Jul 1st, 12:00 AM

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Linking wildfire behaviour and land-use modelling in Northern Mongolia

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Abstract: 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 a newly developed wildfire module into a land-use model, 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 areas, 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 sub-module 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 first 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.

Keywords: Land-use modelling; Wildfire; Mongolia; MODIS burned area

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 and 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. soil, hydrology). Integrated modelling approaches could provide helpful insights in wildfire-environmental interactions. Globally, the majority of wildfires are caused by human activities in a direct or indirect form. An anthropogenic influenced wildfire regime (frequency, distribution) will potentially affect human acting. This inter-relationship between humans and wildfires has initiated 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.

In this paper we present preliminary results from a modelling approach which captures the wildfire behaviour 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 newly developed a wildfire module on the basis of a well established wildfire model and linked it to our dynamic land-use model integrating new model capabilities of 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.

2 STUDY REGION

As living in Mongolia is very much dependent on the biophysical environment, the country is extremely vulnerable to natural disasters. Cold winters with heavy snowfall, 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.

The presented 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 15,000 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 the source of runoff generation, providing the whole basin with drinking water which is usually extracted from the surface waters by the rural population.

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 2000). Figure 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 forested areas (A). Within the observed period, 2.7 % (40,600 ha) of the study area was affected by wildfires, 60 % occurred in forested areas and 40% in the grassland steppe region. The seasonality of wildfires (B) shows a clear pattern of two wildfire seasons, spring and autumn, which is reported as a typical phenomena observed in Mongolia [Goldammer, 2001].

Figure 1. Area statistics and wildfire seasonality extracted from MODIS. (A) - Total annual area burned. (B) - Wildfire seasonality for 2001- 2008. Note: Due to poor pixel quality and sensor calibration tasks, the year 2000 was not included. The year 2004 could be neglected due to the absence of wildfire scars.
3 DATA & METHODS

The simulation of wildfire behaviour is depending on various, mostly highly 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 a process based ecosystem model. The core components are presented in the following paragraph, emphasising the wildfire sub-module and its data requirements. For a detailed description of the data used by the land-model and by the third party model DayCent, please refer to Priess et al. [2010] and Schweitzer and Priess [2010].

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 and Priess, 2008, Schweitzer and Priess, 2010]. The regional land-use model (SITE-Mongolia) was developed in 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., 2010]. Simulations are performed on a 1km x 1km 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. crop, grassland, settlement, forest) 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.

3.2 Wildfire sub-module

A new ‘wildfire sub-module’ was developed in addition to the existing sub-modules in SITE-Mongolia to simulate wildfire behaviour and analyse feedbacks (Figure 2). The simulation of wildfire behaviour is based on spreading algorithms described by Rothermel [1972], using a semi-empirical mathematical approach. For our study we use a modified version which is derived from the BEHAVE fire model [Andrews, 1986] and optimized for highly iterative cell-based fire growth simulations [Bevins, 1996]. The new wildfire sub-module consists of several components: (a) a file handler which executes the third party models (e.g. the wind model) including necessary pre- and post-processing steps, (b) the ‘risk analysis’, which performs a multi-criteria analysis to identify the cells which are most ‘suitable’ to burn, (c) a wind model to simulate wind speed and direction for the location of each grid cell, and (d) the wildfire model itself, executing the routines for predicting the spread rate and intensity of free-burning wildfires. Finally outputs of the wildfire sub-module (spread, intensity and flame length) are translated into net change in carbon, which is implemented using a lookup-table to establish the link to the DayCent model. Figure 2 presents a simplified scheme of the modified SITE-Mongolia model. The wildfire sub-module is executed first, calculating wildfire risk maps and wildfire behaviour for the current year. The suitability analysis then excludes wildfire affected cells in the grassland and forest use suitability. Burning intensity is translated to net loss in biomass using the DayCent model. Alteration in biomass availability influence wildfire risk, fuel availability, fuel moisture and affect land-use decisions in subsequent years.
3.2.1 Wildfire risk analysis

In a first step we perform a ‘wildfire risk analysis’ which has two objectives: (i) the identification of areas showing a significant fire risk, (ii) identification of highly suitable cells for potential wildfire ignition. Wildfire risk is computed as a function of three weighted independent categories resulting in a normalized ‘overall fire risk’ (OFR) for each cell (ranging between 0 for no risk and 1 for high risk) comparable to the suitability assessment of the SUIT module (Figure 2). The three OFR categories are: (i) Fuel availability (ii) Weather and (iii) Location. Each category consists of multiple weighted input datasets. A complete calibration and validation process (to be performed in future) can achieve 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. Weather factors (temperature, relative humidity and wind) generally belong to the 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%) 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. Hussin et al. [2008] have reported (from a district located in the study area) a positive relationship between wildfire occurrence and distance to road and distance to rivers and a negative relationship to distance to settlements. In our analysis these factors were used besides an additional settlement buffer excluding areas where wildfires are very unusual.

3.2.2 Wildfire input data

As mentioned above, wildfire modelling is dependent on detailed input to reflect the environmental conditions for starting and propagation of wildfires. In the following subsections we describe the input data required by the wildfire sub-module for the simulation of wildfire behaviour.

**Topography:** An important factor influencing the direction and speed of the wildfire spread is the terrain (slope and aspect). Combinations of wind effects and changes in slope result in the fire propagation exposing potential fuel to additional convective and radiant heat [Rothermel, 1972].
**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 is a key factor influencing wildfire propagation and assessing wildfire risk [Chuvieco et al., 2003]. In the model this parameter is described by five input maps consisting of three dead and two live fuel moisture classes. Dead fuel moisture is classified by 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 (e.g. 1-hour, 10-hours, 100-hours). The two live categories represent the fuel moisture in herbaceous and woody components. 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 lookup 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 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. As input the model requires a digital elevation model and user specified wind speed and direction values. We are glad to be able to use at least one weather station (Baruunkharaa), located in the centre of the catchment, that provides daily wind speed and direction data.

**Ignition:** To avoid 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 fire scar (spatially and temporal) and creates a ‘fire-cluster’. Within this cluster one cell with the earliest date of burning is selected as potential location and time for ignition. For the period 2000 to 2008 it is observed that on an average 16 ignitions occurred annually (60 % in spring and 40 % in autumn).

**RESULTS**

Model runs were performed for risk analysis and wildfire behavior 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

### 4.1 Wildfire risk and behaviour

Wildfire risk was simulated (see Section 3.2.1) and risk values calculated for all three categories and OFR (Table 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 1. Comparison of risk categories and OFR between Set I and Set II.

<table>
<thead>
<tr>
<th>Year</th>
<th>Set I fuel availability</th>
<th>Set I weather</th>
<th>Set I location</th>
<th>Set I OFR</th>
<th>Set II fuel availability</th>
<th>Set II weather</th>
<th>Set II location</th>
<th>Set II OFR</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>0.40</td>
<td>0.31</td>
<td>0.59</td>
<td>0.58</td>
<td>0.71</td>
<td>0.62</td>
<td>0.57</td>
<td>0.48</td>
</tr>
<tr>
<td>2002</td>
<td>0.38</td>
<td>0.31</td>
<td>0.59</td>
<td>0.57</td>
<td>0.70</td>
<td>0.62</td>
<td>0.55</td>
<td>0.48</td>
</tr>
<tr>
<td>2003</td>
<td>0.40</td>
<td>0.31</td>
<td>0.56</td>
<td>0.58</td>
<td>0.69</td>
<td>0.62</td>
<td>0.55</td>
<td>0.48</td>
</tr>
<tr>
<td>2005</td>
<td>0.39</td>
<td>0.31</td>
<td>0.53</td>
<td>0.49</td>
<td>0.75</td>
<td>0.62</td>
<td>0.55</td>
<td>0.46</td>
</tr>
<tr>
<td>2006</td>
<td>0.37</td>
<td>0.31</td>
<td>0.69</td>
<td>0.58</td>
<td>0.79</td>
<td>0.62</td>
<td>0.62</td>
<td>0.49</td>
</tr>
<tr>
<td>2007</td>
<td>0.39</td>
<td>0.31</td>
<td>0.58</td>
<td>0.55</td>
<td>0.71</td>
<td>0.62</td>
<td>0.56</td>
<td>0.47</td>
</tr>
<tr>
<td>2008</td>
<td>0.41</td>
<td>0.30</td>
<td>0.54</td>
<td>0.59</td>
<td>0.67</td>
<td>0.62</td>
<td>0.54</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>Ø 0.39</td>
<td>0.31</td>
<td>0.58</td>
<td>0.56</td>
<td>0.72</td>
<td>0.62</td>
<td>0.56</td>
<td>0.48</td>
</tr>
</tbody>
</table>

Note: The average number of cells used (denominator) for Set I is 117 and Set II is 12449.

From Table 1, it 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 3 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 DayCent 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.

4.2 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 sub-module. Figure 4 presents the comparison of both model runs, showing an increasing trend in diverging biomass availability, which could be related to the amount of wildfire occurrences extracted from MODIS (presented in Figure 1-A). As we know from MODIS observations, wildfire affected areas increase in subsequent years (2007, 2008) which may increase the difference. Due to the lack of daily climate data we are not able to continue the time series for the latter years until now. A considerable reduction in 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. Furthermore we analysed the distance from settlements to ‘highly suitable’ (>10% of max. suitability; providing sufficient biomass and adequate re-growth for a sustainable management) forest-use cells to explore changes in utilization activities. We observed (for the period 2001-2006) a 3 % (Ø 350 m) farther distance to ‘highly suitable’ cells. We conclude that an increase in wildfire disturbances in Northern Mongolian forests will enlarge the effort related with firewood collection and influence transportation costs in commercial timber production.

5 DISCUSSION & CONCLUSIONS

In this paper we present first results from the process of integrating a wildfire sub-module 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 purposes, (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 support these efforts providing an appropriate tool to study the impacts and feedbacks to the socio-environment, identify interactions responsible for the increasing wildfire risk and occurrence.

Acknowledgements

The authors thank Subhashree Das for the valuable comments to this manuscript and Jason Forthofer and Kyle Shannon from the USDA Forest Service for providing the latest version of the WindNinja model.

References


