International Congress on Environmental Modelling and Software

6th International Congress on Environmental Modelling and Software - Leipzig, Germany - July 2012

Jul 1st, 12:00 AM

Dynamic Modelling of Silvopastoral Landscape Structure: Scenarios for Future Climate and Land Use

François Gillet

Alexander Peringer

Gillet, François and Peringer, Alexander, "Dynamic Modelling of Silvopastoral Landscape Structure: Scenarios for Future Climate and Land Use" (2012). *International Congress on Environmental Modelling and Software*. 341.
https://scholarsarchive.byu.edu/iemssconference/2012/Stream-B/341

International Environmental Modelling and Software Society (iEMSs)
2012 International Congress on Environmental Modelling and Software
Managing Resources of a Limited Planet, Sixth Biennial Meeting, Leipzig, Germany
R. Seppelt, A.A. Voinov, S. Lange, D. Bankamp (Eds.)
http://www.iemss.org/society/index.php/iemss-2012-proceedings

Dynamic Modelling of Silvopastoral Landscape Structure: Scenarios for Future Climate and Land Use

François Gillet[1,2], **Alexander Peringer**[2,3]
[1] *Université de Franche-Comté – CNRS, UMR 6249 Chrono-environnement, France, francois.gillet@univ-fcomte.fr*
[2] *Ecole Polytechnique Fédérale de Lausanne, Laboratory of Ecological Systems, Switzerland*
[3] *University of Stuttgart, Institute for Landscape Planning ILPOE, Germany, ap@ilpoe.uni-stuttgart.de*

Abstract: Pasture-woodland landscapes result from a long history of silvopastoralism in mountain regions and provide valuable ecosystem services. They include a mosaic of grasslands, forests and wood-pastures, which is the heritage of a multipurpose management in the variable socio-economic and biophysical context of the last millennium. In the perspective of ongoing climate and land-use changes, it is crucial to assess the resilience and the adaptive capacity of such socio-ecological systems at different spatial and temporal scales. For this purpose, we developed a hierarchical, process-based, dynamic model, WoodPaM, and we simulated six scenarios of climate change and management in a real landscape of the Swiss Jura Mountains. Realistic climatic scenarios for the next century are likely to provoke critical changes in vegetation structure and composition, leading to a breakdown of resilience. This is due to the predicted fast decline of present dominant tree species, which will be slowly replaced by more adapted species. Assisted migration could reduce the risk of temporary forest breakdown, as suggested by simulations with enhanced immigration rate during the warming period. Logging could lead to landscape simplification or introduce shifting mosaic cycles depending on warming intensity. Active adaptive management involving modellers and stakeholders is a promising strategy to face such future changes.

Keywords: Adaptive management; Climate change; Landscape complexity; Pasture-woodland mosaic; Vegetation dynamics

1 INTRODUCTION

In most developed countries, the intensification of agriculture has generally resulted in landscape changes from small-grained heterogeneous patterns towards more monotonous and mono-functional landscapes (Brandt 2003). Particularly the multi-functional pasture-woodlands of Western Europe are threatened by a strong tendency towards segregation of land use (van Lier 1998), which leads to the spatial and functional isolation of large patches of intensively used grasslands from forests. Wood-pastures are ecosystems of high conservation value (Olff and Ritchie 1998, Svenning 2002, Poschold et al. 2005, Kleyer et al. 2007) and serve as refuge habitats for threatened species, because of their richness in vegetation types embedded into a dynamic forest-grassland mosaic. Furthermore, silvopastoral systems are among the most promising approaches for sustainable management of mountain areas world-wide (Etienne 1996). In the perspective of ongoing climate and land-use changes, it is crucial to assess the resilience and the adaptive capacity of such socio-ecological systems at different spatial and temporal scales (Holling 1973, Walker et al. 2004, Zurlini et al. 2006).

At fine scale, wood-pastures are typical examples of shifting mosaics of different short and tall stands or successional stages being driven by grazing herbivores (Olff et al. 1999, Mouissie et al. 2008). Shifting mosaics may also occur at landscape scale with more or less wooded patches (Vera 2000, Gillet 2008). In mountain pastures, dynamics is very slow because of the longevity of trees and the harsh climate. As a consequence, the impact of management actions and climate change on landscape structure may be delayed for decades. Nevertheless, due to the complex interactions that drive the dynamics of the grassland-forest mosaic, wood-pastures are supposed to be very vulnerable to the currently occurring coincidence of land-use and climate changes (Buttler et al. 2009). Overall, livestock stocking rate and climate both directly influence the establishment of trees, their regeneration being a critical stage in grazed systems determining landscape structure in the long run. Moreover, climate also determines forage production of the herb layer, which influences the spatial pattern of cattle activities such as grazing, dunging, trampling and browsing (Kohler et al. 2006). Considering such feedback loops and the unknown balance of counteracting processes, integrative long-term predictions of successional trends are required to support management decisions. Given that landscapes in Central Europe emerged during a diverse climate and land-use history, both factors explicitly have to be considered and their interactions have to be understood fundamentally when looking for future adaptation of management to climate change (Swetnam et al. 1999).

In the Swiss Jura Mountains, pasture-woodlands represent a traditional form of semi-natural landscape that is rich in biodiversity (Dufour et al. 2006). They depend on a long history of multiple and extensive land-use, including cattle stocking and logging. During the last century, socio-economic constraints for agriculture in mountain areas have changed several times, affecting both qualitative and quantitative aspects of silvopastoral management (Chételat et al. submitted, Huber et al. submitted). Thanks to various research projects on wooded pastures in the Jura Mountains, the interactions between vegetation patterns, silvopastoral management, cattle activity, grassland dynamics and tree regeneration are well known (Gillet and Gallandat 1996, Buttler et al. 2009). The spatially explicit dynamic model WoodPaM (Gillet 2008) incorporates most of the processes necessary to predict the long-term impact of silvopastoral management and temperature increase on plant communities and cattle habitat use in heterogeneous pasture-woodlands. However, critical features of climate change (temperature fluctuations and heat waves, precipitation shift from summer to winter and drought) were not implemented into this strategic model and simulation studies based on explicit time series of historical and projected climate (Moberg et al. 2005) required further model development. For this purpose, Peringer et al. [submitted] recently improved the climate sensitivity of tree species in WoodPaM based on the forest landscape model LandClim (Schumacher and Bugmann 2006). From an innovative combination of retrospective and prospective simulation experiments, they derived general rules for future adaptive management of silvopastoral systems that aim at the maintenance of the landscape mosaic and ecosystem services.

In this paper, we go beyond these studies and evaluate forest management strategies (assisted migration and logging) to alleviate impacts of future climate change on the spatial structure of a typical pasture-woodland landscape in the Swiss Jura Mountains.

2 METHODS

2.1 Model description

WoodPaM (Gillet 2008) is a spatially explicit model of pasture-woodland dynamics that is able to simulate the emergence of a semi-open landscape structure from the interactions between vegetation and large herbivores (cattle). During simulations, selective foraging of cattle causes local impacts on vegetation (grazing, browsing, trampling and dunging), which in turn and together with the general trend of forest development drive the dynamics of the landscape structure. In WoodPaM, the landscape is represented by a mosaic of square grid cells, each 25 m wide, aggregated into four spatial hierarchical levels. Each cell features three main submodels: (i) the herb layer (consisting of four ecological community types with contrasted pastoral value: eutrophic pastureland, oligotrophic pastureland, fallow and understory), (ii) shrubs (grouping all species of mostly thorny shrubs which provide safe sites for tree recruitment through protection from browsing) and trees (13 species, divided into four life stages: seedlings, saplings, small trees and big mature trees), and (iii) cattle. Local succession in the herb layer is driven by local intensity of grazing, trampling, dunging and shading. Local woody plant succession is driven by seeding input, safe-site availability in the herb layer and browsing intensity. Local successions within cells are influenced by neighboring cells through seed dispersal of trees (von Neumann connectivity) and are connected at paddock level by cattle behavior. Selective habitat use by cattle among cells within each paddock considers the attractiveness of each cell, which depends on local forage production, distance to watering points, tree cover and geomorphology (slope, rock outcrops).

In order to simulate the dynamics of pasture-woodlands for alternative scenarios of land-use and climate change in real landscapes, we developed a climate submodel and refined the tree submodel, both based on the forest landscape model LandClim (Peringer et al. submitted). Climate impacts on tree establishment and growth in semi-open landscapes have been calibrated to the suboceanic climate prevailing in the Jura Mountains. For a detailed description of the first version of the model, refer to Gillet [2008]. Recent model refinements are presented in Peringer et al. [submitted]. Finally, we added another submodel for forest management, allowing simulation of various logging and clearing options (Pradhan 2009).

2.2 Simulated landscape

We applied the model to a real pasture, La Bullatonne Dessous, located at high elevation (from 1225 to 1480 m a.s.l.) in the Jura Mountains, for which retrospective simulations showed a good fit with previous analyses of historical aerial photographs (Peringer et al. submitted). Geomorphology (altitude, slope, curvature of the landscape surface and rock outcrops), farming constraints (fences of pastures and paddocks within, watering points) and vegetation units (classes of tree cover) were arranged in a geographical information system and used to initialize the model. The pasture of 41.1 ha was divided into 9 paddocks, according to the rotational grazing system currently applied to this pasture, with an average stocking density of 1.09 livestock unit (LU) per hectare, a total stocking period of 120 days per year and an overall stocking rate of 135 LU d ha^{-1} yr^{-1}.

2.3 Design of simulations

We simulated two scenarios of future climate change, and combined them with three forest management strategies. The resulting six scenarios explore the options to adapt management practices to different degrees of climate warming. For all scenarios, we assume the persistence of current constraints on overall cattle stocking: the same grazing management was applied, consisting in adapting every year the grazing duration in each paddock to its relative forage production while maintaining a constant overall stocking rate. This adaptive grazing management mimics the traditional practice of farmers in rotational grazing systems. Future climate scenarios (Figure 1) are based on regionalized monthly temperature and precipitation time series for the 2001-2100 period. Climate data from the Climatic Research Unit of the University of East Anglia, Norwich, UK and the Tyndall Centre for Climate Change Research for two IPCC emission scenarios (IPCC 2000) has been downscaled to the 25-m grid of the model taking into account altitude, aspect and slope. The scenarios pinpoint two extreme possible futures of our world, a fuel-intensive future with drastic warming (A1FI, +8 K) and a moderate development with less warming (B2, +4 K). We assume the real development to be situated in the range between the two scenarios. After 2100, a stochastic climate time series was generated based on the means and standard deviations of temperature and precipitation of the 2091-2100 period of each scenario. Simulations are prolonged until 3000 to investigate equilibrium patterns that emerge from the climatic conditions reached at the end of available projections of climate warming. A spin-up period between 1950 and 2000 was simulated with observed climate conditions to allow adaptation of the herb layer to grazing pressure before starting the virtual experiment.

Forest management strategies consider: (i) no management (NM), assuming baseline, low and uniform immigration rate for all tree populations (0.2 1-year old seedling of each species in each cell per year); (ii) assisted migration (AM), assuming an increased immigration of 20 seedlings of each species in each cell per year during the warming period 2001-2100, and baseline immigration thereafter; (iii) forest management (FM), assuming logging every 20 years of 25% of the trees in randomly selected cells that contain at least 20 trees of the same species, and baseline immigration. The six resulting simulation experiments are subsequently named B2-NM, B2-AM, B2-FM, A1FI-NM, A1FI-AM and A1FI-FM.

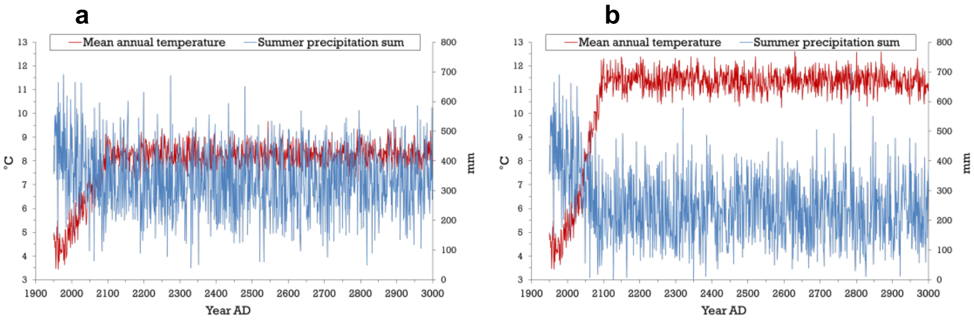

Figure 1: Example of climate time series (annual mean temperature and total precipitation in summer) resulting from two IPCC scenarios. **a**: B2, **b**: A1FI.

2.4 Model outputs

Four structural vegetation types are used for visualization of landscape mosaics (Gillet and Gallandat 1996, Gillet 2008), which represent distinct land-cover categories associated with classes of tree cover: unwooded pastures with tree cover below 1%; sparsely wooded pastures with tree cover between 1% and 20%, trees and shrubs being mostly scattered; densely wooded pastures with tree cover within the range 20-70% and a coarse-grained structure; grazed forests with tree cover higher than 70% and small clearings included in a forest matrix. Overall mosaic structure can be described by various landscape metrics. An aggregation index was computed for each land-cover class (He et al. 2000). The landscape aggregation index, ranging between 0 and 1, is the weighted mean of these four class-specific aggregation indices and is an inverse measure of the spatial complexity of the landscape, related to habitat fragmentation and edge density.

3 RESULTS AND DISCUSSION

3.1 Impact of climate change without any forest management

The simulations showed that climate-change impacts are delayed for decades and centuries after warming started in calendar year 2001, and that future landscape structure is strongly dependent on the degree of warming (Figure 2, a-b).

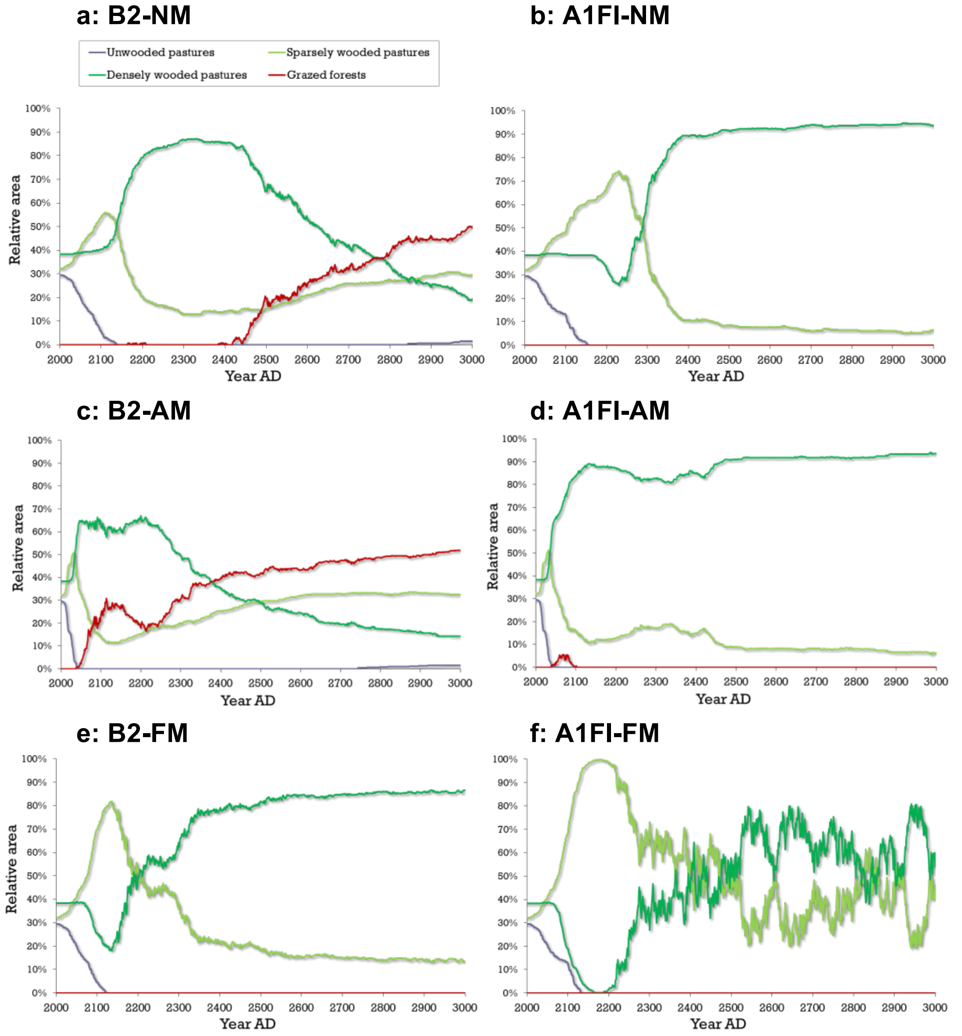

Figure 2: Land-cover dynamics following a combination of two scenarios of climate change (B2: moderate, A1FI: extreme) and three forest management strategies (NM: no management, AM: assisted migration, FM: logging and clearing).

Until 2050, only minor changes occurred with transformation of unwooded pastures into sparsely wooded pastures. This period was initiated by the first years of warming, which facilitated establishment and growth of Norway spruce (*Picea abies*), the currently dominant species in the study area. Afterwards, however, succession lines diverged according to the degree of warming. Just after the warming period, sparsely wooded pastures transformed into densely wooded pastures in the moderate scenario B2-NM (progressive succession), while in the extreme warming scenario A1FI-NM, densely wooded pastures decreased and sparsely wooded pastures temporarily dominated (regressive succession). Thereafter, progressive forest succession took place again in both scenarios, however towards very different landscape patterns: in the B2-NM scenario, a segregation between grazed forests and sparsely wooded pastures with some open grasslands took place, while in the A1FI-NM scenario, grazed forests never developed and the mosaic turned into a homogenous landscape consisting basically of densely wooded pastures.

The temporary decrease in tree cover between 2050 and 2200 corresponded to the shift in tree species composition driven by climate change (Peringer et al. submitted). In both scenarios, spruce declined dramatically from year 2000 on and its decline was accelerated with warming, due to its sensitivity to drought stress. In the moderate scenario B2-NM, spruce was replaced by beech (*Fagus sylvatica*) from year 2100 on, but waiting year 2300 to reach significant cover at landscape scale. At this time spruce cover was reduced to approximately one third of its initial value. Pioneer species, such as rowan (*Sorbus aucuparia*), played an important role in this successional transition phase. In the extreme warming scenario A1FI-NM, spruce disappeared more rapidly and was very slowly replaced by Scots pine (*Pinus sylvestris*), accompanied by downy oak (*Quercus pubescens*), a submediterranean species.

The landscape structural complexity decreased in the period 2000-2200, as indicated by a high landscape aggregation index (Figure 3, blue lines). Thereafter, tree species shift increased landscape complexity in both scenarios, but while aggregation continued to decrease in scenario B2-NM due to the diversification of the landscape, it was not the case for scenario A1FI-NM: here, landscape complexification was only temporary, and the development of densely pine-wooded pastures led to the emergence of a highly simplified spatial pattern since year 2400.

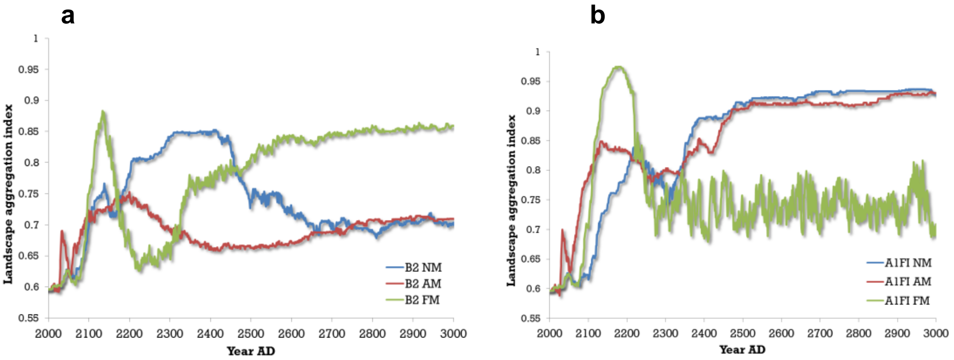

Figure 3: Time series of the landscape aggregation index following two scenarios of climate change and three strategies for forest management. **a**: B2, **b**: A1FI.

3.2 Impact of forest management

Assisted migration, which is simulated in our AM scenarios simply by a temporary higher immigration rate of all tree species, does not change the final configuration of the landscape but reduced the time required for species replacement, thus preventing forest breakdown due to the decline of the dominant species (Figure 2, c-d). This acceleration of plant succession was accompanied by a smoothing effect on landscape dynamics, evidenced by the small variation in landscape aggregation index after year 2200 (Figure 3, red lines). While scenario B2-AM led to a rapid dominance of beech in the landscape, scenario A1FI-AM allowed many tree species to establish, among them downy oak, Scots pine and beech being the most abundant at long term.

Logging turned out to have a qualitative impact on long-term vegetation dynamics and landscape structure (Figure 2, e-f). Periodic cutting of abundant trees prevented any development of both grazed forests and unwooded pastures. The first phase of the succession was characterized by a peak of sparsely wooded pastures in both warming scenarios. In B2-FM scenario, a stable equilibrium was reached at year 2600 with a landscape dominated by densely wooded pastures with beech and rowan as dominant species. By contrast, for A1FI-FM scenario, no stable state was reached and a shifting mosaic of sparsely and densely wooded pastures occurred from year 2300, with Scots pine, downy oak and rowan as dominant species. Logging showed very different effects on landscape complexity depending on warming intensity (Figure 3, green lines). After a peak just after the warming period, landscape aggregation index increased again dramatically from 2200 in scenario B2-FM (stable simplified landscape) whereas it fluctuated around a lower value since 2300 in scenario A1FI-FM (complex and unstable landscape).

4 CONCLUSIONS AND RECOMMENDATIONS

Silvopastoral landscapes established from the Middle Ages in the Jura Mountains proved to be resilient to past climate and land-use changes (Peringer et al. submitted). According to our simulations, resilience and adaptive capacity will be challenged in the future due to inexorable changes in tree species composition and landscape structure driven by warming and drought stress.

Our simulations clearly outline the potential of forest management to alleviate these effects of climate change. Assisted migration is capable to prevent forest breakdown during the climate-driven shift in tree species composition and the subsequently building of new forest communities, thereby supporting the continuous provision of forest ecosystem services. Logging triggers inverse effects on landscape structure than undisturbed succession following climate change. Moreover, the same logging strategy may lead to either relative simplification (B2) or complexification (A1FI). Due to the difficulty to foresee the consequences of forest management at long term in such complex systems, we recommend careful selective logging strategies. Any direct human intervention should focus on the maintenance of landscape heterogeneity and complexity, by use of the traditional selective felling of single trees instead of extensive clear-cutting.

While extensive grazing is obviously causal for dynamic grassland-forest mosaics, forest management is complementary in order to maintain landscape complexity and biodiversity. However, grazing management needs adaptation to new climatic conditions. Since the vegetation period will increase with warming, a progressive increase of stocking period would be adequate to prevent tree colonisation in unwooded and sparsely wooded pastures. This could also be achieved by the use of mixed herds (cattle, horses, sheep and goats) in an adapted rotational system.

Considering uncertainties in future dynamics of these socio-ecological systems, adaptation to climate change would require a strategy based on the principles of active adaptive management, i.e. implementing policies as experiments (Holling 1978). This implies a strong collaboration among field ecologists, modellers and stakeholders in order to improve long-run management outcomes based on a learning process.

ACKNOWLEDGEMENTS

This research was supported by the CCES (Competence Center Environment and Sustainability of the ETH Domain, Switzerland) as part of the Mountland project, and by the State Secretariat for Education and Research (SER C07.0112) in the framework of the COST Action FP0603.

REFERENCES

Brandt, J., Multifunctional landscapes: perspectives for the future, *Journal of Environmental Sciences-China, 15*, 187-192, 2003.

Buttler, A., F. Kohler, and F. Gillet, The Swiss mountain wooded pastures: patterns and processes, pp 377-396 in A. Rigueiro-Rodriguez, J. McAdam, and M.R. Mosquera-Losada (eds), *Agroforestry in Europe: Current Status and Future Prospects*, Springer, New York, 2009.

Chételat, J., M. Kalbermatten, K. Lannas, T. Spiegelberger, J.B. Wettstein, F. Gillet, A. Peringer, and A. Buttler, A contextual analysis of observed land-use and vegetation changes applied to two wooded pastures in the Swiss Jura Mountains, *Ecology and Society*, submitted.

Dufour, A., F. Gadallah, H.H. Wagner, A. Guisan, and A. Buttler, Plant species richness and environmental heterogeneity in a mountain landscape: effects of variability and spatial configuration, *Ecography, 29*, 573-584, 2006.

Etienne, M., *Western European Silvopastoral Systems*, INRA Editions, Paris, 1996.

Gillet, F., Modelling vegetation dynamics in heterogeneous pasture-woodland landscapes, *Ecological Modelling*, *217*(1-2), 1-18, 2008.

Gillet, F. and J.D. Gallandat, Wooded pastures of the Jura Mountains, pp. 37-53 in M. Etienne (ed.), *Western European Silvopastoral Systems*, INRA Editions, Paris, 1996.

He, H.S., B.E. DeZonia, and D.J. Mladenoff, An aggregation index (AI) to quantify spatial patterns of landscapes, *Landscape Ecology, 15*(7), 591-601, 2000.

Holling, C.S., Resilience and stability of ecological systems, *Annual Review of Ecology and Systematics, 4*, 1–23, 1973.

Holling, C.S. (ed.), *Adaptive Environmental Assessment and Management*, Wiley, Chichester, 1978.

Huber, R., S. Briner, A. Peringer, R. Seidl, S. Lauber, Q.B. Le, A. Buttler, F. Gillet, and C. Hirschy, From vegetation dynamics to farm structural change and policy assessment: modelling feedback effects in the pasture woodlands of the Swiss Jura Mountains, *Ecology and Society*, submitted.

IPCC, Emissions Scenarios: Summary for Policymakers, A Special Report of IPCC Working Group III, Intergovernmental Panel on Climate Change, 2000.

Kleyer, M., R. Biedermann, K. Henle, E. Obermaier, H.J. Poethke, P. Poschold, B. Schröder, J. Settele, and D. Vetterlein, Mosaic cycles in agricultural landscapes of Northwest Europe, *Basic and Applied Ecology, 8*, 295-309, 2007.

Kohler, F., F. Gillet, S. Reust, H.H. Wagner, F. Gadallah, J.M. Gobat, and A. Buttler, Spatial and seasonal patterns of cattle habitat use in a mountain wooded pasture, *Landscape Ecology, 21*, 281-295, 2006.

Moberg, A., D.M. Sonechkin, K. Holmgren, N.M. Datsenko, and W. Karlen, Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data, *Nature, 433*, 613-617, 2005.

Mouissie, A.M., M.E.F. Apol, G.W. Heil, and R. van Diggelen, Creation and preservation of vegetation patterns by grazing, *Ecological Modelling, 218*, 60-72, 2008.

Olff, H., and M.E. Ritchie, Effects of herbivores on grassland plant diversity, *Trends in Ecology and Evolution 13*, 261-265, 1998.

Olff, H., F.W.M. Vera, J. Bokdam, E.S. Bakker, J.M. Gleichman, K. de Maeyer, and R. Smit, Shifting mosaics in grazed woodlands driven by the alternation of plant facilitation and competition, *Plant Biology, 1*, 127-137, 1999.

Peringer, A., S. Siehoff, J. Chételat, T. Spiegelberger, A. Buttler, and F. Gillet, Past and future landscape dynamics in wooded pastures of the Jura Mountains under land-use and climate change, *Ecology and Society*, submitted.

Poschlod, P., J.P. Bakker, and S. Kahmen, Changing land use and its impact on biodiversity, *Basic and Applied Ecology, 6*, 93-98, 2005.

Pradhan, P., Implementation of forest management strategies and natural episodic events in a dynamic model of silvopastoral system, STSM Report, COST Action FP0603, Besançon, 2009.

Schumacher, S. and H. Bugmann, The relative importance of climatic effects, wildfires and management for future forest landscape dynamics in the Swiss Alps, *Global Change Biology, 12*, 1435-1450, 2006.

Svenning, J.C., A review of natural vegetation openness in north-western Europe, *Biological Conservation, 104*, 133-148, 2002.

Swetnam, T.W., C.D. Allen, and J.L. Betancourt, Applied historical ecology: using the past to manage for the future, *Ecological Applications, 9*, 1189-1206, 1999.

van Lier, H.N., The role of land use planning in sustainable rural systems, *Landscape and Urban Planning 41*, 83-91, 1998.

Vera, F.W.M., *Grazing Ecology and Forest History*, CAB International, Oxford, 2000.

Walker, B., C.S. Holling, S.R. Carpenter, and A. Kinzig, Resilience, adaptability and transformability in social-ecological systems, *Ecology and Society, 9*(2), 5, [online] URL: http://www.ecologyandsociety.org/vol9/iss2/art5, 2004.

Zurlini, G., K. Riitters, N. Zaccarelli, I. Petrosillo, K.B. Jones, and L. Rossi, Disturbance patterns in a socio-ecological system at multiple scales, *Ecological Complexity, 3*, 119-128, 2006.