CHANGE DETECTION IN MIRE ECOSYSTEMS: ASSESSING CHANGES OF FOREST AREA USING AIRBORNE REMOTE SENSING DATA

L.T. Waser [a, *], E. Baltsavias [b], H. Eisenbeiss [b], C. Ginzler [a], A. Gruen [b], M. Kuechler [a], P. Thee [a]

[a]Swiss Federal Research Institute WSL, Research Unit Land Resource Assessment, Zuercherstr. 111, 8903 Birmensdorf, Switzerland - (waser, ginzler, kuechler, thee)@wsl.ch
[b]Institute of Geodesy and Photogrammetry, ETH Zurich, Wolfgang-Paulistr. 15, 8093 Zurich, Switzerland; - (manos, ehenri, agruen) @geod.baug.ethz.ch

ISPRS WG VII/1

KEY WORDS: Swiss Mire Protection Program, fractional tree/shrub cover, LIDAR, CIR-orthoimage, digital surface model (DSM)

ABSTRACT:

The objective of this paper is to present an approach for assessing tree growth and shrub encroachment between 1997 and 2002 in open mire land using CIR-aerial images, DSMs and LiDAR data. The study area is located in the Pre-alpine zone of Central Switzerland. The present study was carried out in the framework of the Swiss Mire Protection Program, where changes of forest area are a key issue. Automatic DSMs were generated from CIR- aerial images of 1997 and 2002. This automated DSM generation is based on high accuracy, intelligent matching methods developed at ETHZ which are able to produce very dense and detailed DSMs that allow a good 3D modelling of trees and shrubs, and a multitemporal analysis of their growth pattern. Forest masks from both years of various levels of detail were then generated combining canopy covers derived from the DSMs using multi-resolution segmentation and a fuzzy classification. On the basis of these forest masks fractional tree/shrub covers were generated using explanatory variables derived from the DSMs and logistic regression models. The models reveal a general decrease of forest area between 1997 and 2002. On the other side, the models also indicate real shrub encroachment and tree growth in open mire land.

1. INTRODUCTION

The present study focuses on assessing changes of tree / shrub area in a typical mire ecosystem between 1997 and 2002. The study was carried out in the framework of the Swiss Mire Protection Program which aims at conserving mire ecosystems of national importance and outstanding beauty in their present state. This implies no decrease of the mire area and no degradation of vegetation. A monitoring program based on a representative sample of 130 mires was set up in 1996 to examine the effectiveness of the conservation status (Grünig et al.2004; Küchler et al., 2004).
An early detection and evaluation of increase and decrease of the entire wooded area may help for preservation of these biotopes. However, several studies (e.g. St-Onge & Achaichia, 2001 and Watt & Donoghue, 2005) revealed that using traditional methods of field survey or aerial photograph interpretation to gain information on shrub encroachment and tree growth etc. is not feasible for larger monitoring programs regarding costs and time.
In contrast, increase and decrease of forest area and occurrence of shrubs can be estimated using high-resolution remotely sensed data. E.g. canopy height models can be calculated by subtracting a digital terrain model (DTM) from a digital surface model (DSM). Meanwhile, several LiDAR systems are commercially available (e.g. Baltsavias, 1999; Heurich et al., 2003; Hyyppä et al., 2000), enabling the derivation of DSMs and DTMs from such data as well. Some studies suggest the use of DSM data to detect changes in the forest stands (Schardt et al., 2002; Naesset & Gobakken, 2005) and to evaluate growth estimations (including extent of forest area and shrub encroachment).

There is a growing need for sensitive tools to predict spatial and temporal patterns of plant species or communities (Kienast et al., 1996). Spatially explicit predictive modelling of vegetation is often used to construct current vegetation cover using information on the relations between current vegetation structure and various environmental attributes (Küchler et al., 2004). E.g. Guisan & Zimmermann (2000) and Scott et al. (2002) point out that modern regression approaches have proven particularly useful for modelling spatial distribution of plant species and communities. Since old CIR-aerial images are often available and necessary variables of the DSM can be calculated, retrospective analysis of changes in forest area and shrub/tree encroachment in a mire biotope is feasible. Thus, airborne remote sensing data in combination with generalized linear models (GLM) could be useful for modelling these changes in mire ecosystems over time.

The objective of the present study is to assess changes of forest tree / shrub area in a mire ecosystem between 1997 and 2002 using logistic regression models and airborne remotely sensed data. A fractional cover approach was chosen since it is widely known that the discretization of tree covers (Mathys et al., 2006) into a limited number of categories results in a loss of information and that fractional cover has higher potential to describe accurately land cover change over time. For this modelling approach two methods have been implemented: a new image matching method (Zhang & Gruen, 2004) and a method of discrete forest masking that has already been successfully applied for 130 mire objects (Küchler et al., 2004).

* Corresponding author

2. MATERIAL AND METHODS

2.1 Study area

Models have been developed and tested for the mire "Eigenried" which is located on a small plateau in the East of Lake of Zug in the Pre-alpine zone of Central Switzerland (approx. 47°07' N and 8°32' E). The mire site covers an area of 2.61 km^2. The altitude varies from 850 m to 1000 m above sea level. The landscape is highly fragmented and characterized by pastures that are crossed by shrubs and bright broad-leafed woodland (see Fig. 1 and 2). The dominant vegetation types are moist and wet meadows and pastures, low sedge poor fen, bog forest and broad-leaved woodland and willow Carr. The bordering forested area is mostly characterized by opened mixed forest (approx. 40%) and coniferous forest (approx. 60%).

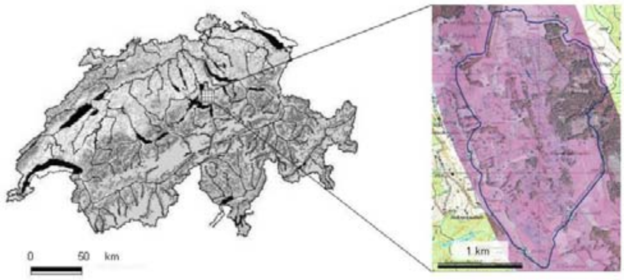


Figure 1. Overview of the testsite (CIR-orthophoto © WSL 2003 and pixelmap © 2006 Swisstopo JD052552).

Figure 2. The mire is characterized by bog and fenland, bright broad-leafed woodland and shrubs.

2.2 Remotely sensed data

This study uses three different sets of input data: The first data set consists of CIR-aerial images: 4 (1 strip) of 1997 and 12 (2 strips) of 2002, scale 1:10000 and 1:5700, respectively. Orthoimages were produced with a spatial resolution of 0.5 m As second data set DSMs were generated automatically from the above images of the years 1997 and 2002, respectively with a spatial resolution of 0.5 m. Third data set: national LiDAR data of the Swiss Federal Office of Topography (Swisstopo) was acquired in 2001 with leaves off. From the raw data, both a DTM and DSM are generated by Swisstopo (as raw irregularly distributed points and regular grid; the first dataset was used in this study). The average density of the DSM data was 1-2 points / m^2 and the height accuracy (1 sigma) 0.5 m for open areas and 1.5 m for vegetation and buildings. The DTM has an average point density of 0.8 points / m^2 and height accuracy (1 sigma) of 0.5 m (Artuso et al. 2003). The DTM was interpolated to a regular grid with 0.5 m grid spacing for reasons explained below.

2.3 Automatic generation of digital surface models

Since accurate surface information in forested and open mire land is very important for this modelling approach high-resolution DSMs of 1997 and 2002 are indispensable. Thus, a matching method which is described in detail in Zhang (2005) and Zhang and Gruen (2004) was used. This method can simultaneously use any number of images (> 2), matches very densely various primitives (grid points, feature points with good texture and edges), uses geometrical constraints to restrict the search space, combines two matching algorithms (sum of modified cross-correlation, and least squares matching) to achieve speed but also higher accuracy if needed, combines the matching results of the three primitive types with another matching approach to ensure local consistency, and performs an automatic blunder detection. The matching method is implemented in the operational, quasi-complete photo-grammetric processing package Sat-PP which supports satellite and aerial sensors with frame and linear array geometry. The result was a regular grid DSM with 0.5 m spacing which was interpolated from a matching point cloud of similar density (ca. 15 million match points per stereo-pair). The matching DSMs of 1997 and 2002, and the LiDAR DSM and DTM were co-registered, using a point cloud co-registration procedure described in Akca (2005), Gruen and Akca (2005) and Akca and Gruen (2005). This co-registration uses a 7-parameter 3D similarity transformation to remove systematic differences (bias) between two datasets, e.g. due to different image orientation. For the estimation of these parameters, we used control surfaces, i.e. DSM parts that did not change in the two datasets, i.e. bare ground, and also removed large differences due to matching errors with a robust filtering. After co-registration, different products could be generated and conclusions drawn. The difference 2002-1997 matching DSM gives the changes between the two epochs, especially regarding vegetation. After co-registration, the Z-component of the Euclidian distances (sigma a posteriori) was 3.4 m, showing a clear reduction of trees and other wooded plants from 1997 to 2002. The difference matching DSMs minus LiDAR DTM gives the normalized DSMs, i.e. the 3D objects in the scene and especially the canopy models (Fig. 3). The LiDAR DSM was also subtracted from the 2002 DSM, in spite of the small time difference.

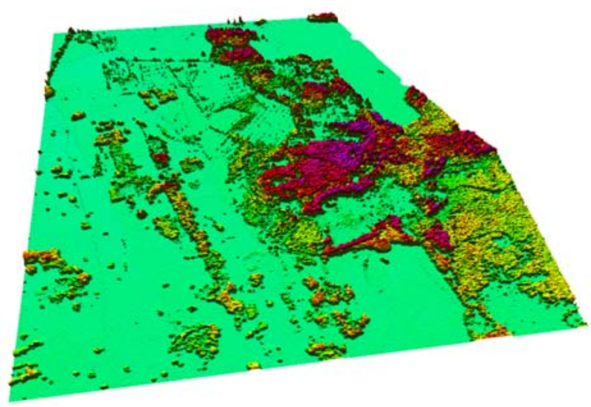


Figure 3. The 2002 matching DSM minus the LiDAR DTM, showing 3D objects on the terrain, especially trees and shrubs. Non-vegetation objects like buildings could be detected and eliminated by using multispectral classification, size and shape etc., thus leading to a true canopy model (see section 2.4).

2.4 Forest masks

In the present study, two forest masks serve as basis (response variable) for the fractional modelling approach. Two canopy covers were calculated by a multistage procedure using slope data of the normalized DSMs. This simple but robust algorithm incorporates a slope threshold, minimum area for tree canopy and minimum area for forest gaps in the normalized DSM data. In a second step, non-tree objects (buildings, rocks etc.) of the canopy covers were removed by an object-oriented image analysis using spectral information of the CIR-orthoimages. This implies a two stage process with a multi-resolution segmentation of the canopy cover and CIR-orthoimages and a fuzzy classification using *eCognition* (Baatz & Schäpe, 2000). The resulting forest masks of 1997 and 2002 are a product of different slope thresholds, minimum tree canopy area and minimum gap size. These thresholds for the three parameters have been set empirically but have been successfully tested for fine-scale modelling of forest area in mire ecosystems in Küchler et al. (2004). Only pixels with slope values higher than 20 degrees, a minimum tree canopy area on single tree level (5 m^2) and a maximum gap size of 120 m^2 were considered.

2.5 Fractional tree/shrub covers

Whether a pixel belongs to a forest mask or not can be attributed to a binomial variable. Logistic regression is adapted for modelling such data (see e.g. McCullagh & Nelder, 1983). The result is a fractional tree/shrub cover, i.e. a probability for each pixel to belong to the class "tree/shrub". The training data for the model were selected in a way to enable estimation of bias: only pixels were used which belong to the same class in both surveys i.e. that were either corresponding forest pixels or open land pixels in the 1997 and 2002 forest masks. The explanatory variables consist of five commonly used topographic parameters derived from normalized DSMs (slope, aspect, curvature, and local neighbouring functions), see table 1 and for further details see Burrough (1986). Most of these parameters have successfully been applied for ecological modelling purposes in mires (Küchler et al., 2004) or in biodiversity studies (Waser et al., 2004). Two fractional tree/shrub covers of 1997 and 2002, respectively were produced using the forest masks described in section 2.4.

Name	Derivation
curvature	curvature of the surface at each cell center (3x3 window)
plan	curvature of the surface perpendicular to the slope direction, referred to as the planform curvature (3x3 window)
prof	rate of change of slope for each cell, curvature of the surface in the direction of slope (3x3 window)
slope	rate of maximum change in z value from each cell
top	assessment of topographic position (4 classes: ridge, slope, toe slope and bottom), the resulting grid displays the most extreme deviations from a homogenous surface

Table 1. Overview of the five explanatory variables (derived from nDSM) used to generate the fractional shrub/tree covers.

2.6 Bias estimation

A possible bias may result from different data quality of the CIR-aerial images from the two survey times, e.g. different spatial resolution, different image scanning facilities, varying radiation etc. In the context of predictive modelling, bias denotes a systematic error in predicted values which might be misinterpreted as a change. Küchler et al. (2006) present a method of estimating bias arising from different data quality in two surveys.

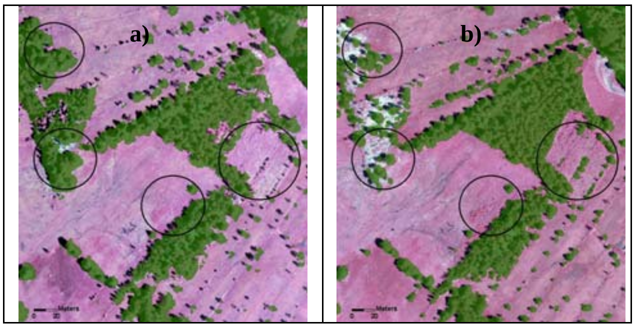
In the present study, bias was estimated by the following procedure: The probabilities of each pixel of the corresponding smoothed fractional cover (i.e. *model_uncorr*) were added together and the sums stratified into 20 classes. Lowest class (0.0 - 0.1) of model sums corresponds to "non-tree/shrub" whereas the highest class (1.9 - 2.0) corresponds to "tree/forest". Intermediate classes represent either partly forested areas or areas that have been deforested or areas where shrub encroachment occurred. To estimate bias, the smoothed fractional covers (2002 - 1997) were subtracted. Then distributions of the resulting differences were analysed separately within each of the 20 classes. As result, discrete bias estimations for each class were obtained. To have a continuous bias estimation the discrete values were smoothed by Loess regression with span 0.3.

2.7 Validation data

For validation purposes ground truth data was produced using digitized samples from stereo-images. Three types of samples were distinguished and a total number of 3 x 20 samples were digitized from the aerial images: 1. Tree/shrub-less areas in 2002 that belonged to tree/shrubs in 1997 (decrease), 2. Tree/shrub-less areas in 1997 that are covered with trees/shrubs in 2002 (increase) and 3. Tree/shrub areas and tree/shrub-less areas those are unchanged between 1997 and 2002 (equal).

3. RESULTS

Fig. 4 a-d visualizes the difference between the forest masks and fractional covers of both years in a typical part of the mire where small shrubs and single trees are well present. The tree area extracted by both data sets is 0.901km^2 (*forest_mask97)* and 0.832km^2 *(forest_mask02)*, respectively.



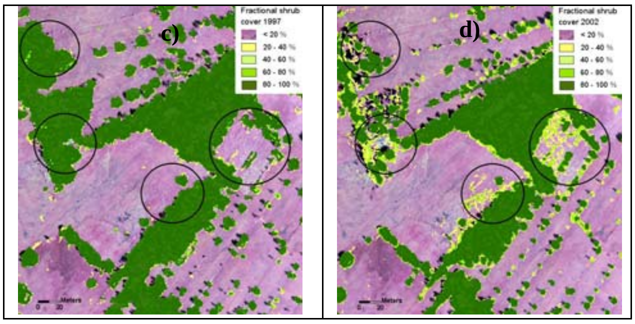


Figure 4. a) CIR-orthoimage with forest masks of 1997 and **b)** of 2002, **c)** and **d)** corresponding fractional tree/shrub covers. The two circles on the left side mark areas with decreased tree/shrub cover due to deforestation/loggings. The two circles on the right side mark increased tree growth / shrub encroachment.

Visual image inspection revealed that several shrubs and small single trees are still not extracted in the remaining open mire land. Therefore two fractional tree/shrub covers of 1997 and 2002 were produced using the forest masks described in section 2.4 as training data sets. A tree/shrub cover stratum of e.g. 0.1 - 1 (10-100%) means, that all pixels with a probability higher than 10% are assigned to shrub/tree etc. Fig 4c-d) shows the five predicted tree/shrub cover strata for a typical part of the mire. Tree/shrub area that is previously missed by the forest masks is extracted as well – dependent on the threshold of probability. Area of extracted trees/shrubs increases with lower probability thresholds. At the same time errors increase too. E.g. visual stereo image analysis revealed that a cover stratum of 10-100% also considers other vegetation than shrubs such as tall grass or herbs. In contrary, considering only a cover stratum of 0.5 – 1.0 (50-100%) leads to a significant underestimation of shrubs and trees in the open mire land.

Decrease and increase of forest area and other wooded area (1997-2002) is given in table 2. The forest mask reveals a decrease of tree/shrub pixel portion of -0.059 between 1997 and 2002. Overall, the fractional cover approach revealed a decrease of tree/shrub probability between 1997 and 2002 of -0.029 for the uncorrected model (including bias) and -0.037 for the corrected model.

Differeneces 2002 - 1997	Description	Mean change of tree/shrub pixel portion
forestmask97_02	forest masks 2002 - 1997	-0.059
		Mean difference of tree probability
Model_uncorr (not bias corrected)	based on forest masks	-0.029
Model_corr (bias corrected)	based on forest masks	-0.037

Table 2. Variations of change estimations for tree/shrub probability (1997-2002) as obtained by different methods.

Table 3 summarizes the changes of tree/shrub pixel portion between 1997 and 2002 on the digitized sample areas between the forest masks and the changes of tree/shrub probability of the corrected fractional covers. Both the forest masks and fractional tree/shrub covers reveal no decrease/increase between 1997 and 2002 on the digitized samples where no change occurred. Forest mask and corrected model show a substantial decrease of tree/shrub probability in delineated areas where tree/shrub area declined between 1997 and 2002. Good information on deforestation is also given by *forestmask97_02*. However, shrub encroachment and growth of small trees in open mire land is not or only slightly detected when using the forest mask (+0.081). In contrary, the corrected model (+0.178) shows a shrub encroachment (general increase of tree/shrub probability in areas that were delineated as increase).

Differences 2002-1997	digitized as	Mean change of tree/shrub pixel portion
forestmask97_02	decrease	-0.602
	equal	-0.000
	increase	+0.081
		Mean difference of tree/shrub probability
Model_corr.	decrease	-0.518
	equal	-0.000
	increase	+0.178

Table 3. Mean differences in tree/shrub probability (2002-1997) on the digitized sample areas.

4. DISCUSSION AND CONCLUSION

Combining remote sensing data with regression analysis with fractional cover approaches as it is performed in many studies for land cover mapping (Guisan and Zimmermann 2000; Mathys et al. 2006) also is shown to be appropriate for fractional tree/shrub cover mapping and assessing changes of forest area in a mire biotope. The usage of standard explanatory variables as already applied in other studies (e.g. Küchler et al. 2004 and Waser et al. 2004) derived from the normalized DSM proved to be a good approach for fractional modelling. With a fractional cover approach, also subtle changes of forest area and of other wooded area can be detected before reaching a discrete threshold value. Furthermore, shrub/tree classifications based on the continuous data can be adjusted retrospectively. This may be an advantage also for mire habitat management. However, different quality of the scanned CIR-aerial images and the normalized DSMs from the two surveys 1997 and 2002 caused systematic errors in the predicted values of the models which could be misinterpreted as a change of forest area. In fact, bias proved to occur at a scale which would, without correction, make impossible e.g. a reproducible statement whether the removal of trees and shrubs or the encroachment by growing bushes was predominant in the survey time. Estimation and correction for bias is essential if any change has to be assessed by statistical modelling.

Overall, the present study reveals a general decrease of forest area due to hurricane *Lothar* in 1999 and selective logging of groups of trees in the frame work of the regeneration program. These differences of the corrected fractional tree/shrub covers give us reliable indication of the magnitude of changes of tree area between 1997 and 2002. Information on shrub encroachment is essential for assessing possible impact on the mire environment. Future work will also pursue the retrieval of the type of trees/shrubs by using spectral information of ADS40 data.

However, both the accuracy of the forest masks and the fractional tree/shrub covers strongly depend on the accuracy of the DSM data. Thus, DSMs derived from newly developed, high-quality matching methods are indispensable. The usage of a dense and accurate DSM and DTM are absolute prerequisites

in order to be able to derive accurate topographic parameters which in turn are used to derive the forest masks and the fractional tree/shrub covers. The fact that these topographic parameters alone almost suffice for the generation of the forest masks and the tree/shrub covers underlines the importance of DSM and DTM quality. LiDAR DSMs and DTMs as applied for this study, the latter was used in this study, have smaller point density that the DSM, and during the vegetation season, due also to partial canopy penetration or LiDAR flight with leaves off, are less accurate for modelling vegetation canopy. The present study showed that derivation of DSMs by high-quality matching, compared to LiDAR, has an additional advantage: images of 1997 and 2002 were used to derive multi-temporal DSMs, forest masks and tree/shrub covers, thus permitting a better analysis of changes of tree/shrub area. Regarding the matching DSM, a larger side overlap could reduce occlusions and lead to better modelling of small openings between trees, while increasing the number of image rays per measurement leading to higher accuracy and reliability. Use of modern digital photogrammetric sensors, would lead to avoidance of scanner and film problems, better radiometric quality, and use of the NIR for classification, all factors that would result in a more accurate mapping and change detection of trees and shrubs. Further future investigations will include the direct use of multitemporal matching DSMs and LiDAR DTMs for co-registration, therefore reducing bias errors, and estimation of forest masks and fractional covers using directly these data sets and their differences, possibly in a combination with multispectral classification.
To summarize, high-resolution 3D information as obtained by means of DSMs is indispensable for modelling changes in forest and other wooded areas. Modelling retrospective changes of these areas is feasible since old aerial images are often available and necessary variables of the normalized DSM can be calculated.

5. REFERENCES

Akca, D., 2005. Registration of point clouds using range and intensity information. *International Workshop on Recording, Modeling and Visualization of Cultural Heritage*, Ascona, Switzerland, May 22-27, In E. Baltsavias, A. Gruen, L. Van Gool, M. Pateraki (eds.), Taylor & Francis/Balkema, Leiden, pp. 115-126.

Akca, D. and Gruen, A., 2005. Recent advances in least squares 3D surface matching. In *Proceedings of Optical 3-D Measurement Techniques VII Vol. II*, Gruen, A., Kahmen, H. (eds.), October 3-5, Vienna, Austria, pp. 197-206.

Artuso, R., Bovet, St. and Streilein, A., 2003. Practical methods for the verification of countrywide terrain and surface models. *Proceedings of the ISPRS working group III/3 workshop XXXIV-3/W13*. 3-D reconstruction from airborne laserscanner and InSAR data, 8-10 March, 2003, Dresden, Germany.

Baltsavias, E., 1999. Airborne laser scanning: existing systems and firms and other resources. *ISPRS Journal of Photogrammetry and Remote Sensing*, 54, 164-198.

Baatz, M. and Schäpe, A., 2000. Multiresolution Segmentation – an optimization approach for high quality multi-scale image segmentation. In J. Strobl, T. Blaschke and G. Griesebner (eds.), *Angewandte Geographische Informationsverarbeitung Vol. XII* (pp. 12-23). Heidelberg, Germany: Wichmann.

Burrough, P.A., 1986. *Principles of Geographical Information Systems for Land Resources Assessment*. New York: Oxford University Press, 50 p.

Gruen, A. and Akca, D., 2005. Least squares 3D surface and curve matching. *ISPRS Journal of Photogrammetry and Remote Sensing*, 59(3), 151-174.

Grünig, A., Steiner, G.M., Ginzler, C., Graf, U. and Küchler, M., 2004. Approaches to Swiss mire monitoring. *International Peat Journal*, 12, 55-73.

Guisan, A. and Zimmermann, N.E., 2000. Predictive habitat distribution models in ecology. *Ecological Modeling*, 135(2-3), 147-186.

Heurich, M., Schneider, T. and Kennel, E., 2003. Laser scanning for identification of forest structure in the Bavarian forest national park. *Proceedings of the ScandLaser Scientific Workshop on Airborne Laser Scanning of Forests (pp. 98-107)*, 3-4 September 2003, Umea, Sweden, 2003, Hyyppä J., Naesset H., Olssen H., Granqvist Pahlen T., Reese H. (eds) (Swedish University of Agricultural Sciences, Department of Forest Resource Management and geomatics).

Hyyppä, J., Hyyppä, H., Inkinen, M., Engdahl, M., Linko, S. and Yi-Hong, Z., 2000. Accuracy comparison of various remote sensing data sources in the retrieval of forest stand attributes. *Forest Ecology and Management*, 128, 109-120.

Kienast, F., Brzeziecki, B. and Wildi, O., 1996. Long-term adaption potential of Central European mountain forests to climate change: A GIS-assisted sensitivity assessment. *Forest Ecology and Management*, 80, 33-153.

Küchler, M., Ecker, K., Feldmeyer-Christe, E., Graf, U., Küchler, H., and Waser, L.T., 2004. Combining remotely sensed spectral data and digital surface models for fine-scale modelling of mire ecosystems. *Community Ecology*, 5(1), 55-68.

Küchler, M., Ecker, K., Feldmeyer-Christe, E., Graf, U. and Waser, L.T., 2006. *Predictive Models of Mire Habitats: Bias* in Detection of Change. WetHydro XX. Warsaw Agricultural University Press. (in press)

Mathys, L., Ginzler, C., Zimmermann, N.E., Brassel, P. and Wildi, O., 2006. Assessment of continuous landscape variables for extracting a discrete forest areas. *Forest Ecology and Management*, 229, 111-119.

McCullagh, P. and Nelder, J.A., 1983. *Generalized linear models*. London: Chapman and Hall, 511p.

Naesset, E. and Gobakken, T., 2005. Estimating forest growth using canopy metrics derived from airborne laser scanner data. *Remote Sensing of Environment*, 96(3-4), 453-465.

Schardt, M., Ziegler, M., Wimmer, A., Wrack, R. and Hyyppä, J., 2002. Assessment of forest parameters by means of laser scanning. *Proceedings from the International Society for Photogrammetry and Remote Sensing (ISPRS)*, Commission III Symposium, Vol. XXXIV, Part 3A, 9-13 September 2002, Graz, Austria, 302-309.

Scott, J.M., Heglund, P.J., Samson, F., Haufler, J., Morrison, M., Raphael, M. and Wall, B., 2002. *Predicted Species Occurrences: Issues of Accuracy and Scale*. Covelo, California: Island Press, 868 p.

St-Onge, A. and Achaichia, N., 2001. Measuring forest canopy height using a combination of LIDAR and aerial photography data. *International Archives of Photogrammetry and Remote Sensing,* XXXIV-3/W4, 131-137.

Waser, L.T., Stofer, S., Schwarz, M., Küchler, M., Ivits, E. and Scheidegger, C., 2004. Prediction of Biodiversity - regression of lichen species richness on remote sensing data. *Community Ecology*, 5(1), 121-134.

Watt, P.J. and Donoghue, D.N.M., 2005. Measuring forest structure with terrestrial laser scanning. *International Journal of Remote Sensing,* 26(10), 1437-1446.

Zhang, L. and Gruen, A., 2004. Automatic DSM Generation from Linear Array Imagery Data. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. 35, Part B3, 128-133.

Zhang, L., 2005. Automatic Digital Surface Model (DSM) Generation from Linear Array Images, PhD Thesis, Report No. 88, Institute of Geodesy and Photogrammetry, ETH Zurich, Switzerland. URL: http://e-collection.ethbib.ethz.ch/ecol-pool/diss/fulltext/eth16078.pdf. (accessed: 28 January 2007)

ACKNOWLEDGEMENT

The study was carried out in the frame of the Swiss mire monitoring program initiated in 1996 at the Swiss Federal Research Institute WSL and funded by the Swiss Agency for the Environment, Forest and Landscape (BAFU) and WSL. We acknowledge the support of Ruedi Boesch for providing the LiDAR data (WSL) and Devrim Akca, ETH Zurich for the co-registration of the DSMs.