Provision of ecosystem goods and services by agriculture and forestry in mountainous regions of Switzerland

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Publication Date:
2012

Permanent Link:
https://doi.org/10.3929/ethz-a-007567387

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Provision of Ecosystem Goods and Services by Agriculture and Forestry in Mountainous Regions of Switzerland

A dissertation submitted to

ETH ZURICH

for the degree of

Doctor of Sciences

presented by

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2012
Abstract

Ecosystems provide a wide range of services to human beings, including scenic views, purified water, and protection from natural hazards such as avalanches. The provision of these Ecosystem Services (ES) is the result of a complex interplay between human actions and basic ecosystem processes. Agents managing ecosystems such as farmers and foresters on the one hand side need to consider basic ecosystem processes in their decision but on the other hand side also influence ecosystems, and their capacity to provide certain ES, by their management decisions. Thereby the provision of ES most of the times is only a by-product of food and wood production since most ES cannot be traded on markets and there is no monetary reward for their provision. Hence, in most cases farmers and foresters do not consider the provision of ES in their decision-making process. Thus non-marketable ES often are supplied less than it is desired. To keep the provision of non-marketable ES on an optimal level, government has to support its provision either by using tax money or applying adequate regulations. This task becomes increasingly complex since predicted future changes in climate and economic parameters will influence the capacity of the ecosystems to provide ES in different ways. For the design of policy schemes, these changes increase demand for ex-ante knowledge about the impact of adequate policy measures.

In this thesis two bio-economic model frameworks are described, that provide valuable insights into the mechanisms influencing ES provision. The ALUAM model framework consists of a forest landscape sub-model, a crop yield sub-model and an economic land-allocation sub-model. This modelling framework allows the assessment of the impact of different climate and economic scenarios on land use and the provision of different ES (food provision, biodiversity provision, improvement of greenhouse gas balance, and hazard protection value of forests). The INTSCOPT model is a whole-farm model simulating a representative Swiss suckler-cow farm. In the simulation processes the INTSCOPT model optimizes production structure under different constraints, including a limitation of the amount of greenhouse gases emitted. This allows the assessment of the impact of different management options on the trade-off between food provision and an improvement of the greenhouse gas balance of the farm.

Simulation results show that ES provision in mountainous regions is influenced by direct biophysical impacts of climate change, by shifts in land use indirectly driven by climate change or by shifts land use due to changes in economic parameters. Changes in the pro-
vision of ES by ecosystems dominated by agriculture are more susceptible to land use change that again is mainly driven by shifts in economic parameters and less by changing climate. Whereas climate change is predicted to have a positive impact on yields, supporting more intensive land use, changing market parameters are predicted to decrease profitability of agricultural production and therefore lead to an extensification of land use followed by a lower provision of food and a higher provision of biodiversity. The abandonment of land by agricultural production, however, is only apparent in the scenarios with the highest rates of changes in both, climate and economic parameters. In contrast, the provision of ES by forest ecosystems is more driven by the impact of changing climate on the biophysical processes. Climate change will affect provision of ES by forests on all elevations.

A major topic for governance of ES provision is the appearance of trade-offs between the provision of different ES. Simulation results show that there are mainly trade-offs between marketable and non-marketable ES, for example between food provision and carbon sequestration. Policy schemes targeted at supporting non-marketable ES will therefore negatively impact food production and vice versa. Rates of trade-offs between different ES, however, are not constant but increase the more the target ES is supported. This means that small increases in the provision of an ES can be reached without affecting other ES but large increases in the provision of target ES, however, will substantially reduce provision of non-target ES. Nevertheless, it is possible to mitigate trade-offs between certain ES by applying innovative management measures, such as agroforestry systems, to overcome the trade-off between food production and carbon sequestration. However, it must be considered, that these management options are not available for free.

Results imply that agricultural policy in mountainous regions should focus more on mitigating negative impacts of land use change on ES provision than on climate change. Climate change in mountainous regions is assumed to have a positive impact on productivity of grass- and cropland. In addition agriculture is relatively flexible to react to new challenges because of relatively short time horizons of decision-making. Nevertheless, policy schemes should have a longer time horizon since it is more cost efficient to guide the development of agricultural structure than to change the structures that already exist. For forest policy, a long time horizon is mandatory since decisions in this sector require longer time frames due to the relatively long production cycles of forests. Future challenges caused by climate change in forests, therefore already need to be addressed today.
Zusammenfassung


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1 Introduction

Ecosystems provide a wide variety of important services to humans (MEA 2005). For example, forests regulate water flow and protect infrastructure from natural hazards, agroecosystems provide food and contribute to the maintenance of biodiversity, and both are necessary to form scenic views as we know and appreciate them. In the community of Davos in the Swiss Alps, the monetary value of the protection that forests provide against avalanches is estimated to be 26 Mio. CHF, more than two times the benefits generated by agriculture and forestry in this region (Grêt-Regamey and Kytzia 2007). Because of their high value, provision of Ecosystem Services (ES) is seen as a basic need of humans.

In Switzerland, however, there are very few ecosystems that are still natural and still left to their own resources, i.e. not influenced by humans. For all other sites, the provision of ES is restricted not only by ecosystem processes but also by the way humans manage them (Schröter et al. 2005). In mountainous areas, management is mainly done by farmers and foresters, which manage grasslands and forests in such a way as to reach their goals, such as to generate an adequate income. Since the provision of different ES is linked, the provision of all ES—not only that of food—is the result of the interplay between basic ecosystem processes and the decisions of farmers and foresters. For example, it is the main goal of farmers, when cultivating dry meadows, to produce grass to feed their livestock. An adapted management of these sites, however, also is required for the maintenance of the vast biodiversity present at these sites (Baumgärtner and Hartmann 2001).

These linkages are of high importance since most ES are non-marketable, i.e. farmers and foresters are not rewarded if they provide them (Brown et al. 2007). Hence the provision of ES is not considered in their decision-making process. For example farmers will focus their cultivation of dry meadows only on food provision, a marketable good, accepting a possible negative impact on provision of biodiversity. This can lead to a provision of ES that is lower than the social optimum (Perman et al. 2003). To promote the provision of ES, it is therefore necessary that the supply of ES is governed by public institutions. To accomplish this task, several policy measures (e.g. subsidies) are available for influencing decision making in order to ensure that there is a sufficient supply of non-marketable ES as well. Such policy measures, however, can have extensive consequences not only on the target ES but also on provision of other ES, that is why ex-ante
knowledge about their effect is necessary (Euliss et al. 2010). For example the planned reform of the Swiss direct-payment system—which tries to keep provision of ES on an optimal level applying targeted management schemes - also must be expected to have an impact on the provision of non-target ES.

In mountainous regions, management of ES provision is especially challenging because the current climate and topography make cultivation there rather difficult and especially expensive. This is mainly because yields are low and because specialised machinery and a great deal of manual labour are needed to cultivate these areas (Mottet et al. 2006). Therefore, even small changes in the prices of products or yields can lead to severe changes in management patterns, e.g. the conversion from agricultural to forest land use leads to large changes in the provision of ES. Such developments already are visible in parts of the alpine region of Switzerland (Gellrich et al. 2008): Where there are not enough animals to graze the available fodder, parts of the alpine summer pastures have become reforested. During the last 25 years in the case study region of Visp this led to a decrease in the amount of land used by agriculture by more than 10% (SFSO 2009). Such processes will, however, even be accelerated by global change, i.e. by changes in the climate and in socio-economic parameters. Climate change, on the one hand, will affect ecological processes and subsequently change the ability of certain ecosystems to provide ES. Changes in socio-economic parameters, on the other hand, will influence the decisions of farmers and foresters, leading to further changes in the provision of ES.

In this thesis, two bio-economic models are presented that deal with these challenges. First, a spatial dynamic model is presented that is able to simulate the provision of ES under different climate and market scenarios. This model is part of a modelling framework developed for the interdisciplinary research project MOUNTLAND and is located at the intersection between modelling ecological processes and analysing political processes. Therefore, it is part of two different feedback loops. The first links ecological processes with economic ones. Ecological models are applied to assess the impact of climate on the provision of different ES, mainly on the yields of grasslands, crops, and forests. These data are then implemented in the models presented in this thesis. The resulting land use change is then transferred back to the ecological models in order to simulate vegetation-succession processes. The second feedback loop links economic systems with policy decision making. The results of this simulation model are passed to political scientists who, based on the results, design adapted policy measures. These policy
measures are then re-implemented into the simulation model in order to simulate their impact on the provision of ES. The second model is a whole-farm model simulating a representative Swiss suckler-cow farm. The main strength of this model is its detailed simulation of a farm’s carbon balance. In this model, different management strategies for overcoming trade-offs between food provision and carbon sequestration can be assessed, which is not possible in the above-described large-scale model.

These models are used to assess the impact of different climate and policy scenarios on the provision of ES in mountainous regions of Switzerland. Simulation results are also used to draw conclusions about the ability of different policy measures to overcome future challenges in securing ES provision.

1.1 Overview

This thesis proceeds as follows. In Chapter 2, an overview of research into state-of-the-art modelling ES is given. This includes a short discussion about the concept of Ecosystem Services and about the applied methods. In Chapter 3 the research questions and in Chapters 4 and 5 the case-study region and the applied scenarios are described. In Chapter 6 the Alpine Land use Allocation Model (ALUAM) is presented in detail. In Chapter 7 ALUAM is applied to the case-study region Visp, to assess the impact of different climate and market scenarios on the provision of various ES. Since the results of Chapter 7 indicate that there must be trade-offs between the provision of different ES, this point is further assessed in Chapter 8, in which trade-offs and synergies concerning the provision of various ES under different scenarios are assessed. Whereas these chapters focus on a sectoral perspective, eventually individual farmers have to be convinced to implement certain management options in order to increase the provision of different ES. However, individual farmers face restrictions other than those accounted for in ALUAM. Especially resources such as land are more restricted on a farm than on a regional level since on the regional level land can be allocated free between different farm types. To take this into account, in Chapter 9 a case study is presented that shows the opportunities available to an individual farmer to improve his or her climate balance.

In Chapter 10, the results of the previous chapters are summarised and discussed, and conclusions are drawn.
2 Background literature

2.1 Ecosystem Services

According to Fisher et al. (2009), ecosystem services are defined as “the aspects of ecosystems utilized (actively or passively) to produce human well-being”. ES can be characterized as the biophysical outputs of ecological production systems that enhance the welfare of human (Johnston and Russel 2011). Humans benefit from the provision of goods and services by ecosystems since ever. The value of ES than was recognized already in the antiquity. Mooney and Ehrlich (1997) show that in the works of Plato in ancient Greek, ecosystem services were mentioned. The recognition of ES in science, however, only goes back to the 1970s, to a report called the Study of Critical Environmental Problems (SCEP 1970), in which different ES are listed. This report mentions that there will be a decline in the provision of different ES if ecosystem functions decline. The list of ES in this work was further expanded upon by several authors (e.g. Holdren and Ehrlich (1974) and Ehrlich et al. (1977)) and was completed at the end of 20th century (Grêt-Regamey 2008). In ecological literature, the concept of ES was promoted in a work edited by Daily et al. (1997) (Rapidel et al. 2011, Fisher and Turner 2008). In the same period Constanza et al. (1997) introduced ES in economic research as they estimated total value of the world’s ES to be US$ 33 trillion per year, on average. Though the figures presented in this study are controversial, it increased the recognition of the relevance of ES for policy analysis (Daily 1997). In 2005, the Millennium Ecosystem Assessment report (MEA 2005) synthesized the latest works and provided an overview of state-of-the art science regarding ES. The conclusion of the MEA was that humans’ activities have led to a decrease of the capacity of ecosystems to provide ES (MEA 2005). Additionally, it expanded the classification of ES by dividing such services into four broad groups: provisioning services (e.g. food or fresh-water provision), regulating services (e.g. food or fresh-water provision), cultural services (e.g. climate and flood regulation) and supporting services (e.g. nutrient cycling or soil formation).

Since the concept of ES has become popular, it has taken on multiple definitions (Fisher et al. 2008). Daily (1997) and the MEA (2005) suggest a rather comprehensive definition of the term Ecosystem Services. The MEA (2005) defines ES as “the benefits people obtain from ecosystems”. These rather general definitions, however, are not accurate enough for a proper assessment and valuation of ES. Particularly the lack of differentiation between intermediate and final ES makes an application of these definitions prob-
lematic (Johnston and Russel 2011). In evaluating the provision of ES, confusion between intermediate and final ES can lead to doubly counting different ES since intermediate ES are counted twice. Such flaws in assessment of ES can result in biased conclusions followed by sub-optimal decisions in ES management. To decrease the risk of double counting, several authors suggest more narrow definitions of ES. For example, Boyd and Banzhaf (2007) suggest a rather restrictive definition of ES: “Final ecosystem services are components of nature, directly enjoyed, consumed, or used to yield human well-being”. Fisher and Turner (2008) agree that benefits and services must be separated, but they point out that a definition of ES still has to be operable what they decline for Boyd and Banzhaf’s approach. Like other authors (for a review, see Haynes et al. 2008) they suggest a definition that is less rigorous. Even though the operability of these less rigorous definitions is enhanced Johnston and Russell (2011) doubt that such “one size fits all” definitions are useful to provide clarity required for ES valuation. They therefore suggest an operational mechanism that determines whether an ES is final or intermediate. This operational mechanism consists of four rules: 1) There must be a willingness to pay for an ES; 2) The ES must represent the outcome of an ecological system and may not be refined by human labor, capital or technology; 3) The beneficiary of an ES must be willing to pay for an increase in the provision of this service if the level of provision of all other ES is held constant; 4) Only benefits may be counted where final ES have been identified by the preceding rules. Based on these guidelines, ES considered in this thesis are: food provision, improvement in the greenhouse gas balance protection from natural hazards and provision of biodiversity.

2.2 Ecosystem Services from an economic point of view

From an economic point of view, goods and services are valuable if they are useful to humans, regardless of whether this utility is direct or indirect (Brown et al. 2007). However, being valuable is not the only precondition for attaining an economically efficient allocation of goods and services. An economically efficient state, or a state of Pareto efficiency, is reached only if there is no possibility of reallocating consumption or production in such a way that one group benefits without making another group worse off (Freeman 2003). To reach such an efficient state it is however necessary that goods are exchanged between different groups, since not all of them have the same preferences for a certain good (Brown et al. 2007). A common way of exchanging goods and services is to establish a market for a certain good. If this is possible, Smith’s (1976) “invisible hand” will allocate goods and services in such a way that economic efficiency is reached.
However, goods can only be traded at markets if they fulfil several preconditions. For instance, it must be possible to exclude people from consuming a good, and a good must be a rival good (i.e. the consumption of the good by one person must reduce its ability to be consumed by other persons) (Perman et al. 2003). Only a few ES fulfil these criteria and are thus called “private” or “marketable” goods. These include fuel wood and non-renewable ecosystem goods extracted from contained deposits (Brown et al. 2007). For other ES, efficient markets cannot be established since they lack at least one of the described preconditions. For instance, if there is no excludability, consumers will not reward producers for providing a certain ES. This will result in an undersupply of that ES and Pareto efficiency will not be reached. In such cases, the government must be involved in providing these services by financing them through tax revenues and thus increasing the supply of ES. For example, an increase in the provision of ES has been one of the main aims of agricultural policies in Switzerland and in Europe since the 1990s (Albrecht et al. 2007).

To efficiently govern an ES, however, it is necessary to understand the dynamics of ES and human well-being, which interact on different spatial scales that are sped up by different drivers (Carpenter et al. 2009). This includes necessary knowledge about how humans affect the provision of different ES and what is the value of these ES (Daily 1997, MEA 2005). Assessing the monetary value of ES allows for researchers to compare the impact of different management options (Haynes et al. 2009). Up to now, different valuation methods have been developed due to fact that there are thousands of studies focusing on the valuation of ES (Haynes et al. 2009). Applying the two models in this thesis, ES are not valued, but the costs of the supplies of different amounts of ES are assessed, resulting in a type of supply curve, presented in Chapter 7 and 8.

2.3 Ecosystem Services and Global Change

The governance of ES is becoming even more complicated, given that global change will affect supplies of ES that are important for humans’ well-being (Schröter et al. 2005). Climate change and the subsequent change in precipitation patterns will affect ecosystems as well as ecosystem processes. The impact of the changing climate is already visible (Walther et al. 2002, Parmesan and Yohe 2003), and this change will increase in the future. For example, changing climate is affecting the phenology of birds, i.e. their timetable for migration and nesting (Crick 2004). Another example is the increase in wildfire activity due to changing precipitation patterns (Marlon et al. 2005) and the upward shift
of biomes in mountainous regions, caused by ecosystems coping with climate change (Peñuelas and Boada 2003). Such changes in ecosystem processes will also alter the ability of forests to provide ES such as their protection function (see Beck et al. 2011, Montoya and Raffaelli 2010). However, climate change will affect the provision of ES differently in different locations demanding for adapted policy schemes. For instance, in Europe, climate change will increase the vulnerability of ES provision mainly in mountainous and Mediterranean regions (Schröter et al. 2005, MEA 2005).

Beside climate change land use changes driven by changes in socio-economic parameters will be the main driver for changes in ES provision. Lambin et al. (2001) explain land use change as the reaction of people to economic opportunities. One example is the creation of new local or global markets. These changes in opportunities, however, can be mediated by institutional factors such as changes in economic policy. Changes in agricultural land use are, for instance, driven by agri-environmental policies, agricultural production practices that are more efficient and changes in the availability of infrastructure (Mottet et al. 2006, Gellrich et al. 2008). These can result in changes in the intensity of land use or even in the abandonment of land use on certain locations. Such changes in land use will affect the ecosystems present on specific spatial units and, subsequently, the ES provided by this land (Metzger et al. 2006). For example, in mountainous regions, the abandonment of agricultural land may be followed by a temporarily decreased ability of the ecosystems to provide protection against natural hazards. If after abandonment species communities containing long and soft grass establishes, this may foster the occurrence of snow gliding (Newesely et al. 2000) and erosion (Tasser et al. 2001). As soon as shrubs and trees are established on this land, protection again increases and in the end will be higher than it had been under agricultural cultivation.

There is already a lot of information available about the impact of global change on ES provision, but there are still some gaps in the research that are partially filled by this thesis. For example, most research is focused on direct drivers of change in ES provision. To establish effective management schemes, however, it is also important to gain some knowledge about the impact of indirect drivers, such as socio-economic changes (Carpenter et al. 2006), which are discussed in this thesis.

### 2.4 Spatial complexity influencing ES provision

Spatial links are basic characteristics of ecological and economic systems. These systems are embedded in landscapes as an amalgam of natural, economic and cultural aspects
Background literature

In landscapes, the different systems compete for space, light and other vital resources of which the availability is different at each location. The consideration of these spatial links is especially important for modelling mountainous regions. In mountainous regions, the topographic complexity that defines them has a large impact on land use decisions (Bolliger and Kienast 2010). Additionally, mountain ecosystems are very sensitive to changes, and subtle shifts in the environment can have a large impact on land use dynamics (Houet et al. 2010). Forest growth—and the subsequent provision of services by forest ecosystems—is dependent on local conditions, such as slope and local climate, that influence growth and changes in forest composition and biodiversity. Topographic complexity also affects agricultural land use directly, given that this complexity has a strong influence on microclimate and soil characteristics. Both are factors that determine the potential yield of grasslands and crops. In addition, in order to cultivate steep and varying slopes, specialized, and therefore expensive, machinery is needed. The high amount of time and effort needed to cultivate such parcels makes them especially vulnerable to changes in the environment, such as climate change–induced shifts in production capacity that can lead to important changes in land use. If production potential is affected negatively, land can no longer be cultivated in a profitable manner (Gellrich and Zimmermann 2007). If maximum yield locally increases as a result of climate change, this can also lead to land use that is less intensive: if there is no demand for the additional product (Henseler et al. 2009). In both cases, the parcels with the least suitable topography will be abandoned, leading to a shift in the provision of different ES. Such spatial links between different systems also lead to trade-offs and synergies in the provision of different ES, which is an important topic for future research of ES provision (Carpenter et al. 2006).

Because of the spatial linkages between socio-economic and ecological systems, inter- and transdisciplinary research play a key role in spatially explicit ES modelling (Pauleit 2010, Naveh 2001). Even though, inter- and transdisciplinary research poses a challenge due to (among other issues) different research languages in different disciplines and limited resources in terms of time and funding (Fry 2001), a greater amount of holistic research has become increasingly important.

Such research is accomplished by the increasing communities dedicated to land-change science (Turner et al. 2007)—the study of landscape dynamics (Houet et al. 2010), integrated assessments of land use (Kok 2007, Helming et al. 2008) and agricultural systems (Bezlepkina et al. 2011). They provide comprehensive insights into land use and land-
scape changes from an integrated perspective often using different land use change models. Indeed, modelling plays a key role in integrating knowledge across scales, time and disciplines (Brouwer and van Ittersum 2010). Integrated models of land systems can take different specifications (Schaldach and Priess 2008), and the techniques integrated into inter- and transdisciplinary research range from using agent-based models to combining different models (Verburg and Overmars 2009) or Bayesian probabilistic approaches (Grêt-Regamey 2008).

2.5 Mathematical programming as a method for spatially explicit modelling

Mathematical programming models are widely used for modelling spatially explicit decision making as well as decision making on farms since they are able to capture the core decision-making processes that drive agricultural land use/land-cover change (Lambin et al. 2000). In the literature, extensive reviews of the tools used for spatially explicit modelling are available in Agarwal et al. (2002), Aspinall and Hill (2008), Irwin and Geoghegan (2001), Koomen et al. (2007), Lambin and Geist (2006) and Schaldach and Priess (2008), to name a few. Focusing on different goals, the available models differ mainly in their spatial and temporal scales as well as in their methods. With focus on their methodological approaches, Koomen et al. (2007) divide fifteen reviewed land use models into eight different groups, including models based solely on economic principles, statistical models, rule-based models, cellular automata, and optimisation models. Verburg and Overmars (2009) identify dealing with different spatial and temporal scales as one of the main challenges when spatially explicit modelling land use decisions. For instance, economic decisions are merely made on farm or higher levels, whereas precise land use decisions are made on a parcel level, but still considering the higher-level decisions. This implies that a model needs to cover decisions on different spatial levels. Mathematical programming models are especially valuable for such challenges because they allow for the integration of different sub-models into a larger framework (Buysse et al. 2007).

As of yet, there are few studies available that explicitly consider the impact of global change on land use and its effect on the provision of ES at local and regional scales. Those that are available do not explicitly model decision making on lower spatial levels, but use down-scale approaches. For example, in a study by ATEAM (Advanced Terrestrial Ecosystem Analysis and Modelling) and EURuralis (Europe’s Rural Areas), top-down modelling approaches were used to provide information about land use/land-cover changes on different scales by applying downscaling procedures to continental-
level data (Busch 2006). In the EURuralis framework, climate change feedback is accounted for by reiterating global results from the Integrated Model to Assess the Global Environment (IMAGE) (Meijl et al. 2006) at the national level, using the general economic equilibrium model (GTAP). The allocation of land at the local level is represented using a spatially explicit model that considers variations in biophysical, socio-economic and policy characteristics (Verburg et al. 2006). The validity of the results derived from such downscaling procedures, however, is unclear because consistent land-cover data are rarely available for large areas (Verburg et al. 2006). Additionally, existing heterogeneities within the considered administrative units cannot be represented.

In contrast, the projects ACCELERATES (Assessing Climate Change Effects on Land Use and Ecosystems: From Regional Analysis to the European Scale), RegIs (Regional Climate Change Impact and Response Studies in East Anglia and North West England) and GLOWA-Elbe (Global Change in the Hydrological Cycle) use bottom-up approaches to address decision making at a regional level. The ACCELERATES and RegIs projects use farm models based on linear-programming techniques to evaluate optimal land use allocation at the regional level (Audsley et al. 2006). The GLOWA-Elbe study uses a regional agricultural sector model based on Positive Mathematical Programming (PMP) to simulate land use changes at the county level (Flichman et al. 2006). The impact of climate change is considered in these models by integrating specialised crop-simulation models, such as the ACCESS model (AgroClimatic Change and European Soil Suitability, Holman et al. 2005) in RegIs.

In Switzerland, spatially explicit decision-making models typically include ex-ante assessments of policy measures on the impact of agriculture on the environment. For instance, Flury (2002) applies a sector model to define sustainable land use strategies for agriculture in the Swiss Alps. A similar modelling approach is applied by Zgraggen (2005) to make an ex-ante assessment of ecological policy measures in the watershed of the Greifensee. For this purpose, he expands the spatially explicit sector model such that it is able to calculate different ecological indicators. Lauber (2006) uses an agent-based modelling approach to simulate structural change in a mountainous region of Switzerland as well as to conduct an ex-ante assessment of changes in agricultural policy. Huber (2010) applies a spatially explicit sector model for the evaluation of jointness in the production of ES and agricultural products. Whereas the models of Huber (2010) and Zgraggen (2005) implicitly address the provision of ES, the models of Flury (2002) and Lauber (2006) focus on land use change. Until now, there have been no Swiss studies available
that focus on change in land use and ES provision under different climate and policy scenarios. This tradition was continued by the elaboration of the ALUAM model that expands the knowledge of the existing models by considering climate change and the integration of forest land in the modelling process.

2.5.1 Advantages and caveats of normative mathematical programming models

The two models presented in this thesis are normative mathematical programming models. The main advantage of this approach is that it is based on a sound economic theory: neoclassical economics (Buysse et al. 2007). In this theory, decision makers are assumed to make decisions in a way that maximises their profits. Thus, in the decision-making process, they must consider the limited availability of different resources, such as workforce or capital. These normative-model approaches incorporate the fundamental economic problem of making the best out of limited resources (Buysse et al. 2007).

Another strength of normative mathematical programming models is their modular structure, which allows for the easy integration of different datasets (Belovsky 1994. Hence normative mathematical programming models allow for linking economic elements with ecological and biophysical elements (Buysse et al. 2007, Hazell and Norton 1986). This is especially important because results derived from ecological models have to be integrated into the model in order to take into account climate change or changes in farm management. Whereas data for ecological modelling is needed on a very fine spatial scale and processes are driven from the bottom up (Verburg et al. 2009), economic driving forces influence land use on a coarser resolution, such as on the farm- or regional level (Umstätter 1999). Thus, economic driving forces affect land use change from the top down (Verburg et al. 2009). The modular structure of normative mathematical programming models, however, also makes possible the introduction of new activities (Havlík 2006), such as new crops or irrigation systems. This makes the model suitable for simulating strategies for land use that adapt to global change.

Furthermore, normative mathematical programming models are suitable for dealing with problems caused by different time scales, which is important if agricultural and forest land use decisions are to be integrated into one model. For instance, while decisions in forestry are made with a time horizon of, at the very least, decades, agriculture decisions are measured yearly.

Of course, the decision making of land users is more complex than the goal function of a mathematical programming model; it also considers different types of utilities and non-
linear relationships. This simplification limits the interpretation of the results of such models, to a prescriptive perspective—it assumes that farmers and foresters will succeed in maximising their profits if they behave as the model does (Huber 2008, Sterman 1991). In reality, however, people also aim at other goals that keep their satisfaction high. Nevertheless, studies show that economic drivers are still important for land use change (see Gellrich et al. 2007) or implementing farm-management options. This is why normative mathematical programming models are assumed to be useful for simulating the impact of global change on land use and the provision of ES.
3 Research questions

The goal of this thesis is to contribute to the scientific discussion regarding the links between the provision of different ES in mountainous regions as a result of global change and to provide feasible solutions for possible challenges. For this assessment, it was especially important to design a simulation model for an ex-ante assessment of the impact of global change on ES provision. This model was complemented by a farm-scale model that allows for the assessment of different management options that may overcome trade-offs in the provision of different ES. More specifically, this thesis focuses on the following research questions:

• What are the determining factors for changes in the provision of ES?
• Are there trade-offs in the provision of different ES and are these trade-offs affected by global change?
• On the farm level, is there a possibility of mitigating trade-offs in the provision of different ES?

The importance of these questions is explained in more detail in the following parts of this thesis.
4 Case-study region

In this thesis, the ALUAM model was applied to the case study region of Visp, located in Central Valais (See Figure 6.3). Central Valais is a continental inner-Alpine mountain area and is the driest region of the Swiss Alps. Changes in precipitation patterns are supposed to have a huge impact on vegetation. Thus, this area is suitable for studying the dynamics of mountain and subalpine forests and of grasslands that result from climate change. The study area, the Visp region, has a total of 15'346 inhabitants and includes the Saas Valley (Saas Fee, Stalden), the region around Visp and the Baltschieder Valley. The area is 443.3 km². Unproductive land accounts for 62 % of the area, while 20 % of the area is covered by forest, and about 16 % of the land is used by agriculture. Agriculture and forest lands play an important role as recreation areas and habitats for plants and wildlife. Land use change is an important issue in this region given that about five per cent of the agricultural area was abandoned between 1981 and 1993 (SFSO 2009). Beforehand, a large share of this land had been used as pasture. Currently, farmers in this region only cultivate less than 10 ha of agricultural land, and they house around seven livestock units. The main farming activity on all of these farms is the production of livestock based on grassland. Only seven per cent of the farms cultivate more than 0.5 ha of crops (FOAG 2008).
5 Scenarios

For the assessment of future changes in ES provision two different scenarios based on the Special Report on Emissions Scenarios (SRES) of the Intergovernmental Panel on Climate Change (IPCC) are applied: Scenario B1 and Scenario A1FI (see Table 5.1). These storylines were then refined as described in Chapter 6 to receive a set of values that could be used to parameterize the model.

Table 5.1: Description of the storylines of the future scenarios applied in this thesis

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1FI</td>
<td>The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 storyline family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis whereas fossil intensive (A1FI),</td>
</tr>
<tr>
<td>B1</td>
<td>The B1 storyline and scenario family describes a convergent world with the same global population that peaks in midcentury and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.</td>
</tr>
</tbody>
</table>

Source: Nakićenović et al. 2000
6 Assessing the impacts of economic and climate changes on land use in mountain regions: A spatial dynamic modelling approach

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ABSTRACT
Future land use changes are predicted to be influenced by both climate-driven environmental changes and concomitant changes in local economic conditions. Assessing the impact of climate change on ecosystems, and the goods and services that they provide, therefore requires an understanding of the dynamic link between land-cover, ecosystem services and economic-driven land use decisions. The economic land allocation model (ALUAM) simulates the competition between forest and a range of agricultural land uses to estimate land use conversions in a spatially explicit manner at high resolution. Using a modular framework, ALUAM was linked with the forest-landscape model LandClim, and a crop yield model, that simulate the response of forests and crops to changes in climate. An iterative data exchange between the models allows a detailed assessment of the dynamic changes in the provision of agricultural and forest based services. We apply our model to the temperature sensitive inner-alpine region of Visp, Switzerland. Our results demonstrate that land use is influenced directly by environmental shifts and economic decisions, but are also highly dependent on the interactions between these two components. These shifts in land use will correspondingly affect the provision of ecosystem goods such as food and timber production.

KEYWORDS
Agriculture and forest ecosystem goods and services, Climate change, Land use change, Mathematical programming model, Scenario assessment

6.1 Introduction

Ecosystems in mountain areas provide a range of important ecosystem goods and services (EGS) such as food and fiber production, habitat diversity and protection services (MEA 2005; Messerli and Ives 1997). These services contribute significantly to regional income (Grêt-Regamey and Kytzia 2007) and without their provision life would hardly be possible in these regions.

Most ecosystems in mountain areas are an amalgamation of natural components and components that have been modified by human activity, such as agriculture and forestry (Körner and Ohsawa 2005). Land use and associated EGS are therefore dependent on natural processes and external environmental drivers (Schröter et al. 2005). These factors, such as climate change, modify the capacity of ecosystems to provide EGS. Concurrently, land managers might modify their land use investment in specific goods and services depending on economic conditions such as changes in prices for agricultural products or changes in agricultural policy (Gellrich et al. 2008). Therefore changes in prices for agricultural products, or in agricultural policy, can impact EGS provisioning in a similar extent to climate change. To assess future EGS provisioning, and to evaluate policy measures to mitigate potential future shortages, it is therefore necessary to understand the interplay between climate change, economy and land use change in the provision of EGS (Euliss et al. 2010).

A challenge that has to be resolved when evaluating and modelling land use change in mountainous regions is the topographic complexity that defines these regions and has a large impact on land use decisions (Gellrich et al. 2008). Mountain ecosystems are very sensitive to changes and subtle shifts in the environment can have a large impact on land use dynamics (Houet et al. 2010). Forest growth - and subsequently the provision of services by forest ecosystems - is dependent on local conditions such as slope and local climate that influence growth and changes in forest composition and biodiversity. Topographic complexity also affects agricultural land use directly as it has a strong influence on microclimate and soil characteristics. Both are determining factors for potential yield of grassland and crops. In addition, to cultivate steep and varying slopes specialized, and therefore expensive, machinery is needed. Climate change induced shifts in production capacity can lead to important changes in land use. If production potential is affected negatively, land cannot be cultivated in a profitable manner anymore (Gellrich et al. 2007). If maximum yield increases as a result from climate change in certain locations this
can also lead to a less intensive land use, if the additional production capacity cannot be used profitably since there is no demand for it (Henseler et al. 2009). In both cases the parcels with least suitable topography will be abandoned. Additionally changes in land use are also induced by shifts in the economic environment. To assess changes in the provision of EGS it is therefore necessary to incorporate the topographic complexity into the modelling framework.

When evaluating potential land use changes, differences in the time frame in which different EGS are produced and managed must also be considered. The length of production cycles is different between agriculture and forestry. Accordingly the frequency of decision making and the time needed for adaptation to changes in the environment are different. In agricultural production, cycles are short with decisions made on a yearly base. These short cycles provide the advantage that adaptation measures can be implemented rapidly by changing the management. In forest dominated ecosystems production cycles are rather long, demanding a more enduring management to ensure future provision of EGS. These differences in the frequency of decision-making have to be considered when simulation interactions between different EGS types. There exists a variety of modelling studies which deal with how changes in climate, policy and markets will impact land use (reviews in e.g. Agarwal et al. 2002; Aspinall and Hill 2008; Irwin and Geoghegan 2001; Koomen et al. 2007; Lambin and Geist. 2006; Schaldach and Priess 2008). Furthermore, there is an increasing body of literature focusing on ecological and economic interactions in agricultural and forest areas at different scales. Verburg and Overmars (2009) present a model at the European level which explicitly takes into account national policy and market changes on a national (or even international) level. Holman et al.(2005) present RegIS a modelling approach to assess impact of climate and socio-economic scenarios on EGS provision at a local and regional scale. RegIS however does not consider competition between agricultural and forest land use. In contrast, the InVest modelling framework presented by Nelson et al. (2009) is an approach for assessing the impact of different land use change scenarios on EGS provision. These models provide important knowledge about the influence of climate and economy on land use change and the provision of EGS. Yet, in these studies land use is not simulated at the scale at which land use decisions are made in mountainous regions, and/or climate change is not taken into account.

In this contribution we present a model which provides a detailed assessment of shifts in land use in a mountainous region of Switzerland under the assumptions of two climate
and economic scenarios. Our approach incorporates the combined effect of climate and economy changes on different spatial levels – from parcel to region. Because of its modular framework the model could be adapted to other regions and to other climatic and socio-economic scenarios. This allows a spatially explicit quantification of the provision of EGS, both today and in the future. We focus on two EGS, food and timber, since they are affected by both changes in economic environment and changes in climate, and their provision is one of the goals of Swiss agricultural policy (Herzog et al. 2005). In addition, because of interactions between these marketable EGS and other non-marketable EGS (Nelson et al. 2009), our evaluation of food and timber can be used to extrapolate the impact of land use changes on other ecosystem services.

### 6.2 Method

The assessment of changes in land use and EGS is accomplished in three steps (Figure 6.1). In step one, in the absence of land use change, the direct impacts of climate change on forest development and crop yields are calculated for each year between 2010 and 2080. This step involves amalgamating three data sources 1) Within each simulated parcel (100 by 100 m) the potential yield of all agricultural and forestry activities (for an overview see Table A.1) is simulated by the forest-simulation model LandClim and the crop yield model. 2) Spatially explicit data are calculated for each parcel. A digital elevation model (Swisstopo 2005) is used to calculate elevation and slope of each parcel. Swiss Land Cover Statistics (SFSO 2009) are used to determine which parcels are suitable for cultivation and a soil utility map (FOAG 2000) is used to rate the different parcels according to their suitability for the land use activities. Swiss Land Cover Statistics (SFSO 2009) was used to calculate the distance of all parcels to the next farm. 3) Administrative data, e.g. the production zone the parcel is lying in, are assigned to the parcels.

In step two, these spatially explicit yield estimates are combined with policy and market scenarios in the economic model Alpine Land Use Allocation Model (ALUAM). ALUAM then simulates land use decisions based on a profit maximizing approach. The results show both where land use change occurs and what the combined impact of climate and economic change is. The data assigned to each parcel is thus combined with sources linking spatially explicit data with production parameters such as labour demand (ART 1996), nutrient demand (Amaudruz et al. 2003), fodder production and profitability – considering also the transport costs dependent on the distance between parcel and farm-yard (Boessinger et al. 2010, Erni et al. 2004).
In step three, land use change results are then re-entered into LandClim and the impact of economic-driven land use changes on EGS provision in forests is then re-assessed. In the following, the different submodels of the framework are described in more details.

Figure 6.1: Linkages between the different submodels of the presented framework

6.2.1 Crop model

Projected future yields of relevant crops are calculated using FAO (Food and Agriculture Organization of the UN) data on optimal and absolute crop growing conditions (FAO 2007). The minimum and maximum temperature and precipitation values that support optimal crop development, and the values that define the crops temperature and precipitation extremes, are extracted from the FAO crop data base EcoCrop (Ecocrop 2007). Using these four values, we fit a relative crop yield curve for temperature and precipitation values using an incomplete beta distribution. These species specific crop yield curves are then used to calculate the relative yield for six crops based on monthly precipitation and temperature values, for each landscape cell (100x100m) in the case study landscape. The projected realized yield is taken as the minimum yield value from the temperature and precipitation responses. In the case of irrigated land, yield is only seen as limited by temperature responses. The absolute yield of crops is calculated by standardizing the values against observed yield of crops in 2000 (LBL 2000).
6.2.2 LandClim

Forest dynamics, and forest derived EGS such as potential timber harvest are simulated using the forest landscape model LandClim (Schumacher et al. 2004). LandClim is a spatially explicit process based model that incorporates competition-driven forest dynamics and landscape-level disturbances to simulate forest dynamics on a landscape scale. LandClim was designed to examine the impact of climate change and forest management on forest development and structure (Schumacher and Bugmann 2006, Schumacher et al. 2006). The model has been tested in the Central Alps, North American Rocky Mountains, and Mediterranean forests, and has been used to simulate current forest as well as paleo-ecological (Colombaroli et al. 2010, Henne et al. 2011) and future forest dynamics (Schumacher and Bugmann 2006).

LandClim simulates forest growth in 25 by 25 m cells using simplified versions of tree recruitment, growth and competition processes that are commonly included in forest gap models (Bugmann 2001). Forest growth is determined by climatic parameters (monthly temperature and precipitation), soil properties and topography, land use and forest management, and large-scale disturbances. Individual cells are linked together by the spatially explicit processes of seed dispersal, landscape disturbances, and forest management. Forest succession processes within each cell are simulated on a yearly time step, while landscape-level processes are simulated on a decadal time step. Forest dynamics within each cell are simulated by following tree age cohorts, where cohorts are characterized by the mean biomass of an individual tree and the number of trees in the cohort.

To evaluate potential timber production within each landscape cell we implemented a forest management regime whereby forest stands are evaluated every 20 years to determine if the stand would be entered and timber removed. If the average height of the dominant trees within a stand (largest 100 trees•ha−1) is greater than 15m the stand is entered and all trees with a DBH (diameter at breast height) greater than 20 cm are harvested. This yields harvested trees that have an average DBH between 25 and 30 cm. This management routine is used to get a timber production value for each cell on the landscape that can be returned to ALUAM and used to inform land use conversion.

6.2.3 ALUAM

The mathematical programming model ALUAM integrates the different submodels and simulates land use decisions in the model region. Mathematical programming models have proven to be suitable for policy assessment in different studies such as Flury et al.
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The application of Linear Programming – as done in ALUAM - showed also to be convenient for the integration of different models in other studies (e.g. Henseler et al. 2009, Schönhart et al. 2011). The modular and simple structure of ALUAM offers the possibility to link economic with ecological and biophysical elements (Buysse et al. 2007) and to integrate datasets from different sources (Belovsky 1994). It also makes the introduction of new activities possible, e.g. irrigation, what makes the model suitable to simulate strategies for adaptation to global change.

In ALUAM, we assume that economic agents are profit maximizers. Combined with limited resources, represented by model restrictions, this normative model approach incorporates the fundamental economic problem: making the best out of limited resources (Buysse et al. 2007). This intention underlies the model structure as shown in Figure 6.2: Decisions on the different levels – parcel level, farm level and regional level - are optimized in a way that aggregated land-rent is maximized. This means that the combination of the land use and livestock activities (to know more about livestock activities see section 6.2.4) (I) is optimized in a way that the linear goal-function (II) is maximized. Different constraints (III) assure that restrictions (IV) on different levels are met. On the parcel level decisions are made about the land use activities. In the optimization the characteristics of the location influences the decision about the choice of the land use activity. In mountainous regions a proper design of farm-level decisions is especially important as large parts of the land can only be used as grassland. For generating value, grass has to be utilized by livestock. Decisions about animal husbandry however are made on the farm level and flows for fodder or nutrients between livestock and land use must be considered. Therefore decisions on the parcel level are linked with livestock-activities over different balances represented by the constraints described in Figure 6.2 (See section 6.2.5). Since different parcels can belong to one livestock activity, single parcels have to be summed up for calculating these balances.

For the simulations during the validation period between 2000 and 2005 and up to year 2010 we apply a recursive dynamic approach. When modelling these years the number of stable houses as well as the number of animals of the preceding years are considered in the optimization since the stable houses are assumed to cause fixed costs and there is only a restricted amount of animals available to increase herd size. For the assessment of the impact of different scenarios in 2080 a comparative static approach was applied because the costs of stable houses are assumed to become variable on a longer term. Also,
the amount of capital available for investments is only limited during the validation between 2000 and 2005 period and for simulations up to year 2010. Some resources on a regional level—hireable workforce, number of animals available for grazing on summer pastures—are only available in a restricted amount and therefore balanced over the whole region. For the calculation of these regional balances resource demand of the activities on lower levels had to be summed up, i.e. resource use of different land use and livestock activities have to be aggregated on the regional level to calculate the concerning balances. Production was only restricted over the whole region in the case of milk production as in the current marketing system Swiss dairy market is still highly regulated.

In the goal function of the model (II) the aggregated land rent is calculated. This indicator was chosen for optimization because it is an appropriate and useful approach to measure the potential economic performance of land use systems (van Kooten 1993)

6.2.4 Livestock-activities

The design of the livestock activities in the model is based on the current farm structure as recorded by Swiss agricultural census data (FOAG 2008). All livestock activities represented in the model are based on grassland. They include dairy cows, heifers, suckler cow, sheep and dairy sheep (Table A.2). The existing small scale agriculture leads to economies of scale if farm structure changes. Larger farming systems decrease the relative demand for resources, e.g. labour per animal. To capture the impact of increased farm size on resource demand, each of the seven livestock-activities was modelled in six different categories, which vary in the number of livestock housed per farmer (Table A.2). In addition, a higher number of livestock units per farm induces investments in larger machinery and thus causes economies of scale also in land cultivation activities. Furthermore, farms can substitute between livestock and crop production to adapt to future changes in climate or economics. Data for the design of the activities including knowledge about labour demand are derived from literature (ART 1996, Boessinger et al. 2010, Gazzarin and Albisser Vögeli 2010).
Figure 6.2: General structure of ALUAM: The amount of the different activities \( i \) (I) is optimized such that goal function (II) is maximized. Constraints \( j \) make sure that restrictions in the availability of resources on different spatial levels are considered in the optimization process. If these restrictions encompass more than one spatial level, resource demand or provision of activities on lower spatial levels have to be summed up. \( a_j \) represents a technical parameter different for each combination activity constraint.
6.2.5 Calculation of standardized Food Units

To make the food produced on grassland parcels comparable with cropland production, a standardized Food Unit had to be calculated. Only a fraction of the nutrients in the dry matter produced on a grassland parcel is available as food for humans as forage must first be converted into meat or milk by animals. During this conversion process a large share of nutrients is lost. To make grass and crop production comparable, the amount of grass produced was multiplied by a factor 0.20 and 0.02 for milk and meat production respectively. These parameters were calculated from data presented by Arrigo et al. (1994) and Boessinger et al. (2010). Beside the efficiency of energy-conversion from grass into human food, in these factors also the different energy contents of the end-products are included (Arrigo et al. 1994, Boessinger et al. 2010). The energy content of wheat grains was used for standardization. Hence one Food Unit equals the energy content of 100 kg wheat grains. Because of its low content in digestible nutrients, dry matter produced in the form of straw was disregarded in these calculations. The amount of dry matter produced on each parcel is derived by combining the allocated land use activity and the potential yield on each parcel.

6.2.6 Balances: Linking livestock and land use

Balances for fodder as well as nutrients were derived from the Swiss Integrated Agricultural Allocation Model S_INTAGRAL – a sector model for the assessment of questions concerning environmental efficiency of agroecosystems presented by Peter (2008). These balances link livestock and land use in the model which is a vital characteristic in modelling grassland based agricultural production. The fodder balance guarantees that the amount of fodder produced on agricultural land meets the nutritional needs of the livestock. The nutrient balance on the one hand guarantees that applied manure and fertilizer meets the minimum need for crop acreage and grassland. On the other hand, the nutrients applied are limited by a maximum standard allowance according to the federal law of agricultural.

6.2.7 Labour balance

Demand for labour is an important parameter determining agricultural structure in mountainous regions (Flury et al. 2005, Gellrich and Zimmermann 2007). Agriculture in mountain areas is very labour intensive. Depending on the state of the national economy,
competition for labour influences wages for hired labour as well as the opportunity costs for farmers.

When calculating labour balance the year was divided into three periods: 1) winter when on-farm labour demand is low but farmers have the opportunity to work in the tourism sector, 2) summer where on-farm labour demand is high because growing period is short and fodder has to be harvested for feeding animals during a long winter, and 3) the two periods between summer and winter with low on-farm demand and low off-farm labour demand. In every period labour demand has to match labour supply.

The labour demand of land use activities is dependent on several spatially explicit factors such as potential yield and remoteness. Thereby the slope of the parcels was the primary factor influencing labour demand. Whereas on flat parcels all work can be accomplished by machinery, in steep slopes the use of machinery has to be replaced by labour.

Available on-farm labour is restricted to one farmer and one relative working fulltime on the farm. E.g. for the livestock activity dairy cattle farming (20 cows per farm) there is one farmer available for every 20 cows. Due to the fact that labour is restricted on the level of the livestock activity this amount has to be sufficient for both livestock activity as well as added land use activities. Additional labour can be hired at market wages but total hireable labour is restricted on the level of the region. The number of farmers is restricted to the level in the year 2010, i.e. it is assumed that farms cannot split into smaller farms. More importantly, the amount of highly qualified labour supply is also restricted to this level. This implies that farmers may allocate their labour to other farms but no additional highly qualified labour is available. Based on the characteristics of our case study region (small scale agriculture in a high income country and seasonal fluctuation of labour demand), a permanent employment of a worker with high qualifications at a competitive wage is implausible. In contrast, labour with low qualification is available without restriction.
6.3 Case study region

Figure 6.3: The case study region: Visp in the southwest of the Swiss-Alps (Maps: ©swisstopo)

The central Valais is a continental inner-Alpine mountain area, and is the driest region of the Swiss Alps. Changes in precipitation pattern are supposed to have a huge impact on vegetation. Thus, this area is suitable for studying the dynamics of mountain and subalpine forests and grasslands under climate change. The study area Visp region (See Figure 6.3) includes the Saas-valley (Saas Fee, Stalden), the region around Visp in the main valley and the Baltschieder-valley with a total of 15’346 inhabitants. The area has a size of 443.3 km². Unproductive land accounts for 62% of the area, while 20% of the area is covered by forest-land and about 16% of the land is used by agriculture. Agriculture and forest land use play an important role as recreation area and habitat for plants and wildlife. Land use change is an important issue in this region as about 5% of the agricultural area has been abandoned in the period between 1981 and 1993 (SFSO 2009). A large share of this land was used as pasture beforehand. Currently farmers in the simulated region only cultivate 8 ha of agricultural land and house around seven Livestock Units. The main farming activity for all of these farms is the production of livestock based on grassland. Only 7% of the farms cultivate more than 0.5 ha of crops (FOAG 2008).

6.4 Scenarios

We explored the impacts of climate and economics on land use decisions under current conditions as well as under the two different IPCC scenarios A1FI and B1 for the year 2080. The main assumption of scenario A1FI is a rapid and successful economic growth
accompanied by an economic conversion between poor and rich countries (Nakićenović et al. 2000). This fast economic growth is one of the reasons why it is assumed that the global population under this scenario will only increase to 9 billion people until 2050 and decrease afterwards. This comparably low population growth will lead to a fast increase in average income. Even if energy efficiency increases rapidly demand for fossil energy is predicted to stay high, which will lead to high emissions of carbon dioxide and subsequently an increase in average global temperature by 4°C (IPCC 2007). Scenario B1 is dominated by a high level of environmental and social consciousness (Nakićenović et al. 2000). Under the assumption of this scenario the economy is still growing but slower than under scenario A1FI. Population growth is the same as scenario A1FI but for different reasons. A big difference to scenario A1FI is that more money is invested into green technology and therefore the output of carbon dioxide is reduced. This will lead to an increase in global average temperature by only 1.8°C (IPCC 2007).

Combining the effects of these climate scenarios (no change, A1FI and B1) with and without economic changes plus the baseline scenario results in the calculation of 7 scenarios. In the Baseline scenario current climate and policy data are applied. In the scenarios Economic_Change_A1FI and Economic_Change_B1 the impact of changes in policy and markets in the year 2080 is assessed while climate is kept at the current level. Scenarios Climate_Change_A1FI and Climate_Change_B1 are the opposite as current policy and market parameters are used and changing climate is assumed only. In scenarios Combined_Change_A1FI and Combined_Change_B1 the combined effect of changes in policy and market, and climate are assessed.

### 6.4.1 Climate scenarios

The climate interpolation software “DAYMET” (Thornton et al. 1997) was used to produce daily climate maps with a resolution of 100m for the baseline period of 1961-1990 using data from regional weather stations. Climate scenarios B1 and A1FI derived from the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007). These scenarios were combined with the global climate model HadCM3 to receive monthly climate data with a resolution of 10’ for the years 1900-2080 (Mitchell et al. 2004). Using this data all monthly values of the years 1900-2080 were calculated as anomalies relative to the normal state of the baseline period. The resulting anomaly maps were then downscaled to 100m resolution and then combined with the fine scaled “DAYMET” normal state to obtain fine scaled maps for all the years 1900-2080. For a
detailed description of this method see Mitchell and Jones (2005). In the region around Visp these changes will lead to an increase in average annual temperature of 2.6°C in 2080 under the assumption of scenario B1 and 4.6°C under the assumption of scenario A1FI. Yearly precipitation is predicted to not change much (decrease of 2 mm per year) under scenario A1FI and is predicted to increase by 11.2 mm per year under the B1 scenario. However, in both the A1B and B1 scenario summer precipitation is predicted to decrease and winter precipitation to increase, thereby resulting in the small yearly changes.

6.4.2 Economic Scenarios

Our policy and market scenarios were based on the IPCC scenarios A1FI and B1. In an expert survey, Abildtrup et al. (2006) assessed the impact of these scenarios on commodity prices as well as costs of production factors for farming in the European Union for the year 2080. Whereas Swiss markets for agricultural products nowadays are highly protected, it was assumed that these tariffs will be abolished by 2080. As a consequence, prices for agricultural products will decrease to the EU level. Therefore the base for the calculation of future prices in Switzerland were EU prices of the year 2005 (Table A.3) that were adjusted to 2080 using the parameters provided by Abildtrup et al. (2006). Compared to the year 2010 prices for commodities will decline until 2080 (Table A.3). In 2010 commodity prices were lower in the European Union than in Switzerland and following Abildtrup et al. (2006) commodity prices in the European Union will further decrease until 2080 in scenario A1FI and remain constant in scenario B1. In scenario A1FI costs for production inputs were assumed to be decreasing until 2080, while in scenario B1 they are assumed to increase significantly. In contrast to the scenarios proposed by Abildtrup et al. (2006) it was assumed that government support for the agricultural sector will remain on today’s level as support for agriculture has a long tradition in Switzerland (Haller 2010). The price for timber also was assumed to stay constant until 2080.

6.5 Results

6.5.1 Modelled climate change impact on plant growth

Climate change is predicted to have a positive impact on the growth of crops and grassland but a negative impact on forest growth in both scenarios (Table 6.1). In the simulated region drought stress is currently important at lower elevations, and is sufficient to constrain tree growth. For drought intolerant species such as Norway spruce (Picea abies),
small increases in drought can result in strong decreases in forest yield. Under severe
drought stress even reasonably drought tolerant species such as Oak (*Quercus* spp.) are ex-
cepted to have lower growth. Increased drought stress at lower elevations is predicted to
result in an 81% and 80% reduction in forest yield in 2080 under the B1 and A1FI cli-
mate scenarios respectively.

In contrast, crop yields are primarily constrained by low temperatures and less impacted
by reductions in soil moisture. Climate change driven increases in temperature are there-
fore predicted to increase crop yield since for most of the crops drought conditions are
not predicted to be sufficiently sever such that crop yield will be reduced especially if
they are irrigated.

Table 6.1: Relative changes in potential yields of crops, grassland and trees under the two climate
scenarios B1 and A1FI in the year 2080 compared to them in 2010. Potential yields were aggregat-
ed over the whole region. (Index: Yield without irrigation in 2010 = 100)

<table>
<thead>
<tr>
<th></th>
<th>2000</th>
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<th>2080</th>
<th>2080</th>
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<td>100</td>
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<tr>
<td>Rape seed</td>
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<td>100</td>
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<td>118</td>
</tr>
<tr>
<td>Potato</td>
<td>100</td>
<td>100</td>
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<td>129</td>
</tr>
<tr>
<td>Grassland</td>
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</tbody>
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<table>
<thead>
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<td></td>
</tr>
<tr>
<td>Oak b</td>
<td>100</td>
<td>39</td>
<td>37</td>
<td></td>
</tr>
</tbody>
</table>

a  Example for a temperature sensitive tree species

b  Example for a less temperature sensitive tree species

6.5.2  Land use changes under climate and economic scenarios

6.5.2.1  Climate Change

Under the *Climate_Change* scenarios the reduction in cropland is lower in the *Cli-
mate_Change* B1 scenario compared to the *Climate_Change* A1FI scenario. The main reason for
this difference is that under climate scenario A1FI the growth rate of grassland increases
more than the growth rate of crop yields, therefore improving the relative profitability of
grassland.
Under the assumption of both Climate Change scenarios the increasing production capacity of grassland due to climate change increases profitability of intensive use of grassland. This leads to a shift from extensive to intensive use of grassland on the most suitable sites in both Climate Change scenarios. On the other hand side in both Climate Change scenarios production potential on some parcels is also affected negatively by climate change, leading to a less intensive land use. This impact however is more pronounced under the assumption of the Climate Change B1 than under the Climate Change A1FI scenario (Table C.1).

Under the assumption of the Climate Change A1FI scenario the area used by agriculture decreases. Under this scenario summer pastures are the agricultural land use type that is primarily abandoned. These pastures are mainly located at high altitudes where grazing with sheep is the most suitable activity. To adapt the use of these areas to the climate change driven increased production capacity of the summer pastures more sheep would be required for grazing. However, an expansion of sheep production for grazing summer pastures is not profitable because of the low prices for the product, high costs for the stable houses and the subsidies for summer pastures that are much lower than on agricultural land below the treeline. As a consequence, production capacity of the pastures exceeds the demand for fodder by the available sheep and least suitable land is abandoned, i.e. it becomes unmanaged forest. In contrast to agricultural land use unmanaged forest land use is assumed to not cause a financial loss.

6.5.2.2 Economic Change

With respect to grassland, price decreases in the agricultural sector lead to less intensively used grassland in our simulations. This impact is more accentuated under the Economic Change B1 scenario. In this scenario profitability of livestock activities decreases more than under the Economic Change A1FI scenario. In response to market changes in scenario Economic Change B1, 48% of the intensively used grassland are used less extensively, while under the Economic Change A1FI scenario only 18% of the grassland is used less intensively (Table C.1). Additionally in both Economic Change scenarios cropland is transformed into grassland since the decreasing prices for crops will lead to a decrease in profitability of crops compared to grassland based livestock activities.

6.5.2.3 Combined Change

Under the Combined Change B1 scenario economic and climate change impacts are predicted not to result in shifts between agricultural and forest land use. In contrast, the large
increase in average temperature under the A1FI climate scenario in combination with decreasing market prices leads to the abandonment of large parts of agricultural land in the scenario Combined_CHANGE_A1FI (Figure 6.4, Table C.1). Summer pastures are the primary land use type that is abandoned, for the same reasons as it is abandoned under the Climate_CHANGE_A1FI scenario, i.e. because there are not enough sheep available to graze the additional fodder.

In both Combined_CHANGE scenarios there is a shift from unmanaged forest to managed forest (Table C.1). The costs of timber production in the managed forests are mainly dependent on the amount of timber harvested and not on the area of forest. Simulated changes between managed and unmanaged forest activities due to climate change are based on the shift in tree species composition from low value timber (e.g. spruce), to high value timber (e.g. oak).

6.5.2.4 Comparison of the impact of the climate and economic scenarios on land use change

The area used for crop production decreases in all scenarios, and is abandoned in all scenarios that assume economic conditions at the A1FI level. Cropland is abandoned under the B1 scenario as well if only economic parameters are changed. However climate scenario B1 has a positive impact on the relative profitability of crop production and therefore under these assumptions area used as cropland is reduced less than under economic scenario A1FI.

Under the assumption of the Combined_CHANGE_B1 scenario increase in the area used as extensive grassland is even more pronounced than under the Economic_CHANGE_B1 scenario. The profitability of livestock production under this scenario is lower than under scenario A1FI, which is why less animals are housed that could graze the additional pasture.

Decrease in area used by agriculture is predicted to be higher under scenario A1FI if both climate and economy change occur, as compared to if only climate changes occurs. The decreasing profitability of agricultural production under the assumptions of the economic scenario A1FI limits the number of animals available to graze the additional fodder production, which promotes the abandonment of agricultural land.
6.5.3 Food and timber production

6.5.3.1 Climate Change

Despite a considerable increase in yields per hectare of crops and grassland, food production is predicted to decrease under the Climate_Change_B1 and the Climate_Change_A1FI scenarios by 48% and 66% between 2010 and 2080 (Table C.2). This reduction is driven by the shift from crop- to grassland.

6.5.3.2 Economic Change

The Economic_Change_B1 and the Economic_Change_A1FI scenarios imply a reduction in food production of by 71% and 91%, respectively (Table C.2). Under the projected changes in commodity prices and costs of production factors cropping is not profitable anymore in both scenarios.
6.5.3.3 Combined Change

Whereas under the assumption of the economic scenario B1 milk production remains competitive, the A1FI scenario implies a disappearance of milk production in our case study region. Finally, considering both effects in the Combined Change B1 and the Combined Change A1FI scenario, food production decreases by 49% and 89%, respectively. This is mainly due to the abandonment of crop production as a result of changes in economy. Meat production however only decreases by 8% under the assumption of scenario Combined Change A1FI and milk production is totally abandoned. Under the Combined Change B1 scenario meat production decreases more but milk production decreases less, as compared to the A1FI scenario.

6.5.3.4 Comparison of the impact of the climate and economic scenarios on food provision

Food provision is decreasing under all scenarios. Scenarios that assume changing economic parameters are predicted to have a larger negative impact on food provision compared to only climate changes. This is mainly the case because economic changes are predicted to reduce profitability of crop and, under the assumption of scenario A1FI milk production is also predicted to decrease.

6.5.3.5 Spatially explicit changes in food provision

Figure 6.5 shows the decrease in food production in a spatially explicit manner. While current food production is highest in the Rhône-Valley around the city of Visp, cropland is transformed to grass-land as a result of both climate and economic changes. Food production not only decreases at lower elevations but also on parcels located higher up on the slopes of the Saas-Valley. Only on the most suitable locations on the bottom of the upper valleys is an increase in production per hectare predicted to occur.
Provision of Ecosystem Goods and Services in Mountainous Regions

Figure 6.5: Food provision per hectare in the scenarios Baseline (left map), Combined Change B1 (map in the middle) and Combined Change A1FI (right map) (Maps: ©swisstopo)

Timber harvest is also predicted to decrease between 2010 and 2080 under both climate change scenarios. Reduced tree growth is the main driver for climate induced reductions in timber harvest. At lower and intermediate elevations (800-1400 m a.s.l.) increased drought stress is predicted to result in a shift in forest species composition. The biomass of Norway spruce is predicted to decrease, while more drought tolerant species such as Oaks and Scots pine (Pinus sylvestris), are predicted to become a more dominant component of the forest. However, within the time frame examined the growth of these more drought tolerant species does not compensate for the loss of Norway spruce. The predicted expansion of forest area by 9% under the Combined Change A1FI scenario also does not compensate for the direct negative impact of climate change on timber production.
6.6 Discussion

6.6.1 Results

In the case study region, climate change is predicted to result in reduced timber production in forests, and in an increase in agricultural yields. Our findings are in accord with previous studies on grassland production (Riedo et al. 2000, Riedo et al. 2001), and timber production in drought sensitive regions (Kirilenko and Sedjo 2007, Schlyter et al. 2006). Still, these effects are associated with high uncertainty given the complexity of agricultural and forest ecosystems. A part of this variability is expressed by the huge differences implied by the different climate and economic scenarios.

The combined impact of climate as well as economic changes result in significant land use changes and land-cover shifts in our case study region. The two main effects in agriculture are a) a reduction of cropland and b) less intensive grassland production. This effect of a de-intensification on grassland was also found by Henseler et al. (2009) for the east Bavarian low mountain range and the Austrian Alps. In contrast, these authors find an increase in cropland under good agronomic conditions. Such conditions, however, cannot be found in the Visp region. Moreover, the extent of these changes much depends on the scenario. In the B1 scenarios, land use changes are more severe compared to the A1FI even if climate changes more under the assumption of scenario A1FI. On average, the corresponding loss in food and timber production differs by more than 25% between scenarios.

In the Combined_Change_A1FI and the Climate_Change_A1FI, a large part of the summer pastures are abandoned. This process is mainly driven by climate change. Our results imply that yields on alpine pastures are increasing but the additional biomass will not be consumed without a corresponding increase in the number of animals. Such an expansion of animal production, however, is not profitable even under current economic conditions. As a consequence, least profitable parcels will be abandoned and converted in managed or unmanaged forests. In the assessed region, however, this process is only triggered if climate change exceeds a certain level, i.e. changes as assumed for the B1 scenarios are not strong enough to induce these changes. Therefore, climate change should also be accounted for in the assessment of land abandonment in mountain regions. In addition, our results show a high spatial variability.

In general, climate change improves potential crop yield, and well cultivable parcels are predicted to be used more intensively in the future. Nevertheless food provision ex-
pressed by food units will decrease. This effect originates from a) the conversion of crop-into grassland b) the less intensive grassland use and c) the shift from milk to meat production. In crop production, the amount of nutrients available for human nutrition is much higher compared to a grassland based production of food. Less intensive use of grassland and the substitution of milk by meat production are mainly driven by shifts in the relative prices of the different commodities. Thereby, meat is less efficient than milk production with respect to its nutritional value. The magnitude of these changes however is dependent on the assumed scenarios. Despite the loss of nutritional value, less intensive grassland based meat production offers also some advantages not addressed in this analysis such as a potential reduction in emissions, reduced erosion pressure or biodiversity conservation (Dullinger et al. 2004, Jetz et al. 2007). The assessment of such trade-offs are an important next step in the analysis of the combined effect from climate and economic changes on ecosystem services in mountain regions. To adapt current policy measures to this new environment, knowledge about land use change dynamics can be very valuable. For the analysis of trade-offs further EGS as for example protection or information services should be considered as well (Grêt-Regamey and Brunner, Unpublished results).

6.6.2 Method

To model the impacts of different drivers on land use changes, and to avoid neglecting any spatial and temporal complexity of the ecological and economic processes, different specialized models in an interdisciplinary framework should be combined (Clayton and Radcliffe 1996). Such a framework has to consider biophysical drivers as well as the impact of markets and policy (Lambin et al. 2001). Our framework proved to be suitable for a detailed simulation of the impacts of different ecological and economic drivers on land use and EGS provision. Our results show that the complex topography of mountainous regions requires models that adequately consider spatial complexity since the impact of global change was highly dependent on landscape characteristics.

To incorporate ecological and economic drivers into an integrated framework different spatial scales must be considered (van Delden et al. 2011, Verburg et al. 2006). This inter-scale assessment is also important to cover spatial complexity since ecological processes are bottom up driven and need to be modelled on a fine scale (Verburg and Overmars 2009) but data about economic processes are only available on farm or even regional level (Umstätter 1999). One possibility to consider feedbacks, which straddle different spa-
tional scales, is to model them endogenously and to simulate the whole system applying one model (Veldkamp and Lambin 2001) as is done in ALUAM. The modular structure showed to be suitable for an integrative assessment as it allowed the integration of data from different sub-models and scenarios applied on different spatial resolutions in one land use decision model.

For the assessment of temporal complexity, a fully dynamic model considering different time scales endogenously is suggested to be the best solution (Veldkamp and Lambin 2001). Such an endogenous modelling of the land use system currently is not possible because the model becomes too complex. Moreover, decisions of farmers are made on a yearly basis not considering much more than a decade in future. Thus, assessing different future scenarios applying an iterative approach was not seen as a large inconvenience. In our framework, the models were linked over feedback loops to model forest development. The resulting iterative approach proved to be suitable to model the decision making process of land users and also to reduce computing power dramatically without neglecting much temporal complexity. This detailed simulation, however, is currently limited to the size of the study region (130km² modelled area).

Although Linear Programming is based on a sound theory, it also provides some caveats: It is a simplification of the decision-making process as it is only based on economic rationality. Of course, land use decisions are multidimensional and involve the assessment of different types of utilities (Edward-Jones 2006). As a consequence, the results of our optimization model must be interpreted as prescriptive but not descriptive statements (Sterman 1991). This is an important constraint in the interpretation of model results and differentiates the model from other model types such as agent-based models. Nevertheless, different studies provide evidence that the profit-maximizing approach is a reasonable assumption (e.g. Gellrich et al. 2008, Rounsevell et al. 2003) and therefore the results of the model do not lose validity by this simplification. Following Hazell and Norton (1986) the validation of our model (see Appendix B) also reveals good quality. Therefore the model approach can be seen as suitable for the assessment of different scenarios. In addition, these results of the validation also make it possible to exclude the possibility of flaws in the model parameters (Zander et al. 2008).
7 Which factors are responsible for changes in forests and agriculture ecosystem services in mountain regions: direct climate impacts or economic changes?\(^2\)

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ABSTRACT

Provisioning of ecosystem services (ES) in mountain regions is predicted to be influenced by the direct biophysical impacts of climate changes, as well as by socio-economic driven changes in land use that are indirectly influenced by climate. However, the relative importance of these factors on forest and agricultural derived ES is unclear. Using an integrated economic-ecological modelling framework we evaluated the impact of these different driving forces on the provision of forest and agricultural ES in a mountain region of southern Switzerland. Results predict that forest ES will be strongly influenced by the direct impact of climate change, but that changes in land use will have a comparatively small impact. In contrast, changes to agricultural ES were found to be primarily due to shifts in economic conditions that alter land use and land management. The spatial impact of direct and indirect climate changes on ES provision also differed. The direct influence of climate change on agriculture is only predicted to be substantial at high elevations, while socio-economic driven shifts in land use are predicted to affect agricultural ES at all elevations. Conversely, the direct impacts of climate change are predicted to affect forest ES at all elevations. Our results demonstrate that policy designed to mitigate the negative impact of climate change on forests should focus on suitable adaptive management plans for currently forested areas, while the maintenance of agricultural ES will be driven by economic conditions.

KEYWORDS

Biodiversity; Bio-economic modelling framework; Carbon balance; Food provision; Spatial explicit modelling; Protection value of forests

\(^2\) Briner, S., Elkin, C., Huber, R. (2012): Which factors are responsible for changes in forests and agriculture ecosystem services in mountain regions: direct climate impacts or economic changes? Submitted to Landscape Ecology (Under review).
Which factors are responsible for changes in Ecosystem Services in Mountain Regions?

7.1 Introduction

Mountain ecosystems provide a range of ecosystem services (ES) such as natural hazard protection, habitat diversity and cultural and amenity services (MEA 2005, EEA 2010), that are derived from different land use types. Maintenance of these services is crucial for people living and working in these regions. However, the future availability of ES is expected to depend on climate change and concomitant shifts in the ecological and social environments. ES are predicted to be directly influenced by climate change impacting the biophysical processes that underpin ecosystem dynamics (Gimona and van der Horst 2007, Seppelt et al. 2011), as well as by land use changes that are driven by climate dependent shifts in production capacity and shifts in the socio-economic environment (Schröter et al. 2005, Lindner et al. 2010). The capacity for policy decisions, and adaptive ecosystem management, to maintain ecosystem services will depend on the relative importance of these factors, and where on the landscape they are most influential.

In mountain regions the direct impact of climate change on the biophysical processes that underpin ES provisioning are predicted to be strongly influenced by the geophysical and climatic gradients that define these regions. For example, at high elevations where the growth of forests, meadows and crops is constrained by low temperatures, projected future increase in temperature may increase development and productivity (Torriani et al. 2007, Lindner et al. 2010). Predicted changes in the timing and amount of precipitation may increase or decrease growth depending on site specific conditions that determine whether or not water availability is a growth limiting factor (Fuhrer et al. 2006). In general, a warmer climate is expected to induce an upward shift of ecological biomes (Hanewinkel et al. 2010) and potentially an up-ward shift of the tree line (Harsch and Bader 2011). However, in many mountain regions the upward movement of the tree line will be constrained by the continuation of current land use and agricultural management.

Land use changes that result from agricultural and forestry management decisions are also expected to have a large impact on ES provisioning. For example, land abandonment and changes in production intensity are known to be important driving forces for the provision of ecosystem services (Zimmermann 2010). In mountainous regions these forces are especially important since the topographic complexity means that land use decisions depend on site specific landscape features that influence both the cost and value of agricultural and forest production (Gellrich et al. 2007). Future land use change is predicted to depend on two different factors. First, as described above, climate change may induce shifts in the production capacity of ES, which will lead to changes in optimal land
use (e.g. Gellrich et al. 2007, Gellrich and Zimmermann 2007, Henseler et al. 2009). This therefore represents an indirect influence of climate change on ES provisioning. Second, economic driven shifts in the relative prices of different agricultural products, and changes in the direct payment system, are expected to have a large impact on land use decisions in mountain regions (Acs et al. 2010).

Given the interplay between agricultural and forest land uses in mountain regions, an assessment of the future provision of ecosystem services must jointly consider both agriculture and forestry, and must take into account the direct impact of climate change and that of changes in land use. Previous studies that have examined the impact of climate change on ES have considered the influence of climate and socio-economic changes on the provision of ES on different scales (Nelson et al. 2009, Polasky et al. 2011). However, these studies have not partitioned the direct and indirect impacts of climate change, or have not evaluated their relative importance for the maintenance of agricultural and forest ES in the future.

Here we use an integrated economic-ecological modelling framework that considers the combined effect of climate and economic changes on the provision of agriculture and forest ecosystem services in a mountain region in Switzerland. Using this spatially explicit framework we simulate five different ecosystem services: agricultural and forest commodities, protection from natural hazards, land use diversity and greenhouse gas emission by agriculture. Using this framework we address three research questions: 1) What are the relative importance of direct climatic effects, and socio-economic mediated land use effects on the provision of agricultural and forest ES in the case study region? 2) Where on the landscape are the direct and indirect effects most important? 3) Where on the landscape do the direct and indirect effects have an additive influence on ES, and where are the effects opposite? We discuss our results in the context of providing policy and management relevant information about the impact of global change on the provision of ES in mountainous regions.

7.2 Methods

7.2.1 Case study region

The study area Visp (46°17′32″ N, 7°52′58″ E) is located in a continental inner-Alpine mountain area, with the elevation ranging from 648m a.s.l. to 4010m a.s.l. The region is sensitive to drought as the central Valais is the area with least precipitation in Switzerland.
Which factors are responsible for changes in Ecosystem Services in Mountain Regions? 

(<600mm per year). The area is 443.3 km² in size with 62% being unproductive land, 20% forest, and about 16% agriculture. Agriculture and forest land use play an important role in regional production, maintaining the recreation value of the area, and providing habitat for plants and wildlife. In 2008 there were 186 active farms in this region which cultivated an average of 9.6 ha agricultural land (FOAG 2008). The predominant products are milk and meat (sheep, suckler cows). Forest management is mainly done by regional forest managers, with the primary aim of maintaining healthy forests that provide protection from rockfall and avalanche hazards.

7.2.2 Simulation Framework

Using a spatially explicit framework we modelled the dynamic interactions between agriculture and forest systems by linking three models 1) a spatially explicit forest model (LandClim), 2) a regression based crop yield model and 3) a spatially explicit economic land use model (ALUAM) that simulates the competition between silvicultural and agricultural land use alternatives. The procedure that we used to integrate the three models can be divided into three steps (Figure 7.2; a more detailed description of the modelling framework can be found in Briner et al. 2012).

In step 1, using temperature and precipitation inputs from given climatic scenarios the yields from agricultural activities and forest developments were calculated. Forest development on each parcel (100m by 100m) was calculated using the process based forest landscape model LandClim (Schumacher et al 2004). LandClim, using a forest gap model framework, simulates forest development and structure (Schumacher and Bugmann 2006, Schumacher et al. 2006), while taking into account the impact of climatic change (monthly temperature and precipitation), soil properties and topography, landscape level disturbances, land use and forest management. The impact of climate change on yields of agricultural crops is calculated using a crop simulation model. This model calculates future yields of relevant crops using FAO (Food and Agriculture Organization of the UN) data on optimal and absolute crop growing conditions (Ecocrop 2007).

In step 2 GIS-maps containing spatially explicit data on crop yields and forest development are transferred to the economic land use model ALUAM. These data is combined with processes for agricultural land cultivation and forestry as well as with economic parameters to simulate 14 different land use activities under the assumption of rational economic behaviour (net profit maximization). An economic use of grassland is not possible without livestock, thus different livestock activities were implemented in ALUAM,
too. These activities consider current farming structure as recorded by the Federal Office for Agriculture (FOAG 2008). Activities that are not yet present in the region but could be an option for adaptation to global change are also implemented. Farmers, for instance, have the possibility to irrigate crops and grassland under increasing drought conditions and to choose new cropping activities. ALUAM and LandClim are linked over iterative feedback loops to model forest development on agricultural parcels that are no longer cultivated.

In step 3 the spatially explicit changes in ES provision are assessed using indicators for food production, natural hazard protection, land use diversity and carbon balance (Table 7.1). For the assessment of the protection value of the forests LandClim calculates two different indexes: a Forest Protection against Gravitation Hazards (FPGH) and a Rock Fall Protection Index (RFPI). The FPGH simulates the ability of forests to provide protection against all gravitational hazards considering tree species mixture, structural profile of the forests, rooting stability and regeneration potential. The RFPI assesses the ability of the forests to protect buildings and infrastructure from falling rocks on the base of the density and DBH of trees, and the ability of the trees to withstand the impact of the falling rock. Using these indexes we calculated the potential protection provided by forests for the whole area. Moreover, LandClim also calculates Shannon’s tree diversity index and Shannon’s structural index (SSI) to assess biodiversity in forests. ALUAM calculates spatially explicit indices for food production as well as greenhouse gas emissions and land use diversity using the Shannon index. For the assessment of food production a wheat-equivalent index is calculated that considers the different values of crops and grassland for human nutrition. (For more details about the indices see Briner et al. 2012)

![Figure 7.1: Model framework](image-url)
Which factors are responsible for changes in Ecosystem Services in Mountain Regions?

7.2.3 Simulation experiments

To make sure the climate and economic inputs are consistent our economic scenarios are based on an expert survey done by Abildtrup et al. (2006). Adapting these services to Swiss condition (Briner et al. 2012) guaranteed that our economic simulations can be used in conjunction with the IPCC climate scenarios A1FI and B1. Scenario A1FI assumes very rapid economic growth and an increase in average temperature by 4°C until 2080. Economic parameters are dominated by a large decrease in prices for agricultural products. In scenario B1 temperature is assumed to increase more slowly. In this scenario there is still a decrease in prices for agricultural products but changes are much lower than in scenario A1FI (for more details about the parameters underlying the economic scenarios see supplementary material).

In order to be able to partition the direct impacts of climate change from the economic based land use changes we simulated a Baseline and five different scenarios. In the Baseline land use and the provision of ES was simulated under 2010 climate and economic conditions. The first scenario (Climate_Direct) examined the impact of climate change on ES provisioning in the absence of any land use change.

The second scenario (LUC_Climate) incorporated dynamic land use changes that are driven by climate driven shifts in the capacity for ES to be produced. In this scenario climate change influences yields within each parcel (Figure 7.1, Step 1). These fluctuating yields are then passed to ALUAM which reallocated land use in each parcel. The resulting land use pattern then was combined with the 2010 ES values of each parcel to calculate only the indirect impact of climate change. In this scenario market prices are kept constant at 2010 levels.

The third scenario (LUC_Economic) incorporates land use changes that are driven by projected future changes in market prices as predicted by the regional representation of the IPCC economic scenarios. In this scenario the climate impacts on ES provisioning were excluded by keeping all yields and ES values constant at the 2010 level.

The fourth scenario (LUC_Combined) incorporated both indirect and direct climate driven shifts in the capacity for ES to be produced and predicted shifts in market prices. Within ALUAM, changes in ecosystems capacity to supply ES, and market changes in the price for ES, are incorporated and land use is dynamically re-allocated in response to both of these drivers.
The fifth scenario (*Combined_Change*) assumes a changing climate and changing economic parameters. It therefore is a combination of the scenarios *LUC_Combined* and *Climate_Direct*.

### 7.3 Results

#### 7.3.1 Land use transition

**7.3.1.1 LUC_Climate**

The projected increase in temperature is predicted to increase the potential yields of pastures, particularly if there are no restrictions on the availability of water for irrigation (Briner et al. 2012). Under current economic conditions, this results in more intensive land use in both scenarios (Table 7.1). The increased production capacity of the pastures is projected to have the largest impacts on land use at intermediate (ca. 1500m a.s.l to 2000m a.s.l) and low (below 900m a.s.l) elevations (Figure 7.2).

The number of parcels on which land use shifts occurred varied between climate scenario and between the assessment periods. The transition from extensive to more intensive grassland use as well as from cropland to grassland was greatest with moderate climate change: both scenarios B1 and A1FI in 2050. With large climate change (i.e. A1FI or B1 in 2080) profitability and therefore also intensification of land use is predicted to decreases following the initial rise. This effect can be explained by structural restrictions in the agricultural sector. Additional fodder production cannot be used because an expansion of the sheep herds which graze summer pastures are not profitable. As a consequence, agricultural land is abandoned.
Which factors are responsible for changes in Ecosystem Services in Mountain Regions?

Figure 7.2: Land use changes under scenario A1FI in 2080. Map on the top shows current land use. Maps on the bottom show changes of land use between the current land use and land use in 2080 under the assumption of climate/economic scenario A1FI.

7.3.1.2 LUC Economic

Predicted decreases in the price for agricultural commodities under scenario A1FI, and an increase in production costs assumed in scenario B1, are predicted to result in lower profitability for agricultural products and an associated reduction in intensive land use. This reduction in agriculture land use intensity is assumed to occur predominantly at intermediate elevations (Figure 7.2, supplementary material) where cultivation is expensive due to steep slopes and/or remoteness. In these areas land use becomes less intensive but land is not abandoned since direct payments which are not linked to production decisions maintain the profitability of extensive land use.

A decrease in the profitability of crops also is predicted to reduce the area allocated to crops in all scenarios sharply. These changes are presumed to take place until the year 2050.
7.3.1.3 **LUC\_Combined**

When climate driven shifts in ES provisioning and market changes are simultaneously simulated the impact of economic changes on the area used as cropland or intensive grassland in most cases are more dominant than the impacts of climate change.

In scenario **LUC\_Combined**, two major land use shifts are predicted to take place between 2010 and 2050: at low elevations (400m a.s.l. to 800m a.s.l.) a transition from crop to pasture land, at intermediate elevations (800m a.s.l. to 1800m a.s.l.) a move from intensive pasture usage to extensive pasture usage, and, in the scenarios for 2080, at high elevations an abandonment of agricultural land to forests. In general, a reduction in intensive land use and an increase in agricultural abandonment are predicted (Table 7.1).

Under all climate scenarios, the direction of land use change for these two categories are the same in **LUC\_Combined** and **LUC\_Economic**. In contrast, changes in the forest and extensive grassland area or more dominated by changes in climate, i.e. these categories tend to go in the direction of the **LUC\_Climate** scenario (Figure 7.2).

As a consequence, the combined impact of climate and economic changes do not necessarily result in a sum or the average of the changes if they are assessed isolated (Table 7.1). For example our results indicate that even if **LUC\_Climate** predicts that in the area of intensive grassland is increasing, the area of intensive grassland in 2080 decreases more under **LUC\_Combined** than under **LUC\_Economic** in all but the B1 scenario in 2080. In this case, the climate driven increase in productivity of grassland and crops and the corresponding increase in the relative profitability of both of these activities is outweighed by price changes and structural restrictions. We therefore expect that agricultural land will be used less intensive.

7.3.2 **Changes in ES provision from forests**

Our results suggest that the direct impact of climate change will have a larger impact on forest ES compared to changes in land use induced by climate or economic shifts. Climate change is predicted to impact forest ecosystem state and forest ES at all elevations (Figure 7.3). The different climate scenarios mostly differ in the intensity and the speed of the changes. Therefore, when assessed at the same point in time, scenario B1 is predicted to have a smaller impact on ES provisioning compared to scenario A1FI.

At higher elevations forest growth is predicted to increase while at lower elevations increased temperatures and drought are predicted to have negative impacts (Figure 7.3, first
row). In addition, at lower elevations increased drought stress is predicted to result in a shift towards more drought tolerant species (e.g. Scotts Pine (Pinus sylvestrii)). In contrast to the direct impacts of climate change, land use change that are driven by both changes in the production potential of the different ecosystems as well as changes in the markets mainly affects forest ES provision at high elevations, where agricultural land is predicted to be abandoned. These former agricultural parcels are often more fertile than currently forested areas, which will facilitate forest re-colonization when these high elevation agricultural plots are abandoned. However, compared to the land area at lower elevations, only a small share of the parcels are located on these elevations. Therefore, when evaluated at the landscape level, land use changes that are driven by changes in production potential as well as market driven changes are predicted to be less important than the direct impact of climate change on forest state (Table 7.2).
Table 7.1: Percentage change in land use are presented for two climate changes scenarios (A1FI, B1) and three nested land use scenarios (climate, policy, climate and policy) in the year 2050 and 2080 (100% = Baseline).

<table>
<thead>
<tr>
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<th>A1FI</th>
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<td>Baseline (%)</td>
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<td>100</td>
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<td>0</td>
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<td>24</td>
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<td>73</td>
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<td>100</td>
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<td>92</td>
<td>100</td>
<td>96</td>
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Table 7.2: Landscape level summary of shift in Ecosystem Services provision (ES) by forests. Percentage change in forest ES provisioning, are presented for two climate changes scenarios (A1FI,B1) and three nested land use scenarios (climate, policy, climate and policy) in the year 2050 and 2080. (100% = Baseline)

<table>
<thead>
<tr>
<th></th>
<th>A1FI 2050</th>
<th>A1FI 2080</th>
<th>B1 2050</th>
<th>B1 2080</th>
</tr>
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<tr>
<td>Biomass</td>
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<td>LUC_Climate (%)</td>
<td>LUC_Economy (%)</td>
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<tr>
<td></td>
<td>100</td>
<td>113</td>
<td>101</td>
<td>100</td>
</tr>
<tr>
<td>H-Index</td>
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<td>107</td>
<td>102</td>
<td>100</td>
</tr>
<tr>
<td>SSII</td>
<td>100</td>
<td>101</td>
<td>103</td>
<td>100</td>
</tr>
<tr>
<td>GFPI</td>
<td>100</td>
<td>101</td>
<td>101</td>
<td>100</td>
</tr>
<tr>
<td>RFPI</td>
<td>100</td>
<td>142</td>
<td>102</td>
<td>100</td>
</tr>
</tbody>
</table>

1Total Biomass provision; 2Shannon index; 3Shannon Structural Index; 4General Forest Protection Index; 5Rockfall Protection Index
Table 7.3: Percentage change in agricultural ES provisioning presented for two climate changes scenarios (A1FI,B1) and three nested land use scenarios (climate, policy, climate and policy) in the year 2050 and 2080. (100% = Baseline)

<table>
<thead>
<tr>
<th></th>
<th>A1FI 2050</th>
<th>A1FI 2080</th>
<th>B1 2050</th>
<th>B1 2080</th>
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</thead>
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<tr>
<td></td>
<td>Climate Change (%)</td>
<td>LUC_Climate (%)</td>
<td>LUC_Economy (%)</td>
<td>LUC_Combined (%)</td>
</tr>
<tr>
<td>Baseline</td>
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<td>69</td>
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<tr>
<td>Crop&lt;sup&gt;2&lt;/sup&gt;</td>
<td>100</td>
<td>196</td>
<td>69</td>
<td>11</td>
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<tr>
<td>Milk&lt;sup&gt;3&lt;/sup&gt;</td>
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<td>196</td>
<td>69</td>
<td>11</td>
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<td>Meat&lt;sup&gt;4&lt;/sup&gt;</td>
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<td>196</td>
<td>69</td>
<td>11</td>
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<tr>
<td>CO&lt;sub&gt;2&lt;/sub&gt;&lt;sup&gt;5&lt;/sup&gt;</td>
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<td>196</td>
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<td>11</td>
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<td>H-Index&lt;sup&gt;6&lt;/sup&gt;</td>
<td>100</td>
<td>196</td>
<td>69</td>
<td>11</td>
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</table>

<sup>1</sup>Total food provision; <sup>2</sup>Crop provision; <sup>3</sup>Milk provision; <sup>4</sup>Meat provision; <sup>5</sup>Net greenhouse gas emissions; <sup>6</sup>Shannon Index
Which factors are responsible for changes in Ecosystem Services in Mountain Regions?

Forest biodiversity is predicted to increase due to the direct impacts of climate change, as well as due to changes in land use (Table 7.2, Figure 7.3). Predicted warmer temperatures will encourage the growth of a broader range of species, with deciduous tree species in particular increasing in relative abundance at intermediate elevations (1000-1800m a.s.l.). Only at low elevations (<1500m a.s.l. in 2050, <700m a.s.l. in 2080) is forest biodiversity predicted to decrease as a result of severe drought stress. The predicted greater reduction in biodiversity at lower elevations in 2050 compared to 2080 (Figure 7.3), reflects the fact that during this time drought stress is predicted to already increase the mortality of less drought adapted species, such as Norway spruce, while more drought tolerant species have not had sufficient time to establish. The impact of land use change on biodiversity is predicted to only be relevant at high elevation sites. However, at the landscape scale the increase in forested area results in only a minor change in biodiversity provisioning (Table 7.2).

The protection functions that forests provide against gravitational hazards (avalanches, rock fall etc.) are in general predicted to be positive influenced by direct climate change. Protection against rockfall (RFPI) is predicted to increase at most elevations due to climate change (Figure 3), with only very low elevation forests (<700m a.s.l.) providing less protection.

Our more general measure of forest protection against gravitational hazards (GFPI) is predicted to increase primarily at higher elevation sites (2000-2300m a.s.l) where increased temperatures will allow increased forest growth (Figure 7.3). At elevations below 2000m climate change is predicted to slightly reduce the forests general protective capability due to increased mortality and decreased growth of Norway spruce (Picea abies) and other less drought resistant species (Figure 7.3). Both of our forest protection metrics are predicted to increase at high elevation sites as result of agricultural land being allowed to transition into forests. Again however, when evaluated at the landscape scale, this increase is minor (Table 7.2).
Figure 7.3: Change in ES (Rockfall Protection Index RFPI, General Forest Protection Index GFPI, Shannon's Structural Index SSII, Shannon's species Index and Total Biomass production) provision by forest ecosystems depending on the elevation between 2010 and 2080. Differences were calculated using the median value of all parcels within 20m elevation bands. The grey shadow represents the relative land surface area at each elevation.

7.3.3 Changes in ES provision from Agriculture

Changes in food provisioning primarily occur at low (below 1000m a.s.l.) and higher altitudes (above 2000m a.s.l.) (Figure 7.4), with lower impacts predicted at intermediate elevations. Pasture based milk and meat production at high elevation sites is predicted to increase as a result of higher temperature and a longer vegetation period under climate change. In contrary economic changes lead to a reduction of the production on these elevations since already marginal profitability of food production is further reduced. On low elevations change in food production is dominated by a substantial reduction of crop production under all LUC and Combined Change scenarios (Table 7.3). On these elevations milk and meat production is predicted to replace crop production as a result of a combination of changes in the relative price of these commodities, shifts in production costs, and changes in production capacity. As a consequence, at the landscape level food
provision in terms of a wheat-equivalent index decreases, even if meat production is expanded as in the LUC_Climatic scenarios (Table 7.3). At the landscape level therefore only the direct impact of climate change, i.e. the Climate_Change scenarios, is predicted to result in an increase of total food provision since crop area stays on the 2010 level and number of animals is assumed to be increased. In contrast, predicted economic change scenarios (LUC_Combined and LUC_Economic) are expected to have a negative impact on food provision at most altitudes (Figure 7.4, column 2-4) that also cannot be outweighed by the impact of direct climate change in scenario Combined_Change. Our results therefore indicate that the impact of changing economic parameters on food production is much larger than the indirect climate impact.

Under the climate change scenarios (Climate_Direct, LUC_Climatic and Combined_Change) the total number of cows and sheep increases, resulting in higher emissions in nitrous oxide and methane. In contrast, under the economic change scenarios (LUC_Economic, LUC_Combined) lower greenhouse gas emissions by agriculture are predicted since the number of cattle and the amount of nitrogen turnover on the fields are reduced.

Under the assumption of both scenarios A1FI and B1, land use diversity on low elevations (below 700m a.s.l) mainly decreases because of the loss of cropland. On intermediate elevations change in land use diversity differs between the two scenarios. Given the scenario A1FI the extensification of the grassland at elevations ranging from 700m a.s.l. to 1200m a.s.l. leads to a more uniform land use. At the same elevation band in scenario B1 in 2080, land use diversity increases since there is grassland transformed to cropland, grassland used less intensive and vice versa. On high elevations above 2000m a.s.l. land use diversity is mainly increasing since currently grassland is the dominant land use which is partially converted into forest under the A1FI and B1 scenarios. All of these changes are most dominant if climate and economic changes take place simultaneously.
Provision of Ecosystem Goods and Services in Mountainous Regions

**Figure 7.4**: Change in ES provision by agricultural ecosystems between 2010 and 2080 depending on the elevation of the specific parcels (median of parcels inside a range of 20m). The grey shadow represents the relative land surface area at each elevation. (Changes in the crop production are not shown in this since the low number of parcels under cropping do not allow to calculate graphs that have explanatory power).

### 7.4 Discussion

#### 7.4.1 Relative importance of climate and economic effects on the provision of ES in mountain regions

Our results indicate that future changes to agricultural and forest based ecosystem services in mountain regions will differ with respect to the main drivers of change (climate vs. economic) and where on the landscape each ecosystem service group will experience the greatest modification. Our simulation indicate that the direct impact of climate change that is mediated through biophysical changes that influence growth, competition and mortality, based on our simulation results potentially will have a large influence on forests and forest derived ES, but will have smaller impacts on agricultural ES. In contrast, economic changes and associated shifts in land use are predicted to have a large impact on agricultural ES, while forest derived ES are predicted to be only marginally influenced by shifts in land use.
Which factors are responsible for changes in Ecosystem Services in Mountain Regions?

The large direct impact of climate change on the provision of forest ES in the Valais region reflects the fact that at low elevations, increased drought stress is predicted to both reduce forest biomass and promote a transition towards more drought tolerant tree species (Bigler et al. 2006). At intermediate elevations forests currently contain a large percentage of Norway spruce. Increased drought is predicted to result in lower growth rates and increased mortality for these and other drought intolerant species (Lerner et al. 2002), and allow for the expansion of more drought tolerant species such as Scots pine and Oak (Quercus sp.) (Jolly et al. 2005, Eilmann et al. 2009). The impact that these transitions in forest composition will have on forest ES will depend on the rate of climate change. If the rate of climate change is slow then a gradual increase of more drought tolerant species (Bolte et al. 2010) will reduce the negative impacts on forest ES. Alternatively, our simulation results indicate that large climate shifts that occur quickly can result in the increased mortality of the current forest exceeding the establishment rate of more climate suitable trees. Under these conditions forest ES such as avalanche and rock fall protection that relies on resilient stand structure may be negatively affected (Brauner et al. 2005, Bigot et al. 2009). Our simulations indicate that even under the moderate climate change scenario that we tested (B1) that the rate of change in environmental conditions is sufficiently high to produce negative impacts on most of the considered forest ES at low and intermediate elevations.

The small impact of land use change on forest ES reflects that there are several factors that keep the forested area relatively static within the case study regions. First, wood production is currently not profitable in the study region, partially due to the difficulties and costs associated with harvesting in steep areas that are not easily accessed. As a result, there are no economic incentives for increasing forested area. An increase in timber prices, that could result from increased support for renewable energies, would likely result in forest production still not being competitive compared to agriculture. In addition, agricultural production in remote areas is supported through direct payments and investment support, which further magnifies the comparative profitability between agriculture and forestry, and effectively limits the expansion of the forest area. Secondly, maintenance of the forested areas is also driven by restrictive Swiss forest laws.

Agricultural ES are predicted to exhibit the opposite pattern on the landscape compared to forest ES. Direct climate impacts on agriculture ES are expected to occur primarily at high elevations, while land use changes are predicted to influence agricultural ES at all elevations with the biggest impacts at low and intermediate elevations. One reason why
the direct impact of climate change on agricultural ES remains low is that increases in agricultural yields in mountain regions can only be utilized with an additional harvest which also increases the cost of production per hectare. In addition, economies of scale are limited due to the topography and the relatively short length of the vegetation period (Gellrich et al. 2007). Our simulations do indicate that at higher altitudes climate change driven increases in agricultural production can be sufficient to alter agricultural ES provisioning. These results correspond with the findings of Berry et al. (2005) who demonstrated that the positive impact of climate change on production capacity can decrease the vulnerability of agriculture at high altitudes.

The processes that influence the spatial explicit provisioning of agricultural ES are complex and cannot be explained through climatic gradients only. Our model results indicate that changes in agricultural ES depend on a variety of different location factors such as the slope or the remoteness of the parcel (e.g. Gellrich et al. 2007), which interact strongly with economic conditions to determine how agricultural ES are distributed on the landscape. Only at higher elevation summer pastures, where the range of factors controlling agricultural production are comparatively simple, are climatic gradients predicted to be main drivers of change.

Agricultural and forest ecosystems also differ with respect to how quickly they can respond to climatic, economic or land use changes. Forest ecosystems will react comparatively slowly to changes in the environment as these ecosystems are dominated by long-lived organisms whose ability to withstand adverse environmental conditions produces time lags between the climatic and ecosystem state (Bugmann et al. 2005). As a result of these time lags forest’s ES will often exhibit a delayed response to climate change. Forest management also works on a longer time scale, with the full impact of management decisions on forest ES potentially not realized until decades later (Lindner 2000, Hans Rudolf 2010). On the other hand, in agriculture systems the choice of crops and intensity of production can be adjusted every year, and can therefore be more responsive to climatic shifts. Thus, the corresponding production cycle in agriculture is more adaptive to climate and socio-economic changes, and the impact of these drivers on agriculture ES is predicted to be relatively quick.
7.4.2 Additive and opposite effects of direct climate impacts and land use changes on the provision of agricultural and forest ES

Land use change driven shifts in ecosystem services may either augment the direct impacts of climate change if both factors influence the ES in the same way, or they may dampen the direct climate change impact if they are in the opposite direction. Our simulations indicate that for forest ES interactions between direct climate impacts and land use change will occur only at high elevations and that the two factors will intensify each other’s positive impact on forest ES in this region. This additive interaction may be most beneficial for the ability of forests to provide protection against gravitational hazards (Kulakowski et al. 2011). For example, in avalanche sensitive areas artificial defence constructions (e.g. avalanche barriers) are often used at or above the current tree line in order to reinforce natural protection forests (Bebi et al. 2009). In these regions, increased forest growth, and an increase in forest area, will both serve to increase protection against gravitational hazards. In contrast to forest ES, our results suggest that for agricultural ES the influence of direct climate change and land use change will often be in opposite directions. At higher elevation sites the direct impact of climate change is predicted to increase agricultural production, while land use change is predicted to have the opposite effect. At intermediate and lower elevation sites this negative interaction is also predicted, but that it will occur primarily under moderate climate change.

7.4.3 Implications for management and policy

Management plans that aim to maintain valuable ES, and mitigate negative impacts of climate change, should target locations on the landscape were climate change is predicted to be concentrated, and should focus on factors that are predicted to have the largest impact on ES provisioning (Vihervaara et al. 2010, Bullock et al. 2011). As such, our results suggest that the application of adaptive forest management to the current forested area will be more effective than management that focuses on influencing changes in forest area (i.e. land use changes). Our results indicate that the forest ES that we considered will generally improve, but that climate change will lead to strong changes in forest composition and structure. In order to make sure that forest ES are not negatively impacted as the forests transitions towards more drought tolerant species management actions within the current forest area are needed. Forest management can potentially ease the transition to a more drought prone environment by using management that promotes more drought tolerant species (Bigler et al. 2006), alters forest state to dampen the negative
impact of drought (Gea-Izquierdo et al. 2009), or facilitates the establishment of different species or genotypes that are more suitable to future conditions (Eilmann et al. 2009, Dobbertin et al. 2010). Our results suggest that management may be most effective if it targets forests at lowest elevations since this is the region where forest state and forest ES are predicted to be most negatively affected.

The provision of food usually implies trade-offs with respect to non-marketable ES (Seppelt et al. 2011). For example, an enhancement of meat production followed by a more intensive land use will induce a negative impact on carbon balance and biodiversity. Given a societal demand for non-marketable ES, policy schemes should balance the different outcomes. Targeted and tailored payments for ES (PES) are seen as the way forward in this direction (Engel et al. 2008). The dominant effect of economic changes on the provision of agricultural ES facilitates the implementation of such schemes since the effect of price changes is much more direct than the effect of changing natural production conditions. In contrast, our results also imply that climate and economic changes may amplify or damp the impact on ES provision depending on altitude and scenario considered. This makes sound implementation of PES in mountain regions challenging and may involve prohibitive administrative costs. Moreover, providing economic incentives to upkeep the production of food and non-marketable ES from agriculture in mountain regions may involve high costs for the taxpayers. Without the direct payment schemes in our scenarios, more land would be abandoned. Our results imply that this may increase forest ES at higher elevations. As mentioned above, this might produce only marginal benefits since forest ES at this elevation are predicted to be positively influenced anyway. This supports our initial claim that ES provision in mountain regions should jointly consider both agriculture and forest developments as done in this study.
8 Trade-offs between Ecosystem Services in mountainous regions

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ABSTRACT
Mountain ecosystems provide a broad range of different Ecosystem Services (ES). Applying a framework consisting of the economic land allocation model (ALUAM), the forest-landscape model LandClim, and a crop yield model the relationships between different ES were assessed for the mountainous region of Visp (Switzerland). Results show that there are mainly trade-offs between marketable ES (food provision) and non-marketable ES (biodiversity, protection against natural hazards and carbon sequestration). Under 2010 conditions an increase in a biodiversity indicator leads to a decrease in food provision by 37%. In contrary under a 2080 climate and market scenario food provision is predicted to increase by 88% if biodiversity provision is increased by the same amount as in 2010. The relation between different ES however is not proportional but depends on how much the provision of a certain ES is increased. In the implementation of management schemes it should therefore be considered that a considerable support of the provision of a certain ES will lead to a decrease in the provision of another ES. Small changes in the provision of one ES however affect the provision of other ES only to a small extent or even result in a synergistic effect.

KEYWORDS
Agriculture; Climate Change; Ecosystem Services; Forestry; Land use Change; Model-based Scenario Analysis; Mountain Regions; Trade-Offs

8.1 Introduction

Mountain ecosystems provide a wide range of important Ecosystem Services (ES) that form a base for living in these regions. Mountain forests, as an example, often protect buildings and infrastructure from destruction by avalanches, landslides or rockfall. If the protection functions of the forests are degraded expensive artificial protection measures are necessary (Brang et al. 2008). Moreover, the scenic beauty that is provided by forest and agricultural ecosystems is a precondition for a booming tourism sector. Also, the continued production of food and fiber is important since these services provide a living for a large share of the local population and create an authentic landscape for tourism. Many mountain ecosystem services, with exception of food and fiber production, however cannot be traded on open markets and are therefore maintained as public goods (Boyd and Banzhaf 2007). As a result, maintenance of these ES often depends on management at the national or regional level.

Management in mountainous landscapes should take into account the multifunctional use of these regions, and must consider how different ES will be impacted by environmental, economic and social changes (Fry 2001, Lovell and Johnston 2009, Raudsepp-Hearne et al. 2010). Previously, management schemes often focused on one specific ecosystem function such as providing habitat for endangered species or the production of food. However, such a narrow focus will likely lower the probability of a success when implementing management schemes (Redford and Adams 2009) since often it is not possible to mobilize enough resources to maintain only one single non-marketable function (Fry 2001). Multifunctional approaches are therefore more promising means to reach the level of ES desired by the public. Multifunctional approaches also recognize that landscapes are a spatial matrix of interacting organisms, land types and ecosystems. In this spatial matrix different components are coupled with each other (Naveh 2008), such that different ecosystem’s components compete with each other for space or are synergistic. As a result of these links, management that is designed to enhance the provisioning of one ES will also affect the provisioning of other ES (Nelson et al. 2009).

To consider these links in an adequate way multifunctional ecosystem management approaches must incorporate an evaluation of trade-offs and synergies between different ES. Trade-offs are predicted to primarily occur between marketable and non-marketable ES (Power 2010, von der Dunk et al. 2011, Rodríguez et al. 2011). Managing these trade-offs must take into account their spatial distribution on the landscape, as well as how the
trade-offs will change through time. In mountainous regions consideration of the spatial
dynamics is especially important since topography and other landscape characteristics can
have a strong influence on ES levels and ES interactions (Bolliger et al. 2008). Temporal
dynamics mainly are driven by changes in climate and socio-economic factors on different
levels (Gellrich et al. 2007). Climate change will have an impact on the ecosystems and
therefore also affect the links between the different ecosystems directly (Mooney et al. 2009, Power 2010). Additionally climate change, as well as changing socio-economic
parameters lead to land use change affecting the provision of different ES. Both, changing
climate and changing socio-economic parameters therefore affect trade-offs between
ES and have to be considered in management decisions (Opdam et al. 2009).

A precondition for efficient multifunctional management of the landscapes is knowledge
about trade-offs between different ES (Farber et al. 2006), where on the landscape these
trade-offs occur, and how the magnitude and distribution of these trade-offs will be im-
pacted by different climate and economic scenarios. As a result, integrated socio-
ecological models that incorporate both, the decisions of land users as well as the under-
lying ecological processes must be used (Benett et al. 2009). There exists a variety of
modelling studies which focus on the simulation of socio-ecological systems in agricu-
lultural and forest areas at different scales. For example, Polasky et al. (2008) used a spatially
explicit landscape-level model to analyse the biological and economic consequences of
alternative land use patterns. Holman et al. (2005a, 2005b) used the model RegIS to as-
sess the impact of climate and socio-economic scenarios on ES provision at a local scale,
but they did not explicitly link the provision of the different services. In contrast, the In-
Vest modelling framework used by Nelson et al. (2009) and Polasky et al. (2011) is an
approach for assessing the impact of different land use change scenarios on ES provision
and to assess trade-offs between different ES. These models provide important
knowledge about the influence of climate and socio-economy on the provision of ES as
well as trade-offs between them. However, in these studies land use decisions concerning
the provision of ES were either not simulated, or were not simulated at the scale at which
decisions are made in mountainous regions. To assess trade-offs between different ES
under future global change scenarios, and to derive suitable management and policy op-
tions, these factors must be taken into account. Secondly, decisions about land use
should be simulated endogenously so as to evaluate the impact of policy and economic
incentives on ES management.
In our study we assess trade-offs and synergies between the provision of different ES under current climate and market conditions, and under scenarios for climate and market conditions in 2080. Our modelling framework simulates trade-offs between the spatial explicit provision of food, protection against avalanches, carbon sequestration and biodiversity. These ES have been chosen since they are prioritized by Swiss agricultural and environmental policy (Herzog et al. 2005, Mann 2008). Using this model framework we answer the following research questions: 1) Which trade-offs between different ES must be considered in order to develop robust management schemes, 2) How do these trade-offs change if the desired amount of a certain ES is changed and 3) How are these trade-offs affected by changes in climate and markets?

8.2 Methods

We assessed trade-offs and synergies between different ES using the ALUAM modelling framework (Briner et al. 2012) which is an activity based spatial explicit land allocation model. To adequately simulate different trade-offs the ALUAM framework was expanded so that the provisioning of biodiversity, protection and carbon sequestration can be calculated. The framework consists of three different sub-models: a forest-landscape model, a crop yield simulation model and an economic land-allocation model. Here we first describe the three steps that define how these models interact (for a detailed description of the model interactions please see Briner et al. 2012).

1) We used the process based forest landscape model LandClim (Schumacher et al. 2004) to simulate forest dynamics and to estimate potential wood production. LandClim is a spatially-explicit model that was specifically developed to assess the importance of climatic effects, natural disturbances and management on forest dynamics (Schumacher et al. 2004, Schumacher et al. 2006). Within each parcel (100 by 100m) on the landscape level the species specific volume of potential harvested wood was calculated. The impact of climate change on crop yields was calculated for every parcel by using a crop simulation model based on the EcoCrops database of the Food and Agriculture Organization of the United Nation (FAO). In addition to the data provided by these models different spatially explicit data, e.g. slope, elevation, soil properties and administrative zones are assigned to each parcel.

2) These spatially explicit data were combined with knowledge about processes in agricultural production to create 14 different land use activities in the Alpine Land Use Allocation Model (ALUAM). Thirty five different livestock activities as well as policy and mar-
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Market scenarios were integrated in ALUAM. ALUAM then optimized land use and livestock activities in a way that the aggregated land-rent is maximized. Thereby the model had to consider different constraints on parcel, farm and regional level, e.g. nutrient or labour balances (see Briner et al. 2012 for details).

3) We specifically focused on trade-offs associated with increased food production, carbon sequestration, field biodiversity and the protection value of forests. For each of these four ES we performed simulations where we iteratively increased the derived value of the focal ES (de Wit et al. 1988). Within each of these simulations land use was optimized so as to maximize land rent, subject to the constraint that the desired level of the focal ES was maintained. For each simulation the aggregated land rent, and level of each of the other three ES, was calculated. These values were then compared to the levels obtained in a non-constrained economic optimum simulation. This allowed us to assess the changes in the provision of all ES if the level of one was increased over constraints.

To assess the trade-offs in a spatially explicit framework we first assessed the maximum possible amount that can be provided from each of the focal ES. Then the change of the land use on the different parcels between the non-constrained economic optimum and the state in that the provision of a certain ES was increased at its maximum was assessed. These land use changes were then compared between the different ES. If land use changed in the same way if two different ES were maximized this was assumed as a synergy between the provisions of two ES. If the direction of land use change did differ this was interpreted as if there was a trade-off between two different ES.

8.2.1 Calculation of ES provision

Based on data provided by LandClim, the Crop Simulation model, and ALUAM, indicators for the provision of food, biodiversity, carbon sequestration and protection were calculated in each simulation.

8.2.1.1 Protection from gravitational hazards

The ability of forests to provide protection against gravitational hazards depends on the location of the forest stand as well as tree species mixture, structural profile, rooting stability of live trees and regeneration potential. Frehner et al. (2005) developed guidelines for forest attributes that need to be maintained in order for the forests to provide a protective function. Based on these guidelines we developed a metric that assesses the general protective value of forests (Gravitational Protection Forest Index, GPFI). The GPFI
simulated the ability of forests to provide protection against all gravitational hazards considering tree species mixture, structural profile of the forests, rooting stability and regeneration potential (For a detailed description of the GPFI see Appendix D).

The potential GPFI was calculated for every parcel that is located either inside a rockfall protection-zone or inside an avalanche protection zone. Since forests only can prevent avalanche releases at the very beginning (first ca. 150 m after release), it was assumed that forest stands only provide protection from avalanches if they are located inside the starting zones of avalanches (Bebi et al. 2009, DGBG 2012). This calculation of the potential GPFI was done by LandClim for the different climate scenarios and then the values were transferred to ALUAM. This gave ALUAM the ability to assess the impact of climate change and changes in markets and policy on the protection value. ALUAM then calculated the protection value on the different parcels considering their potential GFPI. For the assessment of regional trade-offs the GFPI of the different parcels was aggregated.

8.2.1.2 Biodiversity

In mountainous areas biodiversity is generally highest in alpine dry meadows (Baumgartner and Hartmann 2001), and only slightly lower in extensively managed meadows and pastures (Weyermann et al. 2006, Herzog 2005, Dullinger et al. 2003, Zoller and Bischof 1980). In ALUAM we therefore used the share of extensively cultivated meadows and dry meadows as an indicator for biodiversity. This indicator was assessed at the regional as well as at the field level.

8.2.1.3 Food provision

For the assessment of food production a wheat-equivalent index is calculated that considers the different values of crops and grassland for human nutrition. This index considers the fact that grassland has a lower value for human nutrition since grass first has to be converted into milk or meat through animals. Crops as wheat can be digested by human so they have a higher value than grassland. For a detailed description of the Index see Briner et al. (2012).

8.2.1.4 Carbon sequestration/release

For the calculation of the net greenhouse gas sequestration both, the amount of greenhouse gas emitted by agriculture and carbon sequestered by forests was calculated. In these calculations only emissions inside the region were considered. Emissions caused in
the fabrication of inputs for production, e.g. artificial fertilizer, machinery, buildings, as well as emissions that are caused by burning the harvested wood were not considered.

In ALUAM, we accounted for all GHG emissions of agricultural activities, including indirect N$_2$O emissions associated with N losses. On-farm emissions were calculated using the IPCC (1997 and 2000) methodology. Since emission levels are climate- and management-specific, these methodologies had been adapted to Swiss conditions. The methods that were used to calculate the various on-farm emissions are summarized in Table 8.1.

**Table 8.1: References of methods applied in ALUAM to calculate on-farm GHG emissions**

<table>
<thead>
<tr>
<th>GHG</th>
<th>Emission Source</th>
<th>Influencing factor</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_4$</td>
<td>Enteric fermentation</td>
<td>Number of animals, Animal-specific methane rate, feed mix, lipid supplementation</td>
<td>IPCC 2000, Minonizio et al. 1998</td>
</tr>
<tr>
<td></td>
<td>Manure</td>
<td>Amount of different manures, feed mix, housing system, pasture management</td>
<td></td>
</tr>
<tr>
<td>N$_2$O</td>
<td>Manure</td>
<td>Amount of different types of manure, manure management</td>
<td>IPCC 2000, Schmid et al. 2000, 2001</td>
</tr>
<tr>
<td></td>
<td>Land use</td>
<td>Fertiliser</td>
<td>Schmid et al. 2000</td>
</tr>
<tr>
<td></td>
<td>Indirect emission</td>
<td>Loss of N in different compounds</td>
<td></td>
</tr>
<tr>
<td>CO$_2$</td>
<td>Tractor/</td>
<td>Land use intensity</td>
<td>IPCC 1997, Gazzarin and Albisser Vögeli 2010</td>
</tr>
<tr>
<td></td>
<td>Machinery</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The amount of greenhouse gases that are emitted is primarily dependent on the number of livestock housed in the region. Since the diet of the animals was not subject to the optimization process the model had no possibility to optimize this in a way to decrease emissions. Other mitigation measures, such as supplementing the diet with fat, were not considered since they are not yet ready for use or too expensive (Briner et al. 2011). Land use also had an impact on greenhouse gas emissions since on extensive used grassland number of tractor hours is lower and so CO$_2$ emissions were lower as well. In addition, on extensively used land nitrogen throughput is lower causing lower nitrous oxide emissions.

Carbon sequestration by forests was calculated as the amount of carbon immobilized in aboveground tree biomass. Although additional carbon could also be stored in soil organic carbon stock (Lal 2005), these processes were not considered in this study.

### 8.2.2 Study region

We applied this modelling framework to the central Valais, a continental inner-Alpine mountain area in the south of Switzerland. The study area includes the Saas-valley (Saas Fee, Stalden), the region around Visp in the main valley and the Baltschieder-valley with
a total of 15'346 inhabitants. The area has a size of 443.3 km². Unproductive land accounts for 62% of the area, while 20% of the area is covered by forest-land and about 16% of the land is used by agriculture. Agricultural production is mainly focused on milk and meat production. Agriculture and forest land use play an important role as recreation area and habitat for plants and wildlife. For more details about the study region see Huber et al. (2012).

8.3 Scenarios

We first examined ES provisioning under the current climate, policy, and market environment. In a second analysis we assumed changing climate and socio-economic parameters as they can be expected for year 2080 following IPCC scenario A1FI (IPCC 2007). This scenario – a worst case scenario – assumes an increase in global mean surface temperature of 4°C.

Observed daily climate data from regional weather stations was provided by MeteoSwiss (www.meteoswiss.admin.ch). This point data was interpolated to gridded climate maps with a resolution of 100m using the DAYMET algorithm (Thornton et al. 1997) and a digital elevation model from Swisstopo (2005).

Monthly climate data according to the A1FI scenario (2001-2100) and observed climate data (1900-2000) at a resolution of 10' was obtained from the Climatic Research Unit (CRU) of the University of East Anglia, Norwich, UK (Mitchell et al. 2004). We then applied the change factor method to downscale the observed data and the output of the global climate model HadCM3 to 100m (Mitchell and Jones 2005): we calculated difference anomalies relative to a baseline period of 1961-90 for temperature and relative anomalies for precipitation. The anomalies were interpolated to 100m and then recombined with the DAYMET data of the same baseline period to obtain the fine scaled A1FI and observed climate maps for all the years 1900-2100.

Policy and market scenarios were based on the same IPCC scenario. Abildtrup et al. (2006) used an expert survey to assess the relative impact of IPCC scenario A1FI on the prices for agricultural products, and production factors, in the European Union. We used the results of this study to calculate absolute parameters using current prices and costs in agricultural production in Switzerland as well as the gap in these parameters between Switzerland and the EU. The elaboration of the economic scenarios is described in more detail in Briner et al. (2012).
8.4 Results

8.4.1 Trade-offs by increased food provision

Trade-offs between food production and the other ecosystem services are large for carbon sequestration (Figure 8.1). This trade-off however only occurs when food provision has increased by 35%. Up until this point increased food production is managed by an expansion of cropland. Increasing food production above 25% is achieved by expanded milk production, which results in greenhouse gas emissions increasing by up to 13%. In 2080 increased food production initially results in a decrease in greenhouse gas emissions because on suitable parcels grassland is replaced by crops leading to a reduction in the number of animals. Identical to current conditions, when food production increases above 110% greenhouse gas emission increase considerably. This shift also leads to a decreasing income since the land user cannot choose the most profitable activities anymore.

Biodiversity is also predicted to be negatively impacted by an increase in food production. Increased food production is only managed through a conversion of grassland to cropland, and an increase in the grazing intensity by dairy cows on the remaining grassland, which results in a decrease in the biodiversity index in 2010 by 78%. In contrast, the food production has no impact on the protection function since the forest areas are protected by law and therefore are not reduced.
Figure 8.1: Trade-offs between the provision of food and other ES as well as the sectoral income today (continuous line) and in the year 2080 (dashed line). Lines show the deviation of ES provision from the economic optimum in 2010 and 2080, respectively, if provision of food provision is increased over constraints. 100% equals food provision in 2010. Since in 2080 food provision in the economic optimum is lower than in 2010 deviation already starts at 15%.

8.4.2 Trade-offs of increased biodiversity provision

Under the future 2080 scenario, our results indicate that an increase in biodiversity by more than 17% will facilitate an increase in food production (by 88%) (Figure 8.2). This increase in biodiversity is mainly due to an expansion of the extensively used hay-meadows instead of forests that would grow on a substantial part of the summer pastures (Briner et al. 2012). In contrary under 2010 conditions there is a clear trade-off between biodiversity and food provision. In 2080 an increase in biodiversity also positively impacts carbon sequestration (20%), but results in a loss in income as high as 20% after an increase in biodiversity of 25%.
8.4.3 Trade-offs of increased carbon sequestration

By increasing the intensity of forest management and removing more trees, carbon sequestration can be increased (Figure 8.3). This increased sequestration in forests compensates for an increase in greenhouse gas emissions by agriculture. Since an intensification of forest management is relatively inexpensive, income only decreases by about 4% if greenhouse gas balance is improved by 108%. The benefit from carbon sequestration will however decrease in the future, as climate change has an impeding impact on carbon sequestration. If one wants to compensate for the carbon sequestration decrease, the number of animals would have to be decreased, causing a reduction in sectoral income of 60% in the future. Protection value of forests does not change if greenhouse gas emissions are reduced, that is partly done by planting new forests. Under today’s condition almost all protection zones already are forested, i.e. an expansion of the forest area in our framework is not considered as additional protection value.
Figure 8.3: Trade-offs and synergies caused by a change in the greenhouse gas balance in 2010 (continuous line) and in 2080 (dashed line). Lines show the deviation of ES provision from the economic optimum in 2010 and 2080, respectively, respectively, if greenhouse gas emissions are reduced over constraints. 100% equals greenhouse gas emissions in 2010. Since in 2080 greenhouse gas emission in the economic optimum is higher than in 2010 deviation starts at 118%.

8.4.4 Trade-offs on the field level

Land-abandonment and forest expansion are predicted to result in both trade-offs and synergies between different ES. On about 29% of the area increased management in favor of carbon sequestration causes decreases in the provision of biodiversity or food provision on the same parcel (Figure 8.4). The carbon balance in a single parcel can be improved by planting trees or by natural forest ingrowth on agricultural land, but this results in a decrease in the provision of food and field biodiversity. These trade-offs occur on all parcels of land which are currently not forested (Figure 8.4). The current forest law prohibits cutting forested areas in favor of other land use, such that these areas remain static. Increased forest area and forest density have a positive effect on both carbon sequestration and protection against natural hazards. However, these synergies are limited to less than 100 ha since most of the protection zones are already forested and clear-cuts are not allowed there. Trade-offs between ecosystem services, which are related to forest cover change are thus most pronounced between carbon sequestration and protection against natural hazards on the one hand and biodiversity and food provision on the other hand (Figure 8.4).
The steep and complex topography of the study area means that more intensive land use trade-offs between biodiversity and food provision are limited to 1400ha, located mainly at lower elevations (Figure 8.4). On 200 ha synergies can be seen between the provision of biodiversity and food. The provision of both biodiversity and food demand for a continuation of agricultural land use and a stop of forest expansion. These parcels are located in marginal locations where profitability for agricultural use is low.

![Figure 8.4: Trade-offs and synergies between different ES on parcels of a size of 100 by 100m; Relationship between food and biodiversity provision (right); Relationship between carbon sequestration and food provision (left) (Maps: ©swisstopo)](image)

8.5 Discussion

We found that increasing the provisioning of marketable goods results in a decreased sectoral income as compared to what is achieved under an economic optimum scenario; a finding that corresponds with previous work done by Polasky et al. (2011). Moreover current relationship between ES in a mountainous region shows trade-offs between the provision of marketable and non-marketable ES. An expansion in food production – a marketable ES - leads to a change in land use that is unfavourable for the provision of biodiversity and the carbon balance, a fact already shown by Nelson et al. (2009), Reidsma et al. (2006), and Raudsepp Hearne et al. (2009). Increased production of mar-
ketable goods results in a decrease in biodiversity and carbon sequestration. This is mainly because an increase in the amount of food produced demands a more intensive land use that leads to a loss in biodiversity. An increase in food provision demands also a higher number of animals to graze the parcels that are not suitable for crop production. Since they emit methane and increase the amount of nitrous oxide emitted they will deteriorate the climate balance. Between non-marketable ES we also found synergies. This is mainly the case between the protection function of forests and the carbon balance since both ES are improved if the forest area is expanded.

Spatially explicit on all agricultural land there is a fundamental trade-off between carbon sequestration and food provision, and carbon sequestration and field biodiversity. Synergies between these components did not occur in any of our simulated parcel. Management schemes that aim to increase food production or biodiversity should therefore take into account that there will be a negative impact on carbon sequestration. In contrast, the relationship between food and field biodiversity exhibits strong synergies. These synergies mainly appear on land that is threatened by re-forestation located at the edge between current agricultural and forest land. Management schemes that assure cultivation of these parcels by agriculture will most probably improve the provision of both food and biodiversity. Based on the results of Dullinger et al. (2003) in these calculations it was assumed, that the value of forests for biodiversity is lower than for extensively used meadows. In future work this indicator should be refined since there are also forest types that provide a high value for biodiversity (Küffer and Senn-Irlet 2005). Too, recent work from Hanley et al. (2012) showed that extensification is not necessarily a suitable indicator for every aspect of biodiversity in grassland, that is why in future this indicator should be calculated more in detail, e.g. improving the link between location factors as for example altitude and land use.

If there are trade-offs or synergies is up to a certain degree dependent on the state of the system in the economic optimum. In 2080 when in the economic optimum no land is used for crops and a part of the summer pastures is abandoned by agriculture a small increase in food provision shows synergies with biodiversity provision and the carbon balance. If under these conditions food provision is increased a part of grassland is converted into cropland what reduces greenhouse gas emissions. Also forest expansion on extensive summer pastures would be avoided what increases biodiversity. If food provision is increased over a certain limit there are again trade-offs with biodiversity and the carbon balance. The increase of a certain ES by a small amount is therefore possible without af-
fecting the provision of other ES much (see also Bennett et al. 2009) and without a high loss – or even an improvement - in income. Management schemes aiming at small increases in the provision of ES therefore only cause very low opportunity costs. To know the size of the impact such management schemes shall have and to find the amount of ES provided in a social optimum supply functions of the different ES like them shown in this study are assumed to be helpful.

Today trade-offs between marketable and non-marketable ES in the assessed region are limited through Swiss forest laws, prohibiting an active decrease of forest cover. Hence trade-offs currently are limited to agricultural land, which potentially lowers how reactive the landscapes can be to external drivers. To prevent from wasting resources this fact needs to be considered in management schemes since they cannot influence land use on forest land. However, sustainable use of the forests or temporary loss of forests through large scale natural disturbances are still possible. Too, other studies show that there are also synergies between timber production and biodiversity (Spieker 2003). However, these synergies cannot be addressed directly by the current modelling framework what should be improved in further work. On agricultural land trade-offs between marketable and non-marketable ES in the Valais region are limited by the topography that limits the profitability of an intensification of most parcels. That is why the model shows no trade-off between food production and biodiversity on these parcels. Thereby we assume that extensively used grassland is richer in biodiversity than intensively used grassland and we do not distinguish if these parcels are mown or grazed.

Our results indicate that external drivers could have the potential to intensify trade-offs between ES. For example, if prices for food increase in future, instead of declining as is assumed in our scenario, the trade-offs that we examined would be magnified. Higher prices for food and a potential concomitant increase in the intensity of land use on marginal parcels, may also result in trade-offs between food production and biodiversity and carbon sequestration. Rising food prices also could lead to a discussion of a maceration of the restrictive Swiss forest laws. This would bring trade-offs to parcels that are protected by this law today demanding a better coordination of agriculture and forest policy. The comparably high subsidies for the cultivation of agricultural land compared to forest land otherwise would lead to a high pressure on forest land and therefore the provision of ES would be enhanced at the cost of a reduction in the provision of forest ES.
Robust ecosystem management schemes must take into account projected climatic and economic changes. Climate and socio-economy shifts will affect the ability of ecosystems to provide certain ES, and will influence land users decision making process, a fact also stated by Polasky et al. (2011). These changes will also influence the relationship between different ES. For example, an improvement in biodiversity provision or in the carbon balance in future will have a positive impact on food provision whereas today there is a trade-off between them. On the other hand this improvement will also be followed by larger reductions of the income than this is the case today. To maximize the gain from these synergies current policy and management should aim to promote an agricultural structure that facilitates these synergies since investments in new machinery and buildings will limit the flexibility of agriculture to adapt to optimal future management schemes quickly.

8.6 Conclusion

Management schemes for multifunctional landscapes only will be successful if they consider the trade-offs and synergies between different ES. In the Valais region unfortunately there are mainly trade-offs that have to be considered. The areas where synergies between different ES mainly between carbon sequestration and protection occur are small but still should be targeted by future management.

Management schemes must consider that there is no linear relationship between the provision of different ES or the sectoral income but in most cases marginal costs are increasing. To meet the social optimal mix of different ES it is therefore necessary to know the supply functions of the different ES in detail.

Changes in climate and socio-economic parameters also will affect trade-offs between different ES. To profit from these changes management schemes should be forward looking and should consider the time frame in which environmental and management changes will impact ES provisioning.
Greenhouse gas mitigation and offset options for suckler cow farms: an economic comparison for the Swiss case

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ABSTRACT

We assessed the economic suitability of 4 greenhouse gas (GHG) mitigation options and one GHG offset option for an improvement of the GHG balance of a representative Swiss suckler cow farm housing 35 Livestock units and cultivating 25 ha grassland.

GHG emission per kilogram meat in the economic optimum differ between the production systems and range from 18 to 21.9 kg CO\textsubscript{2}-eq./kg meat. Only GHG offset by agroforestry systems showed the potential to significantly reduce these emissions. Depending on the production system agroforestry systems could reduce net GHG emissions by 66\% to 7.3 kg CO\textsubscript{2}-eq./kg meat in the most intensive system and by 100\% in the most extensive system. In this calculation a carbon sequestration rate of 8 t CO\textsubscript{2}/ha/year was assumed. The potential of a combination of the addition of lipids to the diet, a cover of the slurry tank and the application of nitrification inhibitors only had the potential to reduce GHG emissions by 12\% thereby marginal abatement costs are increasing much faster than for agroforestry systems. A reduction of the GHG emissions to 7.5 kg CO\textsubscript{2}-eq./kg meat - possible with agroforestry only - raised costs between 0.03 CHF/kg meat and 0.38 CHF/kg meat depending on the production system and the state of the system before the reduction. If GHG emissions were reduced maximally average costs ranged between 0.37 CHF/kg meat, if agroforestry had the potential to reduce net GHG emissions to 0 kg CO\textsubscript{2}-eq., to 1.17 CHF/kg meat if also other options had to be applied.

KEYWORDS

Abatement costs; Agroforestry; Greenhouse gas mitigation; Greenhouse gas offset; Meat; Simulation; Suckler farming; Whole-farm model

9.1 Introduction

The contribution of agriculture to climate-relevant emissions has emerged as a major concern for scientists, policy makers and the public. Methane (CH\(_4\)) and nitrous oxide (N\(_2\)O) constitute crucial non-CO\(_2\) greenhouse gases (GHG). From a global perspective livestock is responsible for around 80% of agricultural and 18% of total GHG emissions (FAO 2006). Moreover 60% of nitrous oxide and about 50% of methane are associated with agricultural activities such as keeping livestock (here in particular from enteric fermentation) and soil cultivation (IPCC 2007). Pressure from policy and consumers to reduce these emissions are increasing worldwide. For example in Australia Government is discussing the implementation of a tax on GHG emissions (Nelson et al. 2010). Even if agriculture is not addressed within these schemes it offers farmers the possibility to trade emission certificates as a new source of income. On the other hand, large retailers in France label their products with a carbon footprint giving consumers the possibility to choose the most climate-friendly product (Cousin 2009).

Strategies to cope with the challenge of mitigating GHG emissions from agriculture can occur through (1) changes in plant and livestock production, (2) changes in the intensity of production activities, and (3) adoption of specific technologies (cf. UNFCCC 2008). While the last group comprises, e.g., slurry additives and coverage of slurry tanks, the first group involves enhanced grazing and agroforestry.

In Switzerland in particular suckler farming is of increasing importance. This development is caused by a rising consumer demand for meat produced by animal-friendly livestock husbandry. In order to reduce the environmental loads from suckler farming, strategies to mitigate climate relevant emissions have to be considered.

Both the high degree of heterogeneity in farming practices and the transboundary character of GHG emissions make it challenging to assess mitigation potentials. Therefore, assessment of mitigation strategies necessitates an analysis at a more disaggregated level (e.g. at the farm level) (Crosson et al. 2011). In addition, the implications of agricultural production imply links between GHG, the nitrogen cycle and other environmental factors. Thus, a holistic view of the agricultural production process is required in order to evaluate different mitigation strategies (Schils et al. 2005, Stewart et al. 2009).

Different studies assess and compare greenhouse gas emissions from different suckler cow farming systems using life cycle analysis approaches (e.g. Beauchemin et al. 2010, Casey and Holden 2006, Foley et al. 2011). However these models do not consider eco-
nomic rationalities (i.e. farmers’ responses) and thus cannot estimate the costs associated with a reduction of GHG emissions. Veysset et al. (2010) present a modelling framework that assesses both, economic performance as well as GHG balance of French suckler cow farms. They show that the production system has an impact as well on the farm GHG balance as on the economic performance. Meyer-Aurich (2005) calculates marginal GHG abatement costs for a cropping farm in Germany, showing that marginal abatement costs at the farm level can help to approach optimal abatement strategies. For the dairy sector different models already exist that have proven to be suitable tools to explicitly assess the economic performance of mitigation options (for a review on such models see Schils et al. 2005).

In this article, we investigate the opportunities of low GHG emitting suckler cow production systems in Switzerland. Moreover, we quantify the marginal and average abatement costs for different mitigation strategies in grassland-based suckler farms. In our analysis, we consider 4 mitigation strategies: (1) switching to alternative production systems, (2) lipid fodder supplements, (3) the coverage of slurry tanks, (4) adding nitrification inhibitors to slurry, and one offset strategy: the use of agroforestry for GHG offset.

To assess the options mentioned above, an integrated bio-economic model, which links the agricultural production process to environmental factors, is applied at a representative Swiss suckler cow farm. In this model, marginal abatement costs are calculated. In addition, we investigate the impact of the reduction of GHG emissions on the price of meat, which is relevant from the consumers’ and farmers’ perspective. Our study provides information for farmers and policy makers about the suitability of the assessed option. To reach this goal we aim to answer the following three research questions: 1) What is the potential of the different options to improve GHG-balance of the farm? 2) What is the (economically) optimal combination of the different mitigation options? 3) What are the supplemental costs (e.g. for consumers) for carbon improved meat?

The remainder of this paper is organised as follows: Section 9.2 presents the methodological framework of the employed bio-economic model and an overview of the here considered mitigation and offset strategies. Results and discussions are presented in Section 9.3, while Section 9.4 concludes our analysis.

9.2 Data and Methods

Our Integrated Suckler Cow Optimisation model (INTSCOPT) was designed to evaluate different GHG mitigation options as well as the biophysical and economic potential of
agroforestry. This model was constructed to allow quantification of all direct and indirect gaseous emissions from suckler cow farms to assess mitigation and offset options.

INTSCOPT is based on linear programming (LP), since this approach has proven to be a suitable method for considering both economic and environmental constraints, especially in the case of farming systems (Janssen and Van Ittersum 2007). The structure of INTSCOPT takes the form of a standard LP model, as described in Figure 9.1. We apply our model to a single existing, exemplary farm. This farm is located in the Swiss highlands on an elevation of 800m a.s.l. It is characterized by a total farm area of 25 ha, and has a maximum housing capacity of 35 livestock units (LU), what is a representative size for Swiss suckler cow farms. Land use activities are grassland based, i.e. no crop production is considered because soil and climate conditions are not suitable. Thus all feed concentrates are assumed to be purchased on the market.

The goal function underlying this model is the maximization of total (i.e. farm-level) gross margins for the farmer. Gross margins are taken as goal function because our analysis focuses on a short time horizon, and farmers can thus not adjust overhead and fix costs, but focus on the adjustment of direct, assignable (i.e. variable) costs of their activities. The objective function is measured in monetary units (Z) and is defined as follows:

\[
\text{Max } Z = \Sigma \text{returns} - \Sigma \text{assignable costs} - \Sigma \text{mitigation costs} + \Sigma \text{subsidies}, \ s.t. \ constraints
\] (9.1)

In the maximization process the model has the ability to optimize the number of animals as well as land use, i.e. the choice of grasslands of different intensities and agroforestry. Since the diet is calculated endogenously also the choice of the amount of concentrate feed or lipids in the diet is part of the optimization process. Also part of the optimization process is the implementation of the assessed GHG-mitigation measures.
<table>
<thead>
<tr>
<th>Activities</th>
<th>Cows</th>
<th>Calves</th>
<th>Feed forage</th>
<th>Feed concentrates</th>
<th>Feed lipids</th>
<th>Grassland intensive</th>
<th>Grassland extensive</th>
<th>Agroforest intensive</th>
<th>Agroforest extensive</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Animal production</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stable size</td>
<td>a</td>
<td>a</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>≤ 35</td>
<td>Limit due to size of the stable house</td>
</tr>
<tr>
<td>Herd structure</td>
<td>a</td>
<td>-a</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>= 0</td>
<td>See chapter 8.2.1</td>
</tr>
<tr>
<td>Diet</td>
<td>+1</td>
<td>+1</td>
<td>-a</td>
<td>-a</td>
<td>-a</td>
<td></td>
<td></td>
<td></td>
<td>= 0</td>
<td>See chapter 8.2.1</td>
</tr>
<tr>
<td>Forage production</td>
<td>a</td>
<td>-a</td>
<td>-a</td>
<td>-a</td>
<td>-a</td>
<td>= 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agronomic constraints</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total farm area</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>= 25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extensive grassland (PEP)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>≥ 1.75</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nutrient balance (PEP)</td>
<td>a</td>
<td>a</td>
<td></td>
<td>-1.1*a</td>
<td>-1.1*a</td>
<td>≤ 0</td>
<td></td>
<td></td>
<td>See chapter 8.2.2</td>
<td></td>
</tr>
<tr>
<td>Nutrient balance (Agronomy)</td>
<td>a</td>
<td>a</td>
<td></td>
<td>-a</td>
<td>-a</td>
<td>≥ 0</td>
<td></td>
<td></td>
<td>See chapter 8.2.2</td>
<td></td>
</tr>
<tr>
<td>GHG-Emissions</td>
<td>e</td>
<td>e</td>
<td>e</td>
<td>e</td>
<td>e</td>
<td>-e</td>
<td>-e</td>
<td>-e</td>
<td>&lt; E</td>
<td>See chapter 8.2.3</td>
</tr>
<tr>
<td>Objective function</td>
<td>+CHF/Head</td>
<td>+CHF/Head</td>
<td>-CHF/ton</td>
<td>-CHF/ton</td>
<td>-CHF/ton</td>
<td>-CHF/ha</td>
<td>-CHF/ha</td>
<td>-CHF/ha</td>
<td>-CHF/ha</td>
<td>=Z</td>
</tr>
</tbody>
</table>

Figure 9.1: General structure of the INTSCOPT model showing its constraints and activities. Constraints marked with (PEP) are part of the ecological cross compliance, a precondition to receive subsidies in Switzerland. All other constraints are either modelling the limitations the farmer is facing because of the size of his farm or the agronomic production capacity of the farm. Thereby a is an agronomic parameter specific for each activity and constraint combination and Z the farm-level gross margin. Also part of the optimization process is the calculation of total greenhouse gas emissions E, whereas e is the emission parameter.
Equation 9.1 shows that farm-level gross margins are maximized subject to specific constraints. An overview over these constraints is given in Figure 9.1. They address for instance, the farm size (i.e. the used area has to be equal to the total farm size), the production of forages (i.e. forages are produced on the farm), but also address cross compliance restrictions that have to be fulfilled to receive general direct payments. For grassland based suckler farms the most important cross compliance restrictions are that at least 7% of the total farm area has to be cultivated with extensive grassland, and the nutrient balance of the farm has to be balanced\footnote{See El Benni and Lehmann (2010) for an overview on Swiss agricultural policy as well as cross compliance restrictions.}

To optimise both profit and GHG emissions, an iterative procedure described by de Wit et al. (1988) has been chosen. The procedure consists of a number of optimisations of the total gross margin, whereas the GHG emissions are lowered in every optimisation round by 2.5 t CO$_2$-eq.\footnote{To make the results comparable between the different production systems it was necessary to reduce GHG-emissions by identical absolute values. Reduction steps of 2.5 t CO$_2$-eq. were chosen as a compromise between high accuracy of the results and required time for computation.} while keeping the animal husbandry system and the amount of meat production constant. Afterwards, the model is applied to 1) calculate the total (i.e. farm-level) gross margins of different production systems, 2) assess the environmental and economic performance of different GHG mitigation and offset options in an integrated approach and 3) to estimate marginal and average abatement costs.

In the following sections, the crucial parts of the model, including the calculation of the emission factors, are described. At the end of this section, a summary table on key-variables and assumptions (i.e. on prices, costs, direct payments, grassland yields, etc.) used in the model is presented (Table 9.4).

\subsection*{9.2.1 Animal production systems and farm structure}

Table 9.1 shows the characteristics of the three considered suckler cow production systems.
Table 9.1: Characteristic parameters of beef production in the three production systems presented in this study: Angus, Charolais and Galloway.

<table>
<thead>
<tr>
<th>Production parameter</th>
<th>Angus</th>
<th>Charolais</th>
<th>Galloway</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of the cow [kg]</td>
<td>625</td>
<td>800</td>
<td>525</td>
</tr>
<tr>
<td>Calves per year [1/year]</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Weight of calf at birth [kg]</td>
<td>36</td>
<td>45</td>
<td>27</td>
</tr>
<tr>
<td>Age at slaughtering day [months]</td>
<td>10</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>Average growth per day [g/day]</td>
<td>1100</td>
<td>1133</td>
<td>700</td>
</tr>
<tr>
<td>Live weight at slaughter (LW) [kg]</td>
<td>364</td>
<td>550</td>
<td>482</td>
</tr>
<tr>
<td>Carcass weight (CW) [kg]</td>
<td>205</td>
<td>310</td>
<td>270</td>
</tr>
<tr>
<td>Milk production [kg/year]</td>
<td>2500</td>
<td>3000</td>
<td>2000</td>
</tr>
<tr>
<td>Max. number of Livestock Units [LU]</td>
<td>35</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Max. number of cows</td>
<td>35</td>
<td>26</td>
<td>18</td>
</tr>
</tbody>
</table>

For the optimisation of the feed mix, the year is split into two periods: winter and summer. Whereas in winter, hay and silage of different qualities are available, during the summer, fodder from pastures also is part of the feed mix. In both periods, forage can be supplemented by concentrates and fat. Determining the composition of the feed mix is part of the optimisation process. The daily energy requirement for every animal is calculated according to its weight and its needs (production, growth) in every period. These constraints are complemented by upper and lower limits of daily dry matter intake calculated on the basis of the animal’s weight. To guarantee the availability of crude protein in the feed mix, an upper and lower bound is defined, depending on the energy intake. The calculations of the feed requirements and the composition of the different feeds are based on data provided by Arrigo et al. (1994).

The model assumes that the animals are kept in free-stall housing in which the number of stalls is flexible according to the age of the animals. Animals older than 15 months are kept in cubicles, whereas younger cattle are kept on deep litter. It is assumed that a change between the housing systems does not require much effort. Therefore, the only building constraint in INTSCOPT is the total number of LU, which in this case is 35 (cf. Table 9.1).
9.2.2 **Nutrient balance and N-cycle**

The outcome of the model is restricted by two different nutrient balances. The first balance ensures that the modelled farm fulfils the cross compliance requirements (Proof of Ecological Performance (PEP), see El Benni and Lehmann (2010) for details), which represents a criteria that must be met to receive direct payments in Switzerland. In order to fulfil the PEP the amount of nutrients spread may not exceed 110% of the nutrient demand of crops and grassland. The calculation of this nutrient balance in the model was done according to the official calculation criteria (for details see Suisse-Bilanz, Amaudruz et al. 2003).

Because GHG and nitrogen emissions are linked, a second refined balance was calculated for nitrogen. This second nitrogen balance integrates the different compartments of the farm nitrogen cycle. The amount of artificial fertilizer that is purchased is calculated as the difference between the demand for nitrogen by the grassland to reach yields as high as specified for the different intensity levels and the nitrogen available in manure. The available nitrogen in manure is calculated as the amount of nitrogen in the feedstuff - including both, roughage and concentrate feedstuff – minus the amount of nitrogen lost by selling animals, gaseous emissions and emissions through leakage. The different parts of the cycle are calculated according to the methods presented in Table 9.2.
Table 9.2: Description of the different compartments of the nitrogen cycle as modelled in INTSCOPT as well as the underlying methods. The amount of nitrogen flowing through the different compartments is influenced by the here shown factors.

<table>
<thead>
<tr>
<th>Compartement of the N-cycle</th>
<th>Source of nitrogen</th>
<th>Influencing factors for the different N-flows considered in INTSCOPT</th>
<th>References for the methods to assess each compartment of N-cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>System inflow</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fertiliser</td>
<td>Type of fertiliser/nutrient content</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concentrate</td>
<td>Type of concentrate</td>
<td>Amigo et al. 1994</td>
<td></td>
</tr>
<tr>
<td>Biological N Fixation</td>
<td>Land-use intensity</td>
<td>Schmid et al. 2000</td>
<td></td>
</tr>
<tr>
<td>System outflow</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meat N-content</td>
<td>Animal</td>
<td>Amount of meat produced</td>
<td>Amigo et al. 1994</td>
</tr>
<tr>
<td>NH$_3$</td>
<td>Manure</td>
<td>Housing system, manure storage and spread, pasture management, manure storage</td>
<td>Reidy and Menzi 2005</td>
</tr>
<tr>
<td>NO$_3$</td>
<td>Land use</td>
<td>Type of fertiliser or manure, manure management</td>
<td>Schmid et al. 2000</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>Manure</td>
<td>Housing system, type of manure, manure storage</td>
<td>Schmid et al. 2000, Schmid et al. 2001</td>
</tr>
<tr>
<td>NO$_x$</td>
<td>Land use</td>
<td>Crop residues, NH$_3$ loss</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Manure and fertiliser</td>
<td>Amount of N in manure and fertiliser</td>
<td>Schmid et al. 2000</td>
</tr>
</tbody>
</table>

9.2.3 Calculation of GHG emissions

In our model, we account for all GHG emissions on a farm, including indirect nitrous oxide emissions associated with N losses and selected pre-chain emissions from imported products. GHG emitted after the products, i.e. meat and timber, have left the farm are not considered. On-farm emissions are calculated applying the IPCC methodology (Houghton et al. 1997, IPCC 2000). Because emission levels are climate- and management-specific (Crosson et al. 2011), these methodologies have been adapted to Swiss conditions. The various on-farm emissions, their sources and the underlying methods are described in Table 9.3. To compare the different emissions with each other, methane and nitrous oxide are converted into CO$_2$ equivalents following IPCC (2007).
Table 9.3: Factors influencing greenhouse gas emissions as considered in INTSCOPT as well as references for the underlying greenhouse gas calculation methods.

<table>
<thead>
<tr>
<th>Greenhouse Gas</th>
<th>Source of greenhouse gas</th>
<th>Factors influencing the emission of the different greenhouse gases</th>
<th>References for methods applied to model the emission of each greenhouse gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_4$</td>
<td>Enteric fermentation</td>
<td>Animal-specific methane rate, feed mix, lipid supplementation</td>
<td>Houghton et al. 1997, Minonzio et al. 1998</td>
</tr>
<tr>
<td></td>
<td>Manure</td>
<td>Amount of different manures, feed mix, housing system, pasture management</td>
<td></td>
</tr>
<tr>
<td>N$_2$O</td>
<td>Manure</td>
<td>Amount of different types of manure, manure management</td>
<td>Houghton et al. 1997,</td>
</tr>
<tr>
<td></td>
<td>Indirect</td>
<td>Loss of N in different compounds</td>
<td>Schmid et al. 2000, see table 3</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>Tractor/Machinery</td>
<td>Land-use intensity</td>
<td>Houghton et al. 1997, Gazzarin and Albisser 2010</td>
</tr>
<tr>
<td>Pre-chain emissions</td>
<td>Production and transport of concentrate feedstuff</td>
<td>Composition of the animal's diet</td>
<td>Van der Werf et al. 2005; Bernesson 2004, Williams et al. 2006</td>
</tr>
<tr>
<td></td>
<td>Production and transport of artificial fertiliser</td>
<td>Land-use intensity, available on-farm manure</td>
<td>Williams et al. 2006</td>
</tr>
</tbody>
</table>

Pre-chain emissions are emissions associated with the buying, i.e. importation into the farm system, of production factors such as concentrate feedstuff and artificial fertiliser. Note that pre-chain emissions for the consumption of electricity on the farm as well as for the construction of buildings and machinery are not considered since this study focuses only on short term optimization hence changes in buildings and machinery are not part of the optimization process. Vergé et al. (2007) show for the Canadian dairy sector that the neglected indirect GHG emissions account only for 5.1% of total GHG emissions. Since use of electricity in the here considered beef production is lower than in dairy production, we assume that our framework covers at least 95% of total GHG emissions.
9.2.4 Selected mitigation and offset strategies for agricultural GHG emissions

Compilations of mitigation and offset strategies for agriculture are provided by, e.g. Martin et al. (2010), Wright and Klieve (2011), and UNFCCC (2008). With a focus on grassland-based suckler farming, this section addresses the mitigation practices and their relative reduction potentials, which are included in this assessment: They have been chosen since they do not require large investments as for example anaerobic digestion, or separation of slurry do. In addition their impact has been proven outside a laboratory environment (Veyssset et al. 2010, Martin et al. 2010, Amon et al. 2006, Weiske et al. 2001) and these mitigation options are feasible for use in practice as also are agroforestry systems (Eichhorn et al. 2006).

9.2.4.1 Different animal production systems

The animal production system has a major effect on the emission of GHG. Veyssset et al. (2010) assessed differences of up to 10% in emitted GHG among grazing suckler farming, depending on the production system. We consider three common Swiss production systems in our analysis named after breeds that are suitable for the respective systems: Angus, Charolais and Galloway. The productivity per LU for Angus and Charolais is quite high because after 10 and 15 months (Boessinger et al. 2010, Mutterkuh Schweiz 2011), respectively, the optimal live weight for slaughter must be attained. While the Angus and Charolais systems need to be managed rather intensively, the Galloway system can be applied on marginal sites using low-nutrient feed mixes (Mutterkuh Schweiz 2011). For a detailed description of the different systems see Table 9.1.

9.2.4.2 Lipid supplements

Whereas different strategies, e.g. defaunating agents, or ionophores, did not yet provide convincing results in the decrease of methane production in ruminant’s digestion, supplementation of lipids to the diet leads to a significant decrease of methane emissions (Wright and Klieve 2011) without decrease in performance (Grainger and Beauchemin 2011). Lipids reduce methane emissions through decreased organic matter fermentation, activity of methanogens and protozoal, and hydrogenation of fatty acids for lipids rich in unsaturated fatty acids (Johnson and Johnson 1995). However, the measured efficiency varies broadly, as Beauchemin et al. (2010) showed in a recent review. On average, a 1% increase of lipids in the feed mix leads to an emission reduction of 5.6%. Martin et al. (2010) indicated an average emission reduction of 4.8% per 1% increase of lipids in the dry matter. In the context of lipid supplements, however, it is important that the level of
lipids must not exceed 6% of total dry matter content or else a depression of fodder intake may occur. Based on these two review studies, our analysis assumes a 5% reduction in emissions per 1% lipid supplementation and a maximum of 6% lipids of total dry matter in the diet.

9.2.4.3 Slurry tank coverage
Covering slurry tanks can reduce methane, nitrous oxide and ammonia emissions. However, depending on the type of slurry coverage and the temperature, the rate of reduction varies. Covering slurry with a wooden lid leads to a reduction in methane emissions of 14% (winter) and 17% (summer), and a reduction in ammonia emissions of 28% (winter) and 54% (summer) (Amon et al. 2006). Based on this study, we assume in our model 15%, 35%, and 50% reductions in methane, nitrous oxide, and ammonia emissions, respectively, if slurry tanks are covered.

9.2.4.4 Nitrification inhibitors
Mineralisation of soil organic matter results in the release of ammonium (NH$_4^+$) or ammonia (NH$_3$) (Firestone and Davidson 1989). In the process of nitrification, ammonium is oxidised via nitrite (NO$_2^-$) to nitrate (NO$_3^-$). Nitrate easily can be leached into the groundwater, causing eutrophication, and both nitrite and nitrate can be denitrified to nitrous oxide (McNeill and Unkovich 2007). The application of nitrification inhibitors (NI) (e.g. 3,4-dimethylpyrazole phosphate (DMPP)) lowers the nitrification rate by reducing the activity of Nitrosomonas bacteria (Zerulla et al. 2001). Weiske et al. (2006) showed a 49% reduction of nitrous oxide emissions when they applied DMPP on fertilised sites. A similar result of 48% (spring) and 61% (autumn) reduction in nitrous oxide emissions was demonstrated by Merino et al. (2005), who applied 1 kg of DMPP per hectare on slurry. Based on these and other studies, we assume a reduction potential of 50% for direct nitrous oxide emissions from pastures through the application of nitrification inhibitors.

9.2.4.5 The agroforestry system
Agroforestry systems contain a combination of a woody permanent crop with a crop or with grassland on the same area. Such systems result in diversified agricultural production, increased soil fertility, reduced nitrogen losses, improved landscape scenery, and enhanced biodiversity (Jose 2009; SAFE 2005). Compared to monocropping, one advantage of agroforestry is the ability to sequester carbon through storage in the perma-
Greenhouse gas mitigation and offset options for suckler cow farms

9.2.5 Land use

All land use activities in our model are grassland-based. These activities differ only in the intensity of the pasture and the presence or absence of trees (i.e. agroforestry). According to Boessinger et al. (2010), three different grassland intensities are considered in INTSCOPT: intensive, mid-intensive, and extensive. For any grassland type, the model can establish an agroforestry system. Because of the increasing competition for sunlight and other resources, the yield of grassland under trees is reduced by 40% (Kern 2006).
Table 9.4: Summary of economic model parameters including prices for farm products, production factors, machinery, and mitigation options based on prices in the year 2009. In the lower part a description of the yields and carbon sequestration rates of the different land use activities is given. Data mainly origins from publication for extension services in Switzerland.

<table>
<thead>
<tr>
<th>Parameter in INTSCOPT</th>
<th>Amount</th>
<th>Unit</th>
<th>Reference for data</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Returns</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meat Calve</td>
<td>10.3</td>
<td>CHF/kg CW</td>
<td>Boessinger et al. 2010</td>
</tr>
<tr>
<td>Meat Cow</td>
<td>7.9</td>
<td>CHF/kg CW</td>
<td>Boessinger et al. 2010</td>
</tr>
<tr>
<td><strong>Subsidies</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grassland intensive</td>
<td>1040</td>
<td>CHF/ha</td>
<td>Swiss Federal Council 1998</td>
</tr>
<tr>
<td>Grassland mid-intensive</td>
<td>1040</td>
<td>CHF/ha</td>
<td>Swiss Federal Council 1998</td>
</tr>
<tr>
<td>Grassland extensive</td>
<td>1740</td>
<td>CHF/ha</td>
<td>Swiss Federal Council 1998</td>
</tr>
<tr>
<td>Cows</td>
<td>1130</td>
<td>CHF/LU</td>
<td>Boessinger et al. 2010</td>
</tr>
<tr>
<td><strong>Costs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Young cow</td>
<td>450</td>
<td>CHF/cow/year</td>
<td>Boessinger et al. 2010</td>
</tr>
<tr>
<td>General costs husbandry</td>
<td>180</td>
<td>CHF/cow/year</td>
<td>Boessinger et al. 2010</td>
</tr>
<tr>
<td>Concentrate feedstuff</td>
<td>700</td>
<td>CHF/t</td>
<td>Boessinger et al. 2010</td>
</tr>
<tr>
<td>Fertilizer Urea</td>
<td>636</td>
<td>CHF/t</td>
<td>Boessinger et al. 2010</td>
</tr>
<tr>
<td>Fertilizer Ammonium Nitrate</td>
<td>385</td>
<td>CHF/t</td>
<td>Boessinger et al. 2010</td>
</tr>
<tr>
<td>Fertilizer Triple Super Phosphate</td>
<td>680</td>
<td>CHF/t</td>
<td>Boessinger et al. 2010</td>
</tr>
<tr>
<td>Fertilizer Potash</td>
<td>640</td>
<td>CHF/t</td>
<td>Boessinger et al. 2010</td>
</tr>
<tr>
<td><strong>Machinery</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hay conservation</td>
<td>106</td>
<td>CHF/ha/Cut</td>
<td>Gazzarin and Albisser Vögeli 2010</td>
</tr>
<tr>
<td>Silage conservation</td>
<td>497</td>
<td>CHF/ha/Cut</td>
<td>Gazzarin and Albisser Vögeli 2010</td>
</tr>
<tr>
<td>Slurry spreading</td>
<td>2</td>
<td>CHF/m$^3$</td>
<td>Gazzarin and Albisser Vögeli 2010</td>
</tr>
<tr>
<td>Manure spreading</td>
<td>18.6</td>
<td>CHF/t</td>
<td>Gazzarin and Albisser Vögeli 2010</td>
</tr>
<tr>
<td><strong>Mitigation measure</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lipids</td>
<td>266</td>
<td>CHF/t</td>
<td>Price for sunflower oil (SwissOlio 2007)</td>
</tr>
<tr>
<td>Nitrification inhibitor</td>
<td>0.65</td>
<td>CHF/kg N</td>
<td>Landi Jungfrau 2008</td>
</tr>
<tr>
<td>Slurry tank cover</td>
<td>2.06</td>
<td>CHF/m$^3$</td>
<td>Peter 2008</td>
</tr>
<tr>
<td>Agroforestry</td>
<td>0</td>
<td>CHF/ha</td>
<td>Discounted value of wood is as high as investments into plantation</td>
</tr>
<tr>
<td><strong>Yields</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grassland intensive</td>
<td>12.2</td>
<td>t/ha</td>
<td>Dütschler-Hermann et al. 2006</td>
</tr>
<tr>
<td>Grassland mid-intensive</td>
<td>8.54</td>
<td>t/ha</td>
<td>Dütschler-Hermann et al. 2006; Kern 2006</td>
</tr>
<tr>
<td>Grassland extensive</td>
<td>2.44</td>
<td>t/ha</td>
<td>Dütschler-Hermann et al. 2006; Kern 2006</td>
</tr>
<tr>
<td>Grassland intensive Agroforestry</td>
<td>7.32</td>
<td>t/ha</td>
<td>Dütschler-Hermann et al. 2006; Kern 2006</td>
</tr>
<tr>
<td>Grassland mid-intensive Agroforestry</td>
<td>5.124</td>
<td>t/ha</td>
<td>Dütschler-Hermann et al. 2006; Kern 2006</td>
</tr>
<tr>
<td>Grassland extensive Agroforestry</td>
<td>1.464</td>
<td>t/ha</td>
<td>Dütschler-Hermann et al. 2006; Kern 2006</td>
</tr>
<tr>
<td>Age of trees at harvest</td>
<td>20</td>
<td>years</td>
<td>Palma et al. 2007</td>
</tr>
<tr>
<td>Carbon sequestration Agroforestry</td>
<td>8</td>
<td>t CO$_2$/ha</td>
<td>Palma et al. 2007</td>
</tr>
</tbody>
</table>

### 9.3 Results

In our simulation highest total gross margin was achieved with the production system based on the Charolais or Angus breed (Table 9.5). Because of the low amount of meat
produced per year in the Galloway system, its total gross margin was 14% lower than in the other systems.

Depending on the production system, GHG emissions per kilogram of meat ranged between 18 kg CO₂-eq./kg CW (Carcass Weight) for the Charolais system and 21.9 kg CO₂-eq./kg CW for the Galloway system. These values were comparable to those reported by other studies, such as Casey and Holden (2006) and Foley et al. (2011), which reported emissions of 20 kg CO₂-eq./kg CW and 15.7 kg CO₂-eq./kg CW to 23.1 kg CO₂-eq./kg CW, respectively for Irish beef production. However, the values reported in INTSCOPT were lower than emissions shown by Veysset et al. (2010) for Charolais based suckler cow systems in France (26.6 – 30.5 kg CO₂-eq./kg CW).

Table 9.5: Model output for the different production systems in the initial state, when they are in the economic optimum: Greenhouse gas emissions in total (GHG<sub>tot</sub>), per kilogram of meat produced (GHG<sub>prod</sub>), relative sources of the different greenhouse gases as well as total meat production and gross margins

<table>
<thead>
<tr>
<th>Description of Output parameter</th>
<th>Unit</th>
<th>Production system</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GHG balance</strong></td>
<td></td>
<td>Angus</td>
</tr>
<tr>
<td>GHG&lt;sub&gt;tot&lt;/sub&gt;</td>
<td>t CO₂-eq.</td>
<td>175</td>
</tr>
<tr>
<td>GHG&lt;sub&gt;prod&lt;/sub&gt;</td>
<td>kg CO₂-eq./kg CW</td>
<td>19.4</td>
</tr>
<tr>
<td><strong>GHG sources</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH&lt;sub&gt;4&lt;/sub&gt; digestion</td>
<td>%</td>
<td>53</td>
</tr>
<tr>
<td>CH&lt;sub&gt;4&lt;/sub&gt; manure</td>
<td>%</td>
<td>5</td>
</tr>
<tr>
<td>N&lt;sub&gt;2&lt;/sub&gt;O</td>
<td>%</td>
<td>37</td>
</tr>
<tr>
<td>CO&lt;sub&gt;2&lt;/sub&gt; machinery</td>
<td>%</td>
<td>1</td>
</tr>
<tr>
<td>CO&lt;sub&gt;2&lt;/sub&gt; inputs</td>
<td>%</td>
<td>4</td>
</tr>
<tr>
<td><strong>Agricultural Production</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meat production</td>
<td>kg CW</td>
<td>9050</td>
</tr>
<tr>
<td>Gross margin</td>
<td>kCHF</td>
<td>138</td>
</tr>
</tbody>
</table>

9.3.1 Mitigation options within the different production systems

Results for the Charolais and Galloway systems are indicated in Figure 9.2. Both covering the slurry tank and adding lipids to the feed mix had a rather low impact and fast increasing marginal abatement costs. The addition of fat to the cow’s feed increased its net energy concentration, which might cause fattening problems. The combination of this limitation and the cow’s large contribution to total methane emissions, the impact of lipids
was limited to a maximum reduction potential of 2% and 3% in the Galloway and the Charolais systems, respectively. Charolais cows required a higher energy concentration in the feed; thus a higher amount of lipids in the diet was tolerable and therefore the addition of fat had a higher potential for GHG reduction in the Charolais system than in the Galloway system. These results were consistent with a study by del Prado et al. (2010), which reported for dairy cows, which need fodder with higher energy concentration than suckler cows, a reduction potential of about 10% per kilogram of milk when lipids were added to the feed.

The curve progression for the marginal abatement costs of covering the slurry tank looked very similar to that of adding lipids to the diet (Figure 9.2). The potential was limited to a decrease of 2% and 4% in the case of the Galloway and the Charolais systems. High abatement cost of the cover resulted from the small contribution of the slurry tank to total GHG emissions and the high cost for the construction of the cover.

Nitrous oxide emissions constituted about 50% of total emissions and our analysis indicated that nitrification inhibitors (NI) could reduce these emissions significantly. In comparison to the mitigation methods of adding lipids and covering the slurry tank, the marginal costs of applying NIs were relatively low (Figure 9.2). The NI method of mitigation produced associated costs that were favourable in comparison to the lipid and cover options also because it reduced the need for expensive artificial nitrogen fertiliser.

With the application of a combination of all mitigation options, GHG emissions could be reduced by 12%. These results were similar to those of other studies. For example, Hartmann et al. (2009) reported a mitigation potential of 5% and 2% with the addition of lipids and the slurry tank cover, respectively.

The above presented analyses focussed on technical mitigation options. In a subsequent step, the option to offset GHG emissions with on-farm agroforestry was taken into account. In the Galloway system, the establishment of an agroforestry system could reduce net GHG emissions to zero. In the case of the Charolais and the Angus systems, carbon sequestration in an agroforestry system had the potential to reduce emissions by 66% and 60%, respectively. In combination with other mitigation options in these systems, respective reductions of 77% and 70% could be reached. Agroforestry had a greater potential for the Galloway system because in the initial state land was managed low-intensively in this system. Hence, land was available to compensate for the smaller forage production caused by the enlarged agroforestry area. In the other systems, land use in the initial state
of the system was relatively intensive, thus, the potential to intensify land use was lower. Compared to the other mitigation options, agroforestry was relatively inexpensive (in terms of costs per mitigated/sequestered ton of CO$_2$-eq.). In all systems, a 50% reduction of GHG emissions was possible at marginal abatement costs of less than 57 CHF/t CO$_2$-eq.

![Figure 9.2: Marginal abatement costs of different mitigation options for the Charolais (similar to Angus) and the Galloway systems. Marginal abatement costs are shown the supplementation of lipids to the fodder (Lipids), for a cover on the slurry tank (Cover), for the application of nitrification inhibitor in manure management (Nitrification inhibitor) and for a combination of these three options (Combination).](image)

In all systems average reduction costs per kilogram of meat were lower for the on-farm offset than for the other mitigation options considered (Table 9.6). Agroforestry was least expensive in the Galloway system since enough land was available for intensive use to compensate loss in fodder production due to expanded agroforestry.
Table 9.6: Average additional costs per kilogram of meat (CHF/kg carcass weight) for the reduction of greenhouse gas emissions per kilogram of meat for the different production systems applying either a combination of only mitigation options (Mitigation w/o agroforestry) or a combination of mitigation and offset options (Mitigation and agroforestry). The values underlined in a grey colour specify the emissions level of the different systems in the economic optimum, i.e. the emission level that is reachable without extra costs. Every cell beyond the grey shaded means a reduction in greenhouse gas emissions applying one of the different options. n.a. means not available, i.e. there is no convergence to a solution for these emission levels.

<table>
<thead>
<tr>
<th>Reduction of emissions</th>
<th>Emissions per kilogram of meat [kg CO2-eq./kg CW]</th>
<th>Mitigation w/o agroforestry</th>
<th>Mitigation and agroforestry</th>
<th>Mitigation w/o agroforestry</th>
<th>Mitigation and agroforestry</th>
<th>Mitigation w/o agroforestry</th>
<th>Mitigation and agroforestry</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>17.5</td>
<td>0.53</td>
<td>0</td>
<td>0.08</td>
<td>0</td>
<td>0.44</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>na</td>
<td>0.01</td>
<td>na</td>
<td>0</td>
<td>na</td>
<td>0.01</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>na</td>
<td>0.24</td>
<td>na</td>
<td>0.11</td>
<td>na</td>
<td>0.02</td>
<td>0</td>
</tr>
<tr>
<td>7.5</td>
<td>na</td>
<td>0.38</td>
<td>na</td>
<td>0.24</td>
<td>na</td>
<td>0.03</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>na</td>
<td>1.14</td>
<td>na</td>
<td>0.5</td>
<td>na</td>
<td>0.11</td>
<td>0</td>
</tr>
<tr>
<td>2.5</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>0.25</td>
</tr>
<tr>
<td>0</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>0.37</td>
</tr>
</tbody>
</table>

With the application of all mitigation options (including agroforestry) within the production system, GHG emissions could be reduced to 5 kg CO2-eq./kg CW or lower. Because agroforestry had the lowest marginal abatement costs compared to the other options, it was applied predominantly, while the other options were applied secondarily. In the Galloway system agroforestry potentially could reduce emissions to zero. A reduction of the emissions to 5 kg CO2-eq./kg CW in this system cost only 0.11 CHF/kg CW. In contrast, in the Angus and the Charolais system, agroforestry alone could reduce emissions only to a level of 7.76 kg CO2-eq./kg CW and 6.12 kg CO2-eq./kg CW, respectively. For this reduction a significant share of the farm area has to be covered by agroforests (Table 9.7). Reductions cost 0.37 CHF/kg CW for the Angus system and 0.32 CHF/kg CW for the Charolais system. To reduce emissions further to 5 kg CO2-eq./kg CW, other options to mitigate GHG must be applied, e.g., supplementing lipids in the diet and utilising NIs. These additional mitigation strategies significantly increased reduction costs to 0.5 CHF/kg CW and 1.14 CHF/kg CW for the Charolais and Angus systems, respectively.
Greenhouse gas mitigation and offset options for suckler co

Table 9.7: Land use of the different production systems if the systems are in their economic optimum (Initially) and if the systems are optimised with respect to their greenhouse gas emissions (GHG-offset).

<table>
<thead>
<tr>
<th>Main land-use activity</th>
<th>Sub-land-use activity</th>
<th>Angus Initially</th>
<th>Angus GHG offset</th>
<th>Charolais Initially</th>
<th>Charolais GHG offset</th>
<th>Galloway Initially</th>
<th>Galloway GHG offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensive grassland</td>
<td>Monoculture</td>
<td>15.09</td>
<td>15.41</td>
<td>21.6</td>
<td>14.2</td>
<td>15.12</td>
<td>9.12</td>
</tr>
<tr>
<td></td>
<td>Agroforestry</td>
<td>0</td>
<td>7.84</td>
<td>0</td>
<td>9.05</td>
<td>0</td>
<td>11.71</td>
</tr>
<tr>
<td>Mid-intensive grassland</td>
<td>Monoculture</td>
<td>8.16</td>
<td>0</td>
<td>0</td>
<td>0.85</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Agroforestry</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Extensive grassland</td>
<td>Monoculture</td>
<td>1.75</td>
<td>0</td>
<td>3.4</td>
<td>0</td>
<td>9.03</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Agroforestry</td>
<td>0</td>
<td>1.75</td>
<td>0</td>
<td>1.75</td>
<td>0</td>
<td>4.17</td>
</tr>
</tbody>
</table>

Reduction costs depend on economic and ecological considerations. Average reduction cost per kilogram meat as well as the potential of the agroforest to offset GHG emissions were highly dependent on the assumed rate of carbon sequestration as indicated by a sensitivity analysis (Figure 9.3). So in the case of the Angus system costs for the offset of 50% of GHG emissions were 21% higher if sequestration rate was at the lower than at the upper level as stated by Palma et al. (2007). It is therefore necessary that they are calculated independently for every country and farming system.

Figure 9.3: Impact of the rate of carbon sequestration of the agroforestry systems on the average reduction costs per kilogram of meat. Sensitivity analysis was conducted at the example of the Angus production system. Maximum amount of greenhouse gas offset is 61%, 69% and 79% for sequestration rates of 6.4 t CO₂/ha/y (lower level stated by Palma et al. 2007), 8 t CO₂/ha/y (default level in this study) and 9.6 t CO₂/ha/y (upper level stated by Palma et al. (2007), respectively.

9.4 Discussion
We used an integrated bio-economic model to analyse the economic and environmental performance of 3 different suckler cow production systems in Swiss agriculture, with a
particular focus on the mitigation of GHG emissions considering four mitigation and one offset strategies. Results confirm other studies (e.g. Casey and Holden 2006, Crosson et al. 2011), which found, that the production system has a large impact on the emission level in the economic optimum. Mitigation options assessed in this study showed a limited possibility to mitigate GHG since they provoke fast increasing marginal abatement costs. The most efficient way to reduce GHG emissions is a combination of mitigation and offset options since marginal abatement costs are always lower than if mitigation options were implemented only. Above all, this combination showed a potential for the production system with the highest emissions per kilogram of meat in the economic optimum - the Galloway system – since in this system average additional costs are lowest and also a reduction of net greenhouse gas emissions to zero is possible. However the large agroforestry area needed might hinder farmers to maximize GHG offset and might limit its implementation on an area that can offset only a smaller share of GHG emissions.

In our opinion agroforestry is especially suitable for extensive production systems not only in Switzerland but all around the world. The costs raised by the agroforestry systems are mainly opportunity costs of decreasing production and a loss in subsidies, i.e. parameters that depend on the local conditions. Farmers that receive lower prices for their products therefore will also face lower monetary losses by the implementation of agroforestry systems. It could therefore also be an opportunity for large scale beef farms, for instance in Australia, that could trade emission certificates when improving their carbon balance.

The use of linear programming (LP) as method for the simulation of decision making provides some caveats. LP is based on the neoclassical economic theory. In this theory, economic agents are profit optimizers. Combined with limited resources, represented by model restrictions, these normative model approaches incorporate the fundamental economic problem: making the best out of limited resources (Buysse et al. 2007). Of course, decision making is, other than the goal function of an LP, multidimensional considering different types of utilities (Edward-Jones 2006), e.g. farmers might be conservative regarding the use of specific methods if they strongly deviate from current practices (Karrer and Tikir 2010). Considering only monetary profit as a utility will neglect additional constraints farmers are facing. Therefore results of such a simulation must be considered as a type of best case solution. In order to overcome these drawbacks, linear programming methods can be augmented, for instance, by considering farmers’ income risks (e.g.
Finger et al. 2010) and integrating decision rules based on survey data (Möhring et al. 2010).

The accuracy of model results can be wrong if the model is based on an unsuitable design or false data. The results of such models therefore should be validated properly (Zander et al. 2008). For this purpose we compared some of the intermediate results with real farm data. For the amount of GHG emission as well as the efficiency of the assessed mitigation options this was not possible due to a lack of real data. The calculation of the emission is based on a widely accepted methodology (e.g. Vergé et al. 2007). The input parameters needed for calculation of emissions however inherent large uncertainty (Rypdal and Winiwater 2001, Schmid et al. 2000). Parts of this uncertainty we tried to address by a comparison of our results with them of other studies as well as with a sensitivity analysis (Figure 3). In further research this uncertainty should be assessed more in depth as for example done by Foley et al. (2011).

We are also aware that carbon fluxes in grasslands vary due to climatic and management conditions (Zeeman et al. 2010). Due to the long time period of 20 years considered in our empirical analysis and the assumption of constant grassland management, we assume that this variability is only of minor relevance for our analysis. Additionally a study of Ford-Robertson et al. (1999) suggests that a conversion of pastures to agroforestry systems does not lead to decreasing net soil carbon stocks of each year in the transition period. However, uncertainties arising from this issue should be addressed in future analyses.

Our analysis was conducted at the farm-level using an existing farm structure that in its size is representative for Swiss suckler cow breeding farms. Stewart et al. (2009) found that heterogeneity in farm structure will lead to different numerical results across farms. Thus, the site-specific, spatially explicit analysis of mitigation options should be addressed in further research. In addition, technical uncertainties arising from specific mitigation options and agroforestry should be empirically addressed in further research.

Our results show that reductions of greenhouse gas emissions per kilogram of meat are not free of costs. Thus, consumers would have to pay for these reductions. Studies on consumers’ willingness to pay for emission reductions, for instance by using alternative electricity and fuel production techniques (Roe et al. 2001, Nomura and Akai 2004) have shown that there is a positive willingness to pay for such environmental service. Different studies also show that consumers are ready to pay in addition for food with a lower
carbon footprint or they at least choose products with a better carbon balance if the products else are identical (Bolwig and Gibbon 2009, Vanclay et al. 2010). Such willingness to pay is expected to be rather high in Switzerland, because the Swiss population has a high demand for environmentally friendly, low emission agriculture (Haller 2011). In addition, we think that the reduction of emissions from meat production, or even an emission-neutral meat production, is a large opportunity for producers because this could be used to label their products and could thus be used for further product differentiation.

As shown in Table 9.5, subsidies in form of general and ecological direct payments as well as the associated cross compliance requirements play an important role in Swiss agricultural production. The reduction of emissions from animal production could thus also be fostered by integrating greenhouse gas emission restrictions in the cross compliance restrictions or by introducing additional ecological direct payments for low- or zero-emission animal production.

### 9.5 Conclusion

In our assessment of the economic suitability of mitigation and offset strategies to reduce GHG emissions for common suckler farming systems in Switzerland, only the agroforestry system, with its carbon sequestration potential, leads to significant GHG emission reductions at reasonable costs.

Other mitigation options considered in our study do not have the potential to reduce GHG emissions on a large scale. They neither have the potential to reduce a large share of GHG emissions, nor are they inexpensive enough to make implementation possible.

Additional production costs for carbon improved meat will be in a moderate range making it marketable. This is even more the case as the farmers’ animal production costs represent only a part of the price the consumer pays for meat in the shop.

Consumers are becoming more and more sensitive to climate change and are modifying their behaviour accordingly when buying meat in the grocery store (Vanclay et al. 2010). For farms to benefit from this consumer trend, the emissions of the whole value chain must be assessed and optimised. For the agricultural link of the value chain, agroforestry is a way to contribute to GHG mitigation and adapt to this future consumer trend.
10 Synthesis

It was the overall goal of this thesis to elaborate a model that has the ability to simulate the provision of ES by agriculture and forestry under different climate and market scenarios. In this last chapter of this thesis the results of these simulations are synthesized to answer the research questions. Then the suitability of the model framework to answer the research questions is discussed, and challenges that should be addressed in future research are outlined. In the last part of this thesis, implications for future land use policy are explained.

10.1 Answers to research questions

10.1.1 What are the determining factors for changes in the provision of ES?

There are different drivers for changes in ES provision, such as changing climate or economic parameters. Directly, the provision of ES can either be affected through changes in the ecosystem processes, such as increasing growing rates because of higher temperature, or by land use change. Land use change again is driven by changes in ecosystem processes, that is, by changes in yields of grassland, crops and forests, or by changes in economic parameters which can then be stated as indirect drivers.

Simulation results show that the provision of ES will change under different scenarios. The direction of change is dependent on the scenario and the time horizon chosen. In general, changes are more severe if there is a higher increase in temperature as in scenario A1FI compared to scenario B1. It is however considerable that even if these changes result in large increase in yields, this does not affect the provision of ES by agriculture on a high level since they are assumed to be compensated through changing land use. The indirect impact of climate change therefore is much smaller than changes in economic parameters. For instance, higher yields would lead to a higher level of food provision if land use is assumed to stay on the current level. If land use is optimized as well, considering also changes in economic parameters, impact of climate change diminishes. Then a transformation of cropland to grassland because of changes in relative profitability results in a decrease in food provision. Thereby the impact of climate change, i.e. changes in yields, on relative profitability is much lower than changes in economic parameters. But changes in prices for products and costs of production show a great impact on the allocation of land and other production factors by agriculture. Since ES provided are joint products of agricultural production (Huber 2010), this impacts provision of ES by agriculture.
In contrast, ES provided by forestry are more affected by the direct impact of climate change than by climate or economic-driven land use change. Changes in temperature and precipitation patterns will affect ecosystem processes in forests in a way that their provision of ES changes, while changes in socio-economic parameters do not much affect them. However, it has to be considered that the impact of changes in socio-economic parameters on forest management was considered only rather simply; in reality these changes may have a greater impact than shown in this work.

Expansion of forests on agricultural land is seen as a current problem in alpine regions (MacDonald et al. 2000). In the case study region Visp the amount of land used by agriculture was reduced by more than 10% during the last 25 years (SFSO 2009). In the modelling results forest expansion however is only visible under extreme scenarios, that is, under scenarios where changes in economic parameters lead to a loss of profitability in agricultural production and changing climate leads to a substantial increase in grassland yields. In this case there are not enough animals available to graze the additional fodder and the least suitable land is not cultivated for agriculture anymore. However, the land abandonment that is currently happening in this region is not visible in the simulation results. This may be because there are more than just economic reasons responsible for these changes but these reasons are not considered in ALUAM. Gellrich et al. (2008) for example found that the possibility of farmers to work outside agriculture and subsequently the share of part-time farmers, a delay in land-consolidation or the single farmer’s attitude towards the use of their own land have an impact on forest expansion. These parameters were not considered in ALUAM. Furthermore the ALUAM framework does not consider gradual expansion of forest area on agricultural land but only purposive decisions to let a parcel fallow. In reality under-grazing can lead to a slow forest re-growth that gradually decreases the pasture value. Then there is even less grazing on this parcel, supporting the growth of shrubs and trees until a point of no return is passed and land cannot be used for agriculture anymore (e.g. Huber et al. 2012). This is a process that cannot be addressed in ALUAM either.

10.1.2 Are there trade-offs in the provision of different ES and are these trade-offs affected by global change?

Simulation results show that there are trade-offs in the provision of different ES. Mainly these trade-offs are visible between the provision of marketable and non-marketable ES. The main reason for these trade-offs is that the area covered by a certain ecosystem can-
not be expanded because the total area that is suitable for cultivation is limited. Hence if the provision of a certain ES shall be increased, ecosystems have to be replaced by others; for example, agricultural land has to be reforested or ecosystems have to be managed in a way that they provide more of the beneficiary ES. Both alternatives will lead to changes in the provision of non-target ES. An increase in food provision, a marketable ES, for example, is either possible by changing grassland to cropland or by an intensification of the grassland. Both management strategies will lead to a decrease in the area used as extensive grassland, which is seen as the most beneficial land use for biodiversity provision, and therefore to a decline in biodiversity provision. The same is true for the trade-off between food provision and carbon sequestration, where an increase in food provision will lead to an increase in the number of animals and therefore to a decline in the carbon balance.

Such trade-offs are apparent under all scenarios but somewhat differed. The applied scenarios affect the trade-offs in three different ways: 1) Changing climate affects ecosystem processes, leading to changes in the production function of different ES. For example the trade-off between food provision and carbon sequestration is less apparent in future climate since higher yields make it possible to produce more food without affecting the carbon balance. 2) Differences in the non-restricted economic optimum lead to different shapes of the trade-off functions. Since the optimal allocation of different ES is dependent on climate and socio-economic parameters, the baseline differs between the different scenarios. In addition trade-offs between different ES do not show a constant rate of change but change if the provision of a certain ES is promoted more. Because of this variable rate of the trade-offs this will lead to different results depending on the scenario and on the case study region. 3) Whereas in future scenarios farmers and foresters are assumed to be free of structural restrictions, these constraints are still valid for farmers today. They limit the farmers’ ability to adapt production, for example because the available stable houses need to be depreciated. This limitation may lead to solutions that show higher trade-offs than if there are no structural restrictions, as it is assumed in the far future.

In the ALUAM model shown in Chapter 8, trade-offs may even be underestimated since it was not taken into account that single farmers may have preferences that prevent them from changing their production patterns in favour of the provision of certain ES. In reality a single farmer’s intention not to adapt his production system has to be compensated for by other farmers. Because of the increasing marginal changes this would lead to high-
On the other hand side in the ALUAM model, however, the possibility of on-farm management measures to reduce trade-offs was not considered. As shown in Chapter 9, such schemes also offer the possibility to reduce trade-offs if the choice of the main production system is inflexible.

10.1.3 On the farm level, is there a possibility to mitigate trade-offs in the provision of different ES?

In comparison to a centralized planning institution, as assumed in the ALUAM model in Chapter 8, a single farmer faces additional restrictions. For example the available land is even more restricted and, even more importantly, the farmer has clear preferences for what he wants to produce (e.g. suckler cows as described in Chapter 9). This limits the possibility to mitigate trade-offs to innovative measures such as the establishment of agroforestry systems to reduce trade-off between meat production and the greenhouse gas balance. Such management measures, however, also have a disadvantage in that they reduce farmers’ incomes. From a farmer’s perspective, such schemes therefore are only an alternative if he gets a reward for his opportunity costs.

10.2 Discussion of the modelling approach

One of the most important issues of economic analyses and especially when designing interdisciplinary models is the validation of such models (Zander et al. 2008, Seppelt et al. 2011). A validation is the only way to exclude the possibility of flaws in the structure of the model as well as wrong data. A validation of both models with a focus on the impact of economic changes on agricultural activities was completed successfully. Hence the use of the normative mathematical programming model proved to be a suitable tool to assess the impact of economic parameters and climate on changes in the number of livestock as well as on land use change. Because of a lack of real-world data it was not possible to validate the simulation of ES provision. Even though the sources of the applied data are highly trusted, uncertainty can be expected to be inherent in the parameters for calculation of the ES mainly in the case of the calculation of the greenhouse gas balance since emission parameters for the different GHGs are highly dependent on climate and other environmental variables (Rypdal and Winiwarter 2001). The use of average values could therefore bear the risk of miscalculations. In future work, additional sensitivity analyses should be conducted with a focus on uncertainties in the calculation of parameters of ES provision. Furthermore, the chosen indicator for habitat diversity is rather coarse. It will be necessary to refine this parameter also considering forest biodiversity in future work.
Despite the sufficient validation the simulation results could be biased since the ALUAM model overestimated the flexibility of the farmers. ALUAM assumes that the land is allocated in a way that land rent is maximized and can be shifted between the different farms without any limitations. Recent work on the Swiss market for leased land, however, showed that landlords distribute their land not just following economic criteria because of, amongst other reasons, the restrictive Swiss land laws (Häusler 2008). Additionally, in the modelling framework it is assumed that farmers are willing to change their production to adapt to changes in economic parameters. Farmers however also have preferences for a certain production system. This may then be the reason that farmers in reality do not expand the number of suckler cows in an amount as suggested by the model. For simulation of states of ES provision far in the future this is not assumed to be a problem since farmers only will have successors if they can generate an adequate income (Mann 2007), that is, if they are ready to adapt to the respective environments. If the model shall be used for short-term and midterm policy assessment, it is necessary to consider that the capacities of farmers to adapt to changes in the environment are overestimated. Both of these problems of overflexibility in future work could be addressed by an expansion of the model to an agent-based model (Berger 2001). The agents could then be given specific characteristics of their real prototype. This could be accomplished, for example, by coupling specialized production models such as the one described in Chapter 9 over a land market as suggested by Lauber (2006).

The choice of a linear model makes the problem solvable but also demands some simplifications. The provision of ES shows different non-linearities and thresholds (Rigling et al. 2012) that cannot be considered in linear models. Such an example is neighbourhood effects on biodiversity; a combination of different structural elements in landscapes generally provides a higher value for biodiversity than one single element (Tilman 1994). The same is true for the calculation of the protection value of a forest patch that is dependent on land use above and below this patch. In the current model such topics can be taken into account if ES provision is calculated after the optimization process is concluded. This way was also chosen by Polasky et al. (2011) in their InVest framework. This sequential calculation however is seen as suboptimal since it is not possible to consider the provision of these ES in the optimization process itself. Using more sophisticated methods, for example genetic algorithms, could help to overcome this challenge, generating even more reliable results.
Compared to the impact of land use change the impact of climate change on ES provision may be overestimated in this thesis because of the focus of the ecological models. The models used to calculate yields of forest, crops and grassland are focussed on the estimation of changes in yields under future climate conditions. These models however take into account the impact of changes in management only to a very limited amount. The impact of socio-economic drivers on changes in forest management were therefore not considered in this thesis even if this could have an impact on the provision of ES (e.g. Eyre et al. 2010). In addition it was not considered that an adaptation in management, such as shifts in sowing dates in agriculture (Olesen et al. 2000) or the choice of tree species in forest management (Hanewinkel et al. 2010), could also have the potential to mitigate impacts of climate change (e.g. Bebi et al. 2009).

In interpreting the results it is always necessary to consider that the results presented here are economically efficient but not socially optimal. It is one of the characteristics of normative mathematical programming that they allocate resources in a way that is, under the considered restrictions, economically efficient (Huber 2008). Our framework, however, only considers the supply side of the ES provision. This means that it is not considered how much of certain ES society demands. To take into account demand side in a modelling framework could therefore be a valuable next step in research. This could probably be done by combining the presented model of the supply side with a framework, modelling willingness to pay for ES as for example presented by Grêt-Regamey (2008).

10.3 Policy implications

To ensure provision of ES by agriculture, in our case-study region it is not necessary to shape today’s agricultural policy – in contrast to forest policy - to climate change. The main drivers for changes in ES provision by agriculture are economic parameters. If policy schemes are focused on ES provision, as it is planned in the re-organisation of the direct payment system (Lanz et al. 2010), this should guarantee the provision of an adequate amount of ES in future. Policy measures then do not yet have to consider climate change. Other studies considering circumstances in the Jura region however indicate that the maintenance of the wooded-pastures in that region would demand an agricultural policy that takes into account climate change already today (Huber et al. 2012). However, the situation is different in forestry. Because of long production cycles and the subsequent time needed for adaptation to changes in the environment, forest management needs to consider a longer time horizon (Lindner 2000). To guarantee the provision of
ES by forestry under a changing climate, it will be necessary to influence forest management today. If nothing is done, there is a high probability that the climate will change faster than forests can adapt, which could result in a decrease in provision of forest ES. In this thesis the higher variability in yields of crops and grassland was not considered. Climate change is supposed to cause higher variability in weather and therefore also in yields (Finger et al. 2010), which could potentially also have an impact on agricultural land use, a point that should be addressed in future research.

A loosening of the current protection of the forest will demand an adaptation in the interplay between agricultural and forest policy. Today, trade-offs between ES provided by forests and ES provided by agriculture are in a large part mitigated through the forest law that prevents forests from being clear-cut and transformed to agricultural land. If this protection is given up this could lead to a loss of forest land since profitability per hectare on suitable parcels is higher if land is used for agriculture than if land is used for forestry due to, among other reasons, governmental subsidies for agriculture. The high difference in profitability between agricultural and forest land use on suitable land would likely make it profitable to transform forests into agricultural land. An abandonment of the restrictive forest laws, therefore, would need a better coordination of agricultural and forest policy and a higher reward for the management of the forest in order to save the provision of ES.

By the implementation of new policy schemes in favour of the provision of one ES, it has to be considered that this probably will have an impact on other ES, that is, it will cause trade-offs. Trade-offs exist mainly between the provision of marketable and non-marketable goods and services. Such a trade-off was, for example, apparent in Swiss post-war agricultural policy that focused merely on food provision, but the management of the ecosystems in order to provide as much food as possible led to a sharp decrease in biodiversity (Herzog et al. 2005). Certainly policy now should not change fundamentally in the other direction and only focus on biodiversity, but it will be necessary to find a balance that leads to an optimal solution. Simulation results in this thesis indicate that optimal solutions are not aimed at providing one ES at its maximal possible level. Following the law of decreasing marginal returns, ES provision in total is higher if policy considers multiple ES.

Policy should be flexible enough to enable innovative means to overcome trade-offs between the different ES. Whereas ALUAM showed a clear and strong trade-off between
carbon sequestration and food provision, an innovative measure, for example an agro-forestry system as presented in Chapter 9, could help to overcome this trade-off. However such systems are not yet part of the agricultural policy, which is why they were not considered by farmers or in ALUAM. An integration of such measures by rewarding such projects could be a promising approach to overcome trade-offs.
References


Bernesson, S., 2004. Life Cycle Assessment of Rapeseed Oil, Rape Methyl Ester and Ethanol as Fuels – A Comparison between large- and small-scale Production. Department of Biometry and Engineering, Swedish University of Agricultural Sciences, Uppsala.


Provision of Ecosystem Goods and Services in Mountainous Regions


References


# Appendix A

## Table A.1: Land use activities implemented in ALUAM

<table>
<thead>
<tr>
<th>Land-use</th>
<th>Intensity</th>
<th>Yield (100% = intensive cultivation)</th>
<th>Irrigation</th>
<th>Area based subsidies</th>
<th>Ecological subsidies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permanent grassland (mown)</td>
<td>extensive</td>
<td>28%</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>intensive</td>
<td>100%</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Permanent grassland (grazed)</td>
<td>extensive</td>
<td>28%</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>intensive</td>
<td>100%</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>extensive/ summer pasture</td>
<td>28%</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grassland in crop rotation</td>
<td>extensive</td>
<td>26%</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>intensive</td>
<td>100%</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Wheat</td>
<td>mid-intensive</td>
<td>90%</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Barley</td>
<td>mid-intensive</td>
<td>90%</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Rape seed</td>
<td>mid-intensive</td>
<td>90%</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Potato</td>
<td>mid-intensive</td>
<td>90%</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Forest</td>
<td>Management and timber harvest</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Only management</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Unmanaged (Fallow)</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table A.2: Livestock activities implemented in ALUAM

<table>
<thead>
<tr>
<th>Livestock activity</th>
<th>Unit</th>
<th>EU 2005</th>
<th>2010</th>
<th>B1 2080</th>
<th>A1FI 2080</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milk</td>
<td>Rp/kg</td>
<td>46</td>
<td>75</td>
<td>53</td>
<td>24</td>
</tr>
<tr>
<td>Beef</td>
<td>CHF/kg CW</td>
<td>4.7</td>
<td>8.1</td>
<td>4.9</td>
<td>4.7</td>
</tr>
<tr>
<td>Beef from sucker cow system</td>
<td>CHF/kg CW</td>
<td>6.8</td>
<td>10.1</td>
<td>7.1</td>
<td>5.7</td>
</tr>
<tr>
<td>Lamb</td>
<td>CHF/kg CW</td>
<td>5.5</td>
<td>9.7</td>
<td>5.7</td>
<td>4.6</td>
</tr>
<tr>
<td>Wheat</td>
<td>CHF/t</td>
<td>151</td>
<td>503</td>
<td>165</td>
<td>51</td>
</tr>
<tr>
<td>Potato</td>
<td>CHF/t</td>
<td>149</td>
<td>407</td>
<td>230</td>
<td>76</td>
</tr>
<tr>
<td>Sugar beet</td>
<td>CHF/t</td>
<td>61</td>
<td>64</td>
<td>35</td>
<td>16</td>
</tr>
<tr>
<td>Barley</td>
<td>CHF/t</td>
<td>149</td>
<td>377</td>
<td>162</td>
<td>50</td>
</tr>
<tr>
<td>Rapeseed</td>
<td>CHF/t</td>
<td>301</td>
<td>760</td>
<td>235</td>
<td>81</td>
</tr>
<tr>
<td>Corn</td>
<td>CHF/t</td>
<td>174</td>
<td>379</td>
<td>207</td>
<td>113</td>
</tr>
<tr>
<td>Pesticides</td>
<td>%</td>
<td>100</td>
<td>266</td>
<td>51</td>
<td></td>
</tr>
<tr>
<td>Machinery</td>
<td>%</td>
<td>100</td>
<td>185</td>
<td>52</td>
<td></td>
</tr>
<tr>
<td>Fuel</td>
<td>%</td>
<td>100</td>
<td>274</td>
<td>62</td>
<td></td>
</tr>
<tr>
<td>Seed</td>
<td>%</td>
<td>100</td>
<td>118</td>
<td>179</td>
<td></td>
</tr>
<tr>
<td>Concentrate feed²</td>
<td>%</td>
<td>100</td>
<td>109</td>
<td>34</td>
<td></td>
</tr>
</tbody>
</table>

1 EU prices in 2005 were the base for the calculation of the prices in the future scenarios (Source: FOAG 2006).
2 It was assumed that prices for concentrate feed behave as prices for cereals.

Table A.3: Development of prices of the most important agricultural products as well as production factors between 2010 and 2080 under the two economic scenarios B1 and A1FI.
Appendix B

Validation of the model

Data about land use and the number of animals was available on the regional level. So a quantitative validation of these indicators is presented in Table B.1. Test values which were based on the geometric absolute percentage deviation of statistical and simulated production data (Winter 2005) were calculated for a six year period. The average deviations were 13.7% and 4% for the livestock and land use activities, respectively.

Table B.1: Validation of the results of ALUAM for a period of six years (2000 – 2005) calculated as the Geometric Absolute Percent Deviation

<table>
<thead>
<tr>
<th></th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crops (ha)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALUAM</td>
<td>136</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>61</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>Statistics</td>
<td>82</td>
<td>71</td>
<td>69</td>
<td>64</td>
<td>70</td>
<td>44</td>
<td></td>
</tr>
<tr>
<td>Meadow intensive (ha)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALUAM</td>
<td>1072</td>
<td>1111</td>
<td>1150</td>
<td>1158</td>
<td>1213</td>
<td>1252</td>
<td></td>
</tr>
<tr>
<td>Statistics</td>
<td>1176</td>
<td>1203</td>
<td>1233</td>
<td>1229</td>
<td>1174</td>
<td>1168</td>
<td></td>
</tr>
<tr>
<td>Meadow extensive (ha)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALUAM</td>
<td>553</td>
<td>551</td>
<td>535</td>
<td>537</td>
<td>534</td>
<td>501</td>
<td></td>
</tr>
<tr>
<td>Statistics</td>
<td>584</td>
<td>577</td>
<td>575</td>
<td>533</td>
<td>527</td>
<td>501</td>
<td></td>
</tr>
<tr>
<td>Not used by year-round agriculture (forest, fallow, summer pasture; ha)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALUAM</td>
<td>11318</td>
<td>11318</td>
<td>11294</td>
<td>11284</td>
<td>11272</td>
<td>11289</td>
<td></td>
</tr>
<tr>
<td>Statistics</td>
<td>11238</td>
<td>11228</td>
<td>11202</td>
<td>11254</td>
<td>11308</td>
<td>11366</td>
<td></td>
</tr>
<tr>
<td>Absolute Percent Deviation(^2)</td>
<td>0.062</td>
<td>0.055</td>
<td>0.075</td>
<td>0.017</td>
<td>0.018</td>
<td>0.012</td>
<td>0.04</td>
</tr>
</tbody>
</table>

\(^1\) FOAG 2008
\(^2\) Winter 2005
## Appendix C

Table C.1: Direction of land use changes as well as the resulting land use on an aggregated level for all assessed scenarios

<table>
<thead>
<tr>
<th>Land-use change to</th>
<th>B1</th>
<th>A1FI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cropland (ha)</td>
<td>Intensive grassland (ha)</td>
</tr>
<tr>
<td>Cropland (ha)</td>
<td>31 101 15 0 0</td>
<td>1 838 247 0 0</td>
</tr>
<tr>
<td>Intensive grassland (ha)</td>
<td>0 100 3327 0 0</td>
<td>0 0 18 2421 817 3256</td>
</tr>
<tr>
<td>Extensive grassland (ha)</td>
<td>0 0 18 2421 817 3256</td>
<td>0 0 18 2707 471 3256</td>
</tr>
<tr>
<td>Managed forest (ha)</td>
<td>0 0 0 1601 3563 5164</td>
<td>0 0 0 1601 3563 5164</td>
</tr>
<tr>
<td>Unmanaged forest (ha)</td>
<td>0 0 0 1601 3563 5164</td>
<td>0 0 0 1601 3563 5164</td>
</tr>
<tr>
<td>Total (ha)</td>
<td>32 1039 3607 4022 4380</td>
<td>3 1138 2802 4757 4380</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Land-use change from</th>
<th>Cropland (ha)</th>
<th>Intensive grassland (ha)</th>
<th>Extensive grassland (ha)</th>
<th>Managed forest (ha)</th>
<th>Unmanaged forest (ha)</th>
<th>Total (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cropland (ha)</td>
<td>0 19 128 0 0</td>
<td>0 556 527 3 0</td>
<td>0 7 3416 3 1</td>
<td>0 0 3 3195 58 3256</td>
<td>0 0 0 0 5164</td>
<td>0 58 89 0 0 147</td>
</tr>
<tr>
<td>Intensive grassland (ha)</td>
<td>0 556 527 3 0</td>
<td>0 91 125 2 0</td>
<td>0 26 610 3 1</td>
<td>0 0 1 3251 4 3256</td>
<td>0 0 0 0 5164</td>
<td>0 91 125 2 0 1085</td>
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<tr>
<td>Extensive grassland (ha)</td>
<td>0 7 3416 3 1</td>
<td>0 35 3384 7 1</td>
<td>0 0 1 3251 4 3256</td>
<td>0 0 0 0 5164</td>
<td>0 35 3384 7 1</td>
<td>0 35 3384 7 1 3427</td>
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<tr>
<td>Managed forest (ha)</td>
<td>0 0 3 3195 58 3256</td>
<td>0 0 1 3251 4 3256</td>
<td>0 0 3 3251 4 3256</td>
<td>0 0 0 0 5164</td>
<td>0 0 1 3251 4 3256</td>
<td>0 0 1 3251 4 3256</td>
</tr>
<tr>
<td>Unmanaged forest (ha)</td>
<td>0 0 0 0 5164</td>
<td>0 0 0 0 5164</td>
<td>0 0 0 0 5164</td>
<td>0 0 0 0 5164</td>
<td>0 0 0 0 5164</td>
<td>0 0 0 0 5164</td>
</tr>
<tr>
<td>Total (ha)</td>
<td>0 582 4074 3201 5223</td>
<td>0 984 3666 3260 5169</td>
<td>0 984 3666 3260 5169</td>
<td>0 984 3666 3260 5169</td>
<td>0 984 3666 3260 5169</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Combined Change</th>
<th>Cropland (ha)</th>
<th>Intensive grassland (ha)</th>
<th>Extensive grassland (ha)</th>
<th>Managed forest (ha)</th>
<th>Unmanaged forest (ha)</th>
<th>Total (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cropland (ha)</td>
<td>3 3 140 0 0</td>
<td>18 397 671 0 0</td>
<td>0 5 3422 0 0</td>
<td>0 0 18 3070 168 3256</td>
<td>0 0 0 1802 3362 5164</td>
<td>0 0 147 0 0 147</td>
</tr>
<tr>
<td>Intensive grassland (ha)</td>
<td>18 397 671 0 0</td>
<td>0 851 235 0 0</td>
<td>0 5 3422 0 0</td>
<td>0 0 18 3070 168 3256</td>
<td>0 0 0 1802 3362 5164</td>
<td>0 0 147 0 0 147</td>
</tr>
<tr>
<td>Extensive grassland (ha)</td>
<td>0 5 3422 0 0</td>
<td>0 57 2579 788 3 3427</td>
<td>0 57 2579 788 3 3427</td>
<td>0 0 17 3239 0 3256</td>
<td>0 0 17 3239 0 3256</td>
<td>0 0 17 3239 0 3256</td>
</tr>
<tr>
<td>Managed forest (ha)</td>
<td>0 0 18 3070 168 3256</td>
<td>0 0 18 3070 168 3256</td>
<td>0 0 18 3070 168 3256</td>
<td>0 0 18 3070 168 3256</td>
<td>0 0 18 3070 168 3256</td>
<td>0 0 18 3070 168 3256</td>
</tr>
<tr>
<td>Unmanaged forest (ha)</td>
<td>0 0 0 1802 3362 5164</td>
<td>0 0 0 1802 3362 5164</td>
<td>0 0 0 1802 3362 5164</td>
<td>0 0 0 1802 3362 5164</td>
<td>0 0 0 1802 3362 5164</td>
<td>0 0 0 1802 3362 5164</td>
</tr>
<tr>
<td>Total (ha)</td>
<td>21 405 4251 4872 3530</td>
<td>0 908 2978 5601 3593</td>
<td>0 908 2978 5601 3593</td>
<td>0 908 2978 5601 3593</td>
<td>0 908 2978 5601 3593</td>
<td>0 908 2978 5601 3593</td>
</tr>
</tbody>
</table>
Table C.2: Amount of food and wood provision on an aggregated level for all assessed scenarios (relative changes compared to scenario Baseline in brackets)

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Baseline</th>
<th>Climate_Change</th>
<th>Economic_Change</th>
<th>Combined_Change</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>B1</td>
<td>A1FI</td>
<td>B1</td>
<td>A1FI</td>
</tr>
<tr>
<td>Food provision</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crop (Food Units)</td>
<td>11580</td>
<td>3401 (-71%)</td>
<td>196 (-99%)</td>
<td>0 (-100%)</td>
</tr>
<tr>
<td>Milk (Food Units)</td>
<td>11546</td>
<td>6856 (-41%)</td>
<td>6197 (-46%)</td>
<td>6863 (-41%)</td>
</tr>
<tr>
<td>Meat (Food Units)</td>
<td>3113</td>
<td>3247 (4%)</td>
<td>2558 (-18%)</td>
<td>678 (-78%)</td>
</tr>
<tr>
<td>Total (Food Units)</td>
<td>26241</td>
<td>13505 (-48%)</td>
<td>8952 (-66%)</td>
<td>7542 (-71%)</td>
</tr>
<tr>
<td>Wood provision (m³)</td>
<td>15597</td>
<td>4676 (-70%)</td>
<td>1466 (-91%)</td>
<td>15597 (0%)</td>
</tr>
</tbody>
</table>

| Land-use           |          |                |                 |                 |
|                    |          |                |                 |                 |
| Crop (ha)          | 165      | 32 (-81%)      | 3 (-98%)        | 0 (-100%)       | 22 (-87%)       | 0 (-100%)       |
| Milk (ha)          | 1196     | 760 (-36%)     | 691 (-42%)      | 1399 (17%)      | 0 (-100%)       | 1508 (26%)      | 0 (-100%)       |
| Meat (ha)          | 3209     | 3887 (18%)     | 3250 (-1%)      | 3258 (-1%)      | 4651 (41%)      | 3149 (-5%)      | 3887 (18%)      |
| Total Agriculture (ha) | 4660    | 4679 (0%)     | 3944 (-15%)     | 4657 (0%)       | 4651 (0%)       | 4679 (0%)       | 3887 (-17%)     |
Appendix D
Calculation of the General Forest Protection Index

The GFPI simulates the ability of forests to provide protection against all gravitational hazards considering tree species mixture, structural profile of the forests, rooting stability and regeneration potential. Based on the guidelines developed by Frehner et al. (2005) the GFPI was calculated as follows:

\[
GFPI = \frac{50 \times \alpha_1 + 25 \times \alpha_2 + 15 \times \alpha_3 + 10 \times \alpha_4}{100}
\]

where,

\[
\alpha_1 = \min \left( \left[ \frac{\text{#trees/ha with DBH > 24}}{400}, 1 \right] \right)
\]

\[
\alpha_2 = \min \left( \left[ \frac{\text{#cohorts with trees > 24 cm DBH}}{4}, 1 \right] \right)
\]

\[
\alpha_3 = \min \left( \left[ \frac{\text{#species}}{3}, 1 \right] \right)
\]

\[
\alpha_4 = \min \left( \left[ \frac{\text{#cohorts with trees < 12 cm DBH}}{2}, 1 \right] \right)
\]

The weighting that was given to each attribute in equation 1 reflects the view that achieving a forest structure that protects against gravitational hazards is of principle important, while maintaining a mixed forest and a high level of regeneration potential is of secondary importance. The index ranges from 0 to 1 with 1 providing the maximum protection from gravitational hazards.
Acknowledgments

I would like to thank everybody who supported me during the time I was writing this thesis.

In particular, I wish to thank Bernard Lehmann for giving me the opportunity to write this thesis. He gave me the space to develop this thesis and provided advice whenever I needed it. I also thank him for trusting me to undertake several miscellaneous tasks, all of which made my work much more varied and interesting life during the last three-and-half-years.

I am very grateful to my co-examiners Adrienne Grêt-Regamey and Peter Bebi. They brought new points of view to the project, and their critical comments substantially improved this work.

I thank all of the people who were involved in the Mountland project, particularly Ché Elkin for helping my work by developing a crop-yield model at little notice and for showing an interest in coupling both of our models into a working framework. I also thank Robert Huber for coordinating my dissertation in the Mountland project and for his many useful comments.

I would like to thank my colleagues from the AFEE with whom I had many fruitful discussions and many enjoyable times. In particular, I thank Simon Peter who gave me his own model for use as a base for the ALUAM model.

I thank the Competence Center Environment and Sustainability of ETH Zürich for financing this project.

I thank my family and my love Livia for supporting me throughout the past few years and that were there when I needed them. This thesis is dedicated to you.
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