Implications of land-use/cover change for carbon sequestration and natural hazard risks

PhD thesis

by

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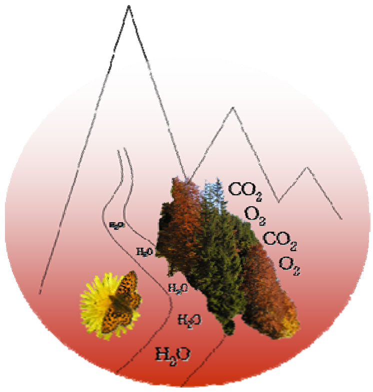
submitted to the
Faculty of Natural Sciences
University of Innsbruck

Innsbruck, March 2009



This work is dedicated in love and gratitude to my family.

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Abstract

The thesis focuses on the impacts of land-use/cover change (LUCC) for different types of *regulating ecosystem services*, namely **carbon sequestration** - as regulating process of global warming - and **protection against natural hazards** in alpine areas. For spatio-temporal evaluation of carbon sequestration, LUCC scenarios have been developed and compared with historical land-use maps for the Stubai Valley, Austria. Phytomass and carbon stocks increased by ca. 20% during the last 140 years and continue to increase in the next 20 years. Regarding natural hazard risks, snow gliding and associated consequences - i.e. erosion, avalanches, and hindering of regeneration of protective forests - as well as surface water runoff – jointly responsible for flash floods in small alpine catchments – are assessed for selected study areas in the Alps. Especially abandoned areas and pastures are highly vulnerable to snow gliding and high surface runoff, respectively.

Accordingly, measures to increase carbon sequestration to meet the Kyoto targets reveal negative implications for natural hazard risks. Finally, the results implicate interdependencies between different types of ecosystem services and important future research questions are discussed.

Chapter 1. Extended Summary

(i.) Introduction

On the basis of former and ongoing socio-economic changes causing extensive land-use changes in alpine areas – more precisely the abandonment of increasingly unprofitable pastures and meadows – land cover is transforming at an accelerating rate (Houghton 1994; Turner et al. 1994; Metzger et al. 2006). Moreover, land-use/cover change (LUCC) is a major driving force of global change (Lambin et al. 1999) and land-use changes are affecting important ecosystem services. Ecosystem services are the benefits people obtain from ecosystems and include (1) *provisioning services* such as food, water, timber, or fiber; (2) *regulating services* that affect climate, natural hazards, disease, wastes, or water quality; (3) *cultural services* that provide recreational, aesthetic, or spiritual benefits; and (4) *supporting services* such as soil formation, photosynthesis, or nutrient cycling (Millennium Ecosystem Assessment 2005). In my thesis I focused on the implications of LUCC for two different types of *regulating ecosystem services*, namely **carbon sequestration** - as regulative process of climate - and **natural hazard** regulation.

The terrestrial C-cycle has strong implications for potential climate change (CC) and the effect of LUCC is currently recognized as one of the critical gaps in our knowledge of carbon sequestration (Houghton et al. 1999; Lambin et al. 1999; Conen et al. 2008). Evaluation of above- and belowground vegetation carbon stocks requires high spatial resolution and analyses of different periods of time – including historical land use/cover – allow for conclusions on possible scenarios.

LUCC in mountain areas are expected to increase the risk of natural hazards (Alewell et al. 2008; Dankers & Feyen 2008; Meusburger & Alewell 2008). Although natural hazards are an omnipresent threat and people living in alpine areas contrived ways and means to handle this immanent danger (Bätzing 2005), global change could lead to events which never happened before, outreaching any precautions. Effects of LUCC on the regulation of natural hazard risks are of particular importance in alpine areas (Cernusca et al. 1999; Tasser et al. 2003) and difficult to assess due to high heterogeneity.

Hence, the present thesis focuses on spatio-temporal dynamics of LUCC effects on introduced ecosystem services and combines plot scale and landscape scale assessments.

(ii.) LUCC and Carbon Sequestration

To assess the impact of LUCC on carbon sequestration, information about the temporal dynamics of carbon stocks are required. Moreover, results from plot studies have to be scaled up and mapped spatially explicit in a geographic information systems (GIS) to answer landscape ecological research. Lambin et al. (2001) proposed that more work is needed on the sampling of case studies to better analyze and model the processes of land-use change and land management in different geographical and historical contexts. To date, there are only a few case studies on European mountains (e.g. Douglas et al. 1996; Andre 1998; Mottet et al. 2006; Bolliger et al. 2007; Cernusca et al. 2008), which explicitly point out regionally and locally varying developments, but these are not concerned with consequences of land-cover change on carbon sequestration. In **Chapter 1** we analyzed above- and belowground vegetation carbon stocks (C-stocks) in relation to historical land use (1865), current land use (2003), and three contrasting scenarios of future land use/cover (2020) in the Stubai Valley, Austria. Phytomass and C-stocks in 1865 amounted to 63.1 Mg ha^{-1} and 30.8 Mg C ha^{-1}, and increased until 2003 to 75.8 Mg ha^{-1} and 37.2 Mg C ha^{-1}, respectively. Mapping of the results allowed evaluations along an altitudinal gradient, indicating the highest C gain to be in the sub-Alpine belt (more than doubling of the C-stock) due to the abandonment of pastures and hay meadows. All future scenarios project only a minor increase in phytomass (0.3–2.8 Mg ha^{-1}) and C-stocks (0.2–1.4 Mg C ha^{-1}) because major elements of the landscape (forests, rocks, screes) will be either largely unaffected or are unimportant in their spatial extent (built environment). LUCC has been driven predominantly by the structural change that occurred after 1950, which was characterized by major advances in technical progress and new sources of income leading to reduced economic dependence on agriculture. These findings add further weight to the hypothesis that major future LUCC will also be driven by pronounced economic momentum, for example, a change of energy prices.

The impacts related to LUCC may be subject to strong time delays. An economic influence resulting in a different management of areas can take one generation, whereas another generation will pass until an abandoned area is naturally reforested, and a third generation is needed before the forest reaches its maximum phytomass.

This implies that only a long-range model is able to accurately capture the influence of economic parameters on C-stocks. If models of land cover and C-stocks have to deal with such long periods, the dynamics of global climate changes cannot be neglected. If global warming resulted in a significant upward shift of the alpine timberline, its effects could potentially override those related to local agricultural management.

(iii.) LUCC and Natural Hazard Risks

It is generally agreed that land use has a major impact on natural hazard risks even though there is very little research on it (Piussi & Farrell 2000; Tasser et al. 2003; Alewell et al. 2008; Meusburger & Alewell 2008). **Chapter 2** describes a Spatial Snow Glide Model (SSGM) to analyze the vulnerability of alpine areas according snow gliding, a key component leading to natural hazards, i.e. avalanches and erosions. Spatial information on snow gliding is important for management purposes, but, to date, lack of knowledge about key drivers for the snow-glide process hindered the development of a SSGM. We report the most important drivers for snow gliding derived from analyzing snow-glide distances taken over five winter periods in two climatically different study areas by ordinary least-squares regression. Six variables (forest stand, slope angle, winter precipitation, surface roughness, slope aspect west, slope aspect east) were revealed as key drivers and enabled us for the first time to establish a SSGM. The variable 'surface roughness' integrates the influence of different vegetation types and different land uses on snow gliding. Both model development ($R^2 = 0.838$) and model validation ($R^2 = 0.823$) exhibit outstanding accuracy of prediction. Hence, the SSGM was used to model snow-glide maps for two study areas: the 'Kaserstattalm' (Stubai Valley, North Tyrol, Austria) and the drier and warmer area of the 'Waltner Mähder' (Passeier Valley, South Tyrol, Italy). The reliability of these maps was validated by intersection with mapped erosions attributed to snow gliding. Thus, our SSGM represents a useful tool for current risk assessment as well as – combined with spatially explicit LUCC scenarios – for future risk analyses.

In forestry management, afforestation of abandoned areas is a commonly accepted measure to impede snow gliding and resulting natural hazards as well as to protect settlements from avalanches and rockfall. However, at the same time snow gliding is the major hazard hindering natural reforestation and afforestation, especially on former managed or steep areas (Tasser et al. 2007). **Chapter 3** determines snow forces on young trees on afforested areas and compared calculation formulae with in-situ observations. Hence, the effect of snow gliding processes on forest plants was investigated. The study area was situated on a south-facing slope (altitude 1900 m a.s.l., inclination 30°) in the Stubai Valley, Tyrol, Austria. The site is characterized by a smooth ground surface and high snow gliding rates lead to a great number of damaged plants almost every winter season. The investigations included snow gliding measurements and experiments to determine those forces which are necessary to uproot juvenescent trees from the ground. The experiments were carried out on Swiss stone pine and larch trees with a height of 0.6–0.9 m (diameter 0.02 and 0.045 m). Our measurements revealed glide rates of up to 46.5 mm d^{-1} and forces between 1000 and 3500 N as sufficient to uproot juvenescent trees. The downslope force was determined by the applicable snow pressure equations and compared with the results of our experiments. The investigations showed that the calculated values correspond to values measured on the plants. Provided that an impact of 50% of the measured forces will no longer result in damage to the trees (extraction or breakage), we calculated that the stagnation depth has to be reduced to about 1.5 m. To conclude, snow forces on forest plants can be calculated by common snow pressure models and in combination with the SSGM, which determines the vulnerability of alpine areas to snow glide damage (**chapter 2**), the study supports forest management with a view to protect young trees and thus to ensure protection from natural hazards.

In addition to snow gliding and directly associated natural hazards, i.e. erosion and avalanches, as well as indirectly associated risks, i.e. hindering of regeneration of protective forests, water balance and flash floods are moving more and more into the centre of interest in alpine areas (Böhm 2006; Brunetti et al. 2006; de Jong 2009). Studies aiming at a better understanding of impacts of LUCC on water budget and consequently runoff formation and associated services (e.g. waterpower) or arising risks (e.g. floods) are necessary to preserve alpine areas as 'Water Towers' for the world (Viviroli & Weingartner 2004). Hence, the capacity to store vital water either as snow or in the soil and to regulate runoff must be understood in much higher detail than we do now. **Chapter 4** aims at understanding of the impacts of LUCC on soil moisture and runoff formation and highlights dynamics of surface water runoff and danger of flood events in alpine catchments. Especially in small alpine catchments (< 10 km^2), convective rainfall events lead to significantly higher surface runoff and consequently to high water flow in draining torrents (Naef et al. 2002; Niehoff et al. 2002). Better understanding of surface runoff quantity for distinct hydrological units becomes increasingly important as many rainfall-runoff models use static surface runoff coefficients and neglect key factors affecting ecohydrological dynamics, e.g. land cover and land use. In our study, the seasonal variability of surface runoff on abandoned areas and pastures in the alpine catchment ‘Kaserstattalm’ (Stubai Valley, Austria, Eastern Alps) was analyzed using a rain simulator along with soil water content and soil water tension measurements. Additionally, seasonal variability of field capacity, soil bulk density, and infiltration capacity were assessed. Analyzing more than 30 sprinkler experiments on 10 m^2 plots at a rate of 90 mm h^{-1} (equivalent to a convective precipitation event, return period of 100 years) revealed a mean surface runoff of 1% on abandoned areas and 18% on pastures. Regarding seasonal variability, relevant surface runoff was limited to pastures in autumn with a maximum of 25%. The field capacities of all soils were found to be stable throughout the season. However, for pastures, cattle trampling led to a significant increase of bulk density of up to +0.33 g cm^{-3} *($p \leq 0.01$)* in the top 0.1 m of the soil and measured infiltration rates decreased by more than 60%. Interestingly, bulk density could ‘recover’ during the winter season presumably due to freeze-and-thaw and bioturbation processes affecting soil compaction. This study highlights that the physical properties of soil along with land management measures make surface runoff difficult to model and that dynamic and interactive factors have to be considered in order to make realistic assessments and accurate predictions of surface runoff rates. Finally, we discuss how land use affects runoff formation in general and highlight the importance of studying this at catchment scale. Assessing surface runoff is important especially for mountain regions and small catchments to successfully avoid potential life-threatening hazards.

(iv.) Concluding remarks

Man benefits from a variety of resources and processes from natural ecosystems (Millennium Ecosystem Assessment 2003). In my thesis, implications of LUCC for selected ecosystem services are assessed and the following conclusions can be drawn:

(1) Above- and belowground carbon stocks increased in the last 140 years and will continue to increase in the future due to abandonment of pastures and hay meadows.

(2) Abandoned areas and pastures are highly vulnerable to snow gliding and high surface runoff, respectively.

(3) Snow gliding hinders afforestation. To successfully perform afforestation measures, snow forces on forest plants have to be calculated.

(4) Snow forces on forest plants must not exceed 500 N on smaller trees (d = 0.02 m) and 1500 N on larger trees (d = 0.045 m) to preserve forest growth.

(5) Alpine pastures revealed high surface runoff coefficients due to soil compaction. On abandoned areas, hardly any surface runoff occurred.

(6) Recovery of soil compaction on intensively used pastures within one winter season is indicated. Reduced grazing intensity on steep slopes will clearly decrease surface runoff, even in the short term.

As ecosystem processes operate on different scales and resulting ecosystem services and products have different values for different groups of persons (human dimension comes in), not every ecosystem service can be maximized at the same place. Ecosystem services are multidimensional and need multidimensional approaches to assign the value of individual measures of maintenance.

This is clearly shown by taking the value of another type of ecosystem service, plant biodiversity into account. Plant biodiversity, which is comparatively low in forests, higher on managed areas and highest on lightly managed areas (Cernusca et al. 1999; Tasser & Tappeiner 2002) is expected to decrease for future land-use/cover scenarios (Tappeiner et al. 2006). It follows that our findings will help to maximize the value of carbon sequestration, protection against natural hazards, and plant biodiversity at the same time; afforesting of areas vulnerable to snow gliding and reducing the management (pasturing) of steep areas significantly reduces the risk for natural hazards by maintaining plant biodiversity and associated recreational value. Concurrently, afforested areas lead to slightly increased carbon sequestration and a more balanced performance of addressed ecosystem services is reached.

However, numerous ecosystem services are intertwined. This strengthens that a comprehensive understanding of individual processes and functions as well as interrelations is necessary. Consequently, process based studies have to prove validity on all scales and spatially explicit results have to be combined with LUCC scenarios. My thesis adds a piece to the unifying concept of cross-scale ecosystem research including process based plot studies and methods to come up with spatially explicit results on landscape level. More precisely, the methods and results presented can be used directly for analyzing spatio-temporal implications of LUCC for carbon sequestration/stocks and natural hazard risks. Additionally, the developed LUCC scenarios form a basis for evaluating natural hazard risks in future. Results will further help to improve vulnerability assessments on global change for regional scale, whereas most findings to date rely on large-scale processes and models (cf. Global Circulation Models (GCM) without number).

Nevertheless, climate and land cover are inextricably linked (Schröter et al. 2005), adding the temporal scale necessitates the consideration of complex back coupling mechanisms between land cover and climate. More precisely, several processes including (1) emission of greenhouse gases; (2) altered albedo; (3) altered evapotranspiration; (4) altered longwave radiation; (5) changes in production of aerosols; and (6) changes in surface roughness may become highly relevant (Chapin et al. 2008). Subsequently, future perspectives based on the results of this thesis are: (1) use of LUCC scenarios to project natural hazard risks; (2) coupling of developed LUCC scenarios to climate models; (3) improve LUCC scenarios by including back coupling mechanisms between land cover and climate; (4) deepen the knowledge of rainfall-runoff formation by expanding plot scale studies to areas with different site characteristics; and (4) determination and spatially explicit mapping of dominant runoff processes for LUCC scenarios including ecohydrological dynamics, i.e. land use and pre-event soil moisture content, to come up with a rainfall-runoff model suitable in ungauged catchments.

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