Adapting mountain forest management to climate change

Robert Jandl

Abstract

Forests that are perfectly accustomed to today's site conditions will need to cope with several pressures that are presently not entirely foreseeable. Climatic change will affect the tree species composition and the competition between trees. Highly uncertain is the intensity and frequency of future disturbances such as insect attacks, storms, drought, and wildfires. Stringent concepts of 'adaptive forest management' are required to ensure that future forests fulfil the manifold functions that society assigns to them. The protective function of mountain forests is ensured in the long term only when precautious measures are developed and applied soon. Concepts for adaptive forest are developed in an international dialogue between practioners and scientists.

Keywords: adaptive forest management, mountain forestry, climate change

1 Introduction

In the context of climate change forests are playing a dual role. The *mitigation* effect with respect to climate change is achieved by the sequestration of atmospheric carbon dioxide in the tree biomass and in forest soils, by the substitution of fossil fuel by bioenergy from forest biomass and by the use of wood products replacing non-renewable materials (Nabuurs et al. 2007). In recognition of the relevance of forests as climate regulators the global aerial budget between deforestation and the establishment of new forests, either by afforestation or by encroachment of areas adjacent to existing forests, is receiving a lot of attention. Currently, the forest area is globally declining, although the rate of deforestation decreases. The European forest area is expanding. The Austrian forest area increases presently by 4,300 hectares per year (FAO 2006; Russ 2011). Enhancing the mitigation effect of forests is beyond the control of single forest enterprises or even single European countries because small-scale efforts are overwritten by global fluxes of greenhouse gases. – From the perspective of a specific region and from the viewpoint of a practical forester the *adaptation* of existing forests to climate change effects poses an urgent challenge. The longevity of forest ecosystems requires managing them in a way that they are able to cope with the natural conditions that will prevail in decades or even more than a century from now. The magnitude of climate change is highly uncertain. The urgent advise is the implementation of policies to limit the warming around 2 °C. The consequences of a stronger warming would harm ecosystems, the economy and society and are presently unpredictable (Lenton et al. 2008; Meinshausen et al. 2009). However, up-to-now policy has not been overly successful. The emissions of greenhouse-gases are still rising and a new record-high energy consumption has been reported for 2010 (Global Carbon Project 2010). With hindsight to the growing global energy demand and the limited availability of renewable energy the consumption of fossil fuels is expected to rise.

Here the information on climate change effects is interpreted from the viewpoint of mountain forestry in Austria. The known emerging pressures to forests are described. Concepts for adaptive management need to leave room for yet unforeseen developments in the forestry sectors that are driven by biological, climatological and societal factors. Simulation models of varying complexity, ranging from forest growth models to ecosystem models accounting for different disturbance scenarios will play an important role in triggering the dialogue between forest science and practical forest management. In addition to the biological component of adaptive forest management the economic implications are briefly discussed.

2 Effect of climate change on Austrian forests

Climatologists are explicitly *not* offering a prediction of the future climate, but are developing climate scenarios based on emission scenarios. The climate models have already a high degree of sophistication and the spatial resolution of regional scenarios is high (Moss et al. 2010). The highest confidence is given to the simulated temperature, whereas the future precipitation pattern and the frequency and intensity of extreme events are less certain. The global warming effect is expected to affect mountain ecosystems over-proportionally strong. The duration and frequency of droughts is expected to increase and the seasonal distribution of the precipitation will change (Züger & Gebetsroither 2011). The general trend according to the IPCC is the elongation of the growing season. The immediate consequence is the increase in productivity and possibly a higher rate of carbon sequestration. However, these positive effects on forests are partially offset or even reversed by increasing risks due to new pathogens and insect infestations, an increased risk of drought and forest fires and a higher frequency of extreme events (Fischlin et al. 2007).

The diversity in site conditions in will also be reflected in the response of forests to climate change. The forests of Austria are diverse and a generalized concept for adaptive forest management any simple solution. For the Austrian forestry sector it is important to distinguish between regions that likely will benefit from climate change and where few measures of adaptive management are required and other regions where substantial changes in forest management are required. The same increase in temperature and decrease in precipitation may lead to a severe drought risk in the already dry low planar regions in Eastern Austria and would enable the forest to populate regions that are above the actual timber line. Recommendations for adaptive forest management need to be region-specific in order to be convincing, credible and implementable. Options are the derivation of concepts for spatial units such as the Austrian growing regions (Kilian et al. 1994) that may be further stratified for the presently encountered dominant forest type, or for site types according to the potential natural forest type. It may be required to evaluate a large number of site conditions with respect to climate change effects. – The second challenge is the understanding of the future pressure from insects (Allen et al. 2010; Kurz et al. 2008; Seidl et al. 2009). Bark beetle (*Ips typographus*) is presently among the most problematic insects for Norway spruce (*Picea abies*) the dominant forest tree in Austria. So far, bark beetle has profited from warmer conditions and has been expanding its habitat into an elevational range where it, according to classical text books has not been found before (Schwerdtfeger 1981). Within its traditional habitats the pressure on forest ecosystems increases because bark beetle develops more generations annually increases. The response of its potential antagonists is not well investigated. In addition to the 'known unknowns' the 'unknown unknowns' will play a role in order to predict mass-outbreaks of insects (Seidl et al. 2011). Potentially damaging insects will be able to migrate and so far unproblematic insects may increase their virulence. Both groups will affect mountain forests in the future. The vivid exchange of goods in an increasingly global economy enables pathogenic insects swift traveling. The temporal development of an mass-outbreaks depends on the initial population size, climate conditions, the disposition of individual trees and the intensity of forest management (Krehan et al. 2009). Forest entomologists will need to increase their efforts in monitoring and are already calling for an internationally binding early warning system to keep track of forest pests. – A third challenge is dealing with extreme events. Without a clear proof for the link with climate change there is evidence for a higher frequency of storm damages in European forests (Gardiner et al. 2010; Schmidt et al. 2010). Forest fires, that presently play a minor role in mountain forests, may become more abundant. The change in the temporal pattern of precipitation is decisive whether – in a benign version – forests are well supplied with water and chemically valuable ground- and surface water is formed or whether peak flows lead to soil erosion, flooding, and dry spells. – Forest fires that are presently mostly a feature of the Mediterranean region, may become more abundant (Liu et al. 2010).

3 Adaptive forest management

3.1 The concept

Neglecting the effect of climate change on is not an option for forest management. Even a mere temperature increase within the predicted margins will change the forest due to a shift in competition between species. Tree species combinations are characteristic for elevation zones (Mayer 1984). At a lapse rate of 0.6 to 0.8 K per 100 meters and the optimistic 2 °C-warming scenario the vegetation would be moved up by 250 to 350 mm along a slope. Considering that the warming effect in mountain regions may be twice as high foresters will need to cope with a strong change in site conditions. Considering that climatic changes is superimposed by changes in the nitrogen availability and by societal changes it is likely that future site properties are not deductible from present conditions (Vitousek et al. 1997). The question for forestry is not whether or not concepts for adaptive forest management need to be sought, but rather how quickly they need to be available. Taking into account that forests develop slowly and climate changes over decadal time spans there is no immediate rush, but there is ample time to develop knowledge-based concepts in an international dialogue between forest practitioners and scientists. A series of papers dealt with adaptive forest management, either conceptually or with emphasis on practical advice (Brang et al. 2008; Lindner et al. 2010; Heinimann 2010; Seastedt et al. 2008).

The primary input to a concept of adaptive forest management is a regionalized climate scenario. It allows the judgment which tree species are most likely successful under future site conditions. Forest ecologists need to open the discussion on the future tree species composition. The traditional approach is the focus on trees that are already part of the species community, an alternative is introducing tree species that are currently absent, but show promising development under different climate conditions. The next step is understanding the future competition between trees within a forest because efficient forest management requires exploiting natural stand dynamics A particular challenge is the assumption of a future ecosystem disturbance regime. Storms, pathogens, insects, fire, drought will add to a highly complex set of possible site conditions (Franklin et al. 2002; Turner 2010).

A great help would be the identification of sites that are especially vulnerable to climate change. Such a mapping exercise would require the development of a set of criteria for vulnerability and would enable focusing on some sites instead on the entire forest.

A requirement for a useful dialogue between practitioners and forest scientists is the definition of the targets of forest management. European forests and especially mountain forests are expected to fulfill several purposes simultaneously and it is possible that several trade-offs between forest functions need to be made (Maroschek et al. 2009). Compromises with respect to the productivity of forests are the economic risk of the forest owner. In situations where the protective function of mountain forests is in question the management choices of the forest owner have many more consequences affecting the entire region.

Interfering with the forest stand dynamics with hindsight to climate change can occur in several phases. Upon stand regeneration it is possible to directly influence the tree species composition. Such interactions are highly affected but are limited to forests that are currently reaching the end of their life cycle. The more common case is the management of already existing forests that need to be made fit for a future climate. In the early phase of stand development the forests are dense and there are many opportunities to influence the later stand structure and tree species composition. In older stands the stand structure is increasingly final and thinning operations can actively favour tree species of choice.

A crucial element is that forest practitioners recognize key-developments of forests as a response to climate change (Peter Brang, WSL, Birmensdorf; pers. commun.). An example would be that in a spruce-dominated forest indications of reduced vitality are observed and simultaneously a deciduous tree like beech (*Fagus sylvatica*) that previously had not played an important role starts to develop more vividly.

3.2 Economic constraints

Adaptive forest management needs to take the economy of the forest sector into account. Timber production is the most important column of forest enterprises as long as ecosystem services provided by forests are not fully and explicitly marketable. The economic risk of adaptive forest management can be considerable and forest owners have a choice to proactive/fast or cautious/slow approach. An example for a proactive concept would be a change in forest type. The intervention would be expensive and can be recommended upon convincing evidence that the present forest cannot cope with future climate conditions. A much slower approach is favouring selected tree species that regenerate but which are presently not successful. An example is to leave a deciduous tree of poor stem quality in the stand during a silvicultural intervention and instead removing a coniferous tree with a presently higher quality. The implied assumption is that the deciduous tree will thrive in several decades, but the coniferous tree would encounter difficulties. – In both cases the forest practitioner faces uncertainty. In case his assumptions about climate change effects are too pessimistic his management decisions will prove wrong and income opportunities from timber production will be lost.

In a mountain forest additional constraints apply. According to the present agreement coniferous tree species are required to ensure the protective functions. Deciduous trees are less effective in retaining snow (Aulitzky 1993; Mayer 1976). In such a situation the forest practitioner is forced to maintain the current tree species composition, even if deciduous tree species would increase their competitivity. Although this example is based on ecological arguments the economic implication is enormous. When forests are not longer able to fulfill their protective functions, engineering solutions need to replace the protection offered by forests. The costs are enormous.

The costs for surveillance of forest conditions are expected to increase. Additional monitoring activities are required to identify problematic situations such as small-scale storm damages as early indicators for insect outbreaks and the occurrence of forest pests will require a higher presence of experts in the forests. Such additional costs need to be factored in when evaluating the costs of timber production in the mountains.

4 Mixed-species forests and forest damage by wildlife

The establishment of mixed-species forests is an integral part of concepts for adaptive forest management. It implies that different species are occupying different ecological niches. Upon a threat to the forest the risk is distributed over several species of different vulnerabilities. Even when one species is strongly affected or killed a sufficient number of trees and tree species can survive. In consequence it is possible to continue with forest management and the positive effects of a soil protection by the forest is ensured. In forest ecology mixed-species forests have been offered as a solution (Mayer 1984; Oliver & Larsen 1990; Püttmann et al. 2009). They have been recommended as remedy against acid rain, against biodiversity loss, against soil acidification and now they are the solution against adverse effects of climate change. A positive effect of mixed-species forests is that they allow considering the uncertainty of future site conditions. A mixture of tree species can exploit the nutrient and soil moisture pool of soil profile better than a mono-tree stand. The differences in rooting patterns stabilize several elements of the forest and make it more stable against storm damage. Moreover, newly invading insects are expected to have a preference for particular species and will destroy monotonous stands more easily than mixed stands. Overall, mixed-species stands are expected to offer a higher stability and are therefore superior when facing the threats of climate change. – The discussion of mixed species forests cannot evade the imminent question of tree damages by ungulates. As long as high densities of deer inhibit the development of additional tree species the entire discussion on the benefits of mixed species forests remains futile.

5 Tools to develop concepts of adaptive forest management

Climate envelops are valuable tools to constrain the availability of tree species in a future climate. They are presence/absence diagrams of tree species in a two-dimensional figure, where in the easiest case air temperature and annual precipitation are used (Gehrig-Fasel et al. 2008; Kölling 2008; Zimmermann et al. 2009). Where the future climate conditions are outside the present range of the occurrence of a tree species is indicated, a specific evaluation of site conditions is required. Two interpretations are possible: (i) the available climate envelope fully describes the ecological range of tree species. When the future site conditions are lying outside of the climate envelop the respective tree species will not be successful at that site; (ii) the available climate envelop does not fully describe the ecological range of a species. A particular tree species may well be successful under future climate conditions, although these conditions are not reflected in the currently available data set. – Irrespective of the interpretation the climate envelop offers an excellent starting point for considerations and for the development of scenarios for the future development of forests.

The future pressure from pathogens and insects needs to be assessed proactively. Transboundary monitoring systems are required in order to issue early warnings on emerging pressures from newly invading or unexpectedly virulent pathogens and beetles. Such programmes are already in preparation and a trilateral prototype is developed in the Interreg Project Manfred (Management strategies to adapt Alpine Space forests to climate change risk; http://www.manfredproject.eu). A European collaboration is planned.

Tree species are genetically not homogenous. Currently there are efforts to identify especially genotypes of species that are successful in a future climate (Wang et al. 2006). In several tests the performance of provenances of Norway spruce and fir is compared (Schüler 2011). The majority of the Austrian trials have been started in 1978 with the intention of improving the productivity of the Austrian forest. As an example for serendipity they are now instrumental for the development of concepts for adaptive management.

A most important element is the simulation of forest development under future climate conditions. A successful simulator of forest growth is PROGNAUS (Monserud & Sterba 1996) that has been continuously further developed. We use a modified version of the simulator Prognaus (Kindermann 2010a, 2010b). It has the working title Caldis and is able to utilize different climate scenarios and contains modules for stand disturbance that have been developed by Thomas Ledermann (BFW). The simulation allows virtual forestry in the sense that known competitive effects and the growth of tree species is embedded in the code. The user can make several choices such as timing and intensity of interventions in order to favor particular tree species. The future pressure from insects is not encoded due to lacking knowledge on the model constraints. The damage by insects is incorporated by expert judgment

6 Delivery of products

For the development of concepts of adaptive forest management it is useful to include the experience and the observations of forest practioners. Some concept proved to be a mobile targets in the past, partly because the guidance was rather general and insufficiently specific for target areas, partly because the expectations in the obtainable guidance was fuzzy.

In an intensive dialogue and based on case studies from many sites a body of information needs to grow. Single experiments need to be documented well and the success or failure of different forms of forest management need to be recorded. As a first approximation the Interreg project Manfred will deliver a handbook of case studies from Southern Germany, Austria, Western France, Slovenia, and Northern Italy in the year 2012. The covered topics are the impact of insect dynamics on spruce forests, the need of maintaining stable forests in areas of rockfall and soil erosion danger, and the shift in forced shift in tree species composition. Several successful examples for regionally valid guidance have been presented (Amann et al. 2010; Fischlin 2008; Landesforstverwaltung Baden-Württemberg 1999). In the future the common elements of the regional concepts will be identified in order to develop an agreed concept of adaptive forest management is foreseen. The concept needs to be based on expert opinion and a sound set of experimental results. Decision-Support Systems can greatly help to trigger the discussion and to narrow the speculative element of forest management in favor of specific primary and secondary targets.

References

Allen, C.D., A.K. Macalady, H. Chenchouni, D. Bachelet, N. McDowell, M. Vennetier, T. Kitzberger, A. Rigling, D.D. Breshears, E. Hogg, P. Gonzalez, R. Fensham, J.C. Zhen Zhangm, N. Demidova, J.H. Limp, G. Allard, S.W. Running, A. Semerci, & N. Cobb 2010: A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management* 250: 660–684.

Amann, G. R. Schennach, J. Kessler, B. Maier & S. Terzer 2010: *Handbuch der Vorarlberger Waldgesellschaften – Gesellschaftsbeschreibungen und waldbaulicher Leitfaden*. Bregenz.

Aulitzky, H. 1993: Die Sprache der ‚'stummen Zeugen". *Interpreavent* 1992: 139–174.

Brang, P., H. Bugmann, A. Bürgi, U. Mühlethaler, A. Rigling, & R. Schwitter 2008: Klimawandel als waldbauliche Herausforderung. *Schweizerische Zeitschrift für das Forstwesen* 159: 362–373.

Food and Agricultural Organization of the United Nations (FAO) 2006: Global Forest Resources Assessment 2005. Progress towards sustainable forest management. *FAO Forestry Papers* 147. Rome.

Fischlin, A., G.F. Midgley, J.T. Price, R. Leemans, B. Gopal, C. Turley, M.D.A. Rounsevell, O.P. Dube, J. Tarazona & A.A. Velichko 2007: Ecosystems, their properties, goods, and services. Climate Change 2007: Impacts, Adaptation and Vulnerability. In: M.L. Parry, O.F. Canziani, J.P. Palutikof,, P.J. van der Linden & C.E. Hanson (eds.): *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: 211–272.

Fischlin, A. 2008: Klimaschutz, das Kyoto-Protokoll und der Schweizer Wald. *Schweizer Zeitung für das Forstwesen* 159: 258–266.

Franklin, J. F., T.A. Spies, R.V. Pelt, A.B. Carey, D.A. Thornburgh, D.R Berg, D.B. Lindenmayer, M.E. Harmon, W.S. Keeton, D.C. Shaw, K. Bible & J. Chen 2002: Disturbances and structural development of natural forest ecosystems with silvicultural implications, using Douglas-fir forests as an example. *Forest Ecology and Management* 155: 399–423.

Gardiner, B., K. Blennow, K., J.-M.Carnus, P. Fleischer, F. Ingemarson, G Landmann, M. Lindner, M Marzano, B. Nicoll, C. Orazio, J.-L. Peyron, M.-P. Reviron, M.-J. Schelhaas, A. Schuck, M. Spielmann. & T. Usbeck 2010: *Destructive Storms in European Forests: Past and Forthcoming Impacts*. Final report to DG Environment EFI, Joensuu.

Gehrig-Fasel, J., A. Guisan & N.E. Zimmermann 2008: Evaluating thermal treeline indicators based on air and soil temperature using an air-to-soil temperature transfer model. *Ecological Modelling* 213: 345–355.

Global Carbon Project 2010: *Carbon budget 2009*. Available at: http://www.globalcarbonproject.org; (accessed 13/06/2011).

Heinimann, H. R. 2010: A concept in adaptive ecosystem management – An engineering perspective. *Forest Ecology and Management* 259: 848–856.

Kilian, W.; F. Müller, F. Starlinger, 1994: Die Forstlichen Wuchsgebiete Österreichs. *Berichte der Forstlichen Bundesversuchsanstalt* 82. Wien.

Kindermann, G. 2010a: Refining a basal area increment model. In: Nagel, J. (ed.): *Deutscher Verband Forstlicher Forschungsanstalten Sektion Ertragskunde*: 82–95.

Kindermann, G. 2010b: Erste österreichweite Jahrringanalyse – Daten, Methoden und Ergebnisse. First tree ring analysis throughout Austria: Data, methods and results. *BFW-Dokumentation* 11.

Kölling, C. 2008: Klimahüllen für 27 Waldbaumarten. *AFZ – Der Wald* 23: 1242–1245.

Krehan, H., G. Steyrer & C. Tomiczek 2009: Borkenkäfer-Kalamität 2009: Ursachen für unterschiedliche regionale Befallsentwicklungen. *Forstschutz aktuell* 49: 9–16.

Kurz, W.A., C.C. Dymond, G. Stinson, G.J. Rampley, E.T. Neilson, A.L. Carroll, T. Ebata & L. Safranyik 2008: Mountain pine beetle and forest carbon feedback to climate change. *Nature* 452: 987–990.

Landesforstverwaltung Baden-Württemberg (ed.) 1999: *Richtlinie landesweiter Waldentwicklungstypen*. Freiburg.

Lenton, T.M., H. Held, E. Kriegler, J.W. Hall, W. Lucht, S. Rahmstorf & H.J. Schellnhuber 2008: Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences* 105: 1786–1793.

Lindner M., M. Maroschek, S. Netherer, A. Kremer, A. Barbati, J. Garcia-Gonzalo, R. Seidl, S. Delzon, P. Corona, M. Kolström, M.J. Lexer & M. Marchetti 2010: Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *Forest Ecology and Management* 259: 698–709.

Liu, Y., J. Stanturf & S. Goodrick 2010: Trends in global wildfire potential in a changing climate *Forest Ecology and Managemen*t 250: 685–697.

Maroschek, M., R. Seidl, S. Netherer & M.J. Lexer 2009: Climate change impacts on goods and services of European mountain forests. *Unasylva* 231–232: 77–80.

Mayer, H. 1976: *Gebirgswaldbau – Schutzwaldpflege*. Stuttgart.

Mayer, H. 1984: *Waldbau auf soziologisch-ökologischer Grundlage*. Stuttgart.

Meinshausen, M., N. Meinshausen, W. Hare, S.C.B. Raper, K. Frieler, R. Knutti, D.J. Frame & M.R. Allen 2009: Greenhouse-gas emission targets for limiting global warming to 2 °C. *Nature* 458: 1158–1162.

Monserud, R.A. & H. Sterba H. 1996: A basal area increment model for individual trees growing in even- and uneven-aged forest stands in Austria. *Forest Ecology and Management* 80: 57–80.

Moss, R.H., J.A. Edmonds, K.A. Hibbard, M.R. Manning, S.K. Rose, D.P. van Vuuren, T.R. Carter, S. Emori, M. Kainuma, T. Kram, G.A. Meehl, J.F.B. Mitchell, N. Nakicenovic, K. Riahi, S.J. Smith, R.J. Stouffer, A.M.. Thomson, J.P. Weyant & T.J. Wilbanks 2010: The next generation of scenarios for climate change research and assessment. *Nature* 463: 747–756.

Nabuurs, G., O. Masera, K. Andrasko, P. Benitez-Ponce, R. Boer, M. Dutschke, E. Elsiddig, J. Ford-Robertson, P. Frumhoff, T. Karjalainen, O. Krankina, W. Kurz, M. Matsumoto, W. Oyhantcabal, N. Ravindranath, M.S. Sanchez & X. Zhang 2007: Forestry. Climate Change 2007: Mitigation. In: Metz, B., O. Davidson, P. Bosch, R. Dave. & L. Meyer (eds.): *Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge: 541–584.

Oliver, C.D. & B.C. Larsen 1990: *Forest stand dynamics*. New York.

Puettmann, K.J. K.D. Coates & C. Messier 2009: *A critique of silviculture – managing for complexity*. Washington.

Russ, W. 2011: Mehr Wald in Österreich. *BFW-Praxisinformation* 24: 3–5.

Seastedt, T.R., R.J. Hobbs & K.N. Suding 2008: Management of novel ecosystems: are novel approaches required? *Frontiers in Ecological Environments* 6: doi:10.1890/070046

Schmidt M., M. Hanewinkel, G. Kändler, E. Kublin & U. Kohnle 2010: An inventory-based approach for modeling single-tree storm damage — experiences with the winter storm of 1999 in southwestern Germany. *Canadian Journal of Forest Research* 40: 1636–1652.

Schüler, S. 2011: *Können geeignete Herkünfte uns bei der Anpassung der Wälder helfen?* Stakeholder Meeting of Interreg Alpine Space IV, Manfred, oral presentation. Vienna, May 5, 2011.

Schwerdtfeger, F. 1981: *Die Waldkrankheiten. Ein Lehrbuch der Forstpahtologie und des Forstschutzes*. Wien.

Seidl, R., W. Rammer, D. Jäger & M.J. Lexer 2008: Impact of bark beetle (*Ips typographus* L.) disturbance on timber production and carbon sequestration in different management strategies under climate change. *Forest Ecology and Management* 256: 209–220.

Seidl R., P.M. Fernandes, T.F. Fonseca, F. Gillet, A.M. Jönsson, K. Merganicová, S. Netherer, A. Arpaci, J.-D. Bontemps, H. Bugmann, J.R. González-Olabarria, P. Lasch, C. Meredieu, F. Moreira, M.-J. Schelhaas & F. Mohren 2011: Modelling natural disturbances in forest ecosystems: a review. *Ecological Modelling* 222: 903–924.

Turner, M.G. 2010: Disturbance and landscape dynamics in a changing world. *Ecology* 91: 2833–2849.

Vitousek, P.M., H.A. Mooney, J. Lubchenco & J.M. Melillo 1997:Human domination of earth's ecosystems. *Science* 277: 494–499.

Wang, T., A. Hamann, Y. Yanchuk, G. O`Neill & S. Aiken 2006: Use of response functions in selecting lodgepole pine populations for future climates. *Global Change Biology* 12: 2404–2416.

Zimmermann, N.E., N.G. Yoccoz, T.C. Edwards jr., E.S. Meier, W. Thuiller, A. Guisan, A., D.R. Schmatz & P.B. Pearman 2009: Climatic extremes improve predictions of spatial patterns of tree species. *PNAS* 106: 19723–19728.

Züger, J. & E. Gebetsroither 2011: *Trockenheit in alpinen Wäldern im Licht des Klimawandels*. Stakeholder Meeting of Interreg Alpine Space IV, Manfred, oral presentation. Vienna, May 5, 2011.

.

Zeitschrift/Journal: IGF-Forschungsberichte (Instituts für Interdisziplinäre Gebirgsforschung [IGF]) (Institute of Mountain Research)

Jahr/Year: 2011

Band/Volume: 4

Autor(en)/Author(s): Jandl Robert

Artikel/Article: Adapting mountain forest management to climate change 193-202