providing a generic interface that allows the implementation of feedbacks between different framework components and different processes, which are considered as an essential aspect of integrated approaches (Verburg, 2006). In recent studies we linked the biophysical model DayCent (Parton et al., 1998) to simulate carbon dynamics, biomass and crop yields (Das et al., 2010; Priess et al., 2007a; Priess et al., 2011; Schweitzer & Priess, 2010). The integration is based on a client-server solution in which SITE acts as client distributing modelling jobs (= annual simulations for cells or clusters) to the DayCent-server. The interface can configure and execute jobs and handle incoming simulation results.

3.2.2 Application domain

The AD is designed as a scripting interface to access functionalities and methods implemented in the SD. Setting up a new model in the AD requires minimally the use of the two functions *Initialize()* and *SimulationStep()*, in which the model’s scheduling has to be included. The sequence of sub-module calls reflects the model’s scheduling hierarchy. Potential users benefit from the existing case studies, which already provide a set of sub-modules that can be modified to cover new research objectives. Figure 3-3 presents a generalized scheduling structure within a Python file that can be executed by SITE, based on the ones we use in current studies.

```
def Initialize(grid):
      # initialize the grid system
      grid.SetGeoreference(x,y,resolution)
      # calculate cluster-layer
      ConfigClusterLayers()
      # count neighbour cells for all lu/lc-types
      NghbCount()
      # calculate distances
      CalcDistances()
      # run DayCent to calculate potential yields
      DayCent.CalcPotYields()

def SimulationStep(grid,step):
      # perform suitability assessment
      CalcSuitabilities()
      # allocate lu/lc
      Settlments.Allocate()
      Crops.Allocate()
      Forest.Allocate()
      Grassland.Allocate()
      # run DayCent to calculate current yield
      DayCent.CalcCrntYields()
```

Figure 3-3. Example of a main Python file used in SITE. The function *Initialize()* generates the simulation grid and sets all attribute values to an initial state, including operations required for further model simulation. *SimulationStep()* includes the model's scheduling that will be repeated every timestep.

3.2.2.1 Initialization

Initialize() first generates the simulation grid, followed by operations setting the cells to an initial status with cell-specific attribute values (e.g. count the number of neighbour cells, perform distance calculations etc.). To reflect identical or almost identical biophysical properties of grid cells and simultaneously reduce the high runtime requirements of DayCent, the cluster algorithm of SITE is grouping cells of the same land-use and land-cover type to derive units of uniform geographical and biophysical properties, comparable to hydrological response units - HRUs, a concept often applied in hydrological studies (Flügel, 1995). Cluster definitions (and resulting cluster size) usually depend on data quality, research question and may apply any cell attribute present in the case study.

3.2.2.2 Simulation step

In *SimulationStep()*, land-use decisions are simulated typically once a year following a three step process: (i) suitability analysis based on a multi-criteria approach, (ii) execution of allocation modules, that are driven by the demand for commodities (e.g. space for housing, food, wood) and (iii) calculation of plant growth, biomass and trace gas fluxes both for natural vegetation and agro-ecosystems, currently using DayCent.

Suitability analysis

The task of the suitability module (SUIT) is the generation of dynamic suitability maps for each of the land-use and land-cover classes expected to change. SUIT employs a multi-criteria approach which is transparent, flexible and has the capacity to integrate large amounts of heterogeneous data (Eastman et al., 1995). SUIT is subdivided into functions computing biophysical suitabilities (e.g. elevation, terrain slope, soil fertility, precipitation) and suitabilities based on socio-economic factors, if necessary (e.g. gross margins, accessibility, farmers' preferences). All suitability values are normalised to a range between 0 (not suitable) and 1 (perfectly suitable) following the equation:

$$s_{kl} = \underbrace{\left(w_B \sum_{i=1}^{m} \beta_i s_{Bikl} + w_E \sum_{i=1}^{n} \varepsilon_i s_{Eikl} \right)}_{\text{suitability}} \cdot \underbrace{\prod_{j=1}^{o} c_{Bjkl} \prod_{j=1}^{p} c_{Ejkl}}_{\text{constraints}} \qquad \text{(Equation 3-1)}$$

with $w_B + w_E = 1$; $\sum_{i=1}^{m} \beta_i = 1$; $\sum_{i=1}^{n} \varepsilon_i = 1$; $s_{Bikl}, s_{Eikl}, c_{Bjkl}, c_{Ejkl} \in [0, 1]$

The calculation of the overall suitability value s_{kl} for each grid cell k and land-use type l consists of two terms. In first part (suitability) the mean value of the partial suitabilities s_{Bikl} for biophysical and s_{Eikl} for socio-economic criteria are weighted using the partial weights β_i / ε_i, where m/n represent the total number of criteria included. The advantage of this approach is the possibility to assign one weighting factor for the entirety of the biophysical (w_B) versus the socio-economic suitability components (w_E). Constraints may reduce the overall suitabilities by applying o/p constraints c_{Bjkl}/c_{Eikl} to each class or land-use type. Constraints can be used to simulate limitations or restrictions, e.g. land-use in protected areas, steep terrain, etc. The determination of reasonable suitability factors usually involves a preliminary selection of the competing factors, studying empirical information and by the application of a correlation analysis. Criteria weights are derived from model calibration or can be achieved using approaches like the Analytical Hierarchy Process (Chen et al., 2010; Saaty, 1980).

Land allocation

The set of maps calculated by SUIT serves as the basis for the LUCC decisions implemented in the allocation module (ALLOC). ALLOC includes a set of modules allocating settlements, crops, forest etc. The hierarchy in ALLOC follows the sequence of regional land allocation preferences, and may differ between case studies. Rules for the allocation are usually implemented in the form of a decision tree. In current studies the allocation of settlement areas has the highest priority and is therefore executed first. At the next hierarchy level demand for agricultural products steers the allocation of different crop types and so on. Next we provide an example for a demand-driven competition for land between different crops. If a cell is selected as change-candidate (e.g. current land use is low-yielding or unprofitable), the algorithm identifies the most suitable crop for this cell. In the crop module, decision criteria are evaluated consecutively, starting with the crop-type with the largest difference between current production and demand. Note that the algorithm switches between crops to avoid allocating the most favourable cells to just one crop. If current crop production is higher than the demand, cells are either converted to other land uses, or to fallow if below a productivity limit (defined as < x % of mean yield in a region or administrative unit). Allocation criteria vary between case studies, but are always based on crop-specific SUIT results (ranking of all cells with suitability > 0), using actual productivity, profitability or potential productivity if a certain crop has never been grown in a cell. Furthermore, ALLOC employs a conversion-matrix, which bars conversions that do not occur in the study area (e.g. conversion of agricultural land to forest or urban to village land).

Simulation of plant growth

In a last step, DayCent calculates carbon and nitrogen dynamics of plants and soils within the respective clusters. Results are fed back to the SUIT and ALLOC modules, updating dynamic attributes (e.g. carbon, nitrogen, biomass, yields), and thus informing subsequent land-use decisions.

3.2.3 Validation methods and automated calibration

The SD includes model calibration and model validation components based on a map comparison toolkit for categorical maps, comprising spatial statistics like Kappa (Pontius, 2002), Figure of Merit (Pontius et al., 2008) and moving window approaches (Kuhnert et al., 2005). All implemented algorithms are suitable to assess the similarity of simulated maps (model output) against a reference map derived from independent sources, using identical sets of land categories.

An automated optimization algorithm is included to identify the best parameter values using a genetic algorithm (GA) (Wall, 1996), which has been shown to be an efficient optimization tool in recent studies (Holzkämper & Seppelt, 2007). The GA works through the *n*-dimensional search space, and assesses the optimal parameter setting (*n:* number of calibration parameters). Note that parameters used in DayCent and parameters used in the AD can be calibrated simultaneously, to account for the fact that yield levels may have a strong impact on both land-use areas and patterns.

3.2.4 Environmental scenarios

A major objective in many land-use studies is to assess potential consequences of future land-use options, or development pathways (Alcamo, 2008a). SITE provides structures to simulate and analyse quantitative scenarios driven by socio-economic and biophysical changes. The GUI provides an interactive scenario dialog-box, an additional feature through which users can directly edit and change scenario data e.g. to respond to implausible land-use changes discovered during simulations, and re-run the scenarios.

3.3 Conclusions

In this chapter the SITE modelling framework was presented, which is designed for spatially explicit regional land-use modelling. SITE uses modular software concepts to enable users to focus on advancing the state of the art of land-use modelling. The GUI supports the execution and analysis of land-use models, facilitating the active participation of researchers / stakeholders / policymakers with limited capacity or prior experience in modelling. The built-in flexibility and adaptability contributes to shorten the process of identifying or developing adequate model constellations, which is usually a very challenging task, especially if the research is embedded in a multi-stakeholder setting (e.g. Sterk et al 2009) with potentially conflicting interests. In this context, SITE supports the increasing number of (participatory) land-use studies, providing fast iterators available for cell, cluster and neighbourhood analyses, without ignoring important system feedbacks or oversimplifying the complexity of terrestrial systems. Furthermore, time-consuming calculations can be parallelized making use of the built-in client-server solution. The use of a scripting language for the AD offers a large degree of freedom for model developers with respect to complexity, for example to simulate land-use decisions, or competition for land, processes typically requiring multiple variables and structures to characterize them. Additionally, this type of programming language provides a user-friendly facility to interact with the complex software generics, advantages also seen by other environmental modelling groups (Kraft et al., 2011).

The next steps include an improved integration of wildfire simulations, for which first results have already been published (Schweitzer & Priess, 2010). In this context it is also envisaged implement a standard model interface such as the Open Modeling Interface and Environment (OpenMI, 2010) and migrate to a platform independent and open source version.

Chapter 4

SITE-Mongolia land-use model

In this chapter, the concept of the SITE-Mongolia land-use model is presented including model components, sub-modules and third-party applications. The outline of the Section 4.1 to 4.7 follows the ODD (= Overview, Design concepts and Details) protocol (Grimm et al., 2006; Grimm et al., 2010), which was developed for describing individual- and agent based models (ABMs). Note, that the model described here is not classified as the ones the ODD protocol originally was designated for. Nevertheless, ODD can be applied for the characterization of CA models as well, although some aspects that characterize ABMs cannot be considered. Providing a simple and standardized description procedure, ODD provides an opportunity to make writing and reading model descriptions more efficient and in addition model comparison much easier (Grimm et al., 2010). Section 4.8 and 4.9 of this chapter are not part of the ODD protocol and include details from of the sensitivity analysis and results from model calibration and testing.

4.1 Purpose

The SITE-Mongolia model was developed to simulate current and future land-use and land-cover dynamics with a focus on studying impacts on water resources. Specifically, the model simulates land-use and land-cover changes on a yearly basis including relevant feedbacks, for example related to soil carbon. Embedded in the collaborative research objectives of the MoMo project, the main aims of the SITE-Mongolia land-use model are: (i) simulation of a transient set of land-use and land-cover changes, (ii) simulation of historical and future environmental impacts reflecting e.g. the influence of weather conditions and the intensity of land use on natural and man made systems (e.g. agro-ecosystems), (iii) simulation of impacts of wildfire on forest and grassland ecosystems.

4.2 Entities, state variables and scales

The area of the Kharaa river basin is represented in the model by a rectangular grid space with a total number of 14,553 cells. Each grid-cell has a dimension of 1 km x 1 km and represents a land-use or land-cover type that is linked to a set of static and dynamic attributes. Static attributes do not change during the simulation but are relevant for model initialization and the derivation of parameters required during the simulation (e.g. elevation, slope). Dynamic attributes change *n*-times (with *n* >= 1) during the simulation (e.g. biomass, soil carbon). Furthermore it is possible that a dynamic attribute can change multiple times between two timesteps (e.g. settlement area).

In the model, various overlapping spatial scales are represented, including administrative units, sub-catchments and vegetation clusters. The different multi-scale layers are linked via the cell level, which serves always as the common unit (Figure 4-1). Besides the layer level, some processes are examined on sub-cell level, simulating spatial changes occurring on fractions of grid cells. For example changes of settlement areas are simulated on one hectare resolution. As soon as a 50 % threshold level is exceeded (for example if an agricultural cell gets occupied by more than 50 % of settlement area) the land allocation module converts the cell to a new settlement cell. Sub-grid calculations are implemented exclusively to track population dynamics and resulting changes in settlement areas.

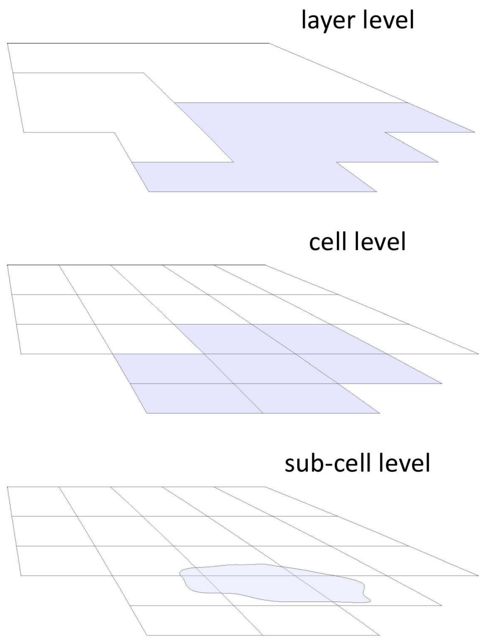


Figure 4-1. Spatial scales represented in the SITE-Mongolia model.

The model simulates land allocation in discrete timesteps on a yearly basis, which is the common practice also performed by other land-use change models (Agarwal et al., 2002; Heistermann et al., 2006). However, any other temporal scheduling is theoretically possible and not limited by technical constraints. In the case of the linked third-party applications, different timesteps are used. DayCent for instance simulates plant growth on a daily basis, while the wildfire model uses a one minute resolution for wildfire propagation. Under the current state of development of the model, scenario storylines and corresponding projected data are available to simulate historical changes for a period of 17 years (1989 - 2006) and future developments until 2025. Nine land use and land cover (LULC) types are implemented in SITE-Mongolia, namely: wheat, potato, fallow, grassland (natural steppe), riparian (floodplain vegetation), closed forest (coniferous), open forest (mixed needle and broadleaf), and urban and rural settlements.

4.3 Process overview and scheduling

All land-use decisions are simulated once a year, in general using a three-step procedure. First, the multi-criteria suitability assessment (SUIT component) is performed resulting in normalised dynamic suitability maps for simulating a suitability ranking of cells that allows competition between different land uses. One cell may suitable for several land uses but differ in the absolute suitability value. In the second step, land is allocated based on sets of decision rules including suitabilities and constraints, driven by the demand for commodities, such as food, space for housing, forest products and others (ALLOC component). Finally, within the GROWTH component, carbon and nitrogen stocks and fluxes of plants, soils and the atmosphere are calculated using the process based biophysical model DayCent (Parton et al., 1998). DayCent simulations are performed for all grid cells under natural vegetation or crops. This step includes the provision of information for crop-specific management or vegetation-specific activities (e.g. fertilization, irrigation, timber removal) and other site-specific settings.

The modular model design of the model offers the ability to perform simulations with different sub-modules or component settings as defined by the user. This feature has been used in one case study by linking a hydrological model (HYDRO component) and in another case study simulating the impacts of wildfires (BURN component). Simulations without GROWTH, which is considered as a standard component, are also possible, however in such conditions, feedbacks of the biophysical system will not be included.

4.4 Design concepts

SITE-Mongolia can be characterized as a spatially explicit land-use change model. Based on the underlying CA concept, the model simulates land allocation based on decision rules and neighbourhood functions to simulate the socio-environmental system (Schaldach & Priess, 2008). The decision rules implemented reflect different aspects of land-use and land-cover changes that are specific to the region. Feedback mechanisms are included (e.g. for the carbon cycle), to improve better representation of land-use dynamics and furthermore strengthen the integration of social and biophysical dynamics, which improves the quality and reliability of CA based land-use models (Verburg, 2006).

SITE-Mongolia was developed within the SITE-framework (see Chapter 3), which serves as a platform for development and integration, testing and validation. The underlying model concept follows a modular, component based structure. The object oriented scripting language Python was used to program the land-use model. Each sub-module of the model is embedded in a separate Python file that can be linked to the main model file that is loaded and executed by the SITE-framework.

4.5 Initialization

During the initialization phase the model generates the simulation grid and initializes all required variables. Most of the cell attributes are initialized with data provided in the MySQL model database. The initialization of the land-use and land-cover distribution is based on an independent generated LULC map from 1989, which serves as initial land distribution. Next, all cluster layers are created, in a procedure in which single grid cells are aggregated to cell clusters that are organized in thematic layers. Clustering is based on the specification of similarity measures (e.g. land-use, soil, elevation) using cluster algorithms implemented in the framework (see Chapter 3.2.2.1, Mimler, 2007). Besides the land-use clusters, the model calculates cluster layers for administrative units (aimags, soums) and sub-basins. An important aspect of clustering is the need for data aggregation to limit the amount of identical or very similar cells for which time consuming calculations have to be done. In the absence of clustering, calculations are performed for each of such cells e.g. daily calculation of the carbon and nutrient cycles performed by DayCent. With clustering such calculations are completed ~ 90 % faster than single cell calculations, based on current cluster definitions (14,000 cells are aggregated to approximately 1000 clusters). Due to the dynamic nature of some attributes, clustering has to be repeated annually. Further, the model calculates the number of neighbours for selected LULC types, which is a prerequisite for suitability assessment. In SITE-Mongolia neighbours for settlement, wheat, potato and potential irrigation cells are calculated. Distance analysis is performed for distance of each cell to road, settlement, river and reservoirs.

4.6 Input data

The input used for the model simulations consist of several primary and secondary data, all spatially explicit, generated on diverse scales for different purposes. All input data were formatted for the grid-cell or cluster levels. Data preparation frequently required several pre-processing steps to aggregate/disaggregate data for the required scales or perform other transformations. Besides different spatial scales, different temporal resolutions are also required. On the one hand, the model needs consistent annual time series e.g. population data or agricultural commodities, on the other hand DayCent requires daily input, e.g. to simulate crop management events. To avoid duplicating the description of input data, in this section only major datasets are presented, which are not explained in detail in the model application sections.

Land use and land cover maps

Limited spatially explicit environmental information is available for Mongolia from Mongolian environmental agencies or research studies on regional land use, land cover or ecosystems. However, regional planning and research usually requires a higher level of detail. The use of global satellite based products, with a higher resolution ranging from 500 – 1000 m, such as AVHRR (Hansen et al., 2000; Loveland et al., 2000), SPOT-Vegetation (Bartholome & Belward, 2005) MODIS (Friedl et al., 2002) or MERIS (Bicheron et al., 2008) was not considered as appropriate in the context of this project. An analysis of those products revealed a disparity in the composition of LULC types (e.g. aggregated land-cover types) or a large mismatch in mapping area. Therefore, we generated LULC maps based on the 30 m resolution Landsat data which followed approaches described in Schweitzer et al. (2005) and Erasmi and Priess (2007), using a hierarchical expert classification based on satellite data, GIS, regional land statistics and expert knowledge. For the application of SITE-Mongolia, two maps were derived, one representing the land-cover distribution of 1989 (which is the starting year in the model) and another for the year 2006 (which is the final simulation year that is used for validation). Both maps are based on the freely available Landsat Thematic Mapper (TM) satellite images provided by the United States Geological Survey (USGS). Data from the Landsat 7 Enhanced Thematic Mapper Plus (ETM+) which was available for the latter date (2006) was not considered appropriate due to the malfunction of the sensor in 2003 (failure of the Scan Line Corrector) and less transferability of the classification methodology among different sensor systems. All satellite images used in the expert classification procedure are listed in Table A-1 in the Appendix. Since the same classification methodology (classification rules) for both images was used, it was important that the images were nearly comparable in their characteristics. This was achieved by several pre-processing procedures. After reduction of illumination effects, using the digital elevation model from HydroSheds (Lehner et al., 2008) and atmospheric correction using the ATCOR software (Richter, 2010) an expert classification approach, based on explicit spectral and spatial rules was applied using the ERDAS IMAGINE Expert Classifier™, '…which provides a rules-based approach to multispectral image classification, post-classification refinement, and GIS modelling' (ERDAS, 2010). To extract the correct land-cover class during classification, we used additional datasets and information, for example detailed vector information for settlement areas and for the boundaries of the agricultural fields in the catchment. This data was mainly provided by the Mongolian Administration of Land affairs, Geodesy and Cartography (ALGAC), based on digitized satellite data, GPS records from field campaigns and expert interviews. Other datasets included were the Landsat NDVI (= Normalized Difference Vegetation Index) and Landsat principle component images. Final classification was performed on a 30 m resolution image. To achieve the necessary resolution required by the model, an up-scaling was performed using 'zonal statistics' in which the median of each 1 km x 1 km pixel was calculated. As accuracy measure, we performed a comparison of the LULC types with the regional statistical information to minimise errors and misclassifications. Figure A-1 in the Appendix presents the final maps used in the model. Table A-2 in the Appendix includes the corresponding area comparison. The 2006 satellite derived classification in its original 30 m resolution is given in Figure 2-3, Chapter 2.2.3.

Soil data

Soil carbon, nitrogen, bulk density, ph and texture are important soil characteristics that are required to simulate plant growth and crop production with the DayCent model. This data is provided in the model database. Other DayCent specific parameters, plant and crop type parameterizations are located in separate DayCent input files. Due to the lack of adequate soil information on the regional scale in Mongolia, a digital soil map of the Kharaa region was generated during the course of the MoMo 1 in cooperation with the Soil Science Laboratory of the Institute of Geography from the Mongolian Academy of Sciences in Ulaanbaatar (Batkhishig & Iderjavklan, 2009). The map is a refinement of the soil map presented in 'Soils of Mongolia' from Dorjgotov (2003). With the major objective of increasing the detail of soil information within the basin, the map from Dorjgotov was revised using additional data and information from soil profiles collected during Russian and Mongolian soil campaigns, and additionally by two sampling campaigns carried out in the MoMo project in September 2008 and October 2009. Figure A-2 in the Appendix presents the different soil categories included in the digital soil map of the Kharaa river basin.

Climate data

The climate data is based on daily observations from local climate stations, provided by the Institute of Meteorology and Hydrology (IMH) in Ulaanbaatar. The DayCent model requires a transient time series of climate input for the simulation period. Minimum input requirement is temperature (minimum and maximum) and precipitation on a daily basis. As weather information was not available in the required resolution, data was spatially and temporarily interpolated using the method applied in Wimmer et al. (2009). With this procedure, climate data was provided for each cell of the entire simulation grid. Additionally, daily wind data was needed for the application of the BURN module; for the wildfire simulation, which was taken from the climate station Baruunkharaa (807m, 48°55'N, 106°04'E) located nearly in the centre of the study area.

Statistical data

Statistical input data in the form of continuous time series are required for transient dynamic modelling. Most of this data was provided by the National Statistical Office of Mongolia (NSO), which is a division of the Ministry of Nature and Environment, Ulaanbaatar. Historical crop production data at province (= aimag) level was used to simulate crop production in the Kharaa catchment for wheat and potatoes. Population data was provided by the NSO on district (= soum) level. Due to differences in population density and the large differences in water consumption, ‘urban’ and ‘rural’ population are simulated separately in the model. Migration was already included in the historical datasets, but had to be calculated based on demographic assumptions for the MoMo scenarios (see Chapter 7). Information on wood production is partly provided by the NSO at aimag level. The World Bank provides supplementary estimation of illegal wood extraction and consumption by private households for fire- and fuel wood or by commercial establishments mostly through illegal logging (World Bank, 2006). The different categories are summarized to total wood demand in the model.

4.7 Submodels

SITE-Mongolia consists of five major components that are subdivided into sub-modules. Figure 4-2 presents a general overview of the design of the model. In this section, the purpose of each of the components and the scheduling performed within the most important sub-modules is presented. All sub-modules in SITE-Mongolia programmed using the Python programming language. Besides the ‘standard’ sub-modules that perform model operation (e.g. suitability, allocation), some components include sub-modules that have the task to initialise, prepare and execute linked third-party applications (HYDRO, BURN, GROWTH).

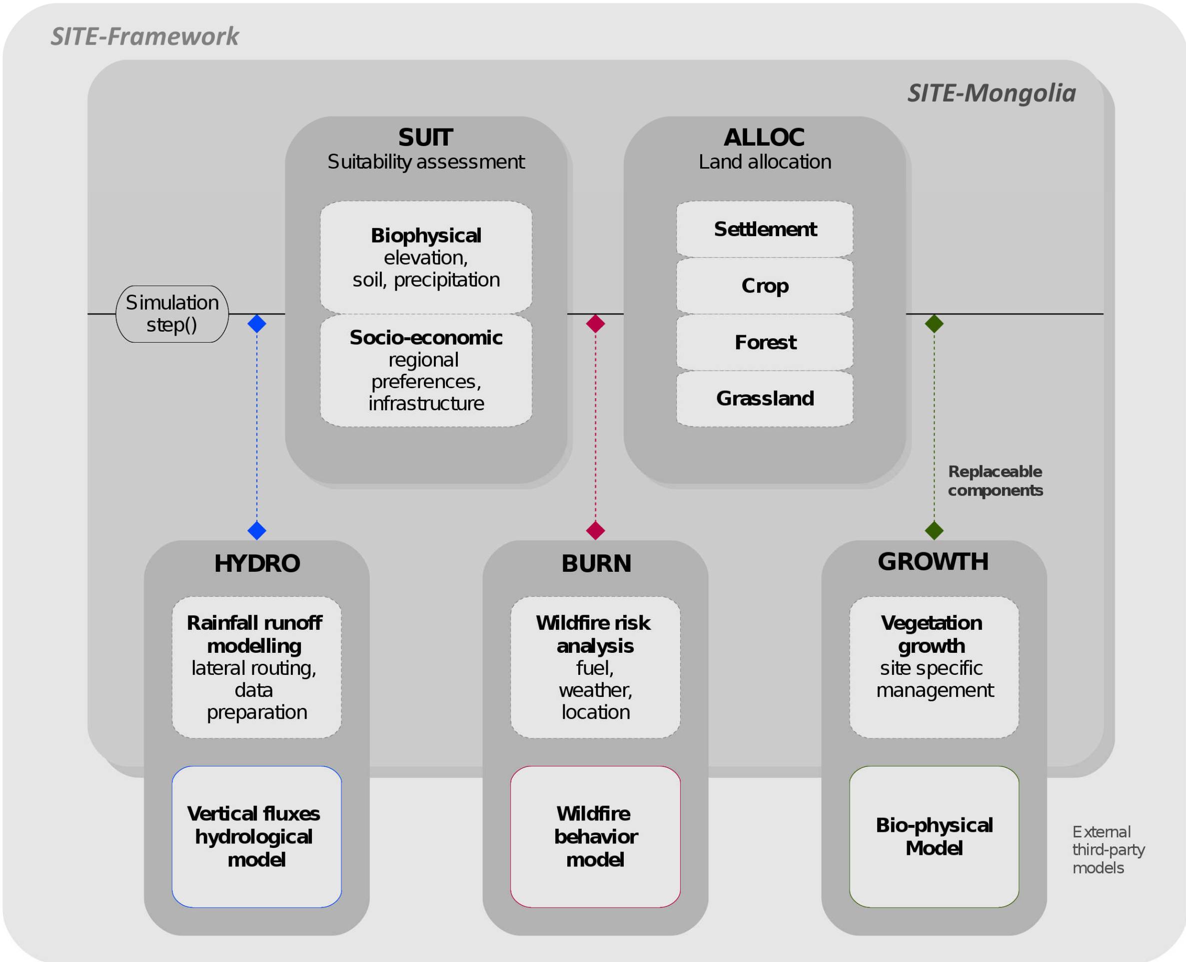


Figure 4-2. SITE-Mongolia overview. The core part consists of the components SUIT and ALLOC. Other components can be linked to address different research questions.

4.7.1 SUIT

The scheduling in SUIT follows the procedure that was described in section 3.2.2.2. SUIT includes routines to create suitability maps based on a multi-criteria analysis. These maps are used to simulate competition between different land-use types and finally to allocate land (= pixels) to a certain land category. The overall suitability of a land-use type is the result of a combination of different factors. Different weights can be assigned to each of the factors. The goal is to find sets of factors, which contribute to explain pattern and magnitude of actual land use, usually using empirical evidence or (spatial) indicators published in literature. An example for this is the integration of the factor 'distance to road', which can also be tested in GIS analyses using reference maps of the study area. SUIT also includes constraints like 'maximum slope' for settlements or agricultural land use, an indicator that can again be derived from spatial analysis. If indicators are judged to be regionally important e.g. by local experts, but empirical evidence is insufficient, the genetic algorithm (GA) implemented in the SITE calibration module can be used to derive adequate parameter values. Testing multiple factor combinations and weights the GA reveals the optimal solution from a known range of values. Further the relative operating characteristic (Pontius & Schneider, 2001) was used to validate the suitability analysis (see Section 4.9). In SITE-Mongolia, suitability maps are calculated for settlement, wheat, potato, grassland, irrigated areas and forest use. The factors and corresponding calibrated weights included in the suitability analysis are listed in Table 4-1.

Table 4-1. Factors and weights used in the multi-criteria suitability assessment. Note that weights are normalized so that they sum up to 1. Constraints indicate the maximum allowed value.

Group	Factor (B = biophysical, S = socio-economic)		Unit	Weight	Constraint
Settlement	B	Slope	[degree]	0.8	8
	S	Distance to main road	[m]	0.35	15,000
		Distance to water	[m]	0.4	10,000
		Number of settlement neighbours	-	0.7	-
Wheat	B	Slope	[degree]	0.2	10
		Elevation	[m]	0.2	1,600
		Soil fertility	-	0.3	-
	S	Distance to settlement	[m]	0.5	35,500
		Number of neighbours	-	0.5	-
Potato	B	Slope	[degree]	0.2	5
		Elevation	[m]	0.2	1,600
		Soil fertility	-	0.3	-
	S	Distance to settlement	[m]	0.2	30,000
		Distance to water]	[m]	0.3	15,000
		Number of neighbours	-	0.4	-
Irrigation		Suitable for crops (wheat, potato) > 0	-	-	-
	S	Distance to settlement	[m]	0.2	10,000
		Distance to water	[m]	0.5	15,000
		Distance to reservoirs	-	0.6	30,000
Grassland	B	Slope	[degree]	1.0	-
		Elevation	[m]	1.0	-
Forest use	B	Biomass	[t/ha]	0.2	-
	S	Distance to dirt road	[m]	0.8	20,000
		Recent use	-	0.6	-

Figure 4-3, Figure 4-4 and Figure 4-5 show some examples of the suitability maps and factors. All maps were derived after the initialization of the model and thus are not representative for consecutive years due to the dynamic behaviour of some contributing factors.

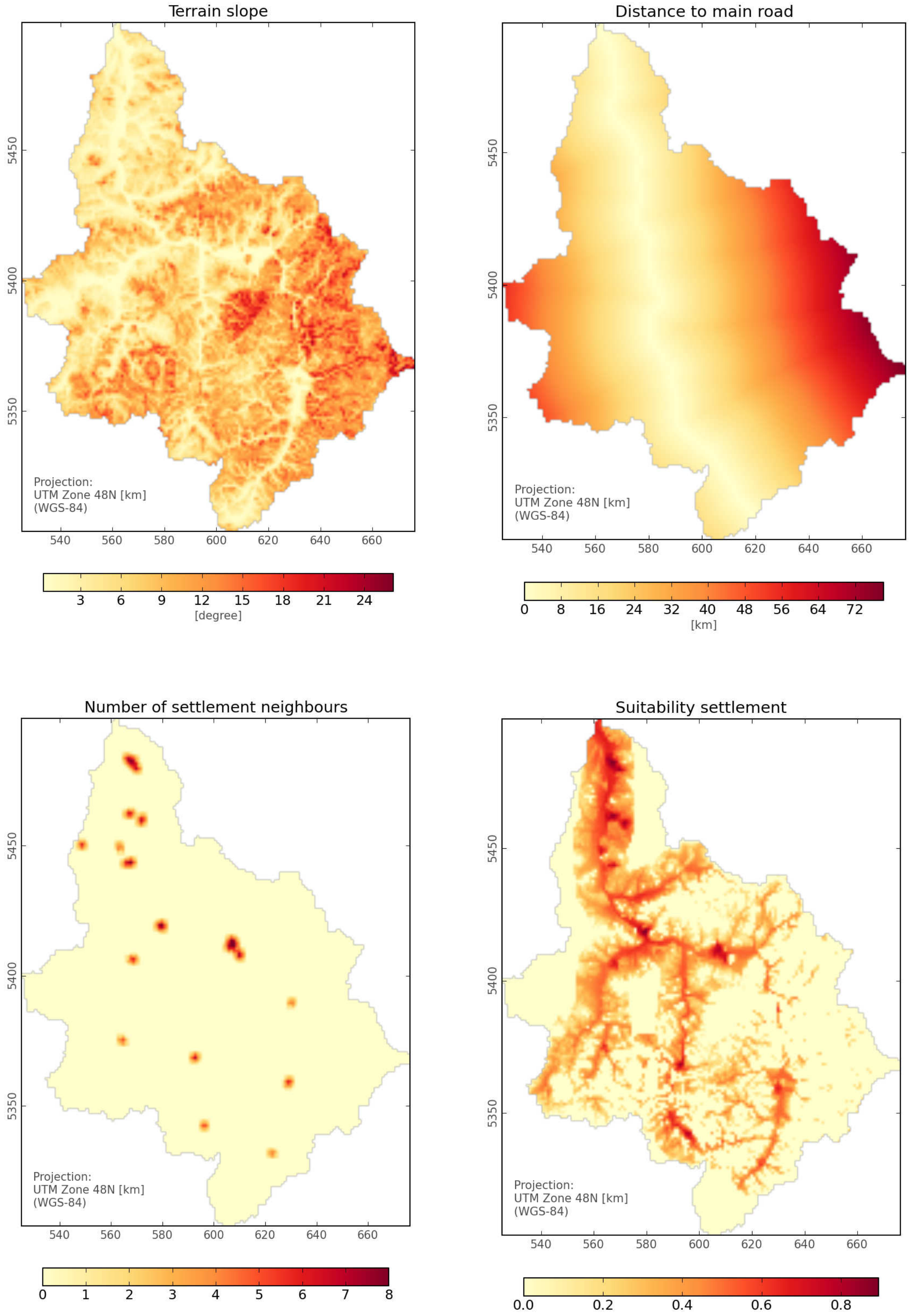


Figure 4-3. Overall suitability map for settlement (bottom right) and example maps of contributing factors.

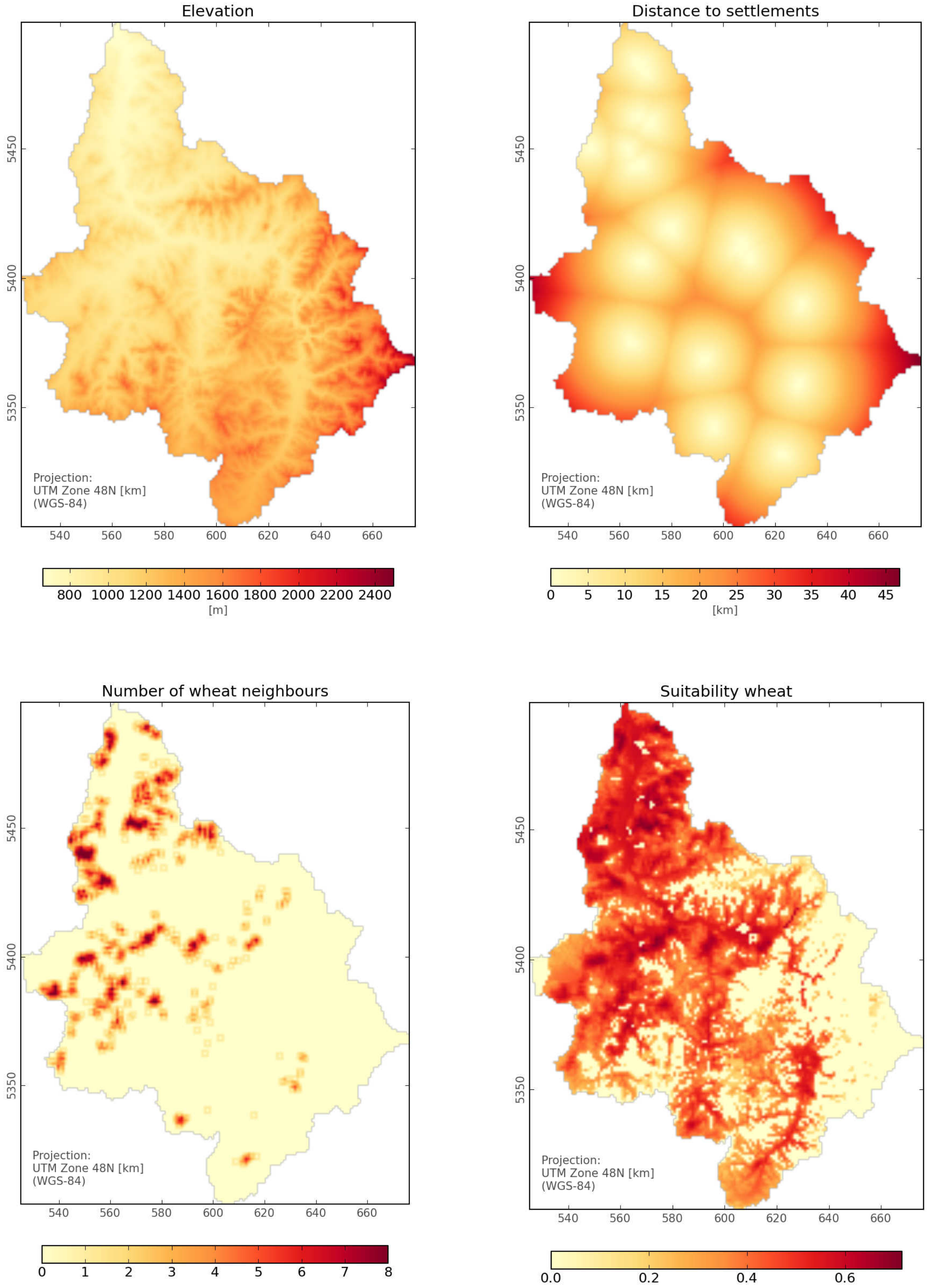


Figure 4-4. Overall suitability map for wheat (bottom right) and example maps of contributing factors.

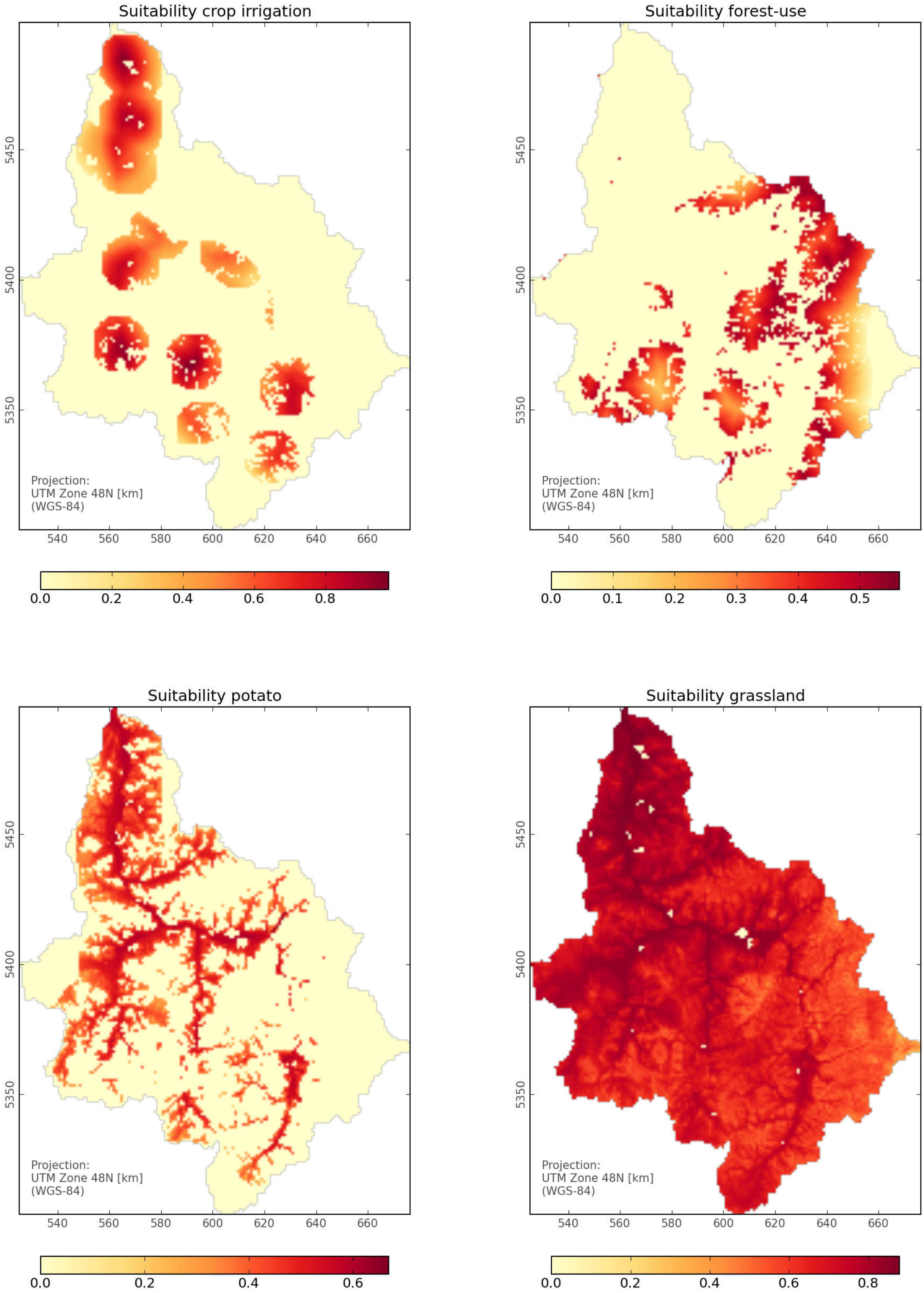


Figure 4-5. Overall suitability map for irrigation (upper left), forest use (upper right), potato (bottom left) and grassland (bottom right).

4.7.2 ALLOC

Land allocation is performed within the sub-modules of the ALLOC component. In general, allocation is driven the by the demands for commodities, agricultural products or space for housing, an approach commonly employed in land-use models (Agarwal et al., 2002; Heistermann et al., 2006; Schaldach & Priess, 2008). The scheduling within ALLOC follows a strict hierarchical order with that reflects regional land allocation preferences. In SITE-Mongolia, we assigned the highest priority to the allocation of settlement areas, followed by the allocation of crops. Subsequently forest-use is simulated which triggers the conversion from ‘closed forest’ to ‘open forest’. Finally, fallow pixels, which are out of use for several years, are converted into grassland. A common feature shared by all sub-modules is that allocation is based on a dynamically updated suitability analysis that allows a preference ranking of cells. Further, ALLOC assesses conversion matrix that enables or disables changes from one land category to another (Table 4-2). From 64 possible combinations, 36 land transitions between or within land categories are allowed in this case-study.

Table 4-2. Conversion matrix used for land allocation (X = allowed).

Settlement	Wheat	Potato	Fallow	Grassland	Riparian	Closed forest	Open forest	**FROM** / **TO**
X	X	X	X	X	X		X	Settlement
	X	X	X	X			X	Wheat
	X	X	X	X			X	Potato
	X	X	X	X			X	Fallow
	X	X	X	X		X	X	Grassland
				X	X			Riparian
				X		X	X	Closed forest
				X		X	X	Open forest

From the software development point of view, nearly all ALLOC sub-modules are programmed with a comparable structure, consisting of one entry point which is the function *Allocate()*. Calling this function with the sub-module name as prefix (e.g. *Settlement.Allocate()*, *Crops.Allocate()*) initializes the sub-module and starts allocation by calling the classes and methods. In the following paragraph the scheduling of each of the important sub-modules in ALLOC is explained.

Settlement sub-module

The allocation of space for settlements is driven by population growth. An increase in population within a district (= soum) determines the expansion of the inhabited area on sub-cell level. If the settlement area exceeds 50 ha (half the cell size) the cell is converted to the category settlement (Figure 4-6). In this case study, we distinguish between different types of settlements. Besides the rural settlements, which are simulating the dominating housing types of fenced yurts and small wooden houses, we also take into account ‘urban’ settlements, simulating that multi-storied concrete buildings occupy the majority of a cell. Urban and rural settlements in the model reflect the contrasting living conditions and population densities as well as large differences in water consumption between the two types, a fact highly relevant in the IWRM context. However, due to the low number of urban cells in the entire catchment, we did not define a separate land-use type ‘urban’.

The settlement allocation starts with the evaluation of suitable cells that are already inhabited, but have sufficient space left to accommodate additional persons. Using the top ranked (= most suitable) cell, population is allocated until the maximum population density is reached. If the cell includes urban structures, corresponding urban densities are used. In parallel, the settlement area on sub-cell level is adjusted to the equivalent amount of new inhabitants. This procedure continues, cell by cell until there are no persons left to distribute. However, if a cell’s maximum capacity is reached, a new (initial) settlement area has to be established within the most suitable neighbouring cells. This step automatically makes a cell a member of the pool of suitable cells in which the model tries to allocate people during the next time step (= year). Finally, after all inhabitants have been distributed among adequate cells, a routine checks if the settlement area has reached the threshold to convert it to a new settlement cell. The typical simulation pattern observed using the above allocation procedure, causes settlement areas to grow roughly concentrically, given that surrounding cells are not barred from conversion e.g. by the conversion matrix or distorted by low suitability values for example caused by steep slopes or other constraints.

Crop sub-module

Allocation of cropland is driven by annual crop demand. Spatial distribution is based on the suitability maps which are calculated for each crop type - wheat and potato. Due to insufficient data at district level, the allocation function in this case loops over each province (= aimag). A simplified flowchart presents the allocation scheduling (Figure 4-8). First, the algorithm collects all cells that are appropriate for at least one crop. For these cells productivity is evaluated, checking whether current yield levels are significantly lower (< 40 %; calibrated value) than the average yield of the district to which the cell belongs.

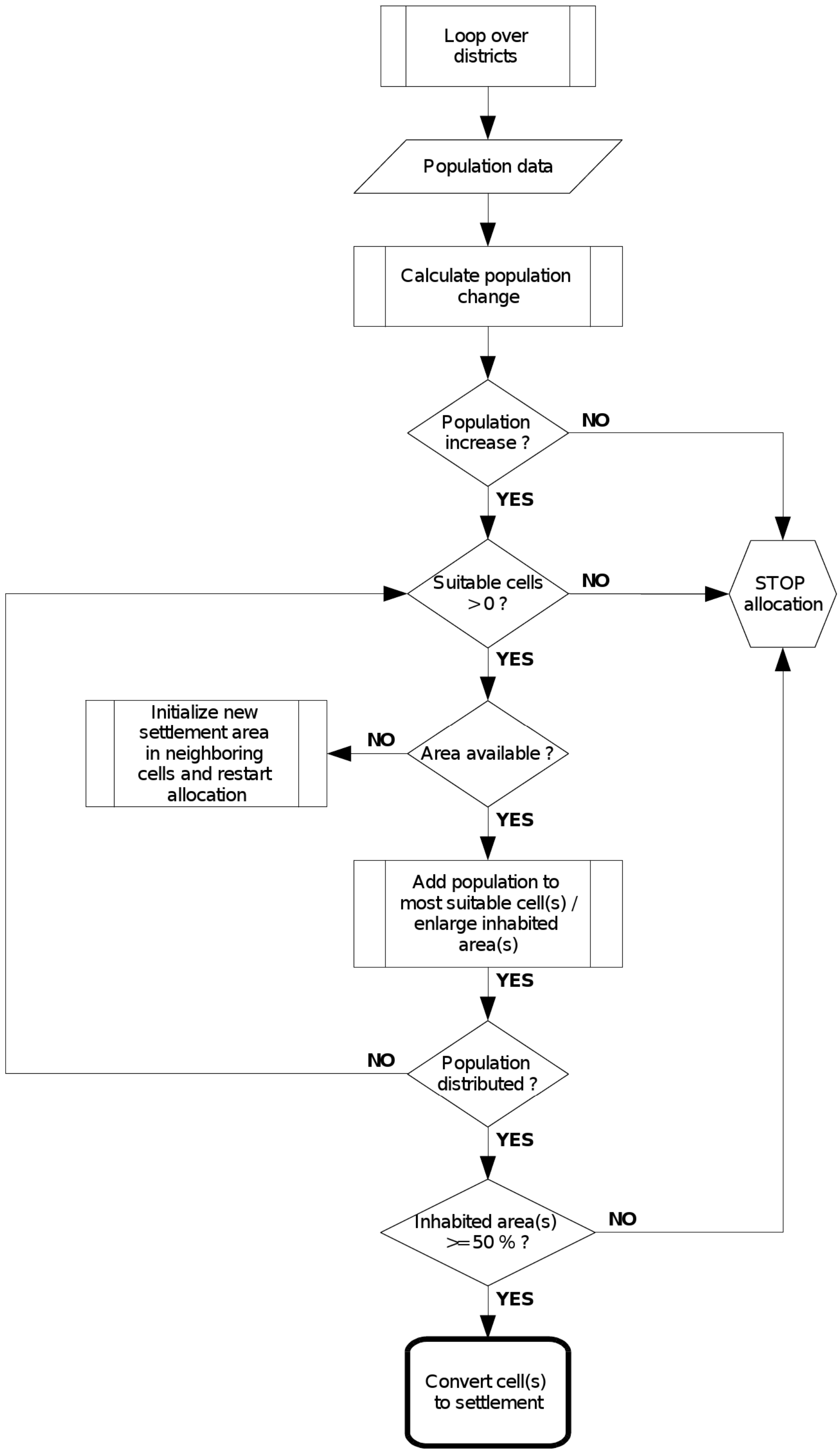


Figure 4-6. Simplified flowchart of the settlement allocation in SITE-Mongolia.

If this is the case, the cell is removed from the pool of crop candidates and marked as a fallow candidate that will be converted at a later stage of the simulation. To represent the crop rotation system applied in Mongolia, we use a look-up table to represent rotation decisions. This involves tracking the duration of crops and fallows in each cell. Usually, wheat is grown two to three consecutive years followed by a fallow period. Potatoes are grown maximal for two years followed by a fallow phase (e.g. Hickmann, 2006). The length of the fallow phase is determined by the need for additional cropping area. The allocation algorithm treats every crop separately starting with the crop having the largest difference between current production and the demand of the coming year. If the result is negative, production will be increased; if positive the production has to be reduced. In both cases the consequence is either an expansion or reduction of the total cropland area. Note that changes in land management are not considered at this stage. The algorithm first tries to balance the negative demand as long as a pre-defined threshold value is not reached i.e. a predefined 'accepted' relative deviation between demand and production (e.g. 10 %). With this, we are able to account for inter-annual fluctuations (e.g. inter-annual climate effects, difference in crop management). All candidate cells are run through a sorting function which arranges the cells according to a defined preference criterion. Besides a high suitability value, a top ranked cell is also expected to gain a high profit. For the latter the model uses potential yields which are available for all cells and all crops, calculated by DayCent at the beginning of the simulation. The allocation method first uses the fallow cells. If no fallow cells are available, the algorithm detects grassland cells preferably the ones that have been cropland and got converted in an earlier step. In Figure 4-7 a screenshot shows part of a typical output from the model log file that we use for observing the model behaviour.

```
CROP ALLOCATION FOR AIMAG Selenge (07-02-2011 12:07:27)
START SITUATION: Step 1

CROP                |     Wheat |    Potato |
--------------------|-----------|-----------|
CURRENT # cells     |       425 |         9 |
CURRENT PROD. [t/ha]|    0.7689 |    8.7444 |
CURRENT PROD. [t]   |   32680.0 |    7870.0 |
CLAIMED PROD. [t]   |   42242.3 |    6886.1 |
DIFF ABS            |   -9562.3 |     983.9 |
DIFF REL            |     -0.29 |      0.13 |

Available cells for reclassification:
# cells  Wheat:    2980  Potato:    1341

GET ADDITIONAL CELLS FOR Wheat - Demand(incl. tolerance): -6294.31

Moving cell ( 1495) Prev.class: Fallow, Suit.for Wheat = 0.6778, Pot.prod. [t/ha] = 0.800
Moving cell ( 1443) Prev.class: Fallow, Suit.for Wheat = 0.6461, Pot.prod. [t/ha] = 0.800
Moving cell (  979) Prev.class: Fallow, Suit.for Wheat = 0.6268, Pot.prod. [t/ha] = 0.700
```

Figure 4-7. Screenshot of the simulation log file showing important sections of the crop allocation procedure.

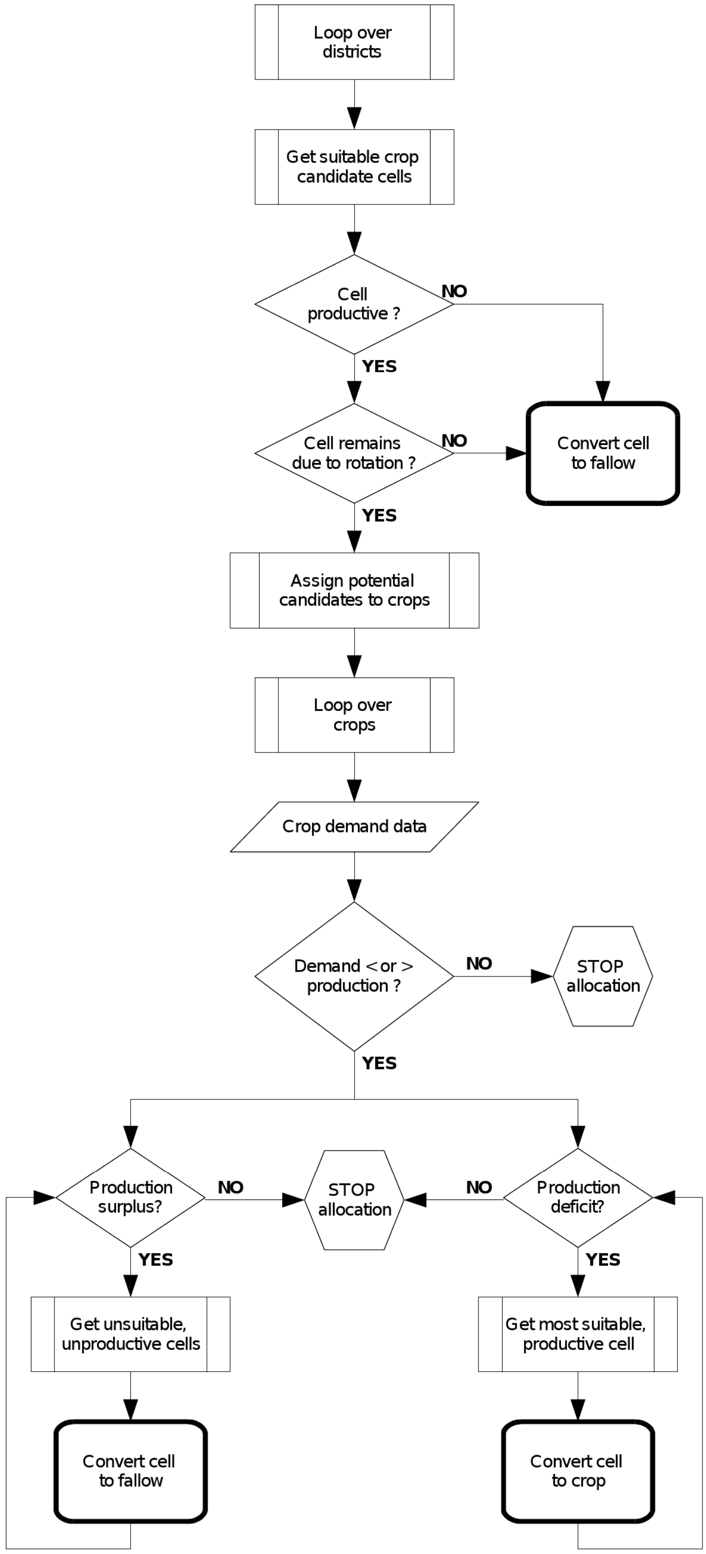


Figure 4-8. Simplified flowchart of the crop allocation in SITE-Mongolia.

In case of a production surplus, the model follows the reverse strategy. Unproductive cells and cells with low suitability values are removed first and added to the pool of fallow candidates. Finally, after the demand deficits and surplus are accommodated, fallow cells are allocated assessing the pool of fallow candidates that either were collected from productivity evaluation, from crop rotation (exceeded duration counter) or allotted reducing the surplus.

Forest sub-module

The forest module simulates the extraction of timber and transition from closed forest to open forest. The spatial information depicting the locations where forest biomass is extracted is specified by the suitability map for forest use (Figure 4-5). The total volume of wood removed (= wood demand) is based on the extraction rates of a district, whereas total demand is computed as the sum of industrial and private demand. In the beginning, the scheduling of the forest sub-module calculates the total demand of a district based on several assumptions. To estimate demands, we use the official timber extraction statistics from the NSO which mainly include the industrial production and timber used for construction and add the estimated the private consumption. Overall extraction rates might be much higher because of the large amounts of timber that were and still are removed illegally (World Bank, 2006). The household demand is based on the assumption that an average size household in Mongolia consumes around ten tons of coal and forest products per household per year including wood for construction, heating and cooking. Reported annual average fuelwood consumption rates vary between 3 – 8.2 m^3. For the simulations, we apply 1.25 m^3 per capita per year, which was reported as average consumption by the World Bank (World Bank, 2006). In the model, we estimate the private fuelwood demand using the latter value in combination with rural population numbers. Based on the ranking of cells derived from the suitability analysis, a certain fraction of biomass from the top ranked cell is removed. This fraction (e.g. 10 %) is usually one parameter that is derived by model calibration during which we compare simulated vs. observed forest areas. Herewith we are highly flexible e.g. to account for the 'missing' illegal extraction. Cell by cell, biomass is removed until the demand is covered. If biomass has been removed from a cell, it is marked with a flag that indicates that the cell has already been used, assuming that now a certain infrastructure is available facilitating potential future use. In the next simulation step, the calculation of forest suitability uses the flags to increase these cells' suitability values. Finally, the function checks whether biomass in 'closed forest' cells is lower than the threshold value defining 'open forest'.

Grassland sub-module

Grassland, the largest land cover class in the Kharaa catchment, is allocated as a result of abandonment of cropland or disappearance of forest due to timber extraction or occurrence of wildfires. For allocation the suitability map of grassland is used (Figure 4-5). The transition from agricultural areas is performed based on the attribute that indicates for how many years fallow cells are out of production, either because of low productivity, low demands or as a component of crop rotation. The allocation is further based on the suitability ranking for grassland. In case of forest as previous land cover, grassland is allocated to a cell if there is no biomass left (due to timber extraction or wildfires) and the cell does not have multiple forest neighbours, which we use as indicators to simulate 'natural' re-growth.

4.7.3 HYDRO

The major function of HYDRO is to simulate important hydrological processes affecting land-use and land management. In this study, the major objective was to perform a process based simulation of water availability within the catchment and simulate effects on current and potential future irrigation-water use. The HYDRO component was developed in cooperation with the hydrology group within the MoMo project. Besides the overview presented here, Chapter 5 includes more details about the model and explains the application using HYDRO. The component included in SITE-Mongolia consists of a sub-module that manages the input and output of the third-party hydrological model and includes the routines for lateral flows. For the simulation of vertical water fluxes of the soil-plant-atmosphere interface the 1-dimensional hydrological model TRAIN is used and linked to the SITE-framework. The model input comprises of daily time series of precipitation, solar radiation, air temperature, air humidity, and wind speed. Additionally, a set of parameters describing the vegetation cover (e.g. leaf area index) and hydrological soil properties (e.g. water holding capacity) is required. The computation of transpiration is based on the Penman-Monteith equation (Menzel, 1996). Interception evaporation is calculated for different canopy layers taking into account the effect of curved droplet surfaces on evaporation rates (Menzel, 1997). In addition, the accumulation and melt of snow cover as well as changes in soil moisture storage are taken into account. In the current version, surface runoff generation is computed as a constant fraction of precipitation exceeding infiltration, while percolation is calculated using an approach comparable to that of the HBV hydrology model (Lindström et al., 1997). Due to the limitation of the TRAIN model to simulate vertical water fluxes, a major purpose of the Python sub-module is distribution of the lateral water flows with the objective to spatially account for changes in water availability. In a related study using the TRAIN model, Wimmer at al. (2009) have presented climate change impacts on snow sublimation rates in the Kharaa catchment.

4.7.4 BURN

The purpose of BURN is to simulate the socio-environmental impacts of wildfires affecting the Mongolian steppe and forest ecosystems. The simulation enables us to study changes in carbon and biomass with adverse effects (i) on forests that are of hydrological and mesoscale climate importance and a main source for fuelwood extraction and (ii) on grassland pastures that are essential for the Mongolian herders searching for fertile grazing plots. The BURN component consists of a sub-module that manages the tasks required to run the third-party wildfire model that simulates wildfire spreading and behaviour, based on a prior risk analysis. As a wildfire model we use the ‘firelib’ library (Bevins, 1996) which is a modified version of the BEHAVE model (Andrews, 1986). The sub-module prepares the input data, executes the wildfire model and imports the results for further analysis. The scheduling is described in detail in Chapter 6. However, an important aspect is the wildfire risk analysis with the objective to identify areas, which are more susceptible to wildfires than others and in addition to locate spots with high ignition probability. The concept of the risk analysis is based the procedure we use for the suitability analyses performed in the SUIT module. An overall wildfire risk is derived from dynamic maps of three risk categories. The criteria included are fuel (availability of burning material), weather (short-term moisture) and location (e.g. distance to roads, to account for the fact that > 90 % of wildfires have anthropogenic caused and are not ignited e.g. by lightings). To account for the changes in carbon stocks, the wildfire processes simulated in BURN are linked to the biophysical model DayCent via the GROWTH component, which is presented in the next section.

4.7.5 GROWTH

The GROWTH component is responsible for the calculation of carbon dynamics, crop yields, plant biomass and related feedback processes. Both HYDRO and GROWTH are connected to the GROWTH component simulating the biophysical environment. GROWTH consists of two units, a process based third-party model and the sub-module, which is responsible for the initialization and preparation of the input, required for the execution of the external model (Figure 4-2). Further, land management (e.g. cultivation, fertilization, irrigation) and site specific vegetation changes (e.g. timber extraction, grazing, fire) are parameterized and scheduled here for every timestep. The module includes several processing steps to prepare a simulation run and if the simulation is finished, the module is responsible to read the results that are fed back into the SITE system. For each pixel covered with vegetation, the ecosystem model DayCent (Parton et al., 1998) is applied. DayCent is a modified version of the Century ecosystem model simulating vegetation dynamics in daily timesteps. Developed to simulate soil and vegetation dynamics at the field or ecosystem scale, DayCent has successfully been applied in regional (Lu et al., 2001) and global studies (Stehfest et al., 2007). In the SITE framework, DayCent in its version 4.5 was employed, which is an enhanced version with improved subroutines to simulate trace-gas emissions (Stehfest, 2005). It is capable to simulate various vegetation types (e.g. crops, natural vegetation, forests) and management options (e.g. irrigation, fertilization, grazing, harvesting) in a sufficiently detailed manner. Data requirements are daily minimum and maximum temperature, daily precipitation and site-specific soil parameters like texture and bulk density.

Equilibrium and parameterisation

To initialize the DayCent soil organic matter (SOM) pools to an equilibrium state, we used a multi-step procedure applied for the main vegetation and crop types. For each class, different states of vegetation succession and conversion (e.g. from grassland to agriculture) were simulated. For cropland, equilibrium simulation started with closed forest cover (e.g. *Larix sibirica*) followed by grasslands (e.g. *Stipa grandis*), first without and then with an increasing seasonal grazing intensity. Grassland was followed by a transition to agricultural land, which emerged in the late 1950s. From the 1960s to the late 1980s the agricultural area was more or less intensively managed (e.g. by fertilizer application, irrigation) (Stadelbauer, 1984). For forest equilibrium, the initial cover was retained, but frequently disturbed by natural wildfire events (simulated every 300 years). For grassland, one transition event from forest to grassland was included and then seasonal grazing with low intensity was simulated. In total, an equilibrium phase of 2000 years was simulated for each grid cell, to start the simulation (in 1989) with adequate SOM levels.

For the historical simulation period (1989 - 2006) agricultural cultivation comprises mainly wheat (*Triticum spp.)*, potato (*Solanum tuberosum*) and very recently also horticultural crops (salad, onions, etc.). In this study, only wheat and potato are considered due to the very limited area covered by horticulture up to 2006. In DayCent, we parameterized a spring-wheat variety, which was adapted to the continental climate conditions (adaptation of the temperature response function). For potato, a cold-temperate variety was parameterized. Land management events were included to reflect average land use conditions in Mongolia, i.e. based on information gathered during field trips (e.g. interviews with farmers, Mongolian crop scientists) (see Table A-4 in the Appendix for selected regional adapted DayCent parameters). Compared to other Asian countries, rates of fertilizer applications are very low in Mongolia. In general, the agricultural system is characterized by low input and low output (Hickmann, 2006). Detailed information on fertilizer consumption at the regional level is rare, thus national averages from FAOSTAT (FAO, 2009b) are applied in the model (see Figure A-3 in the Appendix). In the study region, varieties of irrigation systems are applied, using either surface- or groundwater sources. Many farmers still flood their fields once or twice, while sprinklers or other more advanced technologies are nowadays less frequently used than in the 1980s and 1990s during the socialist period. It is noteworthy that even the most recent information available e.g. from FAO (FAO, 2009a) or IWMI (Thenkabail et al., 2008) relies on the same (outdated) statistical sources from the 1980s and 1990s. Due to these large uncertainties, we aggregated all irrigation systems and simulated them as two irrigation events per cropping season. The typical cropping sequence (Section 4.7.2) is based on alternating cultivation and fallow, with the purpose to increase soil moisture storage, an important aspect for the low input and water limited cropping system (Hickmann, 2006). During the fallow years a mix of C3-grass and legumes are grown on the fields in the Kharaa catchment (and also in the DayCent simulations), contributing to restoration of soil carbon and nitrogen pools and protection the of the soil cover from erosion.

DayCent testing and validation

Based on the above described parameterisation of DayCent, validation was performed with region-specific average yields (for crops) and by using biomass or net primary production levels (for forests and grasslands). In Figure 4-9 the DayCent validation of wheat yields is presented. The simulated average yield over the entire period is 0.93 Mg/ha compared to 0.86 Mg/ha reported in regional statistics.

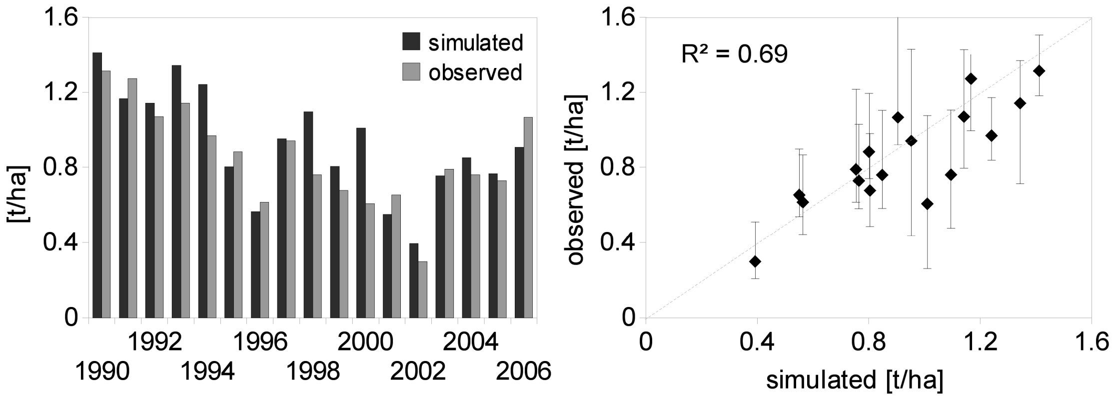


Figure 4-9. Validation of the simulated wheat yields. Left figure: mean simulated wheat yields of the basin compared against yields from province (= aimag) statistics for the period 1990 - 2006. Right figure: annual variation of reported and simulated crop yields (error bars represent lowest and highest yields).

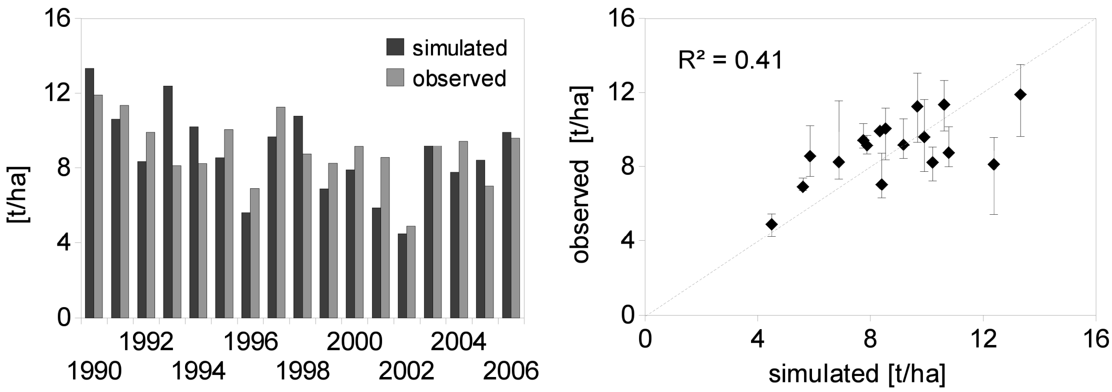


Figure 4-10. Validation of simulated potato yields. Left figure: mean simulated of potato yields are compared against yields from province (= aimag) statistics for the period 1990 - 2006. Right figure: annual variation of reported and simulated crop yields (error bars represent lowest and highest yields).

DayCent validation for potato yields is presented in Figure 4-10. Simulated mean yield for potato is 8.84 Mg/ha, whereas regional statistics reported 8.91 Mg/ha. Note that agreement between reported and simulated yields is lower than for wheat. Furthermore, DayCent was tested/validated for grassland using data from primary production experiments (Togtohyn & Ojima, 1996) and for forest using total aboveground biomass data (Kindermann et al., 2008) Both validations showed an acceptable good fit, comparable as for the crops.

4.8 Sensitivity analysis

The sensitivity analysis (SA) is an approach, where methods are applied to evaluate the relationship between the input and the output of modelling simulations (Chen et al., 2010). The SA forms an important part of the model development and validation process, the understanding in the use of model and investigates whether any simplifications in the model are possible (Saltelli et al., 2000). A detailed SA has the purpose to check the robustness to small changes in the parameter settings, or input data, and is considered an appropriate method to reveal if the model is over-parameterized. Parameters identified as sensitive candidates and in addition associated with a high uncertainty should require special attention and should be considered as candidates for an intensive form of calibration and validation. As a logical consequence, parameters identified with less or no effect on the model behaviour should be aggregated or removed (Newham et al., 2003).

Besides the above-mentioned objectives, a SA forms an important step in SITE to extract one parameter set that is considered most promising for model calibration. Further, a SA assists in improving the model with respect to complexity and runtime, the latter an important aspect of the multitude of simulation runs required for a model calibration. In SITE, we included an automated SA routine that iterates through the parameter set, each parameter associated with a predefined parameter range. The resulting search space is tested by looping over each parameter, testing its parameter range while all remainder parameter values stay constant (= default). Both, selecting the parameter range and finding suitable increment steps are part of the iterative SA process. Once the automated procedure has simulated all possible combinations, the routine uses one of the validation algorithms implemented in SITE (see Section 3.2.3; Mimler, 2007) and extracts accuracy values that are appropriate to compare results from simulation runs. We limit a parameter set in SITE to 10 or maximum 15 parameters, to be able to evaluate the results in an appropriate (visually adequate) manner. The total number of simulations required to evaluate one parameter set is therefore the product of the number of parameters and the number of their increment steps.

In the following paragraph, we present example results from the sensitivity analysis of a specific parameter set that was tested for SITE-Mongolia (see Table 4-3). In total, we tested four sets and used the ‘Figure of Merit’ (Pontius et al., 2008) and the ‘standard Kappa’ (Pontius,

2000) as accuracy measure to evaluate the sensitivity. Figure of Merit is generated from the ratio of the intersection of the observed change and the predicted change to the union of the observed change and predicted change (Pontius et al., 2008). The Figure of Merit is usually expressed in percentage agreement, where 0 % indicates no overlap and 100 % reflects a perfect overlap. A standard Kappa value of 1 is reached if the observed agreement between a simulated map and a reference map is perfect. A Kappa of 0 indicates that the observed agreement is equal to the expected agreement due to change (Pontius, 2002). For LUCC modelling a Kappa > 0.5 is considered as adequate (Pontius, 2000). According to other studies, a Kappa < 0.4 indicates a poor agreement, between 0.4 and 0.75 fair to good agreement and > 0.75 is considered as very good to excellent (Landis & Koch, 1977; Lesschen et al., 2005).

Changing the parameter values has usually quite diverse effects on the model behaviour and land-use patterns, which we examine using a multi-step, multi-stage approach. First, we explore the inter-annual quantity of allocated pixels for all simulation steps and all parameter set constellations. This provides a first overview about the effects that specific parameters or parameter constellations have on allocation patterns through a complete simulation phase. In a next step, we evaluate the overall model sensitivity and the effects on each land-use type separately. Figure 4-11 presents results from the SA performed for the parameter set listed in Table 4-3. Here the result for 14 parameters are presented derived from approximately 70 simulation runs. Note that the validation algorithm (Figure of Merit, standard Kappa) used in the SA have not the primary aim to evaluate the accuracy; furthermore they are used as a common measure to compare different parameter constellations.

From Figure 4-11 it is evident that some parameters are more sensitive, some show no effect at all. On the one hand the overall model (represented by the upper figures) responds to changes within a few parameters (e.g. factDegrad), on the other hand the same parameters have no, or very minor effects on specific land-use types (e.g. wheat, potato). The opposite pattern can also be observed. Whereas the parameters ‘prdctDeficit’ and ‘prdctDiffRel’ have a large effect on the allocation of crops, the effects are minor with respect to the overall model. In conclusion, it is important to evaluate not only with respect to the overall model, but also to the allocation patterns of specific land-use types, which may contribute significantly to the overall quality of the simulations.

Table 4-3. Example of a parameter set tested in the sensitivity analysis. The table also includes the values derived from the final calibration of the model.

No.	Parameter abbreviation	Description	Tested range	(Calibrated) value
1	factDegrad	Threshold for open forest allocation (biomass * factDegrad)	0.2 – 0.8	0.6
2	factRemoval	Percentage of forest biomass removed by timber extraction (0.1 = 10 %)	0.05 – 0.4	0.15
3	prdctDeficit	Crop production deficit of crops accepted by farmer (0.1 = 10 %)	0.1 – 0.8	0.4
4	prdctDiffRel	Difference accepted evaluating total crop demand (0.1 = 10 %)	0.1 – 0.4	0.2
5	stblDifference	Criteria of change: difference in suitability of one crop compared to another	0.1 – 0.4	0.1
6	wBiophys	Weight of overall biophysical suitability (if > 1.0 tested vs. socio-econ. suit.)	0.2 – 5.0	0.75
7	wDistToRoadForest	Weight of the factor distance to road (forest suitability)	0.1 – 1.0	0.8
8	wDistToSettlmPotato	Weight of the factor distance to settlement (potato suitability)	0.1 – 1.0	0.8
9	wDistToSettlmWheat	Weight of the factor distance to settlement (wheat suitability)	0.1 – 1.0	0.5
10	wForestUse	Weight of the factor indicating forests the were already in use	0.1 – 1.0	0.6
13	wNumNghbPotato	Weight of the factor regarding the number of potato neighbours	0.1 – 1.0	0.4
12	wNumNghbWheat	Weight of the factor regarding the number of wheat neighbours	0.1 – 1.0	0.5
13	wSoilFertPotato	Weight of the factor soil fertility (potato suitability)	0.1 – 1.0	0.3
14	wSoilFertWheat	Weight of the factor soil fertility (wheat suitability)	0.1 – 1.0	0.3

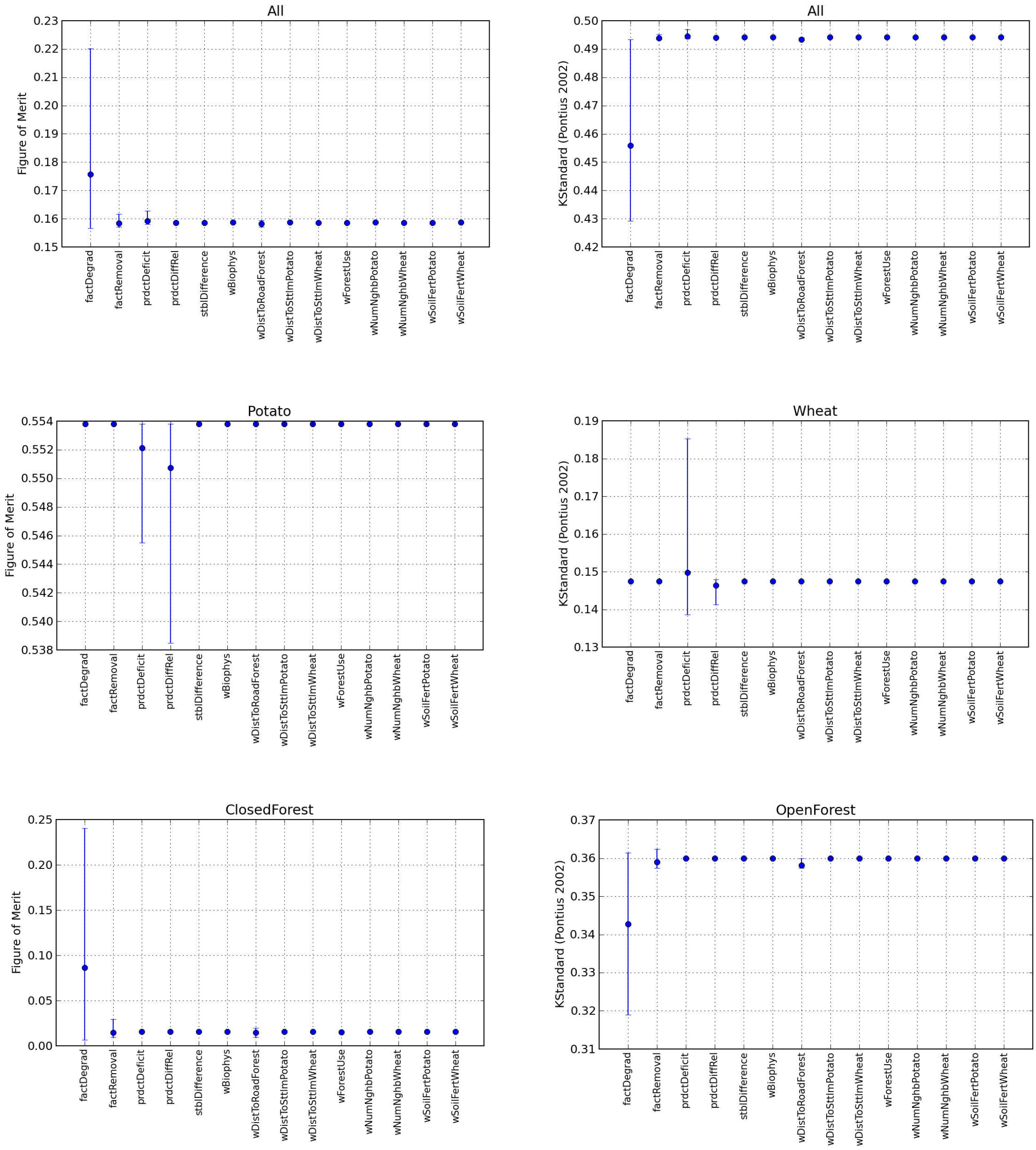


Figure 4-11. Selected results from the sensitivity analysis. The dots indicate the mean score values for Figure of Merit (left) and Kappa (right), the bars indicate minimum and maximum scores values reached. Note: Figure of Merit of 0.1 = 10 %. Note, that the y-axis is normalised and thus not equally scaled among figures.

4.9 Model calibration and testing

Model calibration, evaluation and testing forms an important part of the modelling process and considered as a crucial step in the development chain of land-use models (Oliva, 2003; Straatman et al., 2004). In addition to the basic simulation functionalities in SITE, the system domain provides generic functionality supporting quality aspects of modelling applications and a model calibration part including optimisation procedures (Figure 4-12). The 'Model test' component is a collection of map comparison algorithms that enable quantified assessment of simulation results based on a reference map (see Section 3.2.3). The component 'Calibration' allows automated calibration of user-defined rule set parameters.

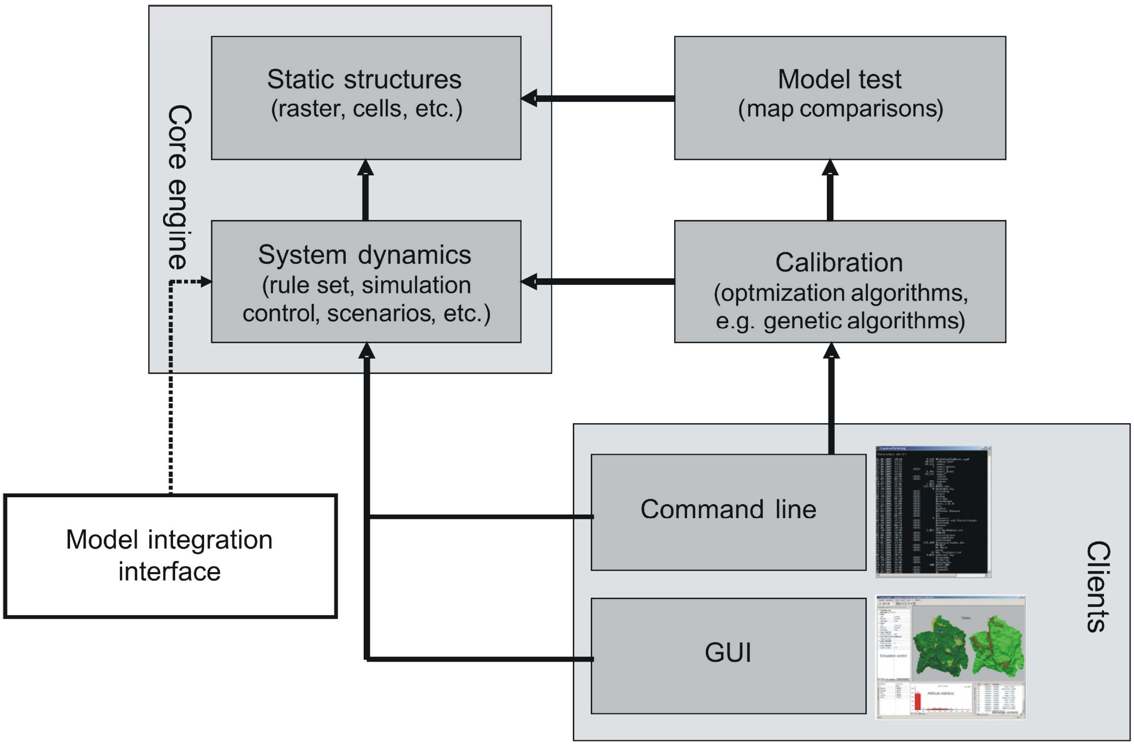


Figure 4-12. Part of the SITE system domain including generic modelling functionalities provided by the core engine, and methods for model testing and calibration. SITE provides two user interfaces, either via GUI or command line, the latter is the choice for sensitivity analysis and model calibration (from Mimler, 2007).

For optimization purposes, a number of methods are applied in the field of ecological and environmental modelling, dealing with different objective functions (Seppelt & Voinov, 2002). Evolved from the field of machine learning, methods like fuzzy logic, rural networks, adaptive agents and genetic algorithms (GA) are widespread used, from which the latter is considered as one of the most promising, concerning ecological and integrative concepts (Recknagel, 2001). GAs are applied in a number of environmental modelling studies were they are used for grid-based optimization of landscape patters (Holzkämper & Seppelt, 2007), or for the parameter optimisation and calibration of a conceptual hydrological model (Wang, 1997) etc. Due to the mature of complex integrated systems, characterized by multiple components and linked models, the parameter space can be tremendous. Consequently, calibration runtime requirements can be very high, especially if a large number of parameters are identified to be sensitive, or if models are applied that do not integrate up to date technical improvements (e.g. multi-core, parallelisation). For the mentioned problems, a GA is considered as an appropriate solution, which traverses the parameter space very efficiently based on an objective function, retrieving adequate results for a comparable low number of simulation runs. In SITE, for model optimization Wall's programming library 'GAlib' (Wall, 1996) is used. The GAlib provides multiple possibilities to characterise the GA settings to be able to adapt the optimisation criteria in favour to the specific optimisation objectives.

In SITE, the optimization goal is to find a good and adequate solution for the parameter values of the parameter set that was derived from the SA. More specifically, the task is to find a set of parameter values that steers the land allocation towards an optimal distribution. Therefore, the optimisation process passes the following steps: first, the search method of the GA forms a random initial population, which consists of potential candidate solutions (in our case a set of parameter constellations) that are derived from the given parameter set. Each candidate solution will be evaluated based on the objective function. The objective function applies a map comparison algorithm to generate and retrieve a score value. In this study, the score value is the accuracy measure generated by map comparison of the simulated LULC map with the independently compiled LULC map from 2006. Theoretically, any of the map comparison algorithms implemented in SITE can be used, supposed that the algorithm returns a value between 0 (no fit) and 1 (perfect fit), which is a required GA boundary condition.

For calibration of the SITE-Mongolia model, the Figure of Merit was chosen due to the possibility to compare the results to the number of other models evaluated by Pontius et al. (2008). After the objective function has returned the score values for each of the candidate solutions, fitness values are determined indicating the degree of fit compared to other candidate solutions. Every new iteration, the GA creates a population that includes the most promising (= best score values) candidate solutions from the last population (parents) combined with a set of new candidate solutions. This form of 'mating' is done just by combining or crossing-over from solutions of the parents' generation. To include some degree of diversity, the GA periodically performs a random mutation. If the GA performs successful, after several generations score values reach the upper boundary of a sigmoid distribution - indicating that a far better solution is impossible with the selected parameters and parameter ranges. Termination of the GA is scheduled using a maximum number of generations or by applying a threshold indicating the accepted accuracy. Both of the criteria form part of the iterative GA testing and parameterization phase.

By using the above-described approach, we are able to optimise the model regarding to the objective function, where the best model accuracy is considered as ultimate optimisation goal. Further details about the GAlib settings and specific configuration possibilities are presented in Wall (1996). Technical details regarding the implementation in SITE are presented in Mimler (2007). The GA settings used in this study are given in Table A-5 in the Appendix.

Calibration of settlements

Due to the hierarchical structure of the land-use model, we applied a two-step calibration procedure. The settlement sub-module, first executed in the chain of allocation modules, has the characteristic that no link or dependency exists to other sub-modules, components or third-party models. This unique setting, together with a negligible runtime (no DayCent required), enables us to perform a separate calibration for all relevant parameters affecting the allocation of settlement. Accordingly, not all these parameters were included in the prior sensitivity analysis. Two groups of parameters were considered, one group consisting of parameters used in the suitability analysis (factors and weights) the other from the settlement allocation routine. Table 4-4 presents the parameters used in the settlement calibration furthermore includes the final calibrated values for the parameters.

Table 4-4. Parameters used for calibration of the land-use type settlement.

No.	Description	Unit	Calibrated value
Suitability parameters			
1	Maximum distance to main road	[m]	15000.0
2	Weighting factor distance to main road	[m]	0.2
3	Maximum distance to surface water	-	10000.0
4	Weighting factor distance to surface water	-	0.4
5	Weighting factor for slope	-	0.9
6	Weighting factor number of populated neighbour cells	-	0.65
Allocation parameters			
7	Maximum area fraction to be covered by settlements in case not all neighbouring cells are inhabited	[ha]	80
8	Maximum initial area fraction covered by settlements	[ha]	6
9	Maximum area share per person in rural settlements	[ha/pers.]	40
10	Maximum area share per person in urban settlements	[ha/pers.]	80

Due to the random heuristic character of the GA (e.g. initial population, mutation), the optimization goal is not solved with a single solution. Due to this, we usually start one calibration run several times using identical GA settings. With this we are able to test if the GA performs correctly, indicated by a low mean variation in the final parameter values among the different solutions and have the choice between different sets of the most capable parameter value constellations.

A typical population progression pattern derived from the calibration with the GA is presented in Figure 4-13 which compares two calibration runs for the land-use type settlement. As quality measure, the Figure of Merit was used to derive the score values. Both runs start with a (random) initial population (in generation 0) with a comparable score value (~ 9 %). The score value of the calibration in the left figure (a) increases faster and reaches saturation after 25 generations. The increase in the second calibration run (b) is slower combined with a larger standard deviation through the generations. Saturation is reached after 27 generations. However, in the second run (b) a better solution for the Figure of Merit was found (19 % versus 17 %). A typical pattern that can be observed is that the initial generations proceeding steady characterized by comparable large standard deviation. The standard deviation decreases increasingly and the score value is typically quite volatile. Finally we used the parameter values which were derived from calibration run presented in Figure 4-13 (b) and assigned the values to the model (see Table 4-4).

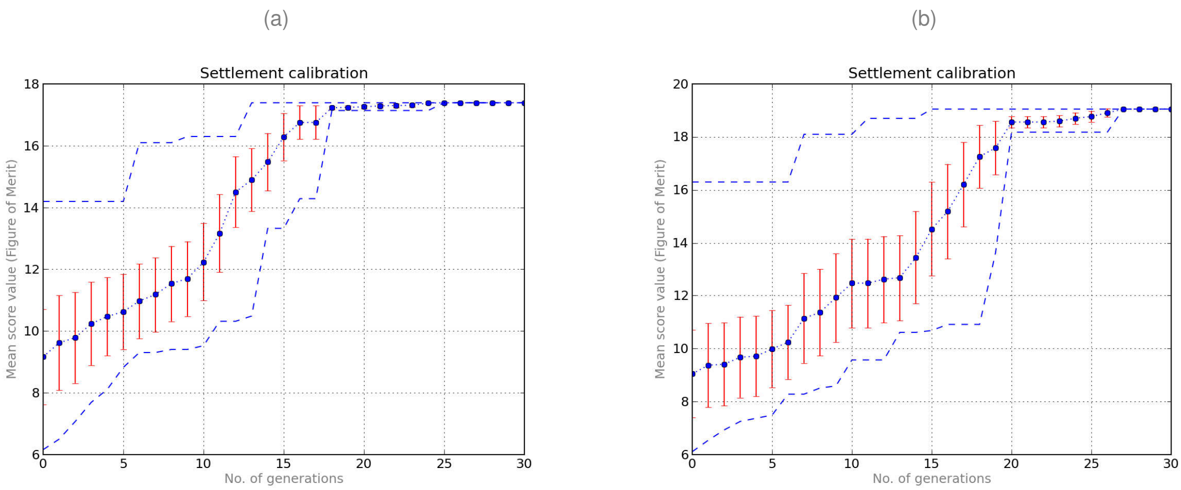


Figure 4-13. Population progression of two calibration runs for the land-use type settlement. Dots indicate the mean score values (figure of merit). Horizontal bars indicate the standard deviation. Upper blue line marks the maximum, lower blue line the minimum score value of the specific candidate solutions.

In addition to the calibration of the land-use class settlement, we tested the accuracy of the simulated inhabited area, which forms the basis for the settlement allocation and is therefore considered to have a strong influence on the score values. In this test, we compared two datasets on sub-cell level: the simulated inhabited area and the inhabited area fraction included in the independent 2006 reference map. From the results (Table 4-5) can be concluded that no significant difference among the coarse resolution (settlement cells) and finer resolution (settlement area on sub-cell level) is evident. If we would observe a large mismatch, this may indicate that the allocation threshold of the land-use type settlement (>= 50 % cell area inhabited) is not very well chosen or not properly calibrated. Alternatively, a better fit in the higher resolution data would indicate an information loss for the aggregated grid cell level.

Table 4-5. Selected accuracy measures for the performance of the settlement allocation. Quality of allocation of settlement pixels (cell level) compared to allocation of inhabitant area (sub-cell level).

Validation algorithm	Reference	Settlement cells (km²)	Inhabited area (ha)
Kappa (pixel-based)	Pontius (2000)	0.8439	0.8585
Kappa standard (moving window 3x3)	Pontius (2000)	0.86	0.8559
Kappa (location)	Pontius (2000)	0.8711	0.981
Moving window ratio (3x3)	Kuhnert et al. (2005)	0.9985	0.9965
Figure of merit	Pontius et al (2008)	0.19	0.192

Final model calibration

After the parameter values from the settlement calibration were assigned to the model, the calibration of the overall model was performed using a number of 9 sensitive parameters that were identified during the SA. Similar to the calibration of settlements, the selection of appropriate parameters, increment steps and GA settings (e.g. termination criteria, mutation rates etc.) was part of an iterative calibration process. Due to the high computing time of one calibration run (approximately 150 hours on a quad-core, 2.6 GHz, 32GB RAM) the testing could not be performed in a very extensive manner - as it was done before for the land-use type settlement.

The result for the final calibration is presented in Figure 4-14. Compared to the curves of the settlement calibration (Figure 4-13) the population progression forms a much smoother shape. The standard deviation of the score values decreases immediately after the first generations, then remains constant and decreases again in generation 23. From other simulations with more generations, we know that at latest after 30 generations the best possible solution was reached. A possible explanation for the different behaviour, compared to the settlement calibration, is that the parameter settings used here (range, increment step and default values) have already been tested in the SA, thus were chosen very carefully to avoid any unrealistic parameter constellations – keeping in mind that any error would result in days / weeks of re-computing. The final calibrated parameters are given in Table 4-4 within the sensitivity section. Finally, for the overall model a Figure of Merit value of 20.3 % could be achieved. Compared to other LULC models evaluated by Pontius et al. (2008) we can conclude that the model performance is considered as good.

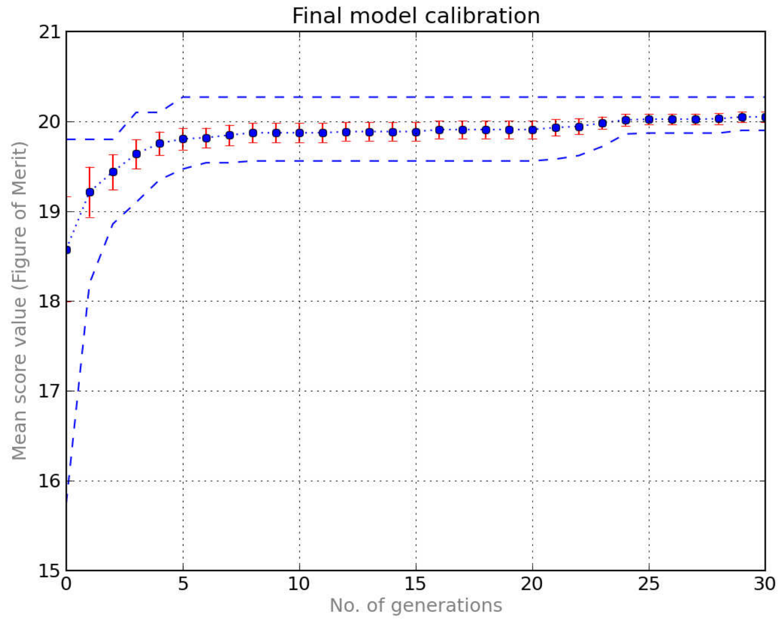


Figure 4-14. Population progression of the final calibration run.

Suitability evaluation

Besides the above described calibration and validation of the model, we tested the model with respect to the reliability of the suitability analysis, due to the fact that suitability forms a major step within the simulation process and a basic part for the land allocation. We integrated and applied the Relative Operating Characteristic (ROC) method, which is considered as an appropriate, quantitative measurement to validate and interpret LULC models (Pontius & Schneider, 2001). By evaluating actual change and actual non-change versus simulated change and simulated non-change, ROC values are extracted from two-by-two contingency tables. From the contingency tables percentage rates of 'true-positives' which are cells that are categorized as change candidates in the simulation and in reality, and 'false-positives', which are cells that do not change in reality but change in the simulated map (Pontius & Schneider, 2001) are calculated. By plotting the rate of true-positives (y-axis) against the rate of true-negatives (x-axis) a curve will generated where the area under the curve (AUC) represents the ROC statistic. In the ROC analysis, any AUC greater than 50 is considered more accurate than random. Roughly, a ROC > 75 is considered as a 'good' and > 90 as 'very good' agreement.

To perform the ROC in SITE, we divide the cells from the suitability map of interest into ten percentile groups. This is done in a way that the first group contains 10 % of suitable cells that contain the largest suitability values, the second group the next 10 % of suitable cells with the second largest suitability values and so on. Now each group is compared to the reference map (in this case the 1989 map) and results are summarized in a contingency table indicating the proportion of cells of each category that are categorized as change versus non-change in reality. Because results are very sensitive to the way the area of interest is defined (i.e. number of suitable cells, number of land-use types included), we applied the ROC for each of the relevant LULC categories separately.

In Figure 4-15 the ROC results for settlement, wheat and potato are presented. Each dot in the figure represents a percentile group of the suitability. The ROC analysis reveals that the model simulates far better than random which the dashed 1:1 line indicates. It is visible, that at least the first three suitability groups match perfectly (suitability versus reality) for all presented land use types. Settlement shows a very good performance. Wheat is better performing than potato, which can be related to the larger number of wheat cells, which makes it easier for the model to simulate certain fractions correctly. Due to this reason, a AUC of 78 % is very good for the small amount of potato cells. The high AUC value for settlement (93.58 %) is not very surprising because settlement is a very static class within the simulation period, furthermore can be mapped much more accurate by the multi criteria suitability assessment using threshold values. From the ROC test, we can conclude that SITE-Mongolia is able to represent allocation patterns via a suitability analysis in an acceptable fashion.

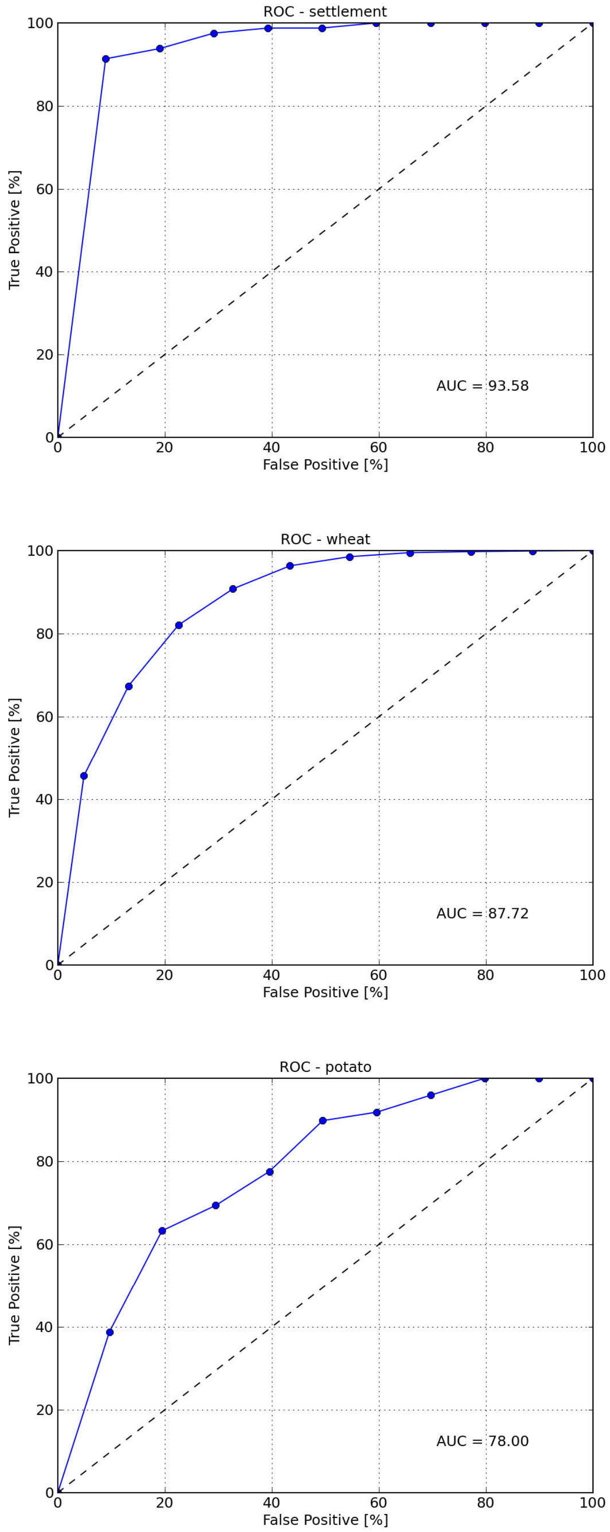


Figure 4-15. ROC analysis for settlement, wheat and potato. The dashed line represents the reference for a random allocation.

Simulated vs. reference land use and land cover

After a calibration routine produces acceptable results as mentioned above, it is necessary to crosscheck and evaluate the plausibility of the LULC pattern with respect to area distribution and spatial allocation. Table 4-6 and Figure 4-16 present the difference between the reference and simulated statistics and maps respectively.

Table 4-6. Comparison of observed versus simulated LULC for the year 2006.

LULC type	Reference (km^2)	Simulated (km^2)	Change (abs.)	Change (% rel.)	Kappa standard [1]
Settlement	83	75	-8	- 9.64	0.8
Wheat	575	495	-80	-13.91	0.5
Potato	13	11	-2	-15.38	0.4
Fallow	96	177	81	84.38	0.15
Grassland	9239	9387	148	1.60	0.66
Riparian	459	458	-1	-0.22	0.9
Closed Forest	1962	2205	243	12.39	0.64
Open Forest	2126	1747	-379	-17.83	0.5

[1] based on Pontius (2000), overall accuracy = 0.6

From the area comparison, it can be observed that fallow land was simulated with a difference of + 85 % compared to the reference map. All other categories are below +/- 20 % and settlement, grassland and riparian are below +/- 10 % compared to the reference map. It is evident that all categories below +/- 10 % are those with less or with gradual changes simulated by the model. Both crops - wheat and potato - show a difference in area of -14 % and -15 % respectively. The total difference in cropland (wheat, potato, fallow) is 55 %, which is due to the large mismatch in fallow area. A possible explanation for the difference in fallow areas is the implementation of crop rotation cycles that strictly follow a look-up table. The difference in total fallow area is inconsistent over the 17-year time-period, varying over a large range. This mainly depends on the successful replication of the initial condition. The difference in forest, + 12 % for closed forest and -18 % for open forest was one of the reasons for the implementation of the wildfire approach (see Chapter 6) and was not reflected in this (earlier) simulation which does not include the wildfire regime. As a result, larger area of closed forest and lesser open forest can be observed in the simulated map (Figure 4-16) in the eastern parts, where most of the wildfires occur. What is evident from the visual map comparison (Figure 4-16) is, that in the reference map land patterns appear far more dispersed than in the simulated map. This is a well-known problem if neighbourhood relationships are included in the suitability assessment. Either the weights and/or criteria have to be further adapted or allocation rules need to be more elaborated to avoid a ‘clumping’.

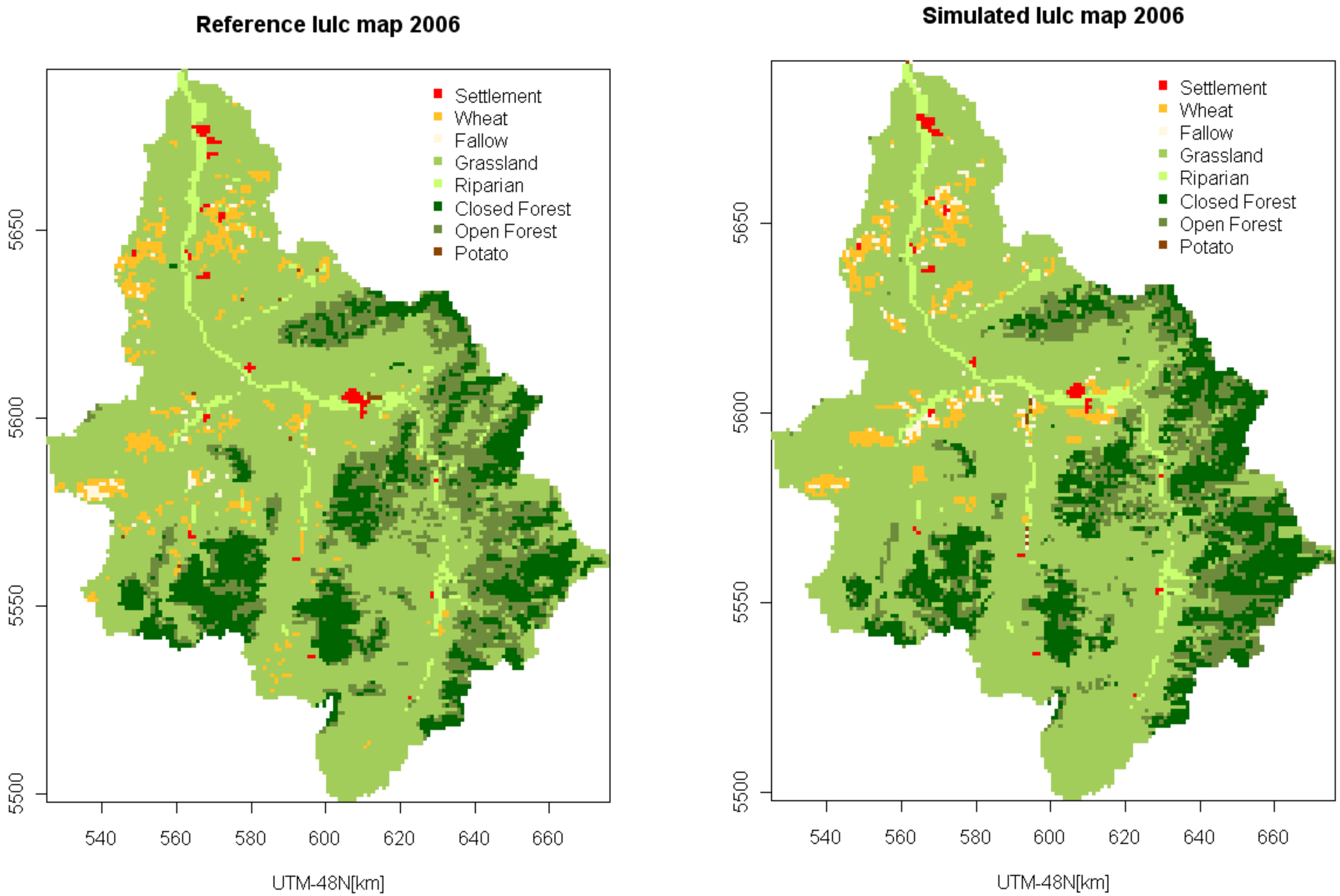


Figure 4-16. Reference and simulated land use / land cover maps for the year 2006.

Chapter 5

A case study on policy driven land-use change [2]

After two decades of decreasing agricultural activities, in 2008 the Mongolian government started the 'Third Campaign of Reclaiming Virgin Lands', aiming at massive expansion and intensification of the agricultural sector. This policy motivated the study presented here, for which we used an integrated modelling approach to investigate the feedbacks between land-use dynamics, agricultural management and biophysical conditions, with a strong focus on assessing availability of water for irrigation. Our simulation results clearly show that under the current extend of irrigated agriculture in several years water demands exceeded water availability, indicating an overexploitation of water resources, mainly in the period 1995 - 2006. Consequently, the targeted massive expansions of agricultural water use will either severely deplete water resources with potential negative effects on other users and the environment, or policies are needed to mitigate or avoid potential adverse effects. As simultaneously Mongolian authorities struggle to implement integrated water resources management (IWRM), the latter might provide monitoring concepts and regulations needed to minimise the potential gap between water demands and availability. In this context, the modelling framework could be a scientific tool to support future land and water management decisions, as researchers already started to integrate views and demands of Mongolian authorities into scenario and

[2] Edited version based on:

Priess, J.A., Schweitzer, C., Wimmer, F., Batkhishig, O., Mimler, M., 2011. The consequences of land-use change and water demands in Central Mongolia - an assessment based on regional land-use policies. Land Use Policy, 28(1), 4–10.

model development (identified during stakeholder workshops), and will continue to do so during the coming years of collaborative research.

5.1 Introduction

Mongolia's transition towards a market economy is still on its way, and in the last two decades almost every economic sector has undergone reorganisation facing the chances and challenges of globalisation. Major changes have also been observed in the most land intensive sectors livestock production, agriculture and forestry. Increasing numbers of cattle and other livestock, and increasing sedentism mostly of wealthy herding families (Fernandez-Gimenez & Batbuyan, 2004) are ongoing processes driven by incentives of living closer to attractive new markets, promising job and trade opportunities and the benefits of social and other services. The agricultural sector faced a period of abandonment of land after the communist period. Formerly state-managed farms were no longer profitable for private farmers and were partly given up. In Mongolia, the agricultural sector is constrained by short growing seasons, and extreme weather events (very cold winters and hot summers), limited water availability and the lack of financial resources for the application of agro-chemicals including fertilizers. Furthermore, most farmers can neither afford to buy irrigation equipment, nor agricultural machinery.

Recent national scale land-use policies are targeted towards a re-intensification of agricultural land use, aiming at the independence of food imports. In the ‘Third Campaign of Reclaiming Virgin Lands’ (Bayar, 2008), which is supported by credits from Russia and the Asian Development Bank, it is planned to achieve the food self-sufficiency target via cheap loans for farmers and subsidies for irrigation equipment, machinery, fertilisers and a new composition of adapted crop varieties. Simultaneously in the (gold) mining sector, highly water demanding activities can be expected to increase, as mining generates the major fraction of the government budget (NSO, 2007) and world market prices for most mining products have been strongly falling since 2007 / 2008. Furthermore, climate change is expected to bring higher temperatures resulting in increased evapotranspiration (ET) rates, and the same or slightly increased amounts of rain (Bates et al., 2008; Batimaa et al., 2005) and an overall increase in rainfall variability (IPCC, 2007). All of the policies, activities and processes mentioned above decrease water availability or increase water demands or both, resulting in challenging scientific, political and management tasks under the present and future semi-arid to arid climate conditions in Mongolia.

An appropriate methodology to analyse and quantify dynamics, interactions and impacts of various components of socio-environmental systems, is provided by the development and application of integrated land-use models (GLP, 2005). Ideally, these models enable us to analyse the complex structure of linkages and feedbacks and to determine the impact of various driving forces (Heistermann et al., 2006). Land-use models are used to project how much land is used where and for which purpose under different boundary conditions or scenarios, and conduct simulation experiments testing our understanding, e.g. of the stability of socio-environmental systems (Veldkamp & Lambin, 2001) and quantitatively describing key processes (Lambin et al., 2000). In their review Schaldach and Priess (2008) point out that even recent approaches of integrated models of the land system represent the links and feedback mechanisms between human activities and the biophysical world, and the resulting socio-environmental impacts mostly in still very simple ways. In accordance with research priorities identified by the Global Land Project (GLP, 2005), they conclude that more research efforts are needed to improve existing and develop new integrated modelling approaches.

In this chapter we study the potential consequences of recent land-use policies and policy goals in Mongolia, analysing and evaluating land-use and land-cover dynamics and impacts on intensified agriculture focusing on water demand and water use. We demonstrate the advantages of coupling models representing land- and water use in a common framework to study land-use policies and their impacts. Furthermore, we discuss new insights generated, comparing coupled and uncoupled land use – water use simulations.

5.2 Material and Methods

5.2.1 Study region

This study was carried out within the project 'Integrated Water Resources Management in Central Asia: Model Region Mongolia' (MoMo), a joint Mongolian-German project aiming at the development of sustainable management strategies adapted to a river basin with typical water related problems (e.g. contamination, over use, potential water-use conflicts). The Kharaa catchment (14,553 km²) in which the study is conducted, is located north of the capital Ulaanbaatar (Figure 5-1). Mean annual precipitation (1970 - 2000) is 250 - 320 mm, of which approximately 90 % is lost via ET. Elevation ranges from 600 to 2500 m.a.s.l. Mean annual air temperature is 0.4 °C. The major land-covers are grasslands (60 %), forests (26 %) and croplands (11 %). Short vegetation periods and restricted water availability during the growing season are main factors limiting the productivity of Mongolian agriculture (and natural vegetation). It is noteworthy that a major fraction of Mongolian agriculture is concentrated in the Kharaa catchment, although it covers only a small fraction of the Mongolian territory.

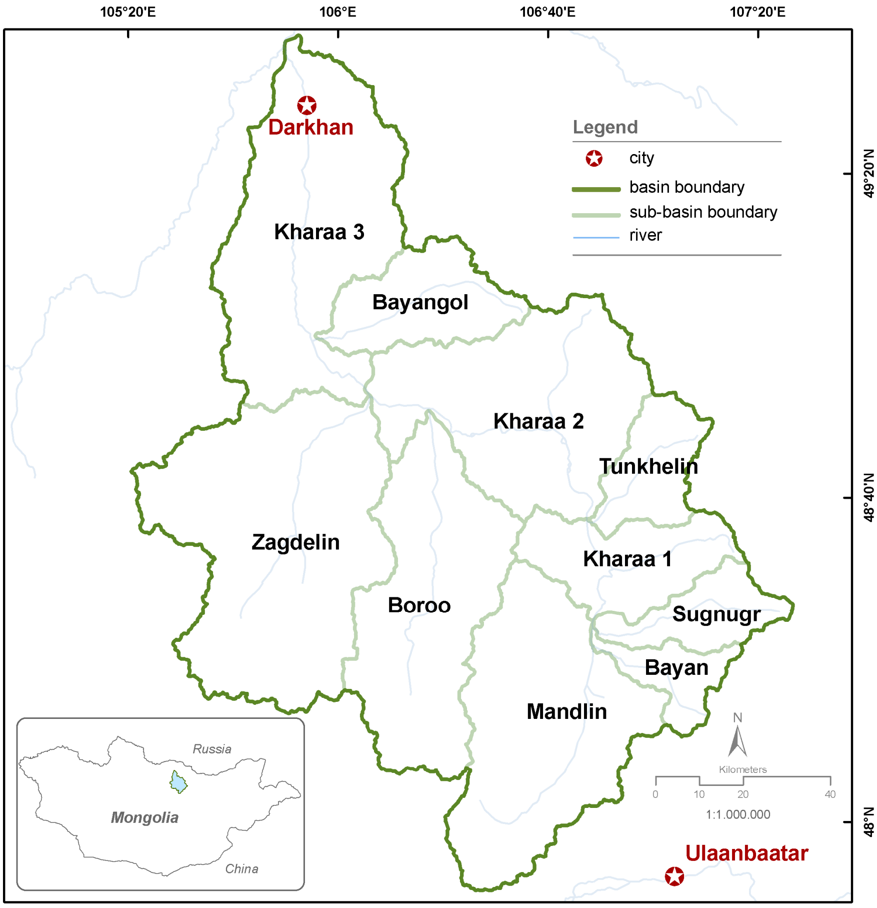


Figure 5-1. The Kharaa catchment and the ten sub-catchments.

5.2.2 SITE-framework

The SITE modelling framework has been developed over the last years as a tool to simulate regional land-use dynamics and their impacts on environmental and socio-economic parameters. SITE has been applied in several studies in Europe, Central-, South- and South-East Asia (Das et al., 2010; Mimler & Priess, 2008; Priess et al., 2007a; Priess et al., 2007b; Schweitzer & Priess, 2010). The software design of SITE follows a modular component based approach to reduce software complexity and to facilitate further development of the software, as well as the adaptation to new research questions and/or regions. The main SITE-components in this case study are:

a) the MoMo land-model to simulate land-use and land-cover dynamics, including a process based biophysical component to simulate the growth of crops and natural vegetation, and

b) the MoMo hydro-model to simulate vertical water fluxes and water redistribution.

Compared to most existing land-use modelling environments, the functionality of SITE is not confined to managing the execution of land-use models, but additionally integrates (i) interfaces to link new models to study different processes e.g. in hydrology or changes in biodiversity, and (ii) tools for simultaneous multi-model calibration and testing (via various map-comparison algorithms). SITE can easily be employed for and adapted to climatically and socio-economically very different study regions and research foci. One of the most important aspects is that the framework greatly simplifies the coupling of different models, by defining a generic interface that allows the linkage of sub models including the implementation of feedbacks between different framework components.

5.2.3 Land-use model

The MoMo land-model (SITE-Mongolia) is being developed to study regional dynamics and future scenarios with a strong focus on water resources and water use. In this case study, the biophysical environment is represented by a regular 1 km x 1 km grid. The model employs a rule-based approach, integrating spatial and statistical data from various sources, as well as knowledge and information provided by experts (Erasmi & Priess, 2007; Priess et al., 2007b). Land-use decisions are simulated once a year in three steps. The first step consists of a multi-criteria analysis based on biophysical and socio-economic parameters (e.g. slope, distances to roads and settlements, rainfall, soil fertility, crop yield), carried out for each land-use category and each pixel individually. The analysis is resulting in dynamic suitability maps, which are updated every timestep. Throughout the suitability assessment normalized values are calculated to enable direct comparison and competition between different land-use types. In the second step, land-use types are allocated (i) driven by the regional demand for commodities such as space for housing, manufacturing or agricultural products, and (ii) based on their relative suitability in a given pixel (Priess et al., 2007b). Finally, for the calculation of crop yields and plant biomass, the well established ecosystem model DayCent is used, simulating plant growth in daily timesteps (Parton et al., 1998; Parton et al., 2001). DayCent was developed to simulate soil and vegetation dynamics at the field or ecosystem scale, but has successfully been applied from regional to global scales (Del Grosso et al., 2006; Lu et al., 2001; Stehfest et al., 2007). In the SITE framework DayCent in its version 4.5 was employed, including enhanced subroutines to simulate the nitrogen cycle (Stehfest, 2005).

DayCent provides the possibility to simulate irrigation events. Options are (i) to apply a certain amount of water at a specific point in time or (ii) automatic mode, which is triggered by the fraction of plant-available soil water and kept above a predefined threshold value. We decided to trigger the irrigation events using the latter mode which is linked to the soil water deficit. In our study we simulated the common practice of irrigation for a two-month period per growing season. The auto-mode eliminates the soil water deficit if it reaches the critical state of 50 % below field capacity. The first irrigation event is simulated in late April, early

May, to reduce salt accumulation during the pre-sawing phase. The second irrigation event was scheduled July 1st, approximately in the middle of the growing period. The simulated schedule reflect current irrigation practise reported by farmers.

5.2.4 Hydrological model

The main task of the MoMo hydro-model is rainfall-runoff modelling, including the simulation of vertical water fluxes with the TRAIN model (Menzel, 1996; Menzel, 1997). The subsequent routing of lateral water fluxes was implemented in the application domain part of the SITE framework. The model estimates potential water withdrawals for irrigation from surface waters based on simulated river discharge. The latter allows setting up an innovative model coupling with the MoMo land-model, dynamically linking biophysical conditions and land management. The simulation follows a step-wise procedure: First, TRAIN computes the vertical water fluxes (e.g. ET, surface runoff and percolation rate) for all grid cells driven by meteorological data. Second, surface runoff and percolation of all cells in the watershed of individual channel reaches are aggregated. In a final step, discharge (Q) in each channel reach is calculated using a cascade of reservoirs with linear storage-discharge relationship (Maniak, 2005). Third, during the growing season (May to August) irrigation of crop cells in a sub basin is simulated if Q > Q30, with Q30 defined as mean daily discharge exceeded in 30 % of events. The actual withdrawal of irrigation water is limited to 2500 m^3d^{-1} per irrigated crop cell ($1km^2$). Withdrawals are multiplied by an efficiency factor of 0.46 (Kulkarni et al., 2006) lumping together water losses of the irrigation system. The resulting available irrigation water is accumulated and applied in two irrigation events following the same schedule as implemented in DayCent (see 5.2.3).

5.2.5 Linking land and water related processes

Figure 5-2 shows a simplified schematic diagram of the coupled modelling approach linking land and hydrological components. The amount of water available for irrigation is calculated by the MoMo hydro-model and provided to the irrigated crop cells. This information is used by the vegetation model DayCent to simulate plant biomass and crop yields. Vice versa the hydrological model receives dynamic maps of land use and land cover, as well as cells suitable for irrigation. Therefore the coupled system enables the representation of changes in catchment hydrology and dynamically calculated irrigation water availability and application. Average cultivated area is approximately 59,000 ha of which approximately 6,000 ha are irrigated. Fallows sum up to 93,000 ha. Note that the transition from socialist to market-oriented agriculture caused a considerable decrease in land-use intensity and spatial extend of agriculture during the period 1990-2006. The described trend is strongly reversed by current policies aiming at (re-)expansion and (re-)intensification of agriculture (see sections 5.1 and 5.4).

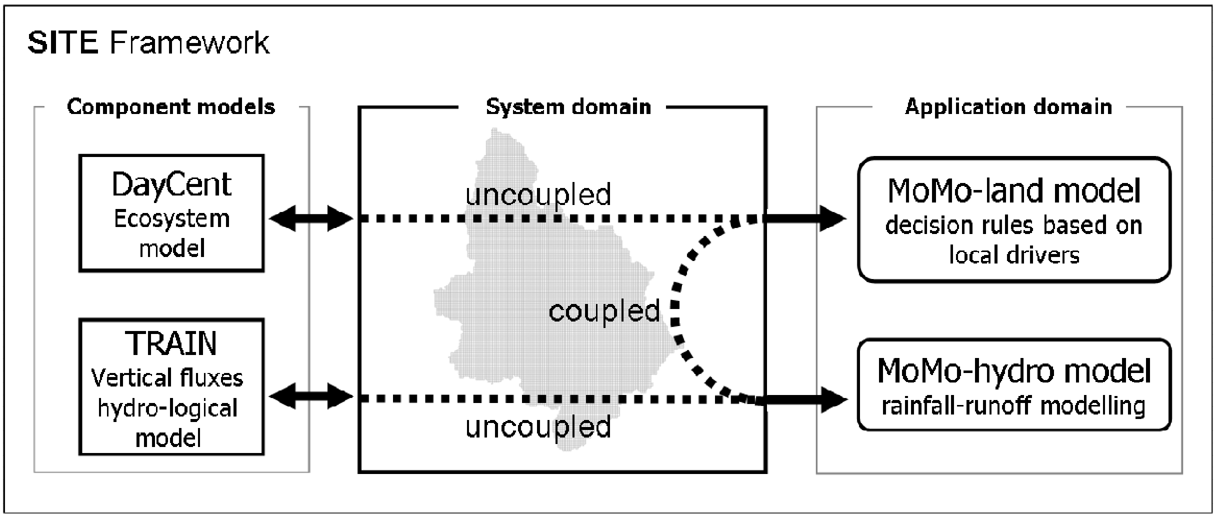


Figure 5-2. The SITE modelling system. Flow of information in the coupled version including the MoMo-hydro model and the uncoupled version.

The models used are driven by spatially explicit data. Both, the MoMo-hydro and the MoMo-land model use spatially interpolated meteorological data provided by the Institute of Meteorology and Hydrology, Ulaanbaatar (Dr. G. Davaa, pers.comm. 2007). Elevation, slope and drainage direction of the grid cells were derived from the HydroSHEDS dataset (Lehner et al., 2008). Soil properties were derived from a refined soil map of the Kharaa catchment based on a large scale soil map of Mongolia (Dorjgotov, 2003) updated with results from soil campains in 2008 and 2009 conducted by one of the authors (O.B.). Reported data of texture and organic content from soil profiles were used to estimate bulk density, hydraulic permeability and volumetric soil water content at saturation, field capacity, and permanent wilting point (AG-Boden, 1996).

5.3 Results

Agricultural yields

Yields of the main crops spring wheat and potato were reported and simulated for the period 1989 – 2006. Yields and cropped areas decreased after the end of the socialist period, during which agricultural production was strongly subsidised. Starting in 1991, decreasing fertiliser inputs were reflected in lower yield levels and production with high inter-annual variability, the latter mainly due to a strong variation in summer rains. Table 5-1 presents an overview of reported and simulated yields grown under rain fed conditions, which were comparable to yields in neighbouring districts (data not shown here).

Table 5-1. Rainfed crop yields in the Kharaa catchment 1989 – 2006 (Mg/ha^{-1}).

Period	Wheat yields		Potato yields	
	Reported	Simulated	Reported	Simulated
1989 - 1991	1.2	1.1	11.9	10.9
1992 - 1994	1.1	1.2	8.8	10.3
1995 - 1997	0.8	0.8	9.4	7.9
1998 - 2000	0.7	1.0	8.7	8.5
2001 - 2003	0.6	0.6	7.5	6.5
2004 - 2006	0.9	0.8	8.7	8.7

Agricultural land under production decreased considerably between 1990 and 2006. In the period 2003 - 2006 reported here, approximately 3/4 of the 135,000 ha of agricultural land were under fallow, while only ~35,000 ha were cultivated, mostly located in the floodplains around villages and cities (Figure 5-3). In the simulations on average, 5,600 ha were irrigated, the spatial extent in dry years increasing up ~20,000 ha. In Figure 5-3 all grid cells irrigated at least once during the simulated period 1989 – 2006 are presented (light blue). Validation and plausibility tests of simulated cropland and irrigated land using GlobCover (Bicheron et al., 2008) and IWMI (Thenkabail et al., 2008) global data products are presented in the next paragraph.

Sustainable and unsustainable irrigation

In order to analyse the potential new insights generated by the coupled modelling system, average crop yields were calculated in coupled (irrigation limited by water availability) and uncoupled (unlimited irrigation) simulation runs and compared on sub-basin scale. Figure 5-4 shows the overestimation of wheat and potato yields by the uncoupled version in comparison to the coupled as reference. In the more intensively used agricultural areas (e.g. Mandlin, Zagdelin, Kharaa2) yields achieved with unlimited irrigation were up to 9 % higher for wheat and up to 15 % for potato. This can be explained by the low discharge within these river tributaries. Contrastingly, in downstream areas (Kharaa3, Bayangol) river discharge accumulates. Hence, the gap between simulated water availability and demand is almost closed, which is mirrored in low calculated crop yield differences with and without water limitation. Due to the absence of irrigated areas in the eastern sub-basins (Bayan, Sugnugr, Kharaa1, Tunkhelin), where runoff rates are high, no increase in yield levels was observed.

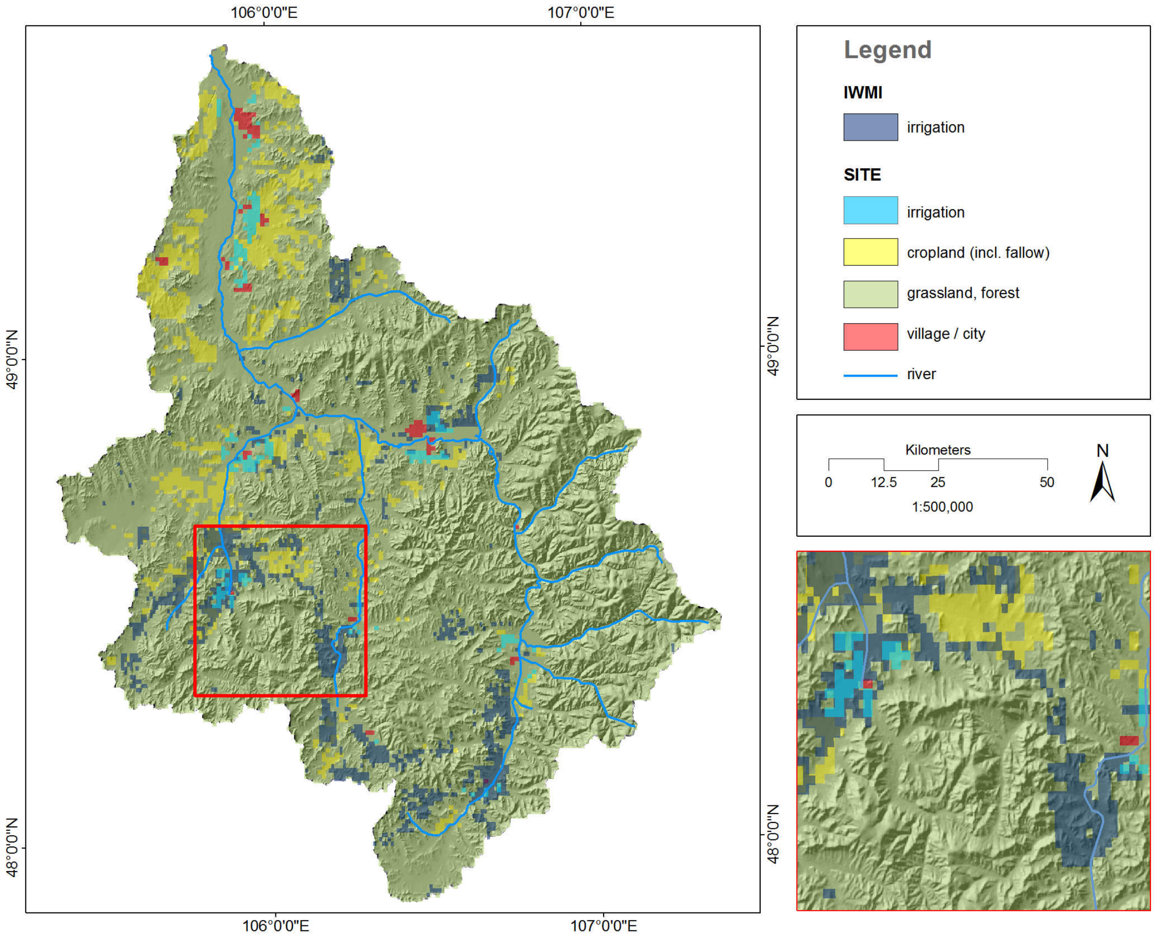


Figure 5-3. Land use and irrigated areas. Land use and land cover simulated for the year 2006 have been aggregated to the classes cropland (yellow: including fallow land), grassland and forest (green) and built up land (red: urban & rural settlements). Simulated irrigated cropland (light blue: comprising all grid cells irrigated at least once during the simulation period 1989 – 2006) and irrigated cropland from the Global Irrigated Area Map (GIAM v 2.0) by IWMI (dark blue). Note that considerable fractions of the GIAM-estimates are located on slopes and ridges (see map detail on the right side).

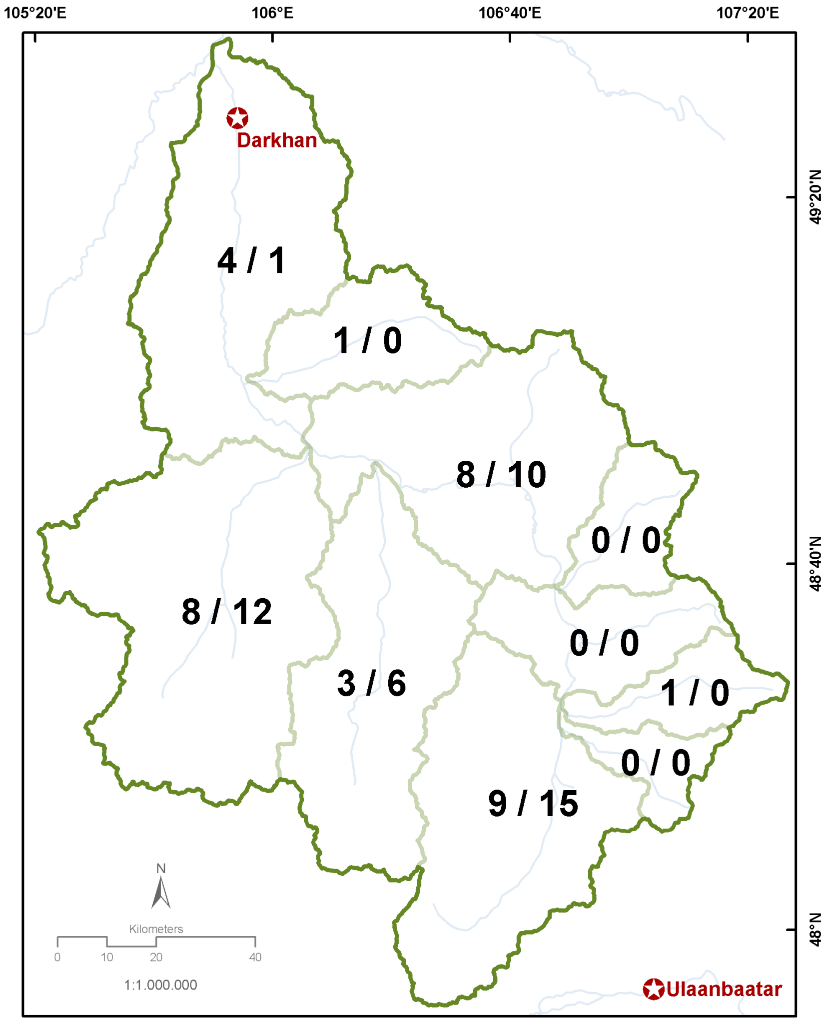


Figure 5-4. Simulated crop yields under water limited and unconstrained conditions. Sustainable (water limited) production is used as reference. First number: overestimation of wheat yields, second number: overestimation of potato yields in percent.

In Figure 5-5 water demand versus availability is presented. In the years 1990, 1992, 1993 and 1994 demands for irrigation water could be satisfied. In fact, availability clearly exceeded agricultural demands. Apparently related to a strong decline in measured river discharge starting in 1995, less than 50 % of the simulated demand could be fulfilled during the second half of the period (without depleting water resources). This can be explained by an increase in potential ET due to higher summer temperatures and lower air humidity. Additionally, even though total annual precipitation does not show a significant trend, winter snowfall tended to increase, while rainfall in summer decreased. These changes in precipitation pattern lead to higher evaporation rates from snow and therefore to less runoff generation (results not presented here).

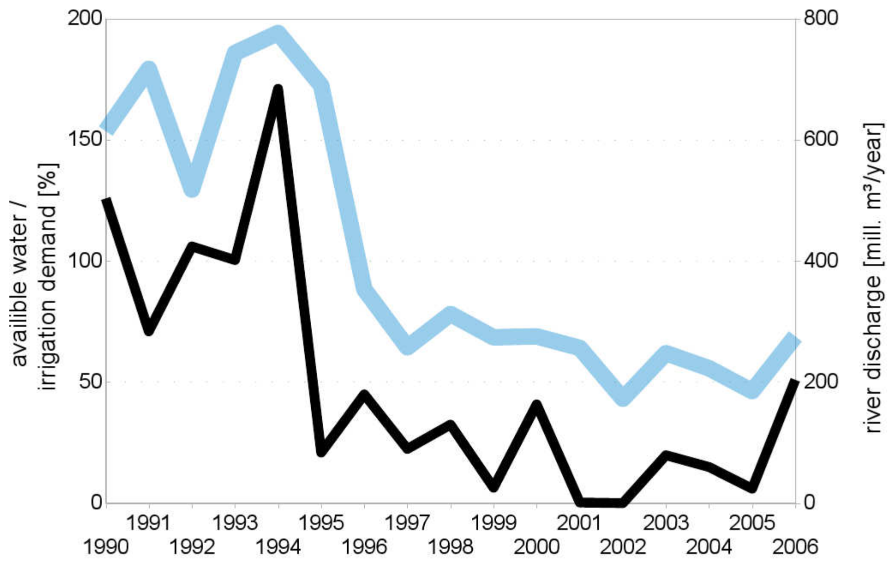


Figure 5-5. Ratio of water available for irrigation to irrigation demand and measured river discharge. Narrow line, left axis: ratio of availability and demand (relevant for the coupled = water limited simulation); wide line, right axis: river discharge.

Figure 5-5 shows the ratio of water available for irrigation to irrigation demand, simulated by the MoMo-hydro model. For illustration, measured river discharge is presented. If crop yields are among other factors limited by the availability of water, the agricultural area needed to produce the same amount of crop is larger under water limited conditions. In our simulation study the known amount of crops produced in the period 1990 - 2006 was simulated both in the coupled (water limited) and uncoupled runs. The demand for agricultural area was on average 10 % (~ 6000 ha) higher in the coupled (often water limited) version, corresponding to the differences in yield levels shown in Figure 5-4.

Test of simulation results

This paragraph presents a comparison of simulated results versus the most recent (i) land-cover dataset GlobCover and (ii) a map of irrigated areas released by IWMI to test and potentially validate the results presented above. As no independent Mongolia-specific land-cover data were available, we compared our results against the most recent global dataset GlobCover covering the period 2005 - 2006. As a first step we aggregated land cover / land use classes in both datasets to increase compatibility between the two classification systems. For the year 2006, 7,650 of 14,408 pixels matched the corresponding categories. The best fitting classes (GlobCover vs. simulated) were forests (95 %) and grasslands (67 %), while croplands matched only 19 % of the simulated map. However, the simulated cropland extent of ~36,000 ha (~135,000 ha including fallow land) corresponds much better to values from regional statistics of ~27,000 ha than GlobCover estimates of 532,500 ha. In the study region, croplands are located mainly in flat valleys and floodplains, nowadays mostly close to villages and cities (see Figure 5-3. Note that many locations of agricultural fields were GPS-measured by the authors during several field trips between 2006 and 2009. The authors collected data for the validation of the classification of a LANDSAT scene of 1989, which we used as the base map).

The croplands of the GlobCover map, which were found to be fourfold larger (532,500 ha) than simulated croplands including fallows, were mainly overlapping with the land cover classified as grasslands in our study. Plausibility tests revealed that SITE (96 %) and GlobCover (84 %) correctly allocated the majority of croplands below 1200 m a.s.l., below which currently most of the crops are cultivated. However, 54 % of GlobCover croplands are from our perspective misallocated on slopes between 3 and 18 % steepness, values clearly too high for Mongolian conditions (see Figure 5-6 and Figure 5-7). SITE allocated 82 % of cropland on terrain with up to 3 % slope. To summarise, we can state that the simulated croplands are plausible with respect to extent and allocation, but cannot be validated with satellite-based global datasets like GlobCover, which have not been regionally tested (or improved) with ground data.

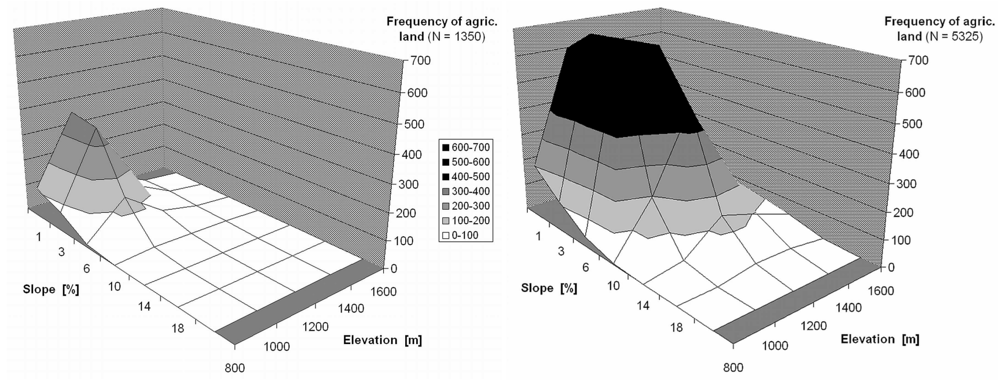


Figure 5-6. Allocation of agricultural land. Frequency distribution of agricultural land in elevation and slope classes. Pixel or grid cells represent 1 km². Left image: distribution of agricultural land simulated by SITE for 2006. Right image: distribution of agricultural land from the GlobCover dataset.

Similarly, we compared and tested irrigated areas simulated by SITE and reported by IWMI. From Figure 5-3 it is obvious that the IWMI-map allocates a considerable fraction of irrigated cropland on slopes and mountains, locations usually un-feasible for irrigation. The second reason for the, from our perspective, large overestimate of irrigated land by IWMI could be related to the fact that their estimate is partly based on remote sensing products of 1 km (nominally 10 km) resolution of the late 1990ies, and on among other sources the only available, but outdated statistical information from the 1980ies and 1990ies also used in AQUASTAT (FAO, 2009a). Contrastingly, most irrigated grid cells (83 %) simulated by SITE in the period 1989 – 2006 were located on slopes less than 3 % and 99 % on terrain lower than 1200 m a.s.l. In Figure 5-7 we present the plausibility test for irrigated areas, again using the criteria elevation and slope. Note that the area potentially suitable for irrigation estimated by the SITE model (Figure 5-7, left image) is similar in extent than the IWMI map (right image in Figure 5-7), but strongly differs in location.

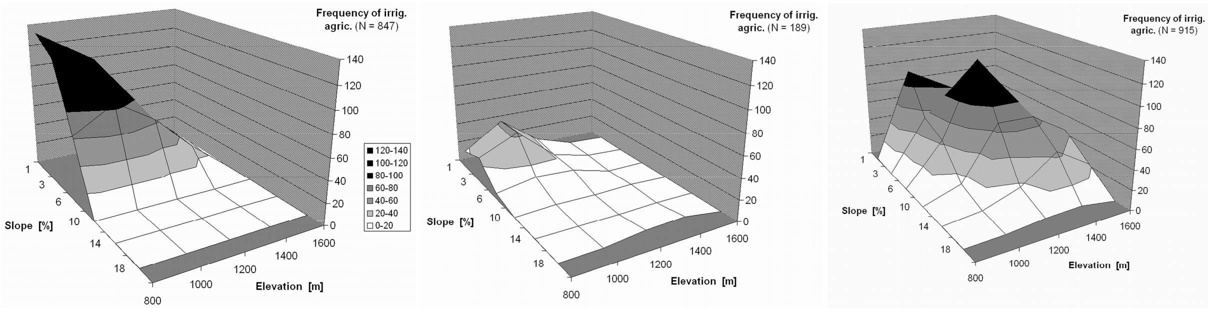


Figure 5-7. Allocation of irrigated land. Frequency distribution of irrigated land in elevation and slope classes. Pixel or grid cells represent 1 km². Left image: distribution of land suitable for irrigation; central image: irrigated land 1990-2006, both simulated by SITE. Right image: distribution of irrigated land from the IWMI dataset.

5.4 Discussion

Recently, the third campaign of land reclamation was launched in Mongolia, aiming to decrease food imports via (re-)intensification of agricultural land use (Badrakh, 2008; Bayar, 2008). This policy has two major consequences. Firstly, since 2008 agricultural areas were increased by 50,000 ha (for the whole country), converting and ploughing natural vegetation (mainly grasslands) and given up land or fallows to agricultural lands (Bulgamaa, 2008). Secondly, the agricultural sector will severely increase the use of already scarce water resources, motivated by subsidised water fees, irrigation equipment and cheap loans (Hantulga, 2009). Consequently, the competition for water, e.g. between water users of different sectors such as households, industry, mining and agriculture is increasing. Comparable developments have been reported from other parts of Asia and Africa, although the importance of economic sectors as water users varies considerably between regions (Batchelor et al., 2003; Kluge et al., 2008; Ngigi et al., 2007). Land- and water use dynamics and the policy process described above motivated the assessment of spatial and temporal variations and seasonal dynamics of water demand and availability, which are presented in this chapter. The set of models coupled in the SITE framework enabled us to assess the potentials and limits of irrigated agriculture via simulating the feedback mechanisms between hydrology (i.e. water availability) and land use (spatial extend, management and crop yields of irrigated crops).

Our results clearly demonstrate the need for and the advantages of approaches, which are sensitive to the regional hydrological variability and allow more realistic estimates of sustainably attainable crop yields. The term sustainable in this context is referring to a management strategy taking limitations in water availability into account, thus avoiding overexploiting water resources (other aspects of sustainability such as social or economic factors are not considered here). Contrastingly, the uncoupled model version only takes into account the irrigation water needed to keep soil moisture above a certain level to maximise plant production, assuming unlimited availability of surface and / or groundwater resources. The latter is representing the present situation in Mongolia. Currently two competing policies are on the way, severely affecting land- and water use, namely agricultural expansion and intensification and implementation of integrated water resources management (IWRM). Firstly, based on the 'Third Campaign of Reclaiming Virgin Lands' (Bayar, 2008), which is supported by a 300 Mio. US$ credit from Russia (Hantulga, 2009), the Mongolian government started in 2008 to convert additional 50,000 ha to agricultural land. To a great extend, suitable land to be converted is located in the research area, the Kharaa basin and the neighbouring Selenge and Tuul basin. As a consequence, the agricultural area will increase approximately 50 – 100 % (depending on whether fallows are included in the calculation or not). We have shown that even under the current extend of agricultural land use; water demands may considerably exceed availability. Thus, even if more efficient (subsidised) irrigation technologies are installed, the demand for water is expected to drastically increase from 2009 onwards. Our results clearly indicate that in the short term it is possible to produce more crops at the cost of depleting (ground-) water resources and / or reducing water availability for downstream users. The effects described above have repeatedly been reported from locations around the globe, and are expected to aggravate in many arid and semi-arid regions due to Climate Change (Bates et al., 2008). It has been argued that comprehensive policies combining land-use planning and integrated water resources management should be able to avoid or solve these problems (Mitchell, 2005). Thus, to assess whether water demands exceed availability, and to ensure long-term resource availability without negative ecological and economic impacts, appropriate monitoring and governance structures are urgently needed. To date, neither the monitoring concepts nor the governance structures, nor rules or regulations are in place to adequately manage water use. However, the Mongolian government currently undertakes multiple efforts to establish regulations and administrative units for a catchment based integrated water management (the second policy affecting land- and water use). These efforts are involving ministries, the National Water Agency and national research institutions as well as various international partners (Badrakh - Water Authority, 2008; R. Mijidorj - National Academy of Science, 2008, pers. comm.).

Simultaneously, recent government assessments of the national water resources documented multiple reductions or complete disappearances of wells and creeks within the last years. Whether the observed changes are caused by climatic factors or human use or a combination of both remains unresolved (Batsukh et al., 2008). Based on historical and current water use and technology, it is obvious from our results that water availability in the catchment might limit sustainable water supply of the targeted additional 50,000 ha of agricultural land (Bulgamaa, 2008), even if we conservatively assume that the fraction of irrigated land remains at the current level of approximately 10 %. The current often almost open access like situation provides little incentives for behavioural changes or the introduction of (costly) water saving technologies. As actual water consumption in agriculture, mining and households faces little or no control at all. Neither the ratio of surface to groundwater use, nor the volume of groundwater available in the catchment is known, and therefore it is currently impossible to predict the immediate and long-term negative consequences of overexploiting the water resources. Besides estimates of current and potential water use, clear rules are needed how water resources can be used, including mechanisms of control and enforcement, a task of the River Basin Organizations (RBOs), which are currently being established. RBO-establishment is considered an important step in the implementation of integrated river basin management (IRBM), as a tool of IWRM. In addition, incentives for water saving behaviour and technologies could help minimise the potential gap between water demands and availability, not only in the agricultural sector discussed in this paper, but just as well in the mining sector, in industries, households and other relevant sectors.

The integrated modelling approach presented in this paper clearly resembles the benefits of the SITE framework's flexible and open IT design. From the viewpoint of integrated modelling, the obvious discrepancy between water demand and availability occurring already in several years before the 2008 agricultural expansion, demonstrates the added value of a framework facilitating the coupling and simulation of important feedbacks of land systems, providing scientific insights as well as information relevant for practitioners such as RBOs at the catchment scale, or the Water Authority at the national scale.

The threshold value to determine water availability (Q30 in this case study) is strongly related to management strategies and legal regulations of surface water abstraction. The lower the threshold value, the higher is the potential risk of unsustainable water withdrawals. A potential future application of the modelling approach is to assess adequate threshold values as a trade off between ecological and economical needs, based on policy goals, or regulations of the Mongolian water authority or RBOs.

The advantage of a coupled approach, as presented here is that it attempts to provide dynamically linked estimation of water availability. The authors as part of a larger team, already started to integrate views and demands of Mongolian authorities into scenario and model development (identified during stakeholder workshops), and will continue to do so during the coming years of collaborative research. Hence, the modelling framework could be a scientific tool to support future land and water management decisions based on the analysis and comparison of alternative policy scenarios.

Chapter 6

Linking wildfire behaviour and land-use modelling [3]

Numerous approaches of modelling wildfires have been published covering the regime itself, ignition probabilities, spreading patterns, risks and impacts. However, there is less research linking these validated mature approaches to dynamics of the terrestrial environment. We contribute to filling this gap via integrating wildfire component into the land-use model SITE-Mongolia, enabling us to include wildfire impacts in dynamic simulations of socio-environmental systems. In the forest-steppe region of Northern Mongolia, wildfires are a major concern, threatening grassland and forest ecosystems, which are already under pressure of droughts, heavy grazing, (illegal) logging and increasing firewood demand. We employ the generic land-use modelling framework SITE, that includes the ecosystem model DayCent and other components, to develop a wildfire component for simulating wildfire spread and intensity. Outputs are translated into net loss of biomass, changes in carbon and returns of nutrients. Burning and carbon cycling affect biomass and thus fuel load and wildfire risk in subsequent years. Our study presents results of a coupled land-use-wildfire modelling approach aiming at (i) increasing the model accuracy in land allocation and potential land usability, and (ii) to a more adequate impact analysis based on potentially fire-affected land.

[3] Edited version based on:
Schweitzer C., Priess, J.A. , 2010. Linking wildfire behaviour and land-use modelling in Northern Mongolia. Proceedings of the 2010 International Congress on Environmental Modelling and Software, Modelling for Environments Sake, Ottawa, Canada.

6.1 Introduction

Wildfire is a paradox; it kills plants and animals and can cause wide-ranging damages to the ecosystem. On the other hand it can be very beneficial in terms of nutrient recycling and forest regeneration (Rowell & Moore, 1999). In some areas, natural wildfires have historically adapted with ecologically positive effects. Other ecosystems are susceptible to severe damages, causing a local extinction of species or considerable changes in ecosystem functions (e.g. fuel wood, recreation). Integrated modelling approaches could offer helpful insights in wildfire-environmental interactions. Globally, the majority of wildfires are caused by human activities in a direct or indirect manner. An anthropogenic influenced wildfire regime (frequency and distribution) will potentially affect human acting. This inter-relationship between humans and wildfires has motivated many scientific studies. Millington et al. (2008) mention in their study, presenting an agent based approach simulated land-use management influencing wildfire risk, that only a few models exist who consider human activities and the interactions with vegetation-wildfire dynamics. This chapter presents results from a modelling approach which captures the wildfire behaviour in the Kharaa river basin in Northern Mongolia. The approach aims at analysing impacts of wildfires on the socio-environment, including feedbacks related to carbon dynamics, biomass availability (in forests and grasslands) and the effects on land use. Therefore we developed a wildfire component on the basis of a well established wildfire model and linked it to our spatial explicit land-use model SITE-Mongolia integrating new model capabilities - simulating wildfire spread and intensity. In the following sections we present the general design of our approach including first results from wildfire risk and wildfire behaviour simulations, including impacts on biomass availability and forest use.

6.2 Wildfire situation

As living in Mongolia is very much dependent on the biophysical environment, the country is extremely vulnerable to natural disasters. Cold winters and hot summers marked by droughts and floods frequently set the environment, people and the economy under pressure. Additionally, wildfires threaten forests and grasslands which have a high ecological and economic value for the country as they provide firewood or grazing opportunities for the omnipresent nomadic lifestyle.

In Mongolia grasslands cover 83 % and forests 12 % of the country's territory (Tsogtbaatar, 2002). From the latter (17.5 million ha), around 4 million ha are considered as disturbed to varying degrees, 95 % by wildfires and the rest by logging activities and forest calamities. Between 1940 and 2002 annually 396,000 ha were affected by forest fires and since 1980 about 100,000 ha by insects and pests (Goldammer, 2007). The highest risk is present in the northern sub-montane areas mostly on seasonally frozen soils or permafrost. However, the majority of wildfires occur in the central and eastern parts of the country, correlated with the occurrence of highly flammable pine and larch stands (Goldammer, 2007). Two major wildfire seasons can be distinguished in Mongolia, one from March to mid June and another from September to October. 80 % of the wildfires occur in the first (spring) and up to 8 % in autumn (Goldammer, 2001). In between only a few fires occur due to the summer peak in rainfall. The causes of wildfires are quite diverse (Tsogtbaatar, 2002). Natural causes (lightning) are most common in the mountainous forest belt. Tsogtbaatar (2004) gives the main causes for wildfires in Mongolia, which are escaped camp fires, forest clearing, sparks from chimneys, smoking, transport and the presence of people who are collecting antlers, berries and nuts in the forest. Usually, after a wildfire, causes remain unclear due the occurrence in remote locations. However, it can be concluded that lightning as a cause in the aforementioned fire seasons can be neglected.

This study was carried out in the Kharaa river basin (105°15'E, 48°41'N) which is located in the forest-steppe region of Northern Mongolia, approximately 30 kilometres north of the capital Ulaanbaatar. The climate is semi-arid, characterized by a mean annual precipitation of 250-300 mm and a mean annual temperature of -0.4 °C. The total area is 14,553 km², covered 60 % by grassland, 26 % by forest and 11 % by arable land. Population trend is increasing due to the vicinity of the capitol, promising trade and job opportunities. Nearly half of the population (70,000 in 2006) could be characterized as rural, living a 'modern' nomadic lifestyle. For them grazing opportunities and firewood are essential environmental goods. Besides providing wood for cooking, heating and construction, forests have an important hydrological function as they are covering the headwater regions, which provide the whole basin with freshwater.

To study the disturbances by wildfires in forest and grasslands, we analysed the historical wildfire regimes using a satellite approach based on the 'MODIS Collection 5 Burned Area Product - MCD45' (henceforth, MODIS burned area) (Roy et al., 2008), which detects the approximate day of burning at a spatial resolution of 500 meters since the year 2000. Figure 6-1 shows the total annual area burned (a) and the wildfire seasonality for the observation period 2001 to 2008 (b). Over the time period 2006 - 2008 the occurrence of wildfires has increased considerably in the forest areas. Within the observed period, 2.7 % (40,600 ha) of the Kharaa river basin was affected by wildfires, 60 % occurred in forest areas and 40 % in the grassland steppe region. The seasonality of wildfires (b) shows the clear pattern of two wildfire seasons, spring and autumn, which is reported as a typical phenomena observed in Mongolia (Goldammer, 2001). Figure 6-2 presents an overview of the spatial occurrence of wildfires for the respective time period. It should be mentioned that the largest burnt areas are visible in the northeastern parts, outside the basin. This particular area is part of the strictly protected Khentii mountain range. In general it is evident that the more rugged the terrain, the more affected it is.

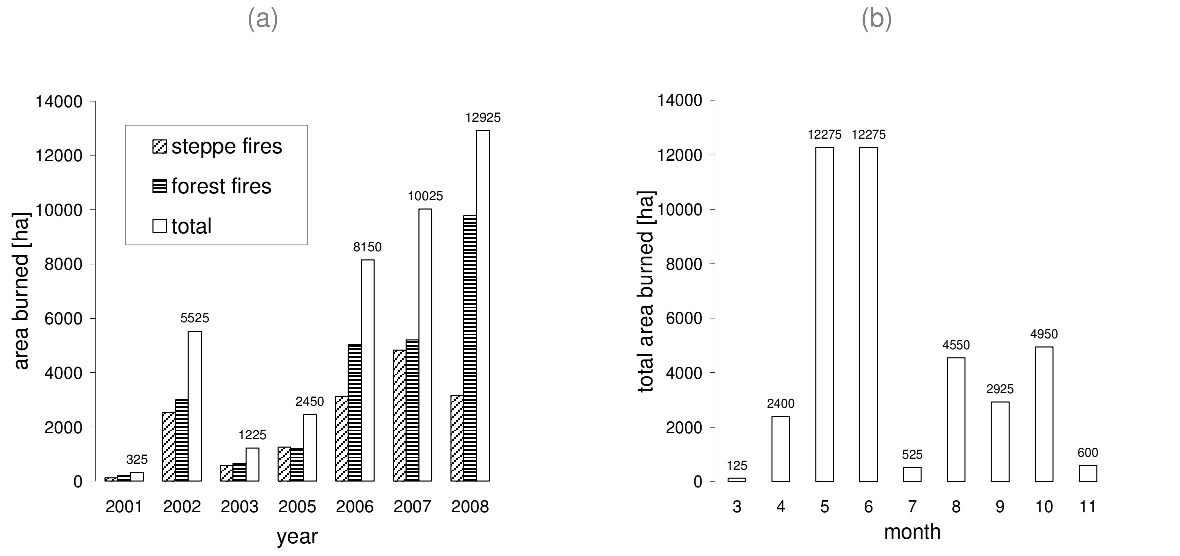


Figure 6-1. Area burned (a) and wildfire seasonality (b) extracted for the period 2001 – 2008 from MODIS data. Note: 2004 was not considered due to the absence of wildfire scars.

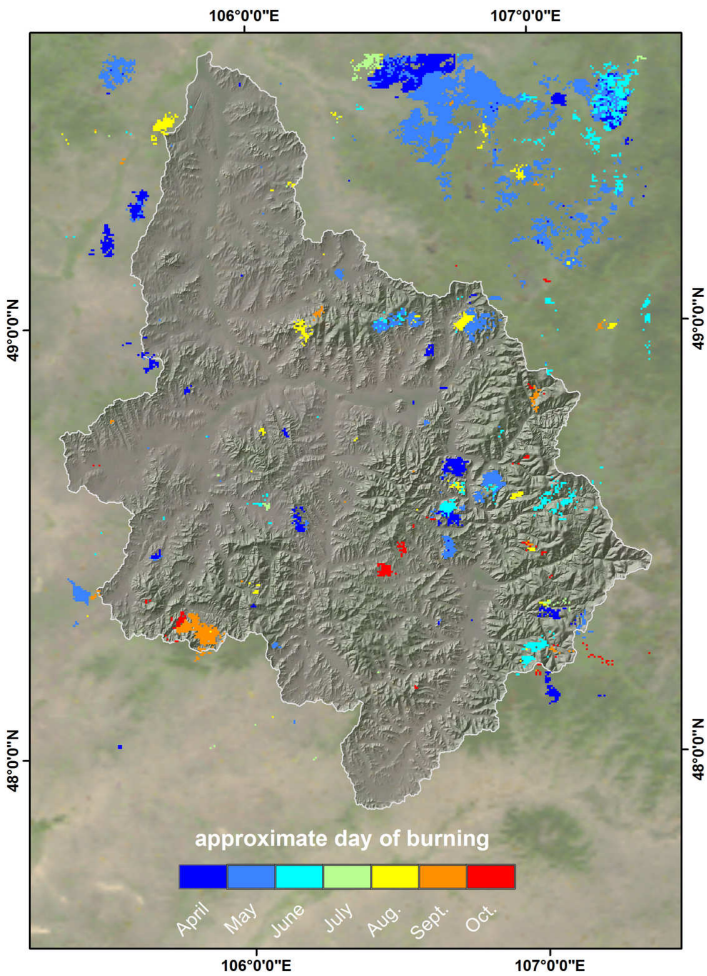


Figure 6-2. Spatial and inter-annual distribution of wildfire scars observed by MODIS from 2001 to 2008.

6.3 Data and methods

The simulation of wildfire behaviour is depending on various, and sometimes uncertain factors such as fuel availability, fuel moisture, weather, and ignition probability. Due to the fact, that the land-use model itself offers a high level of complexity, the challenge was to implement an accurate and efficient (in terms of computing time) spatially explicit wildfire spread model, and link its outputs to the process based ecosystem model DayCent. The core components are presented in the following paragraph, emphasising the wildfire component and its data requirements.

6.3.1 Land-use model

As a platform for model integration and development, we use the SITE-Framework (SImulation of Terrestrial Environments), a generic modelling platform for spatially explicit land-use modelling (Mimler & Priess, 2008; Schweitzer et al., 2011). The regional land-use model (SITE-Mongolia) was developed inside of this framework with the objective to study the dynamics of historical, current and future land-use and land-cover changes including the impacts on water resources (Priess et al., 2011). Simulations are performed on a 1 km x 1 km grid, allocating land-use decisions annually following a three-step process. First, a multi-criteria analysis is carried out for each land-use class and each pixel individually, calculating dynamic suitability maps for each time-step. The resulting normalized weighted values enable a direct comparison and competition between land categories. In the second step, sub-modules are executed (e.g. settlement, crop, forest, grassland) computing land allocation driven by the demand for commodities, space for housing or agricultural products. Finally, the linked ecosystem model DayCent (Parton et al., 1998) computes daily plant growth and calculates yield, biomass and carbon feedbacks in cropping systems, grasslands and forests.

6.3.2 Wildfire component

A new wildfire component (BURN) was developed and integrated in addition to the existing components and sub-modules of SITE-Mongolia. The major aim was to simulate the wildfire behaviour in Northern Mongolia to be able analysing important feedbacks of the socio-environment. The simulation of fire propagation is based on a spreading algorithm first described by Rothermel (1972), which is based on a semi-empirical mathematical approach. In our study we used a modified version of this algorithm which is derived from the BEHAVE fire model (Andrews, 1986) and encapsulated in a C-library called 'firelib' that was optimized for highly iterative cell-based fire growth simulations (Bevins, 1996). Technically, we use the open source software SAGA-GIS (Conrad, 2007), which includes a wrapper module that executes the firelib routines. By the use of the Application Programming Interface (API) of

SAGA we were able to execute the fire simulation through SAGA-GIS directly from our application domain (Python interface). Furthermore we linked a wind model to simulate wind fields (consisting of wind speed and direction) in a spatially explicit manner using the WindNinja model (Forthofer et al., 2009).

In SITE-Mongolia the wildfire component BURN consists of several parts: (i) a file 'handler' which executes the third-party applications (e.g. SAGA-GIS, WindNinja) and performs necessary pre- and post-processing steps, (ii) the 'risk analysis' sub-module, which does a multi-criteria analysis to identify the cells which are most susceptible to burn, (iii) the WindNinja model itself to simulate wind speed and direction for each grid cell, and (iv) the wildfire model, including the routines for predicting the spread rate and intensity of free-burning wildfires. To establish the link to the DayCent model, simulated wildfire intensity and flame length were translated into net change of forest biomass using a look-up table. Figure 6-3 presents a simplified scheme of the modified SITE-Mongolia model. BURN is executed first, calculating wildfire risk maps and then wildfire behaviour for the respective simulation year. Within the suitability analysis (SUIT) burned cells were identified and excluded from the grassland and forest-use suitability calculations. Note that alteration of biomass availability is influencing wildfire risk, fuel availability, fuel moisture and affect land-use decisions in subsequent years. Thus by simulating wildfire events an important new feedback mechanism was included in the SITE-Mongolia model.

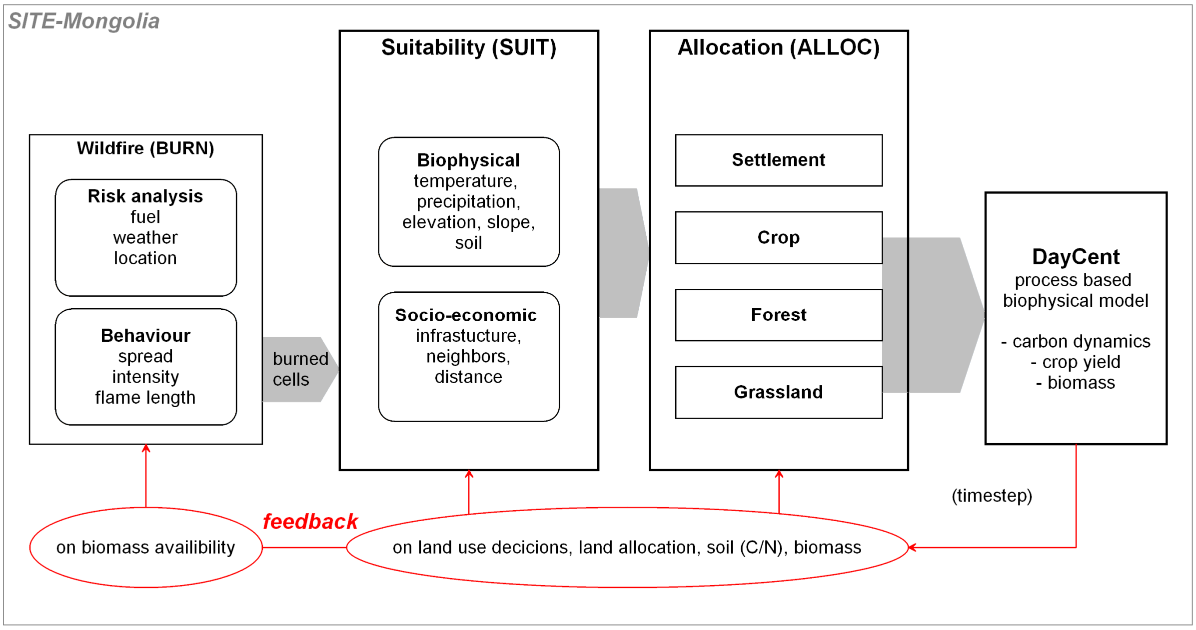


Figure 6-3. Simplified model overview demonstrating the flow of information with the wildfire component.

6.3.3 Input data

As mentioned above, wildfire modelling is largely dependent on detailed input data to reflect the environmental conditions for starting and propagation of wildfires. In the following subsections, we describe the input data required by the wildfire component to be able to simulate wildfire behaviour using the firelib.

Topography

An important factor influencing the direction and speed of the wildfire spread is the terrain (slope and aspect). Different combinations of wind direction and speed together with different slopes result in the fire propagation exposing potential fuel to additional convective and radiant heat (Rothermel, 1972). In this study, we use elevation, slope and aspect to characterize the terrain.

Fuel model

The ‘Fuel Model’ (FM) provides an abstract description of the fuel availability in selected land cover types. Each FM represents a mathematical function that predicts spread and intensity. A numerical value is linked to one of the 13 predefined FMs. Each FM is characterized by the fuel loading for each particle, diameter size class, the surface-area-to volume ratio, the fuel bed depth, the heat content and the moisture of extinction (Bevins, 1996). The FMs which have been used in this study are: ‘Short Grass (0.3 m)’, ‘Tall Grass (0.76 m)’ and ’Timber (grass & understory)’.

Fuel moisture

Fuel moisture determines if a certain fuel type will burn, rate of burning and phases of combustion supported by it. Fuel moisture is a key factor influencing wildfire propagation and assessing wildfire risk (Chuvieco et al., 2003). During periods of high humidity and precipitation there is a net gain in fuel moisture while in dry periods fuels transpire more moisture than they receive. Fuel Moisture Content (FMC) is defined as percentage water content, based on the oven dry weight of the fuel (Britton et al., 1973). In the model, five input maps consisting of three dead and two live fuel moisture classes describe FMC. Dead fuel moisture is classified by a ‘time-lag’, which reflects the time taken by fuels responding to a specified amount to changes in moisture, which is correlated to the burning materials diameter. The dead fuel types of the model are ‘1-hour’ (ø < 0.6 cm), 10-hour (ø =0.6-2.5 cm) and 100-hour fuels (ø = 2.5-7.6 cm) respectively. The two live categories represent FMC in herbaceous and woody components. Due to the short reaction time of the 1-hour fuel with changing environmental conditions, this variable is considered very sensitive as it restricts the efficiency with which particles ignite, then burn, and continues to spread. We estimate the fuel moisture of fine dead components (1-hour) by using a simple index developed by (Sharples et al., 2009) which includes temperature and humidity for the day of ignition. For the other categories, we use a look-up table, which reflects the moisture related to the phenological stage of the plant.

Wind direction and speed

Due to the poor availability of high-resolution (spatial and temporal) wind data in the Khara region, a wind simulation model to estimate average wind speed and direction for the day of ignition has been applied. We integrated the WindNinja model (Forthofer et al., 2009), which simulates micro-scale winds in mountainous terrains. For the simulation of wind fields, the model requires a digital elevation model data for wind speed and direction at least for one location in the centre of the area. For or regional application, we use climate data from the station Baruunkharaa (48°55' N, 106°04' E), located in the centre of the catchment, that provides daily wind speed and direction.

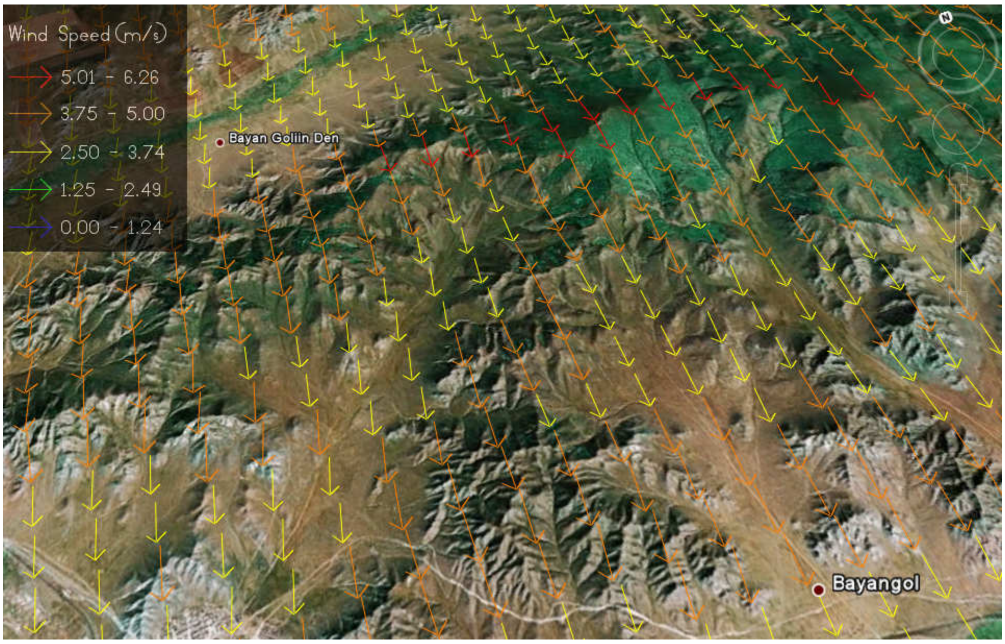


Figure 6-4. Example for wind fields simulated by the WindNinja model for the 6th of May 2000, wind direction: north (5 degree), speed 4m/s. Wind parameters were taken from the climate station at Baruunkharaa (Bayangol). Screenshot from Google Earth with the wind fields map used as overlay image.

Ignition

To minimize stochastic influences in the model, our approach derives ignition patterns from two factors: (i) frequency and distribution of wildfires occurrences in the last years and (ii) competition of cells corresponding to their OFR. To derive the first factor, single ignition points were extracted from the MODIS data. The algorithm used, identifies all pixels which belong to one MODIS fire scar (spatially and temporal) and creates a ‘fire-cluster’. Within this cluster one cell with the earliest date of burning is selected as a potential location and date of ignition. For the period 2000 to 2008 on average, 16 such ignition events per annum could be identified (60 % in spring and 40 % in autumn).

6.3.4 Calculation of wildfire risk

In a first the model performs a ‘wildfire risk analysis’ which has two objectives: (i) the identification of areas showing a significant wildfire risk, (ii) identification of highly susceptible cells as candidates were fire ignition begins. Wildfire risk is computed as a function of three weighted independent categories resulting in a normalized ‘overall fire risk’ (OFR) map. This is done for each single grid cell, in the same manner as SUIT calculates suitability maps (see Section 3.2.2.2), resulting in values ranging between 0.0 for no risk and 1.0 for high risk. The three OFR categories are: (i) fuel availability (ii) weather and (iii) location (Figure 6-5). Each category consists of multiple weighted input datasets (factors). The calibration process using the genetic algorithm can be applied to identify the exact definition of weights for each category, which are currently weighted equally. The estimation of fuel availability is based on biomass. Therefore, total forest and grassland biomass are used in combination with respective ratios of live to dead biomass simulated by DayCent. Weather factors (temperature, relative humidity and wind) are generally considered as most important variables influencing wildfire behaviour. As wind parameters cannot be sufficiently aggregated on an annual scale, we use the relative humidity and the mean annual solar radiation to determine the risk from weather factors. To capture the effect of humidity we count the number of days supporting high flammable conditions (relative humidity <= 45 %, often used as typical rule of thumb) for each cell in the current year. Topographic effects influencing the moisture will be reflected in the mean annual solar radiation provided for each cell. Location is used as a representative for spatial ignition patterns. Since most wildfires in Mongolia are related to anthropogenic activities, a distance analysis was performed. For Mongolia, Hussin et al. (2008) report a positive relationship between wildfire occurrence and distance to road or distance to rivers and a negative relationship for wildfire occurrence and distance to settlements. In our analysis these factors were used besides an additional settlement buffer excluding areas where wildfires are very unusual due to the visibility range.

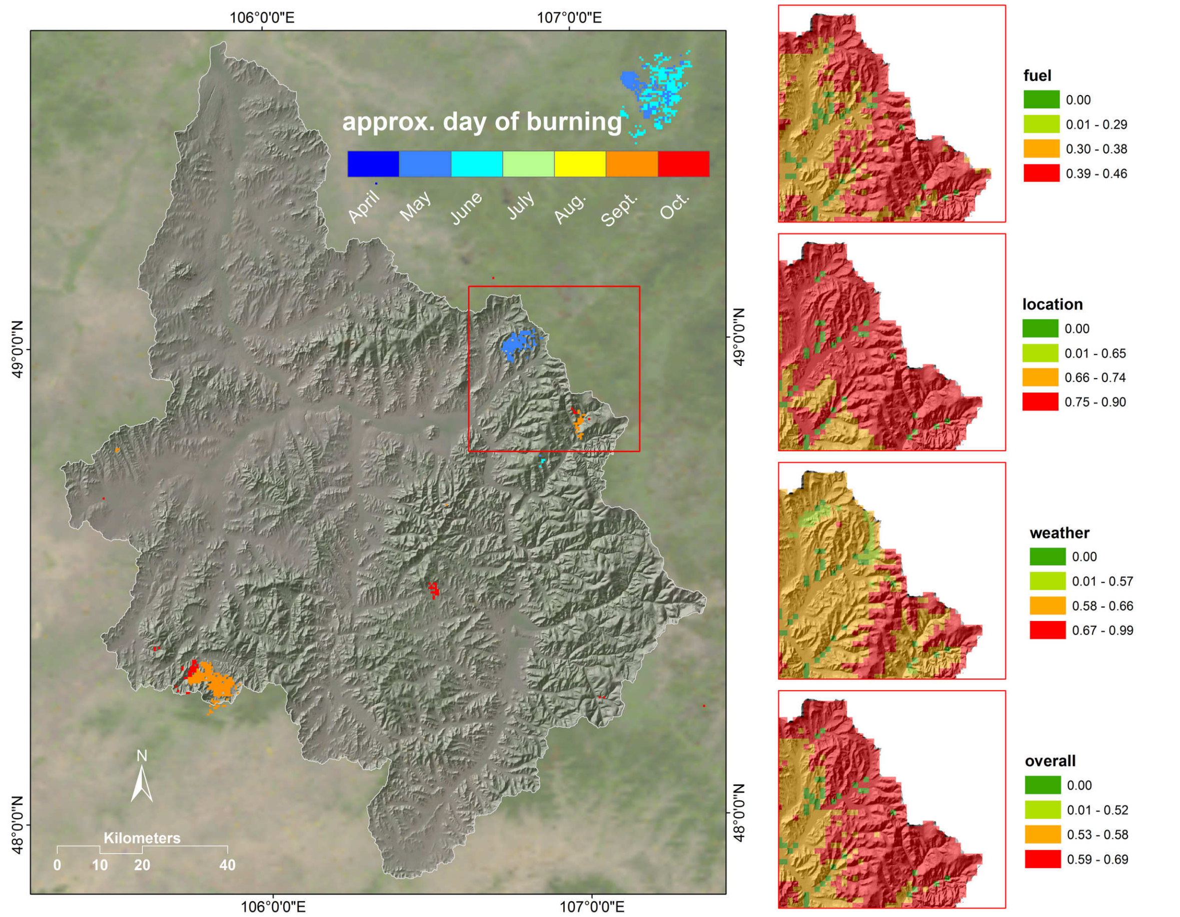


Figure 6-5. MODIS burned area for the year 2006 (left) and corresponding fire risk maps for a selected area of interest (right).

6.4 Results

Model runs were performed for risk analysis and wildfire behaviour using the above model concept. Here we present two segments of results from SITE-Mongolia simulations:

(1) Wildfire risk and behaviour

(2) Wildfire effects on forest biomass, land allocation and forest use

Wildfire risk and behaviour

Wildfire risk was simulated and risk values calculated for all three categories and OFR (Table 6-1). For validation of simulated values we use two sets of grid cells: (i) cells corresponding to wildfire detection by MODIS (Set I) and (ii) cells corresponding to no detection of wildfire by MODIS with OFR >0 (Set II). Set I and Set II are compared for risk categories and mean OFR.

Table 6-1. Validation of risk categories and OFR between Set I and Set II. Note: The average number of cells used (denominator) for Set I is 117 and Set II is 12449.

	fuel availibilty		weather		location		overall fire risk (OFR)	
	Set I	**Set II**	**Set I**	**Set II**	**Set I**	**Set II**	**Set I**	**Set II**
2001	0.40	0.31	0.59	0.58	0.71	0.62	0.57	0.48
2002	0.38	0.31	0.59	0.57	0.70	0.62	0.55	0.48
2003	0.40	0.31	0.56	0.58	0.69	0.62	0.55	0.48
2005	0.39	0.31	0.53	0.49	0.75	0.62	0.55	0.46
2006	0.37	0.31	0.69	0.58	0.79	0.62	0.62	0.49
2007	0.39	0.31	0.58	0.55	0.71	0.62	0.56	0.47
2008	0.41	0.30	0.54	0.59	0.67	0.62	0.54	0.49
Ø	**0.39**	**0.31**	**0.58**	**0.56**	**0.72**	**0.62**	**0.56**	**0.48**

From Table 6-1 can be observed that despite the large difference in the denominator for calculation of means, all single categories and OFR consistently record a higher value in Set I than Set II. This observation validates the accuracy of risk simulation across the range of categories used. Furthermore, we carried out a spatial validation. Here we present results for the year 2006 as it best represents - (a) presence of both fire seasons (b) area burned (c) distribution of wildfires (spatially and temporally). It is important to note that the spread is dependent on conditions occurred on a specific day within the pixel that is ignited. Hence, not all points of ignition in the wildfire model imply that spreading would occur. Only ‘suitable’ conditions (e.g. low fuel moisture, wind) lead to immediate fire spread failing which, fire is extinguished. Figure 6-6 shows the simulated area burned and fire behaviour in two areas of interest (A, B) for the year 2006 (left image). Total area burned from model simulations is 17,500 ha. Modelled variables - fire intensity (A2, B2) and flame length (A3, B3) - are important for further calculations of net change in biomass, carbon and nitrogen using the Day-Cent model. Comparison of simulated burned area (17,500 ha) against MODIS burned area (8,150 ha) show that model simulations to some extent overestimate the burned area in 2006.

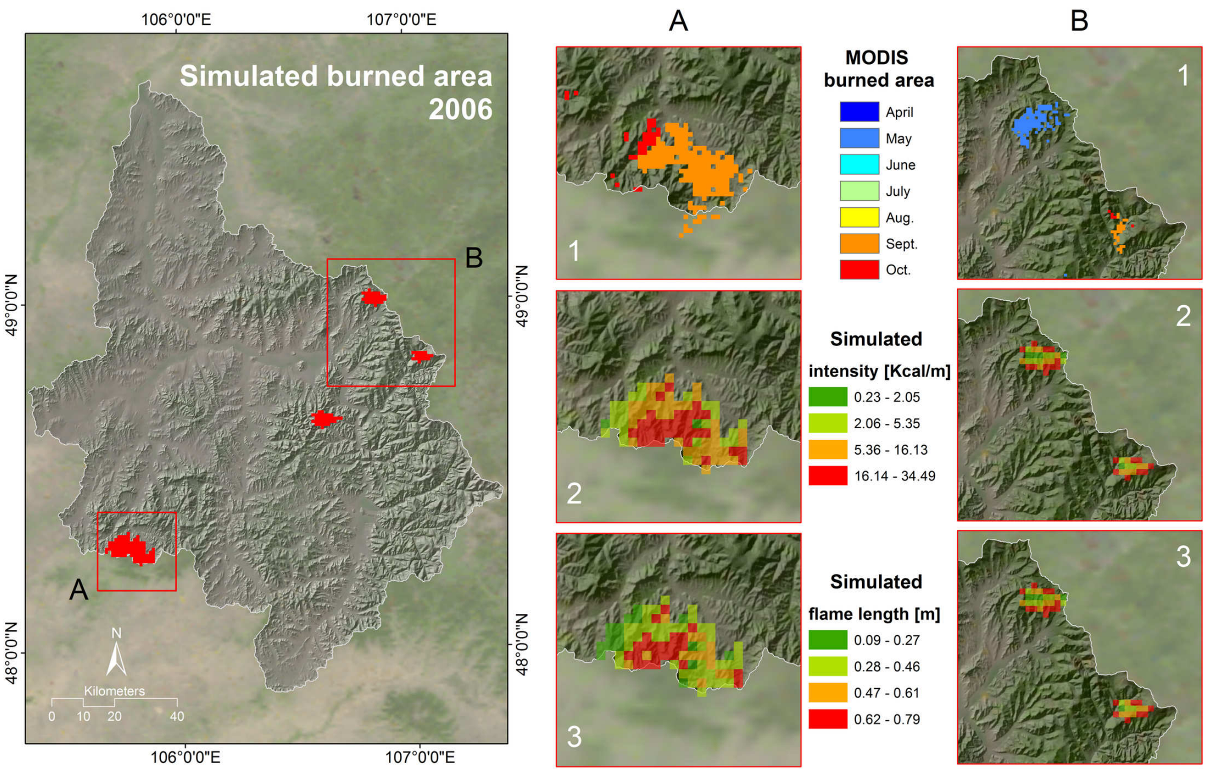


Figure 6-6. Simulated results of fire spread (left) and behaviour (right: A2, A3, B2, B3) for the year 2006. For comparison A1 and B1 presents the satellite derived area burned and the corresponding month of burning.

Wildfire effects on forest biomass, land allocation and forest use

In order to highlight the effects of wildfire on the socio-environment, we have chosen the forest sector to demonstrate some impacts. The forest module is driven by the demand for wood, which is defined as the sum of industrial demand (data from regional statistics) and demand for firewood (linked to rural population dynamics).

We simulated the total aboveground forest biomass including and excluding the wildfire submodule. Figure 6-7 presents the comparison of both model runs, showing an increasing trend in diverging biomass availability, which could directly related to the amount of wildfire occurrences extracted from MODIS (presented in Figure 6-1 a). We know from MODIS observations that wildfires increase in subsequent years (2007, 2008) which will further increase the difference. Due to the lack of daily climate data, required to run the DayCent model, we were not able to continue the time series for years that are more recent. A considerable reduction of total biomass, due to external disturbances (timber extraction, wildfires) will implicate a land-cover change from 'Closed Forest' to an 'Open Forest' class in our model. 'Closed forest' is a coniferous type, while 'Open Forest' is characterized as mixed, mostly broadleaf (secondary) forest. We observed an additional 'Open Forest' allocation of 24 % with the new model setup, indicating the indirect effects on land allocation that is reflected by the model.

Further, we analysed the distance from settlements to ‘highly suitable’ cells (> 10 percentage of max. suitability) to explore changes in utilization activities. We observed (for the period 2001-2006) a 3 % (Ø 350 m) farther distance to cells ‘highly suitable’ for forest-use (providing sufficient biomass and adequate re-growth for a sustainable management). We conclude that an increase in wildfire disturbances in Mongolian forests will enlarge the effort related to fire-wood collection or influence transportation costs in commercial timber production.

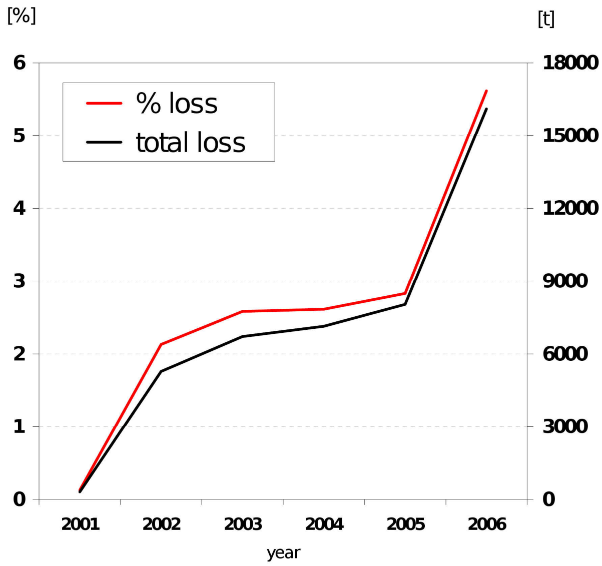


Figure 6-7. Absolute and relative accumulated loss in aboveground forest biomass.

6.5 Discussion and conclusions

In this chapter results from the process of integrating a wildfire component into a dynamic land-use model, enable us to study feedbacks to the socio-environment. Despite the difficulties (mostly of technical nature) associated with integrating third-party applications into an existing model, we demonstrate that the above concept adds value to the overall model approach in terms of (i) a better estimation of biomass availability, (ii) an improved allocation of land (e.g. ‘Open Forest’ and burned cells) and (iii) addressing changes in the usability of land. Furthermore, we expect scientific benefits in: (iv) providing accurate land-use and land-cover information for hydrological modelling, (v) supporting the development of a satellite-based wildfire monitoring concepts (vi) simulation of environmental scenarios. Our results from wildfire simulations indicate good accuracy for fire risk analysis. Simulated burned area in 2006 is higher (53 %) than MODIS burned area at first glance. However, several factors may be possible contributors to this observation. Burned area from MODIS uses surface-reflectance dependent algorithms, which may contribute to underestimations. Furthermore, we use only ‘High Quality’ pixels (most confidently detected) from MODIS for validation. If burned area is extracted with all detection levels, estimations sum up to 15,375 ha. Hence, it is reasonable to conclude that simulated burned area is in an acceptable range.

We also like to mention existing limitations corresponding to the wildfire sub-module. The current state of implementation does not enable handling dynamic input data, (e.g. wind speed and direction) which may affect the spreading pattern simulated compared to real world wildfire scars. Secondly, fuel moisture, which is one of the critical variables of fire behaviour modelling needs calibration. The genetic algorithm implemented in the SITE-Framework could be applied to calibrate the fuel moisture index used in the study. Strengthening the human influence in the OFR (since we know that most fires are anthropogenic origin), could be achieved by assigning different weights to risk categories (e.g. location risk).

The increase in wildfire occurrences in Mongolia has initiated a national wildfire satellite-based monitoring system, which is operational since a few years now. Modelling approaches, as the one presented here, could assist and support these efforts providing an appropriate tool to study the impacts and feedbacks to the socio-environment, identify interactions responsible for increasing the wildfire risk.

Chapter 7

Future perspectives of land and water use

Describing how the future may unfold according to particular assumptions is the main idea of scenario assessments. In the MoMo project, regional scenarios have been developed with the objective to provide plausible boundary conditions for a sustainable management of water resources in the future. Based on national projections, a narrative approach was developed and combined with outcomes from a stakeholder workshop (with Mongolian scientists and authorities) held in Ulaanbaatar in late 2008. The scenario storylines identified the main indicators and drivers for mapping national scale assumptions to regional development trends, combined with quantitative data e.g. rates of change of water consumption. As a result of development strategies and land policies, the scenario storylines presented here will focus on the three main drivers of land-use change and water use in the Kharaa watershed which were identified as demography, mining and industry and agriculture.

7.1 Introduction

The sustainable management of water and related resources is a key issue addressed by Integrated Water Resource Management (IWRM) concepts (GWP, 2000). Sustainability requires a forward-looking management and policies capable of grasping the large diversity of future environmental conditions. For this, scientific methods are needed that reveal different settings of socio-environmental drivers and their impacts ex ante. One of the most commonly used methods for this purpose is scenario analysis. According to Alcamo (2008) a scenario is '… a description of how the future may unfold based on 'if-then' propositions and typically consist of a representation of an initial situation and a description of the key driving forces and changes that lead to a particular future state.'. Thus, scenarios are not forecasts or any type of predictions or extrapolations. Scenario assessments have been applied in a broad range of scientific fields, on different scales with different aims. Prominent examples of environmental studies that applied scenario exercises in their assessments are the Millennium Ecosystem Assessment (MA), the Global Environment Outlook (GEO4) and the Intergovernmental Panel on Climate Change (IPCC). In the MA, scenarios were used as a central element to assess the impacts of ecosystem change on human well-being (MA, 2005a). In GEO4, the implications of various actions, approaches and societal choices for future environment and human-well being were studied using a scenario analysis (Rothman et al., 2007). And the IPCC used emission scenarios representing greenhouse gas and aerosol emissions to address impacts on future global environmental change (Nakicenovic et al., 2000). On the regional scale, several studies have been published that applied scenarios in an IWRM context, mainly associated with future subjects of water availability, water use or water and land management (Feng et al., 2011; Sharda et al., 2009; Volk et al., 2007). The majority of scenario studies have in common, that they use environmental models or decision support systems as platforms to simulate and analyse future trends. This chapter presents results from the scenario exercise applied to the Kharaa river basin. Besides addressing future aspects of water use due to potential change in population, mining, industry and agriculture, a spatially explicit regional land-use model was applied to simulate future land-management options.

7.2 Scenario development

A scenario exercise is seen as a procedure, which includes the process of development of the scenarios, comparison of scenario results and the evaluation of their consequences (Alcamo et al., 2008). In the project wherein this study was embedded - 'Integrated Water Resources Management in Central Asia, Model region Mongolia (MoMo)' - scientists decided to assess future development possibilities based on two different pathways that draw a diverging picture of the future. The scenarios developed within GEO4 were considered as most appropriate as they included a detailed view on important sectors that were considered as relevant for addressing future IWRM options for Mongolia. The GEO4 scenarios are addressing important Global Change issues (climate, economy) and nationally important drivers of change (agricultural intensification, life-style changes, migration) (Rothman et al., 2007). In total four scenarios were developed in GEO4 named: Markets First, Policy First, Security First and Sustainability First. The different scenarios include annual rates of change for the main indicators (e.g. GDP, population, energy use, crop yield and food availability, water use etc.) from 2000 to 2100. Two scenarios, which exhibit maximum levels of divergence for Mongolia - Markets First (MaF), and Sustainability First (SuF) - have been selected as boundary conditions in this study. Despite the 100 years covered by GEO4, the maximum time horizon selected in MoMo was 2050, 2006 to 2025 - for mid-term analysis and 2006 to 2050 - for the long-term assessment. The former has been used in the model simulations due to the urgent need to study management options regarding IWRM issues. For scenario development, a participatory approach was planned and applied in an iterative fashion with respect to the stakeholder feedback, aiming at a minimum of two rounds of discussions between the MoMo (modelling) group and different stakeholders (Figure 7-1). In November 2008 the first stakeholder workshop took place in Ulaanbaatar, which was attended by institutional stakeholders and national experts of different fields (e.g. agronomy, geology, geography, hydrology, etc.) and MoMo scientists. It is noteworthy to mention that a large overlap exists between scientific partners actively involved in MoMo, and the group of stakeholders mentioned above. In two aspects, active stakeholder participation is considered essential. Firstly, to broaden the main scientific views and questions addressed in MoMo, and secondly to adequately include and represent regionally relevant questions and knowledge. Stakeholders have been (are and will be) involved in several steps, which is also seen as a prerequisite for IWRM development and implementation. Currently, the second round of discussions is in preparation. The scenario approach applied in MoMo pursues the concept of 'Story and Simulation' (SAS) which combines qualitative and quantitative scenarios approaches. SAS includes (i) a qualitative scenario exercise, with the aim of developing the storylines and (ii) a part that translates the storylines into quantitative numbers of change, thus combining the advantages of both scenario approaches – qualitative and quantitative (Alcamo, 2008b).

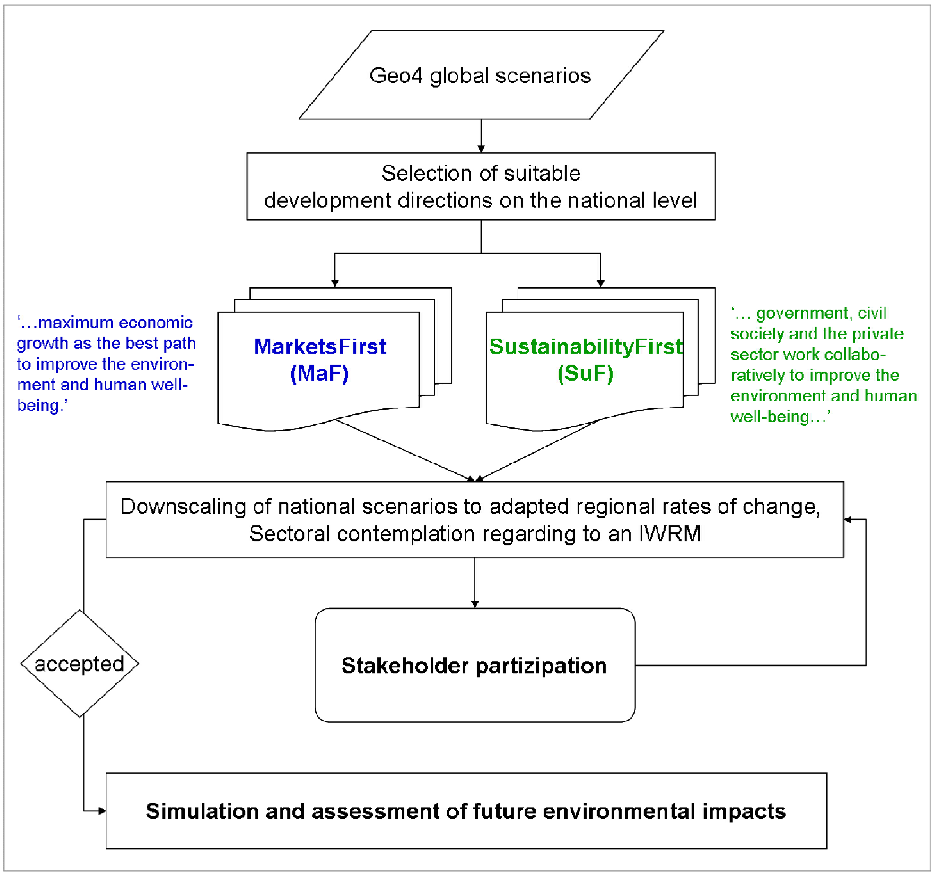


Figure 7-1. Scenario development process applied in MoMo.

7.3 Land-use model and scenario input

Scenario analysis using integrated models of the land system is usually based on a comparison of different future pathways and trends generated by exogenous drivers such as changes in climate, population, economy, policies or land management options such as agricultural intensification (fertilisation or irrigation) (Schaldach & Priess, 2008). In this study, the SITE-Mongolia model was used as a simulation tool to address future impacts on the socio-environment. The model was developed and integrated in the SITE-framework (see Chapter 3), a modelling platform that provides components supporting the modelling process. Each data set underlying the scenario is organised in a separate database that the model can explicitly address. On one hand, the demand driven allocation of land use requires yearly input, while on the other hand the simulation of processes of the biophysical environment, performed by the DayCent model requires daily input (see Chapter 4.7). However, the simulation of future trends in land-use and land-cover needs transient data and cannot be simulated if scenario data is only available in discontinuous time series, which is often the case e.g. for future climate data. Due to the absence of transient sets of (regional) daily climate scenarios, we decided to use a simple approach and 'recycled' historical weather data from the period 1989 to 2006. For each year of the 'mid-term' time span (2006 - 2025), a random choice algorithm depicted a year from the historical climate dataset and assigned it to a year in the future. The new climate data set (consisting of daily precipitation and minimum and maximum temperature) is then used in all scenario simulations (Figure 7-2). A main reason for this procedure was that inter-annual climate variations in the area are expected to be higher than climate changes simulated by any type of global or regional climate model for the respective period.

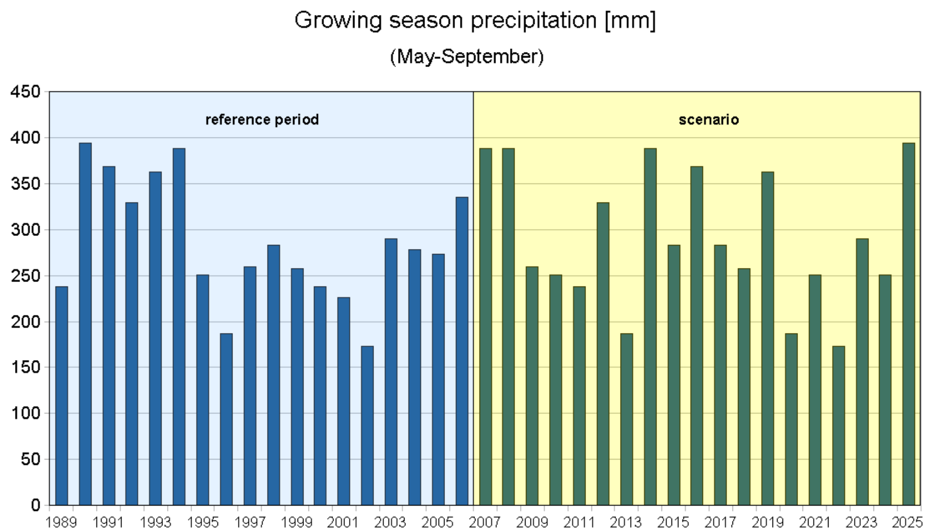


Figure 7-2. Rainfall data used in the scenario simulations.

7.4 Results

The results presented here focus on future aspects of land-use management and water consumption. They represent a selected excerpt of the entirety of outcomes from the scenario exercise conducted in the MoMo project. Results are divided into two parts; the first part includes the outcomes of the storyline development and quantitative assessment. The second part assesses future land-use intensification options based on simulation experiments with the SITE-Mongolia model.

7.4.1 Storylines – drawing images of the future

After a short summary of the main ideas underlying the GEO4 scenarios, the developed storylines will be presented. For more details on GEO4 scenarios, please refer to Rothman et al. (2007). The storylines presented here are based on downscaled national trends with adapted regional rates of change. The figures, which are related to the storylines, are given in the next paragraph. The base year for all scenarios is 2006.

Storyline of the Markets First (MaF) scenario developed for the Kharaa region

'…the private sector, with active government support, pursues maximum economic growth as the best path to improve the environment and human well-being. Lip service is paid to the ideals of the Agenda 21 and other major policy decisions on sustainable development. There is a narrow focus on the sustainability of markets rather than on the broader human-environment system. Technological fixes to environmental challenges are emphasized at the expense of other policy interventions and some tried-and-tested solutions.' (Rothman et al., 2007)

Population development within the Kharaa catchment is driven by the attractiveness of settlement areas and pasture availability. Just a few regional settlement centres (like Darkhan city) are well organized to provide an adequate level of human well-being, especially regarding health care and education. Most of the infrastructure in settlements within the catchment is currently sub-standard. These conditions will further amplify the existing urbanization trend in the coming years. National urbanization rates can be scaled down to currently observed processes in Ulaanbaatar or Darkhan city. Urban population in the Kharaa region will increase by 46% until 2050, characterized by high immigration rates and a continued trend in fewer births as income rises (Figure 7-3). The process of strengthening the private markets even in rural areas will increase the living standard of households especially those of the population working in the agricultural sector. Market situation becomes much better and regional demands for crops, vegetable and animal products increase. Thus positive effects of rural development policy become apparent. Regarding domestic water use, two branches of future developments are possible; improvements in water use and increase in volume of water saved. People living in concrete buildings will gain from the improvement in water supply infrastructure, which is 1 % per year, mainly through avoiding water losses. Besides this, water will be saved with new technologies and with changes in behaviour with respect to water consumption, and the combination of factors sum up to a rate of change of 1 % per year (Figure 7-4). The overall water use per capita decreases from 390 litres per day in 2006 to 250 litres in 2050 (including losses). Water supply will be improved slowly. Most of the water will be provided via water kiosks and water trucks. The number of kiosks connected with pressure pipes is increasing due to the increasing transport costs. In 2006 average rural water use per capita was 22 litres per day.

Mining activities in the Kharaa catchment will increase. The interest of the government in economic growth in combination with favourable tax and other business conditions push further investments. The use of more advanced exploration techniques and raising prices are motivations for private investors to re-launch existing inactive mines. Also new mining areas would be available. Until 2025, the activities will more than double. Thus, water consumption increases, reaching a maximum in 2025 (70 % more than 2006) but then level off in 2050 reaching similar amounts as today (Figure 7-5 a). Development of the industry sector gains from national investments. The expansion and enhancement of road and railway infrastructure is the backbone for industrial development. During socialist times, industry sites have been made available along the north to south infrastructure axes from Russia to China. The industrial area in the south east of Darkhan city was a result of this planning strategy and has large potentials regarding future developments. Industrial water use depends on further improvements in water supply infrastructure, which will be enhanced until 2050 by 36 % (Figure 7-5 b).

The agricultural sector will benefit from large agricultural programs set up by the Mongolian government. Focusing on food self-sufficiency of the country, campaigns will be advertised and subsidized by foreign countries and institutions (such as the 'Third Campaign of Reclaiming Virgin Lands'). To strengthen the private agricultural sector, the Asian Development Bank will provide large funds for fertilizers, tractors and develop knowledge and capacity of local experts. As water and fertilizers are expected to be the limiting factors for crop yield in Mongolia, total production will be amplified by setting up irrigation systems and increasing the amounts of fertilizer consumed and finally, by extending the arable area. The latter will be achieved first by reuse of fallow land and second by converting pastureland for crop production. The irrigated area will increase up to 60 % until 2020 while water use efficiency is increasing annually by 1% (Figure 7-6 a). Fertilizer consumption in 2006 was almost negligible. Within the agricultural programmes, fertilizer consumption increases by the same rates as in the socialist era between 1980 and 1990. Average fertilizer consumption will be 80 kg/ha in 2020 and 125 kg/ha in 2050 (Figure 7-6). Road infrastructure will expand to reduce the transport costs for private traders and better accessibility of local markets. Regional markets in the soum centres become key points of contact and trade among farmers. Due to the large area demands for crop production, pasture availability will decrease. The improvement of job opportunities in the agricultural sector will encourage many local herdsmen to sell their herd and settle down.

Storyline of the Sustainability First (SuF) scenario developed for the Kharaa region

'…government, civil society and the private sector work collaboratively to improve the environment and human well-being, with a strong emphasis on equity. Equal weight is given to environmental and socio-economic policies, and accountability, transparency and legitimacy are stressed across all actors. Emphasis is placed on developing effective public-private sector partnerships not only in the context of projects but also that of governance, ensuring that stakeholders across the spectrum of the environment development discourse provide strategic input to policy making and implementation. There is an acknowledgement that these processes take time, and that their impacts are likely to be more long-term than short-term.' (Rothman et al., 2007)

Increased investments in health, education and environment are included in a nationwide development program. In the coming years, people will be more satisfied with their local environment. Population migration rates are low and birth rates will decrease with growing income. The government will try to achieve a well balanced living standard for the urban and rural population. As observed in other areas, urban growth is prevalent. Until 2050, urban population increases by 30 % (Figure 7-3). The uncontrolled sprawl of ger settlements around the cities will be minimized by domestic development programs like 'Flats for Herdsmen', providing affordable living space for the currently poor rural population. These measures will minimize diseases, sanitation and erosion problems caused by informal ger areas. The rural population will not increase, due to fewer births with increasing GDP per capita. The sensitivity towards environmental issues will expand and regional nomads and herdsmen will reduce the size of their herds due to higher pasture productivity or migrate to regions with less agriculture and less competition for grazing opportunities. Enhanced environmental education records positive results with respect to domestic water withdrawal. People's perception and willingness to save water has increased. In addition, water saving technologies and a fast improvement in water supply infrastructure will reduce domestic water use by more than 50 % from 390 liters to 160 liters per capita per day in 2050. In contrast to this, water use in the ger areas will increase, since a minimum level of water supply has not been gained until 2006 (Figure 7-4).

The mining sector will increase gradually in the next 20 years and will be nearly constant thereafter. Therefore mining activities would be doubled in 2050 compared to 2006. Due to water saving technologies and laws which enforce a reuse of certain fractions of water within the exploration process chain, total water consumption could be reduced by 60 % (Figure 7-5 a) from 2006. Currently, advanced extraction methods use 4 m³ water per m³ ore. In 2050 this will be reduced to 0.8. Similar progress will be observed by industrial water use. But the percentage of industrial growth is much faster and linked to GDP growth. Total water use will increase even if there is much progress in water saving technologies. Until 2050 water use will increase by 25 % (Figure 7-5 b).

There will be national agricultural programs focusing on national crop productivity, which will operate based on sustainability objectives. Further research programs will be carried out to capture regional degrees of erosion sensitivity and possibilities of climate change mitigation. Studies will strongly focus on a well balanced and sustainable water and fertilizer use together with new crop varieties (adapted to the harsh climate conditions), thus achieving the goals of food security and self-sufficiency. Fallow land will be re-cultivated (third agricultural campaign). The irrigated area will expand by 30 % compared to 2006 using advanced irrigation technologies, which will result in a 2 % enhancement in water irrigation efficiency per year. This will minimize water losses and will save 50 % of water compared with today (Figure 7-6 a). With respect to the consumption of fertilizers, a constant increase will be observed in the future, reaching moderate levels of 65 kg/ha in 2050 (Figure 7-6 b). Compared to other Asian countries, levels of crop yields still remain low. Retentive use of chemical fertilizers is well-grounded by an increasing demand for organic procedures of nitrogen fixation via legumes. Furthermore a change in management strategies will be observed regarding soil protection e.g. through green cover during the dormant phases.

Quantification of storylines

Based on the storylines described above and their underlying assumptions quantitative rates of change were generated. This paragraph includes the corresponding figures and additional details of the overall trends, which have not been discussed in the storyline section above. Figure 7-3 presents the population scenarios developed until 2050. It is evident that the total number of people living in the Kharaa region will increase, but trends are different among urban and rural population (see storylines). Total difference between the two scenarios (MaF and SuF) is 12 % in 2050. Note that urban also includes the ger population, which corresponds to the agglomerations of traditional yurts, typically situated in the outskirts of the larger cities (e.g. Darkhan, Ulaanbaatar). On the contrary, rural population includes nomadic families and smaller settlements (e.g. soum centres) which do not have multi storey buildings. However, both - ger and rural - commonly face inadequate water infrastructure (i.e. drinking and wastewater).

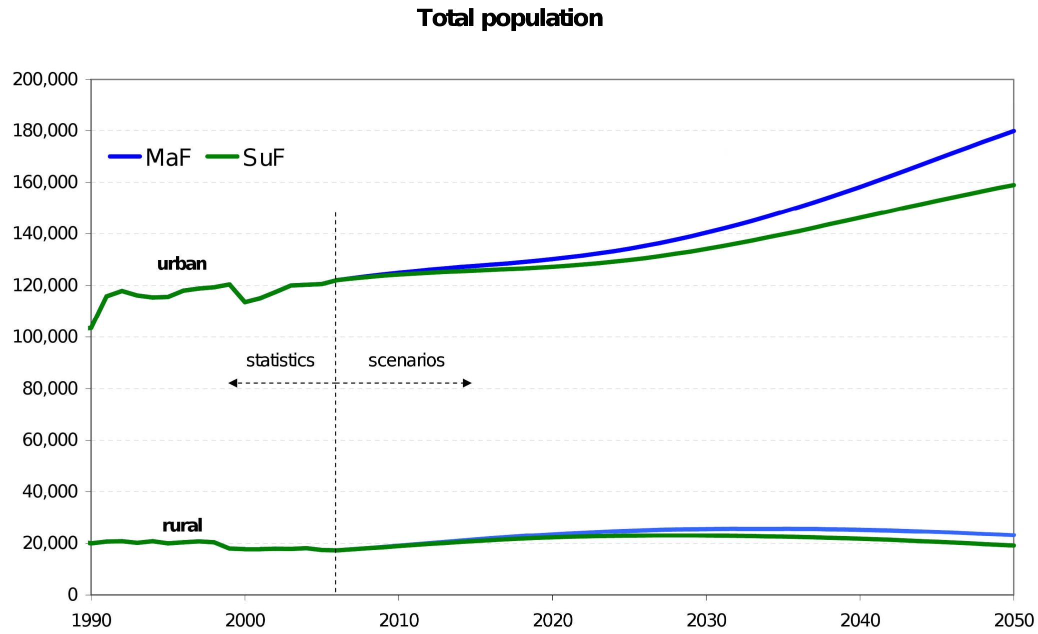


Figure 7-3. Population scenarios for the Kharaa river basin.

Domestic water use for urban and ger population is presented using an example of the city of Darkhan. Current average consumption rates identified in MoMo (MoMo, 2009) have been used as a starting point which is 392 litres per capita per day for the urban population (Figure 7-4 a) and 22 litres per capita per day for ger population (Figure 7-4 b).

Since current amounts of water used by the other sectors (industry, mining, agriculture) could not been quantified until date (see Chapter 2.3), outcomes are relative values in the following. In the mining sector it is assumed that activities will not behave in a linear manner (Figure 7-5 a). Both scenarios expect first an increase in activities and related water consumption, which then declines – in MaF much later then in SuF. The industry shows a constant increase in both scenarios (Figure 7-5 b) which largely reflects the increase expected in the GDP for Mongolia given by the GEO4 assessment.

Agricultural activities are expected to increase in the coming years. This is mainly reflected by the increase in demand for water. Thus, water extracted for irrigation purposes will first increase and after 2020 slightly decrease due to efficiency improvements (Figure 7-6 a). Furthermore, agricultural expansion results in an increasing fertilizer consumption rate (Figure 7-6 b).

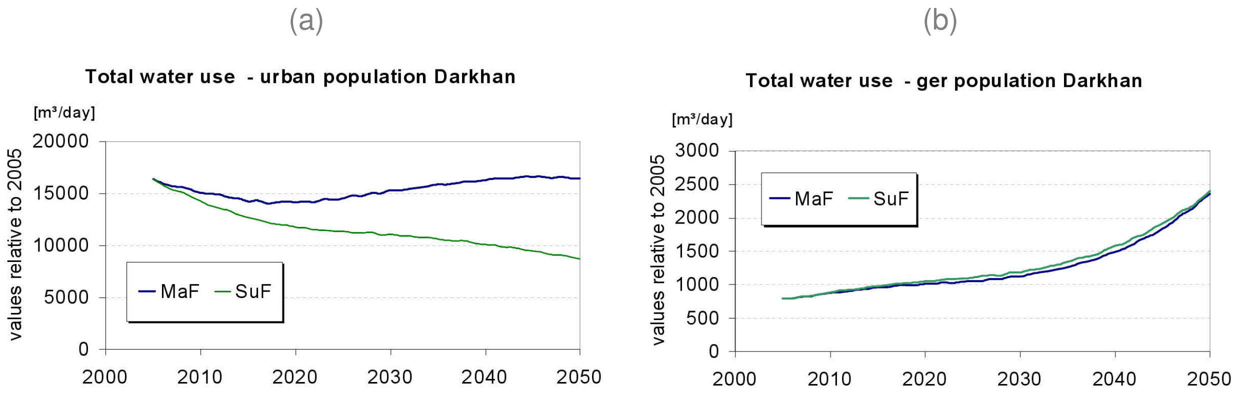


Figure 7-4. Scenarios of domestic water use for the city of Darkhan, representing water use by the urban urban (a) and the population living in ger settlements (b).

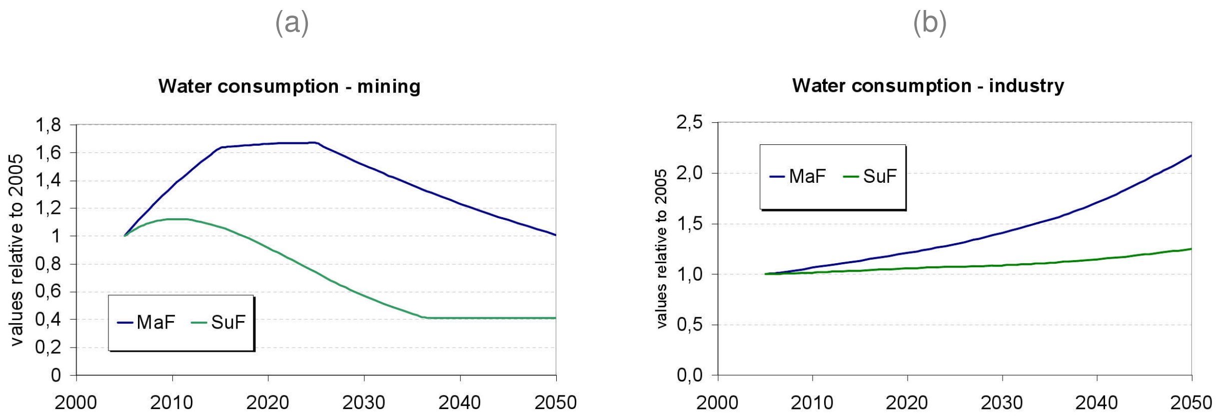


Figure 7-5. Scenarios of water consumption in mining and industry.

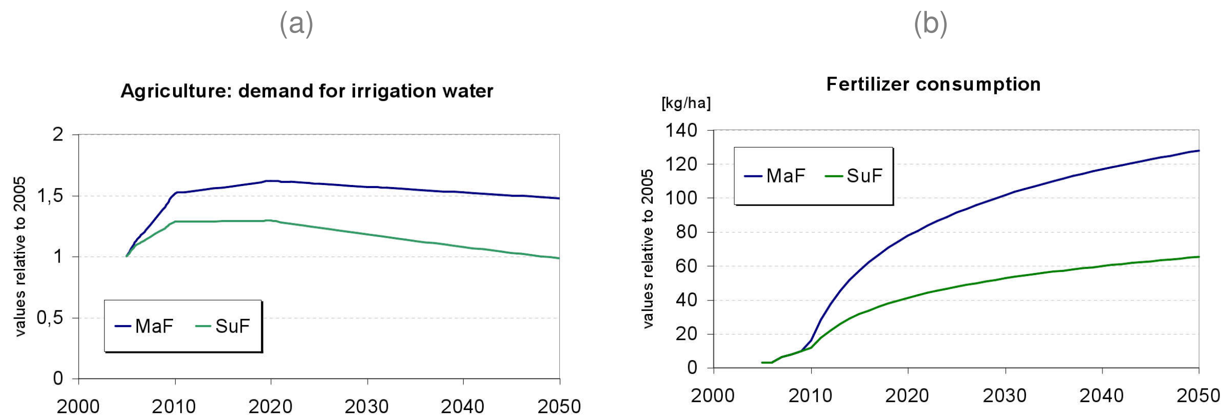


Figure 7-6. Agricultural scenarios. Demand for irrigation water (a) and rates of fertilizer consumption (b).

7.4.2 Simulation of future land intensification

We applied SITE-Mongolia and performed an analysis of future levels of crop yields simulated by the DayCent model. For this, we addressed land use intensification by simulating two sets of fertilizer consumption scenarios (Figure 7-6 b) since this is considered a very realistic future step regarding the current policies in the agricultural sector (see Chapter 5). Figure 7-7 (a) and (b) represent the simulated mean annual yields for wheat and potato in the Kharaa river basin. Additionally, precipitation is plotted to identify if a decline in yields can potentially be related to water stress. The overall trends indicate that with increasing fertilizer application rates wheat and potato yields will increase. In general, the patterns observed confirm by model simulation what was already observed in the fields and reported by farmers – namely that the limiting factors of plant growth and yield are water and nutrients. In the historical period (until 2006), where fertilizer amounts were nearly zero, variations in yield strongly reflect rainfall pattern and thus rain-fed conditions. In general, yields were higher in years with more rainfall and vice versa. Nevertheless, this cannot be applied as a general rule of thumb as it would ignore other important influencing factors. It is noteworthy to mention, that the patterns also reflect differences in soil fertility that occurred as a result of the crop rotation schedule that is applied in Mongolia, and also in the model. Furthermore, inter-annual differences in temperature largely affect plant growth, which might be not apparent here at first glance. In the phase where both the scenarios start, yields are increasing and it is evident that in SuF only half the amount of fertilizer is used. With the highest amounts of fertilizer - 125 kg/ha in MaF and 62.5 kg/ha in Suf - yields nearly triple in both cases, for wheat and potato. As a logical consequence, the same quantities of food can be produced cultivating a smaller area.

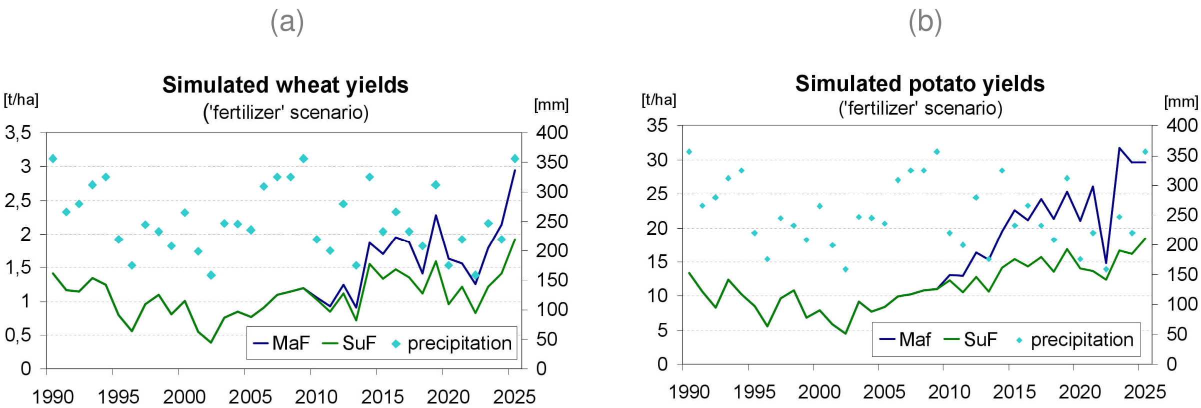


Figure 7-7. Simulated future crop yields based on fertilizer scenarios. Left y-axis is fertilizer application and right y-axis is mean annual rainfall.

However, large amounts of fertilizer are not usable by the plants if water is extremely scarce. Despite the increasing amounts of nutrients applied on the fields, yields collapse in 2022 due to extreme low rainfall amounts (~ 160 mm). This once again underlines the high vulnerability of the farming system in such harsh climate conditions. With increasing growth and yield, the water demand of the plant increases. Hence, we further studied the variations in field capacity of the soil between the two scenarios. For this, we applied the DayCent management options and irrigated the plants as soon as field capacity was lower than 50 %. Thus, we identified that the average irrigation demand between 2007 and 2025 was in both scenarios almost 50 % larger than in the reference period (1989 - 2006).

7.5 Discussion and conclusions

The study aimed at presenting future perspectives of water and land use in the Kharaa river basin. One aim was to raise awareness among scientists and stakeholders on potential impacts caused by future developments and potential conflicts, which may arise among different sectors related to future water availability and water use. For this purpose, a scenario analysis was carried out consisting of the following steps: (i) selection of suitable scenarios providing future trends of the most important drivers of change, (ii) development and formulation of plausible regional storylines considering the boundary conditions given by the previously selected scenarios, (iii) stakeholder participation, discussion and adaptation of the storylines and enriching them with quantitative rates of change, and (iv) quantification of the assumptions and simulation of the potential impacts on the environment. We aimed at applying the SAS scenario approach, which combines both a qualitative analysis that will in a further step be used for a quantitative assessment. Compared to scenarios approaches that are exclusively based on qualitative information - besides their arbitrary nature - the SAS has the advantage that outcomes are numerical and therefore usable to drive environmental models. An important aspect of SAS is that results achieved from the modelling experiments are used to further enhance the storylines and provide new insights of the dynamics to stakeholders and scientists. This step is currently in preparation.

Due to the complexity of process-based environmental models, the scenario exercise may lack transparency for stakeholders (Alcamo et al., 2008). However, simpler methods such as the extrapolation of current trends may not be able to capture non-linear changes (see Figure 7-7) and therefore produce biased results and/or lack scientific credibility. The stakeholder dialog is considered an essential IWRM facilitating component of MoMo and is continued in the current second phase of the project. Using participatory scenario approaches supports e.g. to estimate the impacts of adapting water saving technologies in different economic sectors, or to address the rates of industrialisation, both processes being important components in a water management strategy. However, the stakeholder dialog in MoMo - especially with officials and practitioners in the catchment - needs to be intensified, before any IWRM components can be implemented successfully. In consequence, future land use modelling intends to produce both scientific and stakeholder communicable results to serve the dual goal of MoMo and to provide feedback for the stakeholders already involved in the process.

The outcomes from the scenario exercise and especially the results presented in the simulation section have underlined the need of adapted management strategies in the future. The study showed that a wide range of rates of change can either release or increase the pressure on water and other resources. As shown in the example of the agricultural intensification it became apparent that policies require a set of alternatives of future management options to cope with the Mongolian climate. If a future intensification by adding more fertilizer is not supported by other management options (e.g. irrigation), crop failures are foreseeable. The results clearly show the need for management options, which are better adapted to future socio-economic and environmental boundary conditions. This case study shows that a stronger focus on the feedbacks between society and the environment is needed to support the development of meaningful IWRM strategies.

Chapter 8

Synthesis

In this chapter, outcomes of the thesis are summarized followed by a discussion section which, in addition to the discussions presented in Chapter 5 - 7, also addresses the underlying modelling approach. Finally, a short outlook presents the future perspectives and research needs that have emerged during this work.

8.1 Summary of findings

Globally, 70 % of water use is dedicated to agriculture, followed by industry and domestic demands (MA, 2005b). In principle, the Kharaa river basin is expected to follow the same course in the near future, but quantities are still not exactly known. Current political initiatives of agricultural intensification, increasing mining activities and increasing amounts of water withdrawn for domestic purposes, indicate that the overall water demand will largely increase. Limited rainfall due to the arid to semi-arid climate conditions and the expected effects of climate change together with the above-mentioned aspects are expected to lead to an increasing competition for water resources. In addition, the overuse of pastures and an increasing occurrence of wildfires (both natural and anthropogenic) negatively affect grassland and forest ecosystems with adverse effects on key ecosystem functions, such as the provisioning of freshwater. All these aspects underline an urgent need for sustainable land and water management strategies and future perspectives that maintain and enhance ecosystems and their functions as well as human well-being.

Model development and implementation

The overall objective of this thesis was to study terrestrial changes in the Kharaa river basin and to assess their impacts on ecosystems and other system components such as the hydrosphere, thereby contributing to generating knowledge for the development of IWRM strategies. To accomplish this objective, a spatially explicit regional land-use model was designed, developed and finally applied. As a platform for the integration of cellular automata based models, the SITE modelling framework was used (see Chapter 3). The new land-use model - SITE-Mongolia - includes components for simulating processes of the land system that were identified to be of major importance for analysing current land-use and land-cover changes in the Kharaa river basin in Northern Mongolia (see Chapter 4). The model employs a rule-based approach, integrating spatial and statistical data from various sources, as well as knowledge and information provided by Mongolian and German experts and stakeholders. Simulations were performed for the historical time period from 1989 to 2006 and future scenarios up to 2025. New components were developed for SITE-Mongolia such as HYDRO - representing hydrological features for the simulation of water fluxes and BURN - simulating wildfire behaviour.

A study to assess policy driven land and water use

In the first case study presented in this thesis, SITE-Mongolia was used to analyse and evaluate LULC dynamics and impacts of intensified agriculture focusing on water demand and water use (see Chapter 5). Motivated by current policies that aim at the (re-) intensification of agriculture, a new component (HYDRO) was developed and integrated enhancing the capacity of the model to simulate irrigation based on daily water availability. Furthermore, the implementation of HYDRO enabled simulations accounting for spatial differences in the water regime of different sub-regions (e.g. upstream and downstream conditions), thus reflecting the spatial differences in land-use management. Simulations showed a reduction in potato and wheat yields up to 15 % and 9 % respectively when the new and the more realistic HYDRO approach was used, compared against the typical model setting. Hence, the implementation of the HYDRO module also improved the quantification of land required for food production (total area required increased by an average of 10 % (~ 6000 ha). The simulations showed that although in the short-term it may be possible to produce more crops, by ignoring water availability, it might deplete (ground-) water resources and reduce water availability for downstream users in the long-term. Nevertheless, even if more efficient (subsidised) irrigation technologies are installed in the near future, water demands are expected to continue to increase.

Simulation of wildfire behaviour and impacts

A second case study investigated the impacts of wildfires on the forests in the Kharaa river basin. From 2000 to 2006, in total 40,600 ha of grasslands and forest were burnt in the Kharaa river basin, which corresponds to approximately 3 % of the total area. The majority of wildfires occurred in forested areas of the headwater regions, which are of major importance for regulating the water regime. To account for wildfires, the component BURN was developed linking a wildfire model that is appropriate to simulate wildfire spread and fire intensity (see Chapter 6). With this approach, we demonstrated that wildfire risk and behaviour (spread and intensity) can be successfully linked in dynamic land use simulations. The integration of BURN provided new possibilities to study impacts of wildfires on the carbon cycle. Important aspects such as the quantification of biomass loss and feedbacks to land-use decisions could be addressed. The latter was exemplified by calculating the adverse effects on firewood availability.

Scenario development and analysis

In collaboration between Mongolian and German scientists, a scenario exercise was conducted to study the consequences of alternative future pathways accounting for different drivers of change such as demography, mining, industry and agriculture. Due to the focus on IWRM-related topics, special attention was paid to future aspects of water use and consumption (see Chapter 7). Based on two GEO4 scenarios, Markets First (MaF) and Sustainability First (SuF), a narrative approach was applied, that in combination with a stakeholder workshop, aimed at the development of storylines describing the future until 2050. Results from the scenario exercise clearly indicate that in the years to come total water demand will largely increase. A major contribution to this development could be identified from the agricultural, the mining as well as the domestic sectors. Furthermore, simulations clearly showed that agricultural production under increasing fertilizer applications becomes even more limited by water availability. Results also suggest that the frequent occurrence of very dry years may lead to more severe crop failures under ‘high fertilizer’ conditions, affecting the provision of food as well as farmers’ income.

8.2 Discussion and conclusions

To recall, the major aims of this work (see Chapter 1.2) were

(i) the identification of major drivers of land-use change,

(ii) the development and implementation of the SITE-Mongolia model and

(iii) the application of the model to analyse and quantify important aspects of terrestrial dynamics and their impacts on ecosystems

Concluding the summary given above, we provided evidence that the applied model and the underlying approach, is capable of representing major aspects of land-use change including complex human-environment interactions and problems addressed in Chapter 2.3 and presented in the case studies. The achievements presented in this work may not have been possible without the opportunity to apply the SITE-framework. However, SITE is neither a complete modelling software package, nor provides and includes a readily applicable land-use model. It rather provides a structured interface that assists and guides the modeller in the process of developing and implementing models and additionally facilitates the integration of existing models (see Chapter 3). Very few comparable approaches exist in land-use modelling so far, one is the commercial Geonamica® system (Hurkensa et al., 2008). The SITE framework is designed in a modular object-oriented fashion, using modern programming languages, which provide numerous possibilities to extend the existing components and functionalities or develop and integrate new ones. This is especially important if a new case study addresses thematic issues that were not analysed in previous studies. Nevertheless, the modifications in the core of the software system can become rather complex and require a detailed understanding of the software design as well as the underlying programming concept. The benefits of using two programming language, one tailored together with the scripting Python has also been presented in other modelling approaches before (Kraft et al., 2011; Schmitz et al., 2009). Python is used as a language extension for specific modelling functionalities and provides easier access to the application domain. A major reason for using a scripting language for the integration of land-use models was that it offers a multitude of possibilities with respect to implementation, formulation of rules, processes and logical interrelations that are required to implement the rules in the land-use models (Mimler, 2007).

SITE-Mongolia, and the other models developed in SITE so far (Das et al., 2011; Priess et al., 2007a) incorporate a rule-based approach linked with the process-based simulation of the biophysical environment. In general, rule- and process based models require an understanding of land use related policies and decisions, as well as the interactions of drivers and their consequences (Heistermann et al., 2006). This study and previous studies showed that SITE has a high flexibility and capability to reproduce land-use patterns in space and time and simulate key interactions of humans with their biophysical environment, which is an important aspect of integrated approaches (Lambin et al., 2000), especially when focusing on feedbacks of the human-environment systems (Liu et al., 2007). However, Verburg et al. (2002) point out that the concept of decision or rule-based models could be problematic due to the lack of quantitative understanding of the empirical relations between data and driving factors. This problem may occur in studies with less integration of local and regional knowledge, which, in this study was the involvement of stakeholders and scientists. While (integrated) models become more and more complex, with respect to technical as well as methodological aspects, contrastingly knowledge and theory about environmental systems remains largely unchanged (Seppelt et al., 2009). SITE-Mongolia can be classified as a model of high complexity, a fact which on one hand may provide new insights, and on the other hand makes it less applicable for non-modellers - especially in a setting that employs all linked components and their interaction simultaneously.

A general research objective was defined by the The Global Land Project (GLP) – i.e. 'to measure, model and understand the coupled human-environmental system' (GLP, 2005). The approach presented above made it possible to address some of the aspects considered to be of high relevance for environmental and land-use change science as addressed by GLP (2005), especially in the field of land-use change and their feedbacks on water resources as suggested by Verburg et al (2004). To achieve progress in technical and methodological aspects, the presented integrated regional modelling approach, linking human decisions with process-based simulation of the biophysical environmental, seems an appropriate way to go. Especially the two studies presented in Chapter 5 and 6, focussing on the coupling of land - water and on land - wildfires respectively are considered to be of high relevance as they contribute to broaden the understanding about socio-environmental processes and feedbacks and on the other hand, they presented new modelling approaches. Various approaches have been published, linking land use decisions, land management, or land-cover change with hydrological modelling (Menzel et al., 2008; Sahin & Hall, 1996; Volk et al., 2007). Bormann et al (2007) in their paper emphasize that many of these approaches assume changes in vegetation cover and based on this, analyse the hydrological effects without taking into consideration feedbacks to other processes such as soils etc. This is considered one of the added values of SITE-Mongolia, namely taking into account multiple feedbacks within and between the biophysical environment and socio-economic realm. However, such integration (methodological and technical) would not have been possible without an intensive collaboration between hydrological, social and environmental science, drawing on knowledge from different domains to enable integrated modelling.

The future use of the results presented in this work is difficult to assess at this stage of the ongoing collaborative project particularly in terms of guiding decisions in the Kharaa catchment/national scale towards a more sustainable use and management of water and land resources). Further efforts are needed for a higher level of integration including results from other contributing scientific fields (e.g. groundwater hydrology, economy …) to evaluate management options. Thus, one of the priorities emerging from this study is to quantify and establish the direct link between the spatio-temporal pattern of land-use change and water-use, water demands and potential shortages in water availability. In a second collaborative step, IWRM-strategies need to be developed, possibly including new institutions and authorities such as the River Basin Council currently under implementation, as well as incentives for reduced water consumption and means of enforcement. In order to identify upcoming critical constellations (high water demands – low supply) on top of the analytical tools presented here, a continuous monitoring program is needed to detect and analyse rapid day-to-day as well as long-term changes such as degradation effects observed in forest and grassland ecosystems as well as wildfires.

8.3 Outlook

Considering that the research project funding this thesis will continue until the end of 2013, several aspects and improvements, methodological as well as technical are planned. Wildfire research will be supported by further field campaigns, in addition to one already conducted in September 2010. One of the objectives is to measure and validate simulated forest biomass and wildfire impacts, for example to improve the quantification of rates of forest re-growth. Further, scenario assessment will include a second round of stakeholder involvement and additional scenario simulations (e.g. by using an ensemble of regional climate scenarios). Moreover, it is planned to study erosion and grazing - two important aspects, which have been not considered in SITE-Mongolia so far but are relevant for the development of sustainable land management practices. Finally, but importantly, it is vital to proceed with the quantification of water-use in different economic sectors, which will be done in close cooperation with social scientists. With respect to technical developments, some improvements are on the agenda such as the integration of a new standard model interface such as the Open Modeling Interface and Environment (OpenMI, 2010). This interface would provide new opportunities for model coupling, e.g. an updated version of the ecosystem model (DayCent 5) or addressing basin hydrology with the “Soil and Water Assessment Tool” (SWAT) (Arnold et al., 2010).

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Appendix

Supplement material of Chapter 4

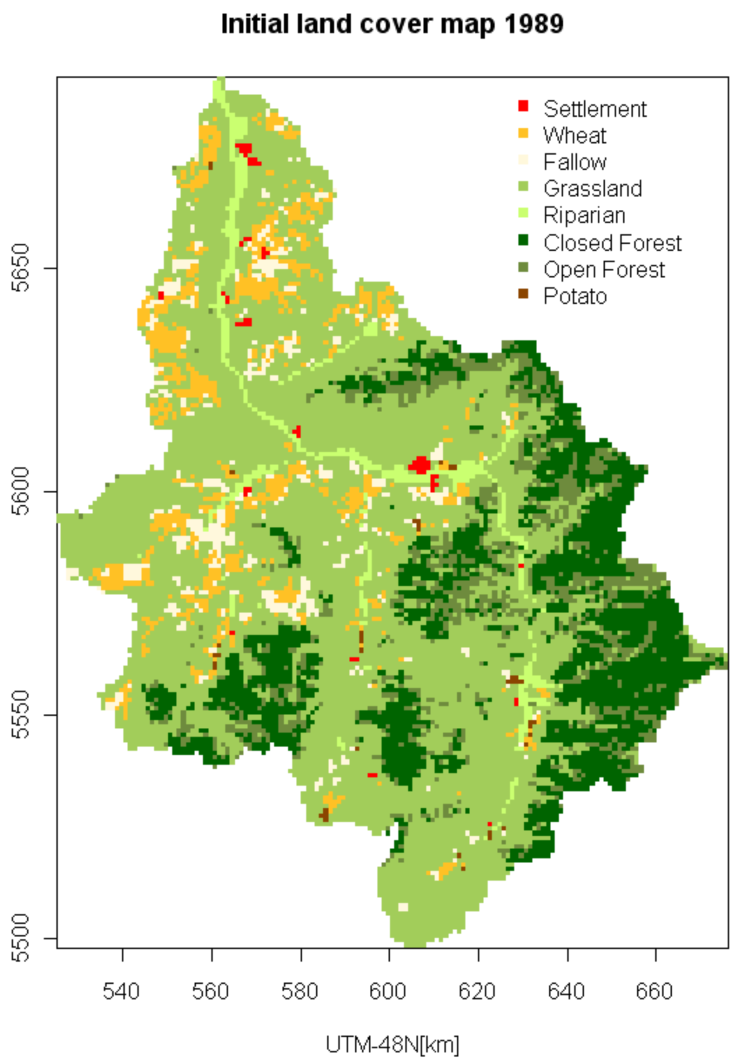
Table A-1. List of Landsat images used in the expert classification approach.

Date	Sensor	Path / Row	Spatial resolution	Scene Identifier
1989/08/21*	TM 4	132 / 026	30 m	LT4132026008923310
1989/08/21	TM 4	132 / 025	30 m	LT4132025008923310
1989/10/01	TM 4	131 / 026	30 m	LT4131026008927410
2006/08/12*	TM 5	132 / 026	30 m	L513202602620060812

* main image covering the study area.

Table A-2. Area comparison between the LULC map from 1989 (initial) and 2006 (reference).

LULC type	1989 (km^2)	2006 (km^2)	Abs. change	Rel. change (%)
Settlement	66	83	17	20.5
Wheat	1015	575	-440	-43.3
Potato	40	13	-27	-67.5
Fallow	575	96	-479	-83.3
Grassland	8570	9239	669	7.8
Riparian	468	459	-9	1.9
Closed Forest	2484	1962	-522	-21.0
Open Forest	1335	2126	791	59.3



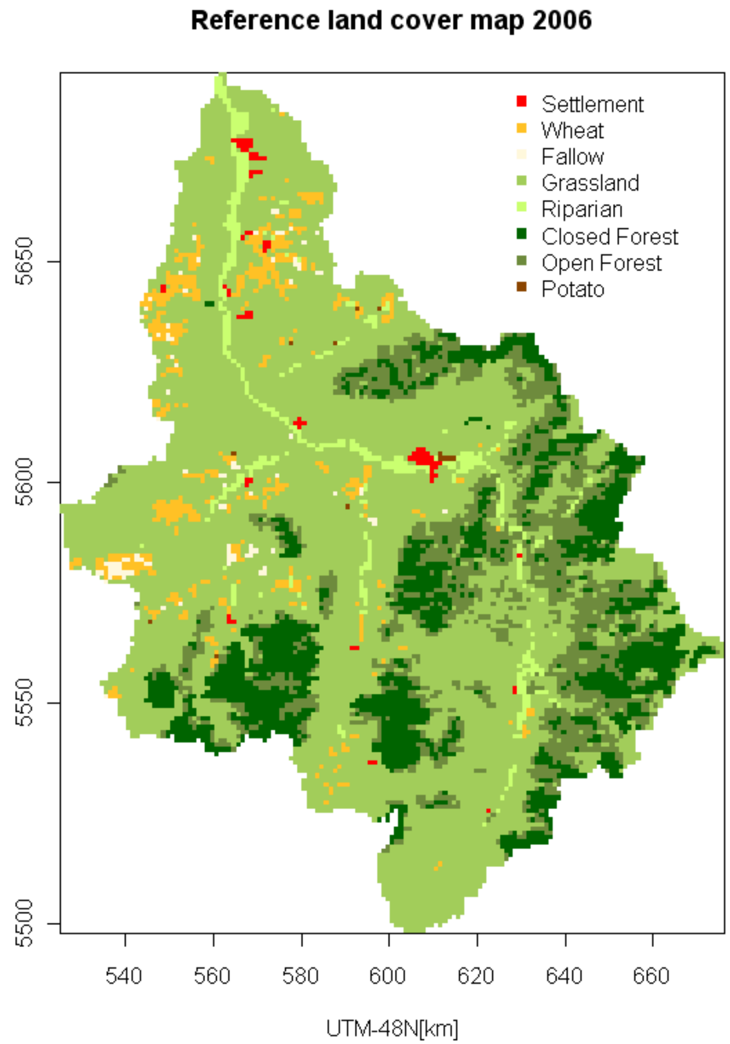


Figure A-1. Land cover maps used as model input. Initial map of the year 1989 (left) and reference map of the year 2006 (right).

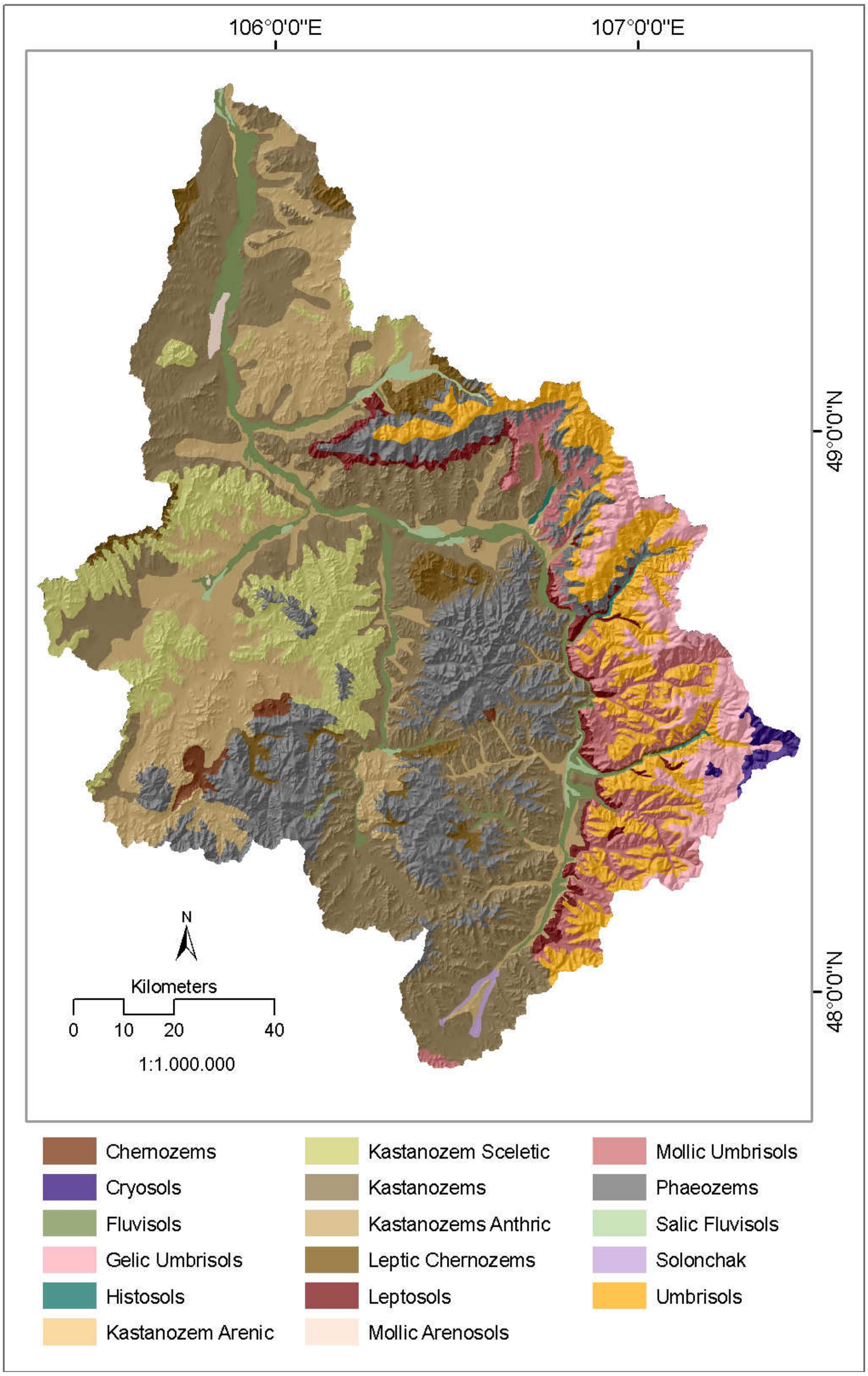


Figure A-2. Digital soil map of the Kharaa river basin.

Table A-4. Adapted values for selected (sensitive) DayCent parameters used in SITE-Mongolia. *

Crop parameters	Short description	Wheat	Potato	Grassland
PRDX(1)	Potential aboveground monthly production for crops	0.28	0.3	0.35
PPDF(1)	Optimum temperature for production of a Poisson Density Function curve to simulate temperature effect on growth	17.0	17.0	22.0
PPDF(2)	Maximum temperature for production of a Poisson Density Function curve to simulate temperature effect on growth	35.0	35.0	35.0
PPDF(3)	Left curve shape for parameterization of a Poisson Density Function curve to simulate temperature effect on growth	0.5	1.2	0.8
PPDF(4)	Right curve shape for parameterization of a Poisson Density Function curve to simulate temperature effect on growth	5.0	5.0	3.5
HIMAX	Harvest index maximum (fraction of aboveground live carbon in grain)	0.35	0.35	0.02
TMPGERM	Germination temperature for the growing degree day sub-model	10.0	8.0	10.0
DDHARV	Required number of thermal units that need to accumulate to trigger a senescence/harvest event	1200	1200	1500
TMPKILL	Temperature at which growth will stop when using the growing degree day sub-model	7.0	5.0	5.0
Tree parameters	**Short description**		**Closed Forest**	**Open Forest**
PRDX(2)	Gross forest production		0.3	0.3
PPDF(1)	Optimum temperature for production for parameterization of a Poisson Density Function curve to simulate temperature effect on growth		15.0	15.0
PPDF(2)	Maximum temperature for production of a Poisson Density Function curve to simulate temperature effect on growth		32.0	32.0
PPDF(3)	Left curve shape for parameterization of a Poisson Density Function curve to simulate temperature effect on growth		1.0	1.0
PPDF(4)	Right curve shape for parameterization of a Poisson Density Function curve to simulate temperature effect on growth		5.5	5.5
BTOLAI	Biomass to leaf area index (LAI) conversion factor for trees		0.004	0.013
MAXLAI	Theoretical maximum leaf area index achieved in mature forest		2.7	3.0

* Further description and units of the parameters can be found in the DayCent / Century online documentation at: http://www.nrel.colostate.edu/projects/century5/reference/index.htm (access 2011-04)

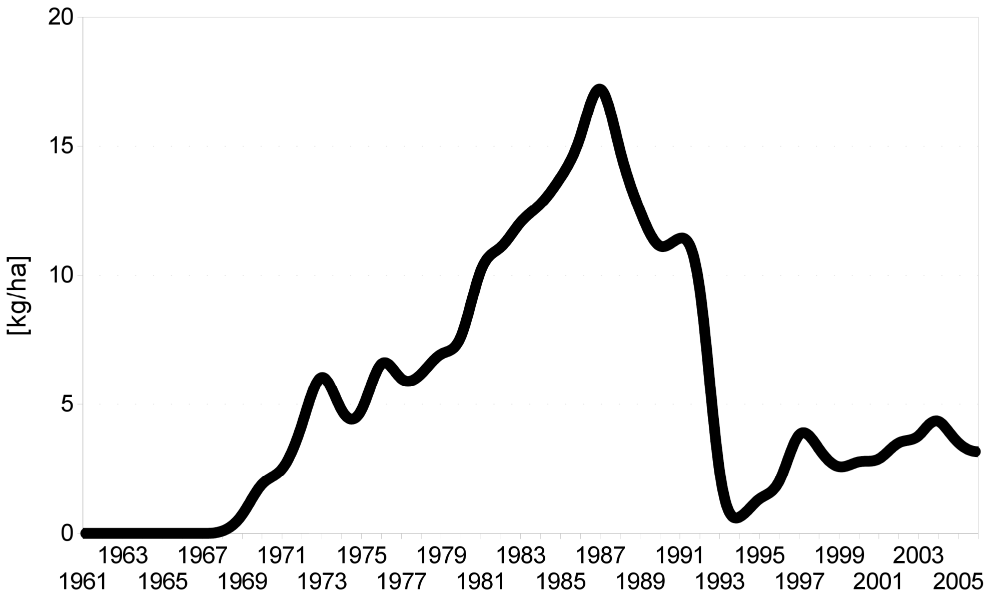


Figure A-3: Fertiliser application rates used in the DayCent model (from FAO 2009).

Table A-5. GA settings used in the calibration.

Genetic algorithm	Settlement	Overall Model
Algorithm class	Steady-state	Steady-state
Validation algorithm	Figure of Merit	Figure of Merit
Population size	30	25
Crossover probability	0.6	0.9
Mutation probability	0.03	0.03
Replacement percentage	0.25	0.3
Score frequency	10	10
Flush frequency	10	10
Number of generations	30	30

Curriculum Vitae

Angaben zur Person

Name	Christian Schweitzer
Geburtsdatum	08.12.1977
Geburtsort	Frankenberg / Eder
Nationalität	Deutsch

Berufliche Tätigkeiten

seit 09/2009	Doktorand am Department Landschaftsökologie, Helmholtz Zentrum für Umweltforschung (UFZ), Leipzig
01/2006 – 09/2009	Wissenschaftlicher Mitarbeiter und Doktorand am Center for Environmental Systems Reseach (CESR), Universität Kassel

Hochschulausbildung

1998 – 2005	Studium der Geographie (Diplom) an der Philipps Universität Marburg Nebenfächer: Geologie und Naturschutz

Berufsausbildung

1997 – 1998	Zivildienst Deutsches Rotes Kreuz Frankenberg, Ausbildung zum Rettungssanitäter

Schulausbildung

1988 - 1997	Gymnasium Edertalschule Frankenberg
1984 - 1988	Wiegand Gerstenberg Grundschule Frankenberg

Eidesstattliche Erklärung

Hiermit erkläre ich eidesstattlich, dass ich diese Dissertation selbstständig und ohne fremde Hilfe verfasst, andere als die von mir angegebenen Quellen und Hilfsmittel nicht benutzt und die den benutzten Werken wörtlich oder inhaltlich entnommenen Stellen als solche kenntlich gemacht habe.

Leipzig, den 20.06.2011

Christian Schweitzer