Climatic Change (2007) 85:195–212
DOI 10.1007/s10584-006-9201-8

Sensitivity of carbon cycling in the European Alps to changes of climate and land cover

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Received: 6 February 2006 / Accepted: 25 August 2006 / Published online: 7 March 2007

Abstract Assessments of the impacts of global change on carbon stocks in mountain regions have received little attention to date, in spite of the considerable role of these areas for the global carbon cycle. We used the regional hydro-ecological simulation system RHESSys in five case study catchments from different climatic zones in the European Alps to investigate the behavior of the carbon cycle under changing climatic and land cover conditions derived from the SRES scenarios of the IPCC. The focus of this study was on analyzing the differences in carbon cycling across various climatic zones of the Alps, and to explore the differences between the impacts of various SRES scenarios (A1FI, A2, B1, B2), and between several global circulation models (GCMs, i.e., HadCM3, CGCM2, CSIRO2, PCM). The simulation results indicate that the warming trend generally enhances carbon sequestration in these catchments over the first half of the twenty-first century, particularly in forests just below treeline. Thereafter, forests at low elevations increasingly release carbon as a consequence of the changed balance between growth and respiration processes, resulting in a net carbon source at the catchment scale. Land cover changes have a strong modifying effect on these climate-induced patterns. While the simulated temporal pattern of carbon cycling is qualitatively similar across the five catchments, quantitative differences exist due to the regional differences of the climate and land cover scenarios, with land cover exerting a stronger influence. The differences in the simulations with scenarios derived from several GCMs under one SRES scenario are of the same magnitude as the differences between various SRES scenarios derived from one single GCM, suggesting that the uncertainty in climate model projections needs to be narrowed before accurate impact assessments under the various SRES scenarios can be made at the local to regional scale. We conclude that the carbon balance of the European Alps is likely to shift strongly in the future, driven mainly by land cover changes, but also by changes of the climate. We recommend that assessments of carbon cycling at regional to continental scales should make sure to adequately include sub-regional differences of changes in climate and land cover, particularly in areas with a complex topography.

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1 Introduction

Carbon cycling in terrestrial ecosystems has been the focus of many recent scientific studies because of the role of the terrestrial biosphere in the global carbon cycle (cf. Smith 2004; Van Dijk and Dolman 2004; Janssens et al. 2003; Churkina et al. 2003). Terrestrial ecosystems represent a large store of carbon, containing about 550 Pg, and forest ecosystems are estimated to contain about 80% of all global aboveground carbon (Waring and Running 1998). Furthermore, terrestrial ecosystems exchange large quantities of carbon with the atmosphere through photosynthesis and respiration. Land-use change is currently estimated to dominate the observed changes in the terrestrial carbon budget in the northern hemisphere (cf. Karjalainen et al. 2003; Goodale et al. 2002). For instance, European forests and the northern hemisphere biosphere in general are thought to act as carbon sinks due to the rebound from past land use practices such as intensive logging (Janssens et al. 2003; Karjalainen et al. 2003; Nabuurs et al. 2003). In the future, the impacts of climate change will become more dominant, and the net effect of Global Change on terrestrial carbon storage will be the result of a number of concurrent and partly interacting processes whose quantification at larger spatial scales is quite difficult and requires the use of dynamic models.

To date, research regarding the effects of global change on terrestrial ecosystems has focused mainly on the local (‘stand’ or ‘patch’) or the global scale, and on changes in climatic variables. Regional-scale assessments that consider both climate and land cover changes, particularly in mountain systems, have received only little attention (cf. Schimel et al. 2002; Mooney et al. 1999). However, in mountain regions, changes in land cover have been widespread over the past decades (cf. Bebi and Baur 2002; Huber et al. 2005). Many mountain pastures have been abandoned already or are likely to be abandoned in the near future, because agriculture and forestry are not profitable any more. The increase of the forested area may have considerable impacts on the continental-scale carbon balance of the northern hemisphere (cf. Schimel et al. 2002). Simultaneously, the changes of temperature observed across the last century have been larger in many mountain regions than at the global scale (cf. Beniston et al. 1997). Therefore, it is likely that the impacts of future changes will be particularly pronounced at high elevations (Huber et al. 2005).

The overall objective of this paper is to assess how the carbon cycle in mountain regions may be altered during the twenty-first century under changing climate as well as changing land cover conditions, focusing on the European Alps as a case study. Furthermore, this study aims to increase our understanding of the regional and altitudinal differences in carbon cycling and the relative importance of the underlying processes such as photosynthesis, respiration, growth, and land use.

Relatively little work has been done on these questions at the regional scale, and most of them were based on the regional hydroecological simulation system RHESSys (Tague and Band 2004; Band et al. 1993). RHESSys was developed specifically to simulate the tightly coupled cycles of water and carbon in mountain watersheds by combining a detailed description of the vertical fluxes of carbon and water with a simple, but effective description of lateral water fluxes. Therefore, our work is based on RHESSys, and we applied the model in five representative catchments from different climate zones of the Alps to investigate daily carbon fluxes and the carbon stocks of terrestrial ecosystems.

The focus of our work was on (1) exploring the altitudinal gradients in the carbon responses of different climate zones of the Alps; (2) investigating the difference in the impacts of a range of climate scenarios derived from the Special Report on Emission

Scenarios of the IPCC – Intergovernmental Panel of Climate Change (2000), using one General Circulation Model (GCM); and (3) evaluating the degree of agreement in the carbon cycle response between climate scenarios derived from four GCMs for one specific emission scenario. By using multiple emission scenarios and the outputs from multiple GCMs, our assessment spans a wide range of possible future conditions and thus allows us to identify the processes that are likely to be most sensitive to global change.

2 Materials and methods

2.1 Case study catchments

We selected five catchments (Table 1 and Fig. 1) representing different climate zones in the Alpine region; they comprise (1) the Alptal catchment, representing the western pre-alpine area with high and intensive precipitation, (2) the Hirschbichl catchment, representing the eastern pre-alpine area with moderate precipitation due to increasing continentality eastwards, (3) the Dischma valley, representing the cold, high alpine area with rather low precipitation, (4) the Saltina catchment, representing an inner alpine dry valley with relatively low precipitation, and (5) the Verzasca catchment, representing the warmer southern pre-alpine area with high precipitation.

2.2 The RHESSys model

We used the Regional Hydro-Ecological Simulation System RHESSys 5.6 (Tague and Band 2004; Band et al. 1993; http://typhoon.sdsu.edu/Research/Projects/RHESSYS). RHESSys is a GIS-based hydro-ecological modeling framework designed to simulate carbon, water and nutrient fluxes in mountain catchments. It combines a set of physically based process models and a methodology for partitioning and parameterizing the landscape. The original process models include the following: The MT-CLIM model (Running et al. 1987) uses topography and user-supplied climatic data from a 'base station' to derive additional climate variables and to extrapolate all climatic variables over topographically complex terrain. An ecophysiological model was adapted from BIOME-BGC (Running and Hunt 1993) to estimate carbon and water dynamics of different canopy cover types. It should be noted that age-structure effects cannot be estimated with BIOME-BGC, as the model does not track age or size structure of forest stands, but considers aggregated compartments of carbon and nitrogen. Finally, the quasi-distributed TOPMODEL approach is employed to simulate soil moisture redistribution and runoff production (Beven and Kirkby 1979).

RHESSys includes a GIS framework that partitions the watershed into environmentally homogenous areas based on landscape attributes such as land cover, vegetation, soil, and topography. The successive partitioning into a nested set of polygons includes:

- Basin, comprising the full watershed
- Hillslopes, dividing the basin into subwatersheds
- Zones, partitioning the hillslopes into climatically homogenous areas
- Patches, providing a partitioning of the zones into a set of areas each with relatively uniform soil and topographical characteristics
- Strata, including one or more vegetation canopy layers that cover the patch and defining the units at which the vertical energy, water, carbon and nitrogen fluxes are computed

Table 1 Description of case study catchments from various climate zones in the alpine region

Catchment	Region	Area (km^2)	Altitude (m)	Land cover (%)		
				Forest	Grass	Other
Alptal	Western pre-alpine	46.75	1,150 (850–1,860)	52	42	6
Hirschbichl	Eastern pre-alpine	44.61	1,460 (680–2,560)	49	36	15
Dischma	High alpine	43.16	2,370 (1680–3,110)	10	54	36
Saltina	Inner dry alpine	77.02	2,010 (680–3,400)	35	34	31
Verzasca	Southern pre-alpine	44.13	1,680 (540–2,500)	64	19	17

The category ‘other’ in the column ‘land cover’ comprises mostly unvegetated areas at high elevations, but also sealed areas such as cities and traffic routes.

Outputs from RHESSys include, among others, the spatially explicit fluxes of carbon, nitrogen, and water between the ecosystems and the atmosphere at a daily time step. In our simulations, the physical properties of various soil types such as sand, loam, and clay and the default ecophysiological characteristics for conifers, deciduous trees, and grassland were used, as provided with the original RHESSys. The only parameters that were changed in this study are the phenological dates and the Q_{10} parameter in the equation for estimating maintenance respiration, as described in detail below.

The importance of the length of the growing season for ecosystem dynamics and the local water balance has been illustrated by various studies (cf. White et al. 1999). As phenological dates strongly depend on temperature and thus on elevation, we included the change of phenological timing along altitudinal gradients in our analysis. To obtain these gradients, we applied the phenological model described by Kramer (1996) to all 100 m-elevation bands within each case study. The model was driven by the daily temperature data described below. The annual dates of bud burst and leaf fall were then averaged over the simulation period to obtain mean dates for every 100 m-elevation band. Thus, interannual phenological variation was neglected in the simulations presented in this paper.

Fig. 1 Location of the five case study catchments

Rates of respiration in plant organs as well as in soil organic matter vary with temperature, although not in simple ways. Yet, the so-called "Q_{10} approach" is used widely to model the dependency of respiration rates on temperature (cf. Tjoelker et al. 2001). In this approach, the Q_{10} parameter controls the sensitivity of maintenance respiration r to air temperature T according to the following generic equation:

$$r_T = r_{\mathrm{ref}} \quad Q_{10}^{(T-10)/10}$$

That is, Q_{10} describes the change of the respiration rate for a temperature change of 10°C, relative to the reference rate r_{ref} at 10°C. Often, a value of Q_{10}=2 is used, which implies a doubling of the rate with an increase of temperature by 10°C. We decided to set the Q_{10} parameter for maintenance respiration to 1.5 for all conifers, because many studies during the last years have found similar low values between 1.3 and 1.7 of Q_{10} for plants growing in cold environments, suggesting that these plants have high respiration rates at low temperatures, but a low Q_{10} (Atkin and Tjoelker 2003; Huxman et al. 2003; Tjoelker et al. 2001). For the more warm-adapted deciduous trees, the value of Q_{10} was left unchanged (2.0), as they predominantly grow at low elevations.

RHESSys and the original process models BIOME-BGC, TOPMODEL and MT-CLIM have been evaluated by various studies against daily data of stream flow, snow water equivalent, net ecosystem exchange, net primary productivity, soil carbon and evapotranspiration (cf. Gordon et al. 2004; Tague and Band 2004; Churkina et al. 2003; Thornton et al. 2002). These studies showed reasonable agreement between simulated and observed data at short time-scales, suggesting that the mechanisms governing the hydrological and biogeochemical processes are represented adequately in RHESSys.

To evaluate whether RHESSys is a suitable tool for long-term global change impact studies in the Alpine region, its behavior was tested against observed long-term data from 1980 to 2000 on runoff and snow depth from the five selected case study areas described above (Zierl et al. 2007). For the comparison of monthly aggregated stream flow, the coefficient of determination varied between 0.82 and 0.97 and modeling efficiency between 0.64 and 0.92. The comparison of stream flow regimes yielded even better results. Comparing daily observed and simulated snow depth, five out of six sites had a coefficient of determination larger than 0.64. To validate the simulated carbon and water fluxes between the biosphere and the atmosphere, net ecosystem exchange (NEE) and actual evapotranspiration (AET) were compared with observed monthly data from 15 EUROFLUX sites across Europe (Zierl et al. 2007; Morales et al. 2005). For the 12 sites located in the temperate and boreal zone, the studies showed good agreement. Regarding NEE, the coefficient of determination was >0.75 for 10 out of 12 sites and the model efficiency was >0.6 for 11 out of 12 sites. Regarding AET, the coefficient of determination was >0.75 for 11 out of 12 sites and the model efficiency was >0.6 for 9 out of 12 sites.

These tests confirmed that RHESSys is able to accurately reproduce water fluxes and snow cover in the Alpine region, particularly on a monthly and annual basis. Regarding carbon fluxes, simulated and observed data agreed reasonably well, too. However, there were some uncertainties that limit the accuracy of futures carbon estimations: (1) the limited knowledge of species-specific values of the ecophysiological parameters, (2) uncertainties in the modeling of maintenance and soil carbon respiration, (3) the lack of data for testing simulated carbon cycling at high elevations, and (4) the fact that plant migration is not modeled explicitly in RHESSys. Taken together, these limitations add to considerable uncertainties in the simulation of the carbon cycle in Alpine catchments. In the present study, we therefore focus on a qualitative assessment of changes in vegetation carbon stocks and consider our analyses primarily as sensitivity studies rather than "predictions."

2.3 Input data and simulation scenarios

2.3.1 Model input data for current and future conditions

To run RHESSys, the following input data are required: daily minimum and maximum temperature; daily totals of precipitation; soil type, vegetation cover, and topographical data. For the four Swiss case study catchments (Table 1), daily climatic data for the period from 1981 to 2000 were available from MeteoSwiss, the Swiss Meteorological Institute. Topographical data were derived from a digital terrain model (DHM25, ©Federal Office of Topography). Vegetation cover was taken from the Arealstatistik (Swiss Federal Statistical Office). Soil type was available from a soil map (Federal Office for Land Use Planning). Daily runoff data for model validation (Zierl et al. 2007) were provided by BWG (Swiss Federal Office for Water and Geology). For the Hirschbichl watershed, all required data layers were provided by the National Park Berchtesgaden. For all five catchments, climatic data were available for the period 1981 to 2000 from two weather stations at different altitudes, thus allowing for the calculation of catchment-specific lapse rates of temperature and precipitation under current conditions.

In addition, monthly data on precipitation, temperature and the diurnal temperature range were available from a set of high-resolution grids ($10 \times 10'$) of transient climate for Europe based on the IPCC SRES scenarios (Mitchell et al. 2004). This data set comprises an 'observed' scenario for 1901–2000 and 16 alternative SRES-forced 'climate-change' scenarios for 2001–2100, i.e., based on four General Circulation Model (GCM) projections each of which was using on one of four SRES scenarios (A1FI, A2, B1, B2). The four GCMs include the HadCM3, the CSIRO2, the CGCM2, and the PCM model. For our study, the 'observed' and seven 'climate-change' scenarios, namely HadCM3 A1FI, HadCM3 A2, HadCM3 B1, HadCM3 B2, CGCM2 A2, CSIRO2 A2, and PCM A2, were used.

2.3.2 Downscaling of climate information to the catchment scale

For each case study, we used the climate scenario data from the two closest grid points to calculate vertical gradients of temperature and precipitation as proxies for future lapse rates, for which there was no other information available. Furthermore, to downscale the monthly data to a daily resolution, the stochastic weather generator LARS-WG (Semenov and Barrow 1997) was employed. First, the actually observed daily data (1981 to 2000) were used to calculate the site-specific statistical weather parameters for LARS-WG. Second, these parameters were used by LARS-WG to generate synthetic 200-year time series of daily climate. Finally, the daily variability of this synthetic time series was superimposed on the two monthly climate scenario data sets (1901–2000 and 2001–2100, respectively), to obtain daily climate scenario data. The climate scenario data are summarized in Table 2.

To test whether the downscaled climate from the European data set to the catchment scale are reasonable, we compared measured data (annual means and seasonality of temperature and precipitation) with values of the 'observed' climate scenario for the period from 1980 to 2000. Regarding temperature, the differences in annual mean values and seasonality are quite small, i.e., <1°C. However, regarding precipitation data, yearly totals as well as seasonality differ by up to ±30% from the observations described above. This

Table 2 Absolute changes in annual mean temperature (*T*), relative changes in summer and winter precipitation (SP and WP), and relative change in forested area (CFA) for seven scenarios and for five case study areas comparing time slice 4 (2051–2080) with time slice 1 (1961–1990)

	Case study	HadCM3 A1FI	HadCM3 A2	HadCM3 B1	HadCM3 B2	CGCM2 A2	CSIRO2 A2	PCM A2
T (°C)	Alptal	+4.2	+3.0	+2.3	+2.4	+2.2	+2.7	+1.7
	Hirschbichl	+4.3	+3.2	+2.5	+2.6	+2.2	+2.8	+1.7
	Dischma	+4.2	+3.0	+2.3	+2.4	+1.8	+2.4	+1.4
	Saltina	+4.3	+3.1	+2.3	+2.4	+2.0	+2.4	+1.5
	Verzasca	+4.5	+3.3	+2.5	+2.6	+2.1	+2.7	+1.6
SP (%)	Alptal	−12.4	−6.5	−3.9	−4.5	−4.0	−0.8	+0.8
	Hirschbichl	−11.9	−5.4	−5.8	−3.9	−2.8	+0.4	−0.2
	Dischma	−12.7	−6.9	−6.6	−5.1	−3.2	−2.0	−0.7
	Saltina	+4.3	+3.1	+2.3	+2.4	+2.0	+2.4	+1.5
	Verzasca	+4.5	+3.3	+2.5	+2.6	+2.1	+2.7	+1.6
WP (%)	Alptal	+26.2	+20.3	+14.1	+15.5	+3.8	+10.9	+7.3
	Hirschbichl	+23.3	+18.8	+14.6	+17.0	+1.7	+7.2	+7.4
	Dischma	+26.9	+22.0	+17.2	+21.0	+6.4	+13.3	+10.5
	Saltina	+27.4	+22.4	+17.3	+21.7	+11.8	+18.8	+15.6
	Verzasca	+25.4	+21.2	+17.0	+20.2	+10.6	+16.2	+13.8
CFA (%)	Alptal	+4.7	+0.2	+2.8	0.0	−1.1	+0.2	+0.2
	Hirschbichl	−2.2	−3.5	−0.6	+1.6	−6.7	−2.4	−3.5
	Dischma	+5.5	+0.2	+2.6	+6.6	−1.1	+0.2	+0.2
	Saltina	−11.3	−12.2	0-0	0-0	−22.1	−12.2	−12.2
	Verzasca	+3.8	−1.0	+1.9	+4.8	−4.7	−1.0	−3.6

implies a large uncertainty of the simulation results even if the RHESSys model did not contain any uncertainties itself.

This downscaling approach is certainly applicable for changes in temperature, as these are known to be large-scale phenomena. Regarding precipitation, however, it involves some uncertainties as both precipitation and precipitation changes, particularly in mountain regions, typically vary strongly at small spatial scales. Using two grid points from the climate scenarios allows us at least to account for changes in vertical gradients of precipitation. However, small-scale variations in precipitation changes cannot be resolved by this method.

Nevertheless, our focus was not on absolute changes in the ecology of specific catchments, but on relative changes between different climate zones in the Alpine region. In other words, we consider the case studies to be representative for larger-scale climate zones. Therefore, we decided to use the ‘observed’ climate scenario directly to drive the model, so as to be consistent with the ‘climate-change’ scenarios described above. An additional reason was that we wanted to be consistent with other assessments that were conducted in the context of the EU-Project ATEAM (www.pik-potsdam.de/ateam), into which our research was embedded.

2.3.3 Scenarios of land cover change

The scenarios of land cover change are based on a socio-economic consideration of the IPCC SRES storylines (Ewert et al. 2006; Reginster and Rounsevell 2003), i.e., they are based on the same social trends and thus fully consistent with the climate scenarios (Mitchell et al. 2004). A set of seven land cover scenarios that are linked to the climate projections are available (A1FI, A2, B1 and B2 driven by climate from HadCM3, and A2 additionally driven by climate from CSIRO2, CGCM2, and PCM). For our study, relative changes in forested area were used from these scenarios and were downscaled to the case study areas. That is, land cover changes were imposed on the RHESSys model by allocating afforestation sites to grassland below or close to the current treeline, whereas deforestation sites were allocated to forested land at the valley bottom. These allocation rules are based on observed changes in forested area in Switzerland, which show that mainly unprofitable high-elevation areas are abandoned (Bebi and Baur 2002).

The focus for the analysis of the simulation results was set on four time slices: the present is defined as the period 1961–1990, and is referred to as ‘time slice 1.’ The three periods 1991–2020, 2021–2050 and 2051–2080 are referred to as time slices 2, 3 and 4, respectively.

The projections of the seven land cover scenarios for the relative changes in forested area over the course of the twenty-first century are given in Table 2. Note that these numbers represent changes in forested area between time slice 1 and time slice 4 only. In many cases, an increase in forested area is projected for time slices 1 and 2, followed by a strong decrease in time slices 3 and 4. Overall, the net effect is a reduction in forested area by the year 2080, even though the forested area may have increased during the first decades of the simulation period.

2.4 Simulation experiments

RHESSys uses the variables carbon, nitrogen and water to describe the amounts of these substances stored in the simulated plant, soil and snow pools. Unless field measurements corresponding to the model’s variables are available, spin-up runs are required to initialize these pools. In the spin-up simulation, the model is run to a steady state to obtain the size of the ecosystem’s carbon, nitrogen, and water pools under the assumption that the ecosystem is in equilibrium with its present environment.

At each case study site, the spin-up simulation continuously looped through the first 50 years of the ‘observed’ climate scenario (i.e., 1901 to 1950) repeatedly, until all state variables in the model had reached their equilibrium, which typically required many centuries. The state variables were then initialized with these values. Clearly, most European ecosystems are not in equilibrium with climate or land use today. Ignoring this fact generally leads to an overestimation of carbon pools. However, it is difficult to obtain land-use history at regional scales, and to implement these data in a consistent manner in an ecosystem-modeling context. Therefore, the current land cover was used for the spin-up runs, and no management was taken into account for the estimation of the ecosystems’ state in 1950.

RHESSys was used to simulate the daily carbon fluxes and pools for the period from 1951 to 2080. Here, net fluxes from the atmosphere to the land are mathematically defined as being negative (sinks). Daily values were aggregated to monthly, annual and decadal values. Vertical gradients of carbon-related variables were calculated by averaging over altitudinal zones. All simulations were run twice, the first time based on the full set of drivers (climate and land cover), the second time neglecting land cover changes (“climate only” scenario). This allowed us to elucidate the relative contribution of climatic vs. land cover changes for the overall flux of carbon.

3 Results

Table 2 gives the projected changes in temperature, summer and winter precipitation as well as in forested area by comparing time slice 4 (2051–2080) with time slice 1 (1961–1990). Annual mean temperature rises significantly for all catchments, with a clear gradation among the SRES scenarios, from the HadCM3 B1 scenario with the smallest increase through B2 and A2 to A1FI with the strongest increase. Within the A2 emission scenario, the HadCM3 model predicts the largest rise of temperature, followed by the CSRIO2, the CGCM2, and the PCM model. Regarding precipitation, winter precipitation increases in all models and all SRES scenarios, while summer precipitation decreases in three catchments and increases in two catchments. The sign of the response is the same across all SRES scenarios and in almost all models (Table 2). The annual totals of precipitation change only slightly (data not shown). For most scenarios, they increase between 3 and 6%, the only exception being the A2 CGCM2 scenario, which projects almost no change in annual totals. However, changes in precipitation show greater spatial variability than changes in temperature. The largest increase in annual totals is projected for the Saltina and the Verzasca catchments; the smallest is projected for the Hirschbichl catchment. Furthermore, there is no clear gradation in the projected changes of precipitation between the SRES scenarios or between the GCMs. Thus, the magnitude of possible precipitation changes is more uncertain than that of temperature, given these scenario data.

Figure 2 illustrates the spatial distribution of the impact of the A2 HadCM3 climate and land cover scenario on vegetation carbon stocks in the Saltina catchment, which is subject to the largest changes of land cover across the five study areas (Table 2). During the first two time slices, some grasslands below treeline are projected to re-grow forests. At such sites, carbon uptake by the vegetation is high, as indicated by the dark green colors. In the following decades (time slices 3 and 4), intensive deforestation at the valley bottom of the Saltina catchment is projected to occur according to the land cover scenario. This results in a strong decrease of carbon storage, as indicated by the dark red colors in Fig. 2.

The lighter colors in Fig. 2 primarily indicate those parts of the catchment where no change in land cover was projected. In other words, they reflect the impact of climate change on vegetation carbon alone. From 1961 to 1990, the flux resulting from climate change is small. In the following decades, forests close to upper treeline in the Saltina catchment profit particularly from the warming, which results in a carbon sink above a certain threshold altitude. Below that altitude, vegetation is predicted to release carbon. From 1991 to 2080, the size of the sink region at high elevations gradually decreases, whereas the size of the source region in the valley bottom increases, and it gradually comprises higher altitudes.

The altitudinal pattern of climatic effects in the absence of land cover changes as evident from Fig. 2 for the Saltina catchment is a consistent feature in all scenarios, and it is roughly similar across the case study areas. Figure 3 shows the altitudinal distribution of changes in vegetation carbon stocks for the Alptal, Hirschbichl, Dischma, and Saltina catchments under the A2 HadCM3 climate scenario. The patterns in the Verzasca valley (data not shown) are quite similar, but the signals are stronger than in the other four catchments (cf. Fig. 4).

Taken together, during time slice 1, the climate-induced changes in carbon stocks are rather small in all catchments. In time slice 2, vegetation carbon stocks increase throughout most catchments, from the valley bottom to the upper border of vegetation. The largest sequestration rates are simulated for the area close to current treeline (1,500–2,000 m). As

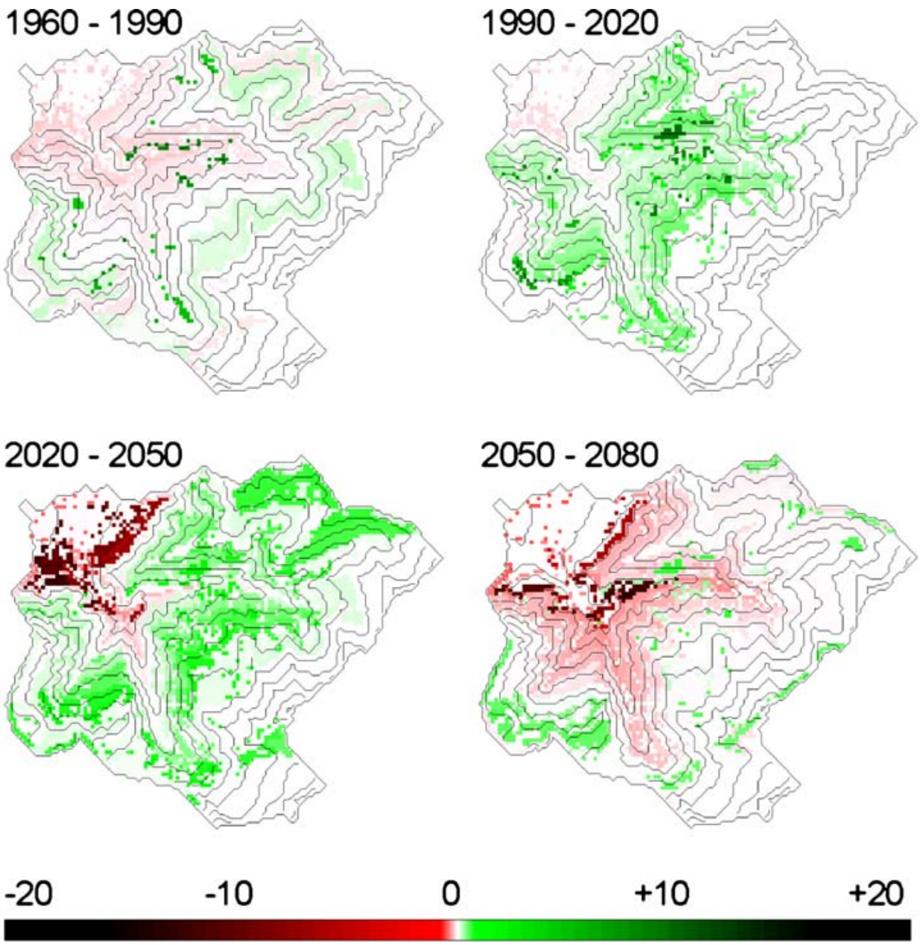

Fig. 2 Changes in vegetation carbon stock (kg C/m^2) in the Saltina catchment for the four time slices of the climate and land use change scenario A2 HadCM3 as compared to the conditions at the end of the spin-up run. *Dark green* colors indicate a change in land use from grass to forest according to the land use change scenario (Table 2), whereas *dark red colors* indicate areas where forests were converted into grassland

treeline in the high alpine catchments Saltina and Dischma is located at higher altitudes (~2,200 m) than in the pre-alpine catchments Alptal and Hirschbichl (~1,800 m), the simulated carbon sink reaches a peak at different elevations. In the Saltina and Dischma catchments, there is still a marked carbon sink above 1,800 m. Above the treeline, changes in vegetation carbon are nearly negligible in all catchments.

During time slice 3, forests at low elevations up to an altitude of approximately 1,200 to 1,300 m become a carbon source due to a changed balance between plant growth and respiration. Above this altitude, the vegetation continues to accumulate carbon. Particularly in the Saltina and Dischma catchments, forests above around 1,500 m still absorb considerable amounts of carbon. Finally, during time slice 4, the borderline between carbon sink and source regions reaches an altitude of approximately 1,800 m. Above this altitude, changes in vegetation carbon stocks typically are slightly positive. Only some alpine tundra

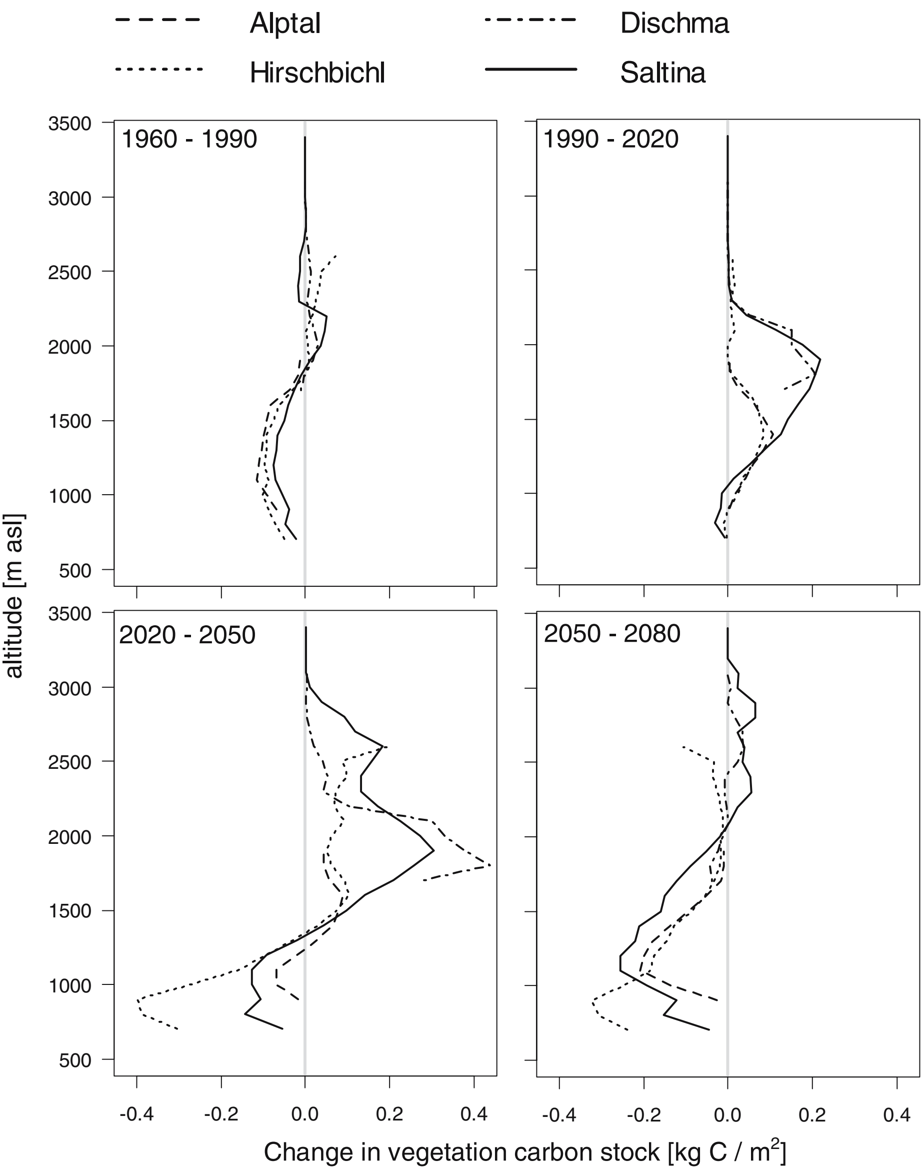

Fig. 3 Altitudinal gradients of net carbon exchange in the Alptal, Hirschbichl, Dischma and Saltina catchments for the four time slices of the climate change scenario A2 HadCM3. Note that land use changes are *not* taken into account in these simulations. Negative values indicate elevations where the vegetation releases carbon, and positive values indicate elevations where vegetation takes up carbon

areas profit from the warming climate and continue to accumulate carbon, whereas the rest of the catchment area turns into a carbon source.

Figure 4 displays the catchment-wide carbon balance, i.e., the average values of carbon emission or uptake over the entire area of each catchment and over the three decades of each time slice. While the climate-induced changes in the carbon stock (Fig. 4 right) are

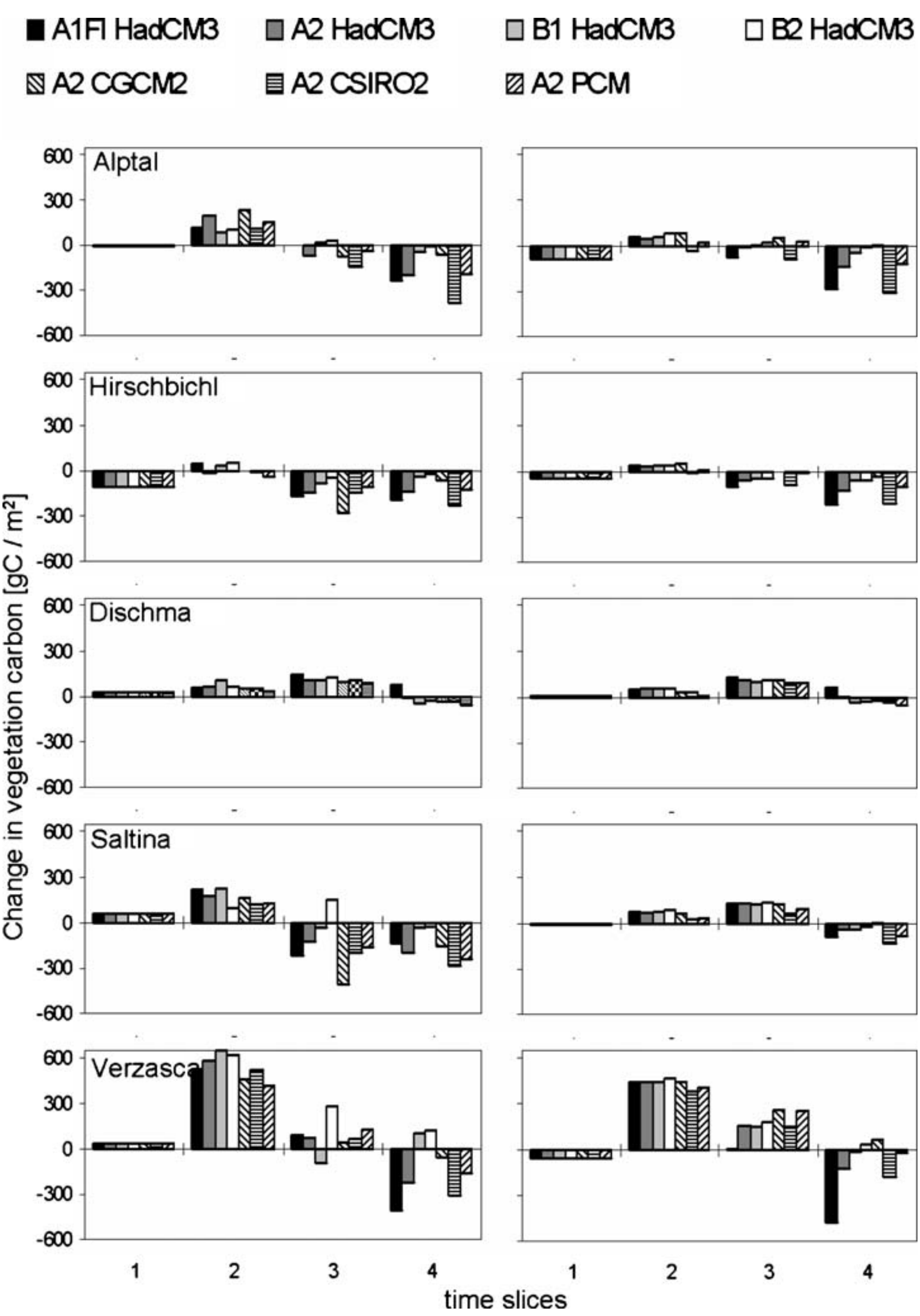

Fig. 4 Catchment-wide averages of changes in simulated vegetation carbon for the four time slices. *Left*: Effects of both climatic and land use changes. *Right*: Effects of climatic change alone. Negative values indicate time slices when the catchment vegetation acts as a carbon source, whereas positive values indicate time slices when the catchment acts as a carbon sink

small during time slice 1, the simulation results indicate that the warming climate strengthens the sink throughout the first half of the twenty-first century, except for the Hirschbichl catchment. Thereafter, the sink capacity due to climate change declines, and under most scenarios the catchments become a carbon source.

Changes in land cover can significantly modify the simulated response to climate change (Fig. 4 left). Particularly in the Saltina and the Verzasca catchments, most land cover change scenarios project increases in forested area during the time slices 1 and 2, followed by substantial reductions during the time slices 3 and 4. As a result, the initial conversion from grasslands to forests adds to the climate-induced sink until 2020. Thereafter, the climate-induced sink is either reduced or even offset entirely by changes in land use, resulting in a net carbon source. In the Alptal and Hirschbichl catchments, the changes in forested area are smaller and the carbon effects thus far less striking. In the Dischma valley, finally, changes in land cover have hardly any effect because most of the catchment area lies above the current treeline. Due to the fact that only about 10% of the catchment area is forested, the small relative change of this area (Table 2) barely affects the catchment-wide carbon balance.

Analyzing the differences between the SRES scenarios (Fig. 4), it becomes evident that within the HadCM3 scenario set, there is a clear gradation of the impacts from A1FI through A2 to B1 and B2, with A1FI producing the largest effects and B2 the smallest effects on vegetation carbon stocks. It is noteworthy that the different A2 scenarios (Fig. 4) produce strongly deviating results. The variation between the simulated impacts of the A2 scenarios is sometimes larger than the variation between the four SRES scenarios within the HadCM3 scenario set. In most cases, the CSIRO2 model shows the largest and the CGCM2 model the smallest effects within the A2 scenario set.

4 Discussion

4.1 Relative importance of land cover vs. climate change at local and catchment scales

Simulating the impacts of climatic and land cover changes on carbon storage in the vegetation of five catchments in the European Alps, it became evident that land cover change is the dominating process at the local scale (100 to 1,000 m). The catchments in our investigations showed strong local signals of carbon emission or uptake as a function of the land cover scenarios (Fig. 2), which suggest considerable changes in forest area ranging between +7 and −22% over the course of the twenty-first century. While we concur with the scenarios that land abandonment will continue to be an important process in remote areas such as the European Alps for the coming decades, we are uncertain about the realism of the increased rates of deforestation in complex terrain that are projected for the second half of the twenty-first century. Compared to these changes in land cover, climatic shifts only marginally affected carbon storage at the local scale in our simulations.

The impacts of changes in climatic drivers become more evident at the catchment scale. According to the model calculations, changes in catchment-wide vegetation carbon stocks are small in the first time slice. This is at least partly due to the fact that we assumed ecosystem properties to be in equilibrium with climate in the year 1950. Thereafter, i.e., in the second time slice, the terrestrial ecosystems act as a sink because the forested area is projected to increase and rising temperatures are simulated to enhance carbon accumulation in temperature-limited forests close to treeline (Fig. 3). In the third time slice, however, the climate-induced sink capacity weakens for most scenarios, in spite of the intensification of carbon sequestration around the current treeline. Simultaneously, forests at low altitudes begin to release carbon, thus compensating for the gains at higher altitudes. Furthermore, the projected decline in forest area contributes to the diminishing carbon sink. In some case study catchments, land cover changes even convert the climate-induced sink into a net source. Finally, in the fourth time slice, both climate and land cover change lead to an increasing release of carbon from the vegetation under most scenarios. It is noteworthy that this pattern, which refers to a few selected catchments in the Alps that were studied with a high-resolution approach in space and time, agrees qualitatively with studies that focused on the behavior of the biosphere as a whole, e.g., using Dynamic Global Vegetation Models (DGVMs, cf. Cramer et al. 2001).

The strength of the catchment-wide carbon source towards the end of the twenty-first century varies strongly with the geographical location of the catchment. While the relatively low-elevation catchments in the northern pre-alpine region, such as Alptal and Hirschbichl, release high amounts of carbon, the high-alpine Saltina and Dischma catchments release considerably less carbon, which is due to the continuation of the temperature-driven small carbon sink at very high elevations. The high variability of the carbon signal within individual catchments as well as across the different catchments suggests that it would be worth while to evaluate whether large-scale approaches such as DGVMs (Cramer et al. 2001) yield quantitatively compatible results, or whether they would need to find a way to include the “sub-grid scale heterogeneity” that we were able to study explicitly using RHESSys.

When neglecting land cover changes, the catchment-scale carbon budget is ultimately a delicate equilibrium between the two large fluxes of photosynthesis and respiration (Valentini et al. 2000). In other words, the balance of these two temperature-dependent processes determines whether the biosphere acts as a carbon source or a carbon sink. Both fluxes tend to increase with rising temperatures, but they do so in different ways. In the RHESSys model, simulated photosynthesis increases more than plant respiration in cold environments, whereas the simulated plant respiration increases more strongly than photosynthesis in warmer environments. As a consequence, under a warmer climate, intensified plant growth at high elevations exceeds the increasing carbon losses due to plant respiration, thus leading to a net carbon sink. By contrast, enhanced plant respiration at low elevations outbalances carbon gains from increased photosynthesis, thus leading to a net carbon source. This is the ultimate reason for the partitioning of the catchments into a low-elevation source region and a high-elevation sink region. With a warming climate, the borderline between these sink and source regions is simulated to continuously shift to higher altitudes (cf. Fig. 3). The elevation of this borderline eventually determines whether the entire catchment will be a net sink or a source of carbon (Fig. 4).

Changes in precipitation played only a minor role for carbon storage in our study. Because precipitation increases with elevation, and in the scenarios the changes of summer precipitation are not very large (Table 2), reduced water supply rarely poses a problem for the carbon balance of these ecosystems under the range of scenarios that we studied. As a consequence, the projected precipitation changes do not limit vegetation carbon stocks, and the large uncertainty in the downscaled precipitation data thus does not constitute a major problem for the results obtained from this study.

4.2 Model uncertainties and research needs

When interpreting these results, a number of uncertainties have to be kept in mind. As mentioned above, changes in carbon storage are the result of two large, counter-acting fluxes, anabolism (photosynthesis and plant growth) and catabolism (respiration and mortality). In both respects, key modeling uncertainties remain, particularly with respect to the temperature sensitivity of these fluxes, as discussed below.

In RHESSys, as in most other biogeochemical models (cf. Sitch et al. 2003; Foley et al. 2000), it is assumed that the 'bottleneck' for plant production is photosynthesis, i.e., that the assimilation of CO_2 into sugars is the limiting process. However, particularly in cold environments there is evidence that the transfer of sugars into structural tissue (e.g., root growth) is limiting for carbon accumulation (Körner and Paulsen 2004), rather than the process of photosynthesis per se (cf. Körner 1998). Therefore, if tissue growth is limited by temperature to a larger degree than photosynthesis, which may be the case at high elevations, then the carbon anabolism simulated by RHESSys and other biogeochemical models may overestimate the actual carbon uptake potential. As a matter of fact, Cairns and Malanson (1998) found that BIOME-BGC (the ecophysiological submodel used in RHESSys) needed to be modified to be able to simulate the carbon balance of treeline forests, as the original formulation of BIOME-BGC strongly overestimated carbon accumulation at high elevations. Also, in a validation effort with BIOME-BGC where simulated carbon storage along an extended elevational gradient in the European Alps was compared against forest inventory data, Schmid et al. (2006) found that the model matches observed carbon storage quite well up to elevations of about 2000 m. Above this elevation, however, simulated carbon is much too high and extends far into the alpine tundra above natural treeline. This anomalous behavior may well be due to the fact that photosynthesis and not tissue growth is considered to be limiting in the model, and that cold hardiness is not considered at all.

The simulation of plant respiration also involves considerable uncertainties (cf. Churkina et al. 2003; Valentini et al. 2000). In RHESSys, maintenance respiration is currently modeled using the common Q_{10}-approach, which assumes that the temperature sensitivity of plant respiration is constant. However, temperature sensitivity of plant respiration is not constant, neither in time nor in space. It should be kept in mind that most data for fitting such relationships were derived from short-term (e.g., day/night) measurements of plant respiration (cf. Mooney et al. 1999). Extrapolating these data to long-term studies (seasonal and interannual) may be misleading. Various authors have suggested that a Q_{10} between 1.3 and 1.7 would be more appropriate for long-term model-based analyses than the commonly used Q_{10} of 2.0 (Gifford 2003; Kirschbaum 2000; Mooney et al. 1999). In addition, extrapolating these relationships to regions with large temperature gradients, such as along elevational gradients in high mountains, may also be a challenge for the Q_{10} approach. For instance, it has been shown that plants growing in cold environments are adapted to the cold and, therefore, have high respiration rates at low temperatures, and thus a low Q_{10} (Atkin and Tjoelker 2003; Huxman et al. 2003).

In our simulations, we did not change the modeled processes on the anabolic side, but we reduced the Q_{10} of conifers to 1.5. Clearly, this is only a first step towards including cold adaptation into the model, and it should be noted that the model is rather sensitive to the value of the Q_{10} parameter. For a more realistic approach, we suggest to model Q_{10} as a function of long-term temperature, as suggested by Tjoelker et al. (2001) or Loveys et al. (2003). This seems essential to us when studying climate change impacts with a long-term perspective in regions with strong vertical gradients, such as in mountain catchments.

Taken together, even though our study gives absolute numbers and differences between catchments and between the scenarios of global change, one should focus on the relative differences rather than on absolute values. Particularly the uncertainties in the temperature sensitivity of important carbon fluxes are large. It is noteworthy that the elevation of the transition between sink and source regions in the five mountain catchments is quite sensitive to the temperature sensitivity of these processes. Small changes in the factor Q_{10}, for example, can lead to considerable shifts of this border. Its exact elevation, however, determines whether a catchment is a net carbon sink or a source.

5 Conclusions

We presented an analysis of the impacts of climate and land cover changes on vegetation carbon stocks in the European Alps. We used a set of transient scenarios of climatic and land cover changes developed for the European continent based on the IPCC SRES scenarios, which represent the current state-of-the-art in the field. These scenarios were downscaled and fed into the Regional Hydroecological Simulation System RHESSys to simulate daily carbon fluxes and pools for five Alpine catchments representing a range of topographic and climatic conditions from the Alpine region.

By using different global circulation models (GCM) and alternative SRES scenarios, our analysis spanned a wide range of possible future conditions. However, our study revealed that the variability in vegetation carbon stocks caused by different SRES scenarios for a given GCM (HadCM3) is of a similar magnitude as the variability caused by different GCMs for a given SRES scenario (A2). Climate projections from different GCMs using the same SRES scenario vary widely. Particularly the precipitation projections are inconsistent across the four GCMs that were included in our analysis. In other words, the effects of uncertainties in GCMs are at least as large as the effects of the different SRES scenarios. Altogether, this implies that additional efforts in global climate modeling are required before we can unequivocally identify the impacts of different SRES emission scenarios, as their variability currently stays within the variability of results from different GCMs.

Nevertheless, this study showed that there is a clear gradation with the HadCM3 set, from the B2 scenario exhibiting the smallest impact through B1 and A2 to A1FI with the strongest impact on vegetation carbon stocks in the European Alps. However, to confirm this finding and quantify relative changes between scenarios, inter-scenario variations for different models would need to be considered. Overall, in spite of these limitations regarding the input variables for our analyses, the variety of scenarios used in our study allows us to identify the processes that are most sensitive to global change.

The simulation results indicate that in the Alpine case studies, the warming climate generally enhances carbon uptake by terrestrial ecosystems over the first half of the twenty-first century. Particularly forests close to the treeline sequester additional carbon under warmer conditions. Consequently, catchments in the high Alpine region are simulated to accumulate additional carbon over the coming decades. In most scenarios, this sink effect lasts until around the middle of the century. Then, forests at low elevations begin to increasingly release carbon due to increased respiration rates, resulting in a net carbon source. The projected land cover changes generally amplify this pattern, first strengthening the initial carbon sink through reforestation, but after 2020, the land use-driven decline in forested land contributes to the diminishing carbon sink, or it enhances the carbon source.

However, these results are subject to considerable uncertainties, as carbon cycling, particularly respiratory processes at high elevations and their temperature sensitivity, are not well understood yet. For more accurate quantitative assessments of the carbon cycle, further developments and adaptations of RHESSys to the Alpine area would be necessary.

Furthermore, it was not possible to validate the carbon fluxes or pools at high-elevations sites, due to a lack of appropriate data. Finally, RHESSys does not simulate changes in ecosystem structure (e.g., changes of plant functional types) or plant migration to higher elevations.

In spite of these limitations, our study provides first estimates of changes of carbon cycling (1) along altitudinal gradients and (2) for various climatic zones of the European Alps. Taking into account the modeling uncertainties, it is clear that these results cannot be taken literally. However, we are convinced that they can be used to derive directions of change and relative differences between the various case study areas and thus the various climatic regions of this large mountain range.

Acknowledgements This study was carried out within the framework of the EU Project ATEAM (Advanced Terrestrial Ecosystem Analysis and Modelling, cf. www.pik-potsdam.de/ateam and http://www.fe.ethz.ch/research/ecosystem/vulnerability/index_EN). The Swiss contribution to this project was funded by the Swiss Federal Office for Education and Science, Project Number 00.0391. Additional funding was provided by NCCR Climate, a research initiative of the Swiss National Science Foundation.

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