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ARANGE PROJECT

# ARANGE Deliverable D2.3

## Analysis of historic & current forest management practices, forest dynamics and related ecosystem services

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## Abstract

In this Deliverable, forest Ecosystem Service (ES) indicators are analyzed following two approaches.

First, in five ARANGE Case Study Areas (CSAs) historic inventory data and management records were used to study the development of ES indicators over several decades. The indicators showed that the importance of timber production has increased during the analyzed period in all CSAs in terms of both timber stocking and productivity. Similarly, following the trend in stand stocking, the provisioning of carbon storage has also increased in all CSAs. However, indicators of biodiversity conservation differed significantly between the CSAs. Management systems that are creating even-aged stands (i.e., clear-cutting system, uniform shelterwood system) decreased the indicators, whereas those techniques that are promoting uneven-aged structures led to an increase in biodiversity indices.

Of particular interest for those CSAs where the management regime had changed during the historic period was whether the ES indicators showed a response that could be attributed to management. However, results from Spain and Slovenia, where such a management change occurred, showed that changes in the provision of ES cannot be attributed unequivocally to management changes, as a multitude of factors are involved.

Second, there is a broad spectrum of silvicultural systems used as Business-As-Usual (BAU) management in the seven ARANGE CSAs. In three CSAs, uneven-aged management regimes are in use, in the Spanish CSA the coppice system is also an element of current management. There is no evident relationship between the management objectives (i.e., demand for ES) in the CSAs and the BAU management. However, even-aged systems based on small- to medium-scale clear-cutting appear to be the favored silvicultural system when timber production is the major ES that is demanded. To some extent tradition seems also to play a role in determining the management regime.

Simulation studies with state-of-the-art forest models showed that there are limitations of BAU with regard to the maintenance of biodiversity, particularly regarding species and structural diversity as well as deadwood abundance. An issue not fully represented by the models is the impact of disturbances such as bark beetles and windstorms. Just in one CSA (Montafon) bark beetle damages were considered explicitly in the simulations.

When BAU management was simulated under a set of climate change scenarios, a substantial variation regarding ES provision resulted, depending on the climate scenarios. Furthermore, the typical altitudinal gradient in mountain regions was reproduced, with mainly negative impacts on forest growth at low elevations due to increasing summer drought and species shifts from conifers to broadleaved species, while at higher altitudes growth benefits from longer vegetation periods and more favorable thermal regimes. This was a consistent finding in all CSAs. However, it is important to note that scenario simulations that do not consider disturbance regimes are likely too optimistic. Intensifying disturbance regimes bear the potential to severely impact ES provision, such as timber production, carbon storage and protection against gravitational hazards.

Another potential conflict exists in small-scale ownership structures, where demand for timber production (usually the interest of forest owners) and the need to protect against rockfall, snow avalanches and erosion and landslides meet. No segregative approaches are possible when ownership size is too small to disentangle ES. However, approaches to balance (i.e., integrate) ES such as timber and protection by fine-grained small-scale silviculture may be severely hampered by technical and economic constraints regarding feasible harvesting technologies.

These results call for the design of ES portfolios with no or low conflict potential and a partial segregation of ES provisioning at the landscape scale. From the BAU simulations, we conclude that setting aside larger areas in coniferous mountain forests may be no option due to intensifying disturbance regimes, which may jeopardize key ES such as protective services.

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# 1 Introduction

The objective of WP2 of ARANGE is (1) to adjust and further develop – where needed – state-of-the-art models for the projection of forest dynamics and the assessment of ecosystem services (ES) in the seven ARANGE Case Study Areas (CSAs), and (2) to apply these tools to simulate past, current and future forest development and related ES. Based on simulated trajectories of ES, the relationships among ES at different spatial scales will be analyzed. The present Deliverable focuses on the historic and currently practiced management regimes. While historic data records are used to look at temporal changes of selected ES indicators and to link such changes to management regimes, the major part of D2.3 sets focus on the analysis of current management practices (BAU; business as usual) and how these are affected by climate change scenarios.

In Chapters 2 & 3, we present an exhaustive analysis of past forest management practices in five CSAs where suitable data were available, and we evaluate the relationship between management schemes and the provisioning of key ES on a per-CSA basis.

Specifically, historical data on management practices and time series of forest characteristics (at the stand and FMU scales) are used to reconstruct past ES as a function of forest management. These results are crucial for better understanding the underlying relationships. For example, in some CSAs changes in management from even-aged to uneven-aged silviculture have occurred, whereas in some places shelterwood or continuous-cover forestry has been employed continuously since many decades. Hence, there is ample scope for evaluating (1) the long-term consequences of constant forest management practices as well as (2) the consequences of changes in forest management practices on the delivery of ES in the case study regions.

In Chapter 4, we report on the simulation results that were obtained when applying the state-of-the-art forest models in the seven CSAs under the assumption that current management practices (subsequently referred to as "Business-As-Usual" management, or simply "BAU management") would be maintained into the future, but taking into account different climate projections that were derived within the ARANGE project.

Specifically, the forest models that were evaluated (cf. Deliverable 2.1) and are capable of providing indicators of ES provisioning (cf. Deliverable 2.2) are employed to simulate forest development for so-called Representative Stand Types (RSTs) in all CSAs, taking current conditions (i.e., time window 2010-2010) as the starting point, and they provide as output the corresponding ES at the stand scale.

Besides the "Business-As-Usual" management, i.e. the continuation of current management practices, Adaptive Management schemes (AM) are also being developed within ARANGE, but they are not in the scope of the present Deliverable (cf. Deliverable 2.4, forthcoming).

# 2 Analyses of historic forest management

The aim of this section is to analyze the historic mountain forest management in European mountain ranges in order to find out what was the management carried out in these forests and how these different management schedules influenced the provision of different ES.

Below, we present the results of our analysis of the historic development of forest state and removals under specific silvicultural management regimes in those CSAs where such historic data were available. Linker functions from D2.2 were used to estimate ES provisioning through time. Two main sources of information were used: (i) historic forest inventory data from the CSAs, and (ii) qualitative information regarding the forest management regime and schedule that had been applied in the monitored forest area. Type and quality of the available data and information varied among CSAs, and so did the size of the represented forest area. In some CSAs the management regime has changed during the observation period. As we do not deal with an experiment, there is no "zero" variant that was run in parallel, thus it actually was not possible to isolate the effect of management changes on ES provisioning. However, what could be made visible is whether there was a change in ES provisioning at all after changes in management regime had occurred, and what the time lag is before such changes in ES become visible.

## 2.1 Description of historical records in the CSAs

### 2.1.1 CSA1 – Montes Valsaín, Iberian Mountains, Spain

The Spanish CSA comprises of 70% of pure even-aged *Pinus sylvestris* (Pinar de Valsaín with 7606,03 ha) and 30% of mixed stands of *Pinus sylvestris* and *Quercus pyrenaica*, pure stands of *Quercus pyrenaica* and pure stands of *Quercus ilex* (Matas Forest with 3046 ha). Being one of the most productive *P. sylvestris* forests in Spain, the main ES from 1889 until 1965 was timber production, thus all the historical records until then refer to *Pinus sylvestris* stands (Pinar de Valsaín), and therefore it is the only species analyzed in the present study.

The Pinar de Valsaín forest has inventory data available from 1941 to 1998 covering a forest area of more than 7'000 ha (54 compartments, each with a size of 130 ha), with 6 successive inventories. Until 1965, inventories had been made by counting all trees with a diameter at breast height (*dbh*) >10 cm and classifying them into 10-cm classes. In these inventories, *P. sylvestris* was the only species recorded because only productive areas were inventoried. Since 1965, however, also *Quercus pyrenaica* was considered (Matas Forest) although the present analysis focuses on *P. sylvestris* forests. The inventories comprise 54 compartments that amount to a total area of 7'606.03 ha.

The inventory method changed in 1988, when systematic sampling was introduced and fixed-area circular plots (288 plots) with a radius of 13 meters m were established. However, the radius was reduced to 9.8 m in the following inventory (1998).

Even-aged FM has been the common practice in *P. sylvestris* stands. Initially, a uniform shelterwood system in permanent blocks with a rotation of 120 years and a 20-yr regeneration period was applied. This method was changed gradually in 1989 to a (shelterwood) group system, extending the regeneration period to 40 years, when deemed necessary, to assure sufficient natural regeneration. Regeneration is always natural after regeneration fellings.

Since 1965, the aim has been to focus the management of these forests on a more conservation-oriented practice. However, at the same time it was observed that the cuttings performed until then had been lower than those prescribed in the Management Plans. Thus, and with the aim of bringing up-to-date the cuttings, the cuttings performed since 1965 were heavier than before.

Stand attributes available for the analysis include total volume per hectare, number of trees per diameter class, and annual volume increment.

### 2.1.2 CSA2 – Vercors, Western Alps, France

The French CSA, Engins forest, is an uneven-aged forest of *Picea abies*, *Abies alba* and *Fagus sylvatica*, an individual-tree selection system was applied, with a cutting interval of 10-12 years according to the Management Plan. All developmental stages are represented at the compartment level, i.e. the stand is a mixture of trees of all age classes. Based on this approach, the diameter distributions should remain constant over time, but in practice they still changed somewhat.

Although *theoretical* cutting intervals were 10-12 years, according to the cutting records that are available for five compartments out of twelve in the Engins forest, the average *real* cutting interval corresponded to 15 years (range 10-18 years). The first cuttings were done in 1918, and the last records correspond to 2005. The number of cuttings over the analysis period was usually 6-7 in each compartment, although one compartment had only 4 cuttings (last cutting in 1994). The harvest ($m^3$/ha/year) was highly variable, depending on the compartment (range 0.9-4.5 $m^3$/ha/year).

The aim of FM in Engins was to increase the proportion of conifers (spruce and fir) generally by reducing competition by broadleaves. The broadleaved species were cut for fuelwood, leading to a promotion of the regeneration of conifer species.

Engins consists of 12 compartments that were measured in four inventories from 1909 to 1993 (1909, 1927, 1954 and 1993). The size of the compartments varies between 6.8 and 23.8 ha, and the compartment sizes did not change throughout the entire observation period.

Data are available at the species level for Norway spruce, Silver fir and European beech, although the two conifers were not distinguished in the first inventories (i.e., from 1909). The quantitative attributes available are basal area/ha, volume/ha and diameter distribution (stem numbers/ha per diameter class [class width 5 cm], with a callipering threshold of with a callipering threshold of 15 cm.

Annual data on the volumes of harvested conifers are available as well as data on the timing of harvests and standing volume. However, it is important to note that the inventories performed at the beginning of the century targeted coniferous species (spruce and fir) and ignored the broadleaved species, although sometimes the latter represented >40% of the standing stock.

### 2.1.3 CSA4 – Sneznik, Dinaric Mountains, Slovenia

CSA Sneznik is characterized by mixed uneven-aged forest stands of three dominant species *Abies alba*, *Fagus sylvatica*, and *Picea abies* with an individual admixture of *Acer pseudoplatanus*, *Ulmus glabra*, *Sorbus aucuparia*, *Sorbus aria*, *Tilia cordata*, *Taxus baccata* and some others. In the CSA, uneven-aged forest management has taken place since the beginning of the 20$^{th}$ century (Klopcic and Boncina, 2011). Until the late 1960s, single-tree ('plenter') forest management has been practiced across the CSA. In the late 1960s and early 1970s, an irregular shelterwood system was introduced, and since then a combination of several silvicultural systems was applied that have led to uneven-aged stands (group selection, single tree selection ['plenter'], irregular shelterwood system on a small spatial scale). The transition of the silvicultural system occurred relatively fast, since the single-tree selection system used prior to the 1960s did not yield the results desired by foresters – for example an increase of European beech, low timber quality of broadleaves, deficient regeneration and recruitment, silver fir decline, etc. (Boncina, 2011).

The study area considered here covers 19 compartments with an average area of 9.4 ha (range 4.4–16.5 ha), totaling 179 ha. Historical data are mainly available for the period 1953-2003 (6 forest inventories in 1953, 1963, 1973, 1983, 1993, and 2003), but some data are available for a longer period (1912-2003, additional inventories in 1912 and 1936).

Data on diameter distribution (number of trees per 5-cm diameter class per hectare) were available from the 1953, 1963, 1983, 1993, and 2003 forest inventories. In 1953, 1963 and 1983, forest stands were fully callipered and the data are available at compartment level (n= 19, average area=9.4 ha, in total 179 ha). In 1993 and 2003, a permanent sampling plot method was applied (n=37 within the compartments included in the study; SFS, 2012). Plots were circular with two concentric areas; on the inner area of 200 $m^2$ (radius 7.98 m) all trees with dbh≥10 cm were measured and registered, while on the outer area of 500 $m^2$ (radius 12.61 m) only trees with dbh≥30 cm were surveyed.

Data on stand volume (total and per tree species) were available on the compartment level from forest inventories in 1912 (only total V), 1936 (only total V), 1953, 1963, 1973, 1983, 1993, and 2003.

Data on annual removals (total and grouped in conifers and broadleaves) were available on the compartment level for the period 1963-2012.

### 2.1.4 CSA5 – Vilhelmina, Scandinavian Mountains, Sweden

The Swedish CSA (here all forest in the whole Vilhelmina municipality, app. 350 000 hectares, are included) is characterized by even-aged forests dominated by *Pinus sylvestris* and *Picea abies,* even if many old spruce stands are unevenaged. Timber production was the only focus of forest policies for decades, yet active management for nature conservation was successively introduced in the 1980s. In the Forest Act of 1993, environmental values are stated to be as important as timber production. The environmental values are clarified in the Forest Act (2014-09-01) as the production capacity of the forest land, the biodiversity and genetic variation, plant and animal species, cultural, aesthetical and social values, Since 1993, most fellings are done with nature conservation concerns considered (ca. 3-7% of the volume at the stand level is set aside permanently). All forest owners have to announce to the Swedish Forest Agency six weeks before clear-felling and inform about environmental consideration. For forests in the area close to where trees form stands, extra precaution are requested by the Forest Agency. Construction of forest roads and clear-felling may not be allowed. But if allowed, the clear-felling areas may not be larger than 20 hectares. Also, *Pinus Contorta* are not allowed in regenerations in large areas. Forest companies and institutional owners, but not NIPF (non-industrial private forest) owners, have to communicate their plans for clear-felling and site preparation to the reindeer herders. This also applies to fertilization, but this activity is not performed in the CSA because of the distance from the forest industry. All forest companies are certified according to FSC from 1995-2000 and onwards, which means they may not do clear-felling in area close to the mountains even if it is allowed according to the Forest Act. Nowadays (i.e., since 5-10 years) most private forest owners that make forest Management Plans for their estate set aside 5% of the productive forest land for nature conservation purposes according to rules for PEFC certification.

Between 1850 and the 1950s, cuttings were done as selection cuttings, cutting first the largest trees that went to the sawmill. These cuttings were typically too strong and led to degraded forests with low stocking and growth. Even-aged FM has been the dominant FM system since the 1950s, when clear-felling were gradually introduced. Regeneration included burning and later mechanical site preparation, and planting genetically improved seedlings. Natural regeneration of pine is used in a small area of the CSA only. A pre-commercial thinning is often done when trees are 3-6 m tall. Thinnings are generally done when stand density reaches ca. 25 $m^2$/ha, bringing basal area down to 17 $m^2$/ha. Clear-felling is done at an age of 90-130 years. Since the 1980s, virtually all thinnings and clear-cuttings are done with harvesters.

During the time period from 1985 (average of 1983-1987) to 2010 (average of 2008-2011, data for 2012 are missing) no treatment has been the most common practice in forests in Vilhelmina. This can be explained by the fact that in a rotation (app. 110 years) none or one (two) thinning are performed and one clear-felling. At each inventory and during the period since the last inventory, typically none or one pre-commercial thinning have been applied. From 1985 to 2010 , 15.2% of the 191 plots in productive forest land were clear-felled, indicating an average rotation period of 151 years; 3.7% of these plots were thinned; other types of cuttings were done in 14.7% of the plots, and pre-commercial thinning were done in 5.8% of the plots. Clear-felling were done at different forest ages in different plots, as there are many different land owners who take their own decisions on management. Only in 10 plots two types of cuttings were applied. The period between these two types of cuttings is usually around 10 years.

National forest inventories (NFI) were performed since 1925, but historical forest management data can only be used from 1983 to 2003, when permanent sampling plots were introduced (359 circular plots, 7 m radius). All trees with a height >1.3 m are measured at breast height (in mm), while small trees are callipered in a smaller plot only. Available data include volume per ha, tree species composition and diameter distribution. These data are available for "productive forest land" defined as those lands having a production potential ≥1 $m^3$/ha·yr in the whole Vilhelmina municipality and represent app. 350 000 hectares. Area and volume of management activities are also available. Data on total volume/ha and number of trees per diameter distribution are available for *Pinus sylvestris*, *Pinus contorta*, *Picea abies*, *Betula pubescens, Salix caprea, Alnus glutinosa* and *Sorbus aucuparia*.

### 2.1.5 CSA6 – Kozie Chrbty, Western Carpathians, Slovakia

The Slovakian CSA features mixed even-aged forests of *Picea abies*, *Abies alba* and *Larix decidua,* with a rotation period between 100 and 160 years. Some other species such as *Fagus sylvatica, Acer pseudoplatanus and Picea pungens* occur as well. Natural regeneration is combined with plantations to ensure stand regeneration. Decennial thinnings from below have been applied since 1977 (records are available for 1977, 1987, 1996 and 2006) in variable areas (up to 3 ha) to obtain between 1 and 50 $m^3$/ha of timber. Sanitary fellings are frequently applied as a consequence of windstorms and insect damage.

There is an annual Forest Management Record that contains three types of information at the compartment level: harvest report, forestation report and planting report. Records on the FM applied include information on thinnings, regeneration fellings, and sanitary fellings.

The summary of the planned interventions (as recorded in the Management Plans) in the 16 compartments of the Slovakian CSA between 1977 and 2012 has been provided by the CSR. All silvicultural interventions refer to beech and spruce.

The Slovakian CSA has historic forest management data from 1977 to 2012 from 5 inventories (1977, 1987, 1996, 2006 and 2012) in 16 compartments of variable size (1.9 to 20.3 ha). The total forest area for the historic analysis is 133.74 ha. The data include total volume/ha, stand age and annual removals/ha for each compartment. The diameter distribution (10-cm diameter classes, callipering threshold 10 cm) is only available for the inventory of 2012.

## 2.2 Analysis of forest inventories and FM practices

The analysis of the different inventories along the timeline of each forest focused on Ecosystem Services (ES) as indicated by linker functions (cf. D2.2). Only three of the four main ES categories included in ARANGE were analyzed here; protection against gravitational hazards was not considered because it was not relevant for most CSAs for which historical data were available. The ES included thus were wood production, carbon storage, and nature conservation.

For all CSAs, the ES were computed through linker functions defined in D2.2. The methodology used to analyze the data for each inventory consisted of computing the values for each ES indicator at the compartment level for each CSA. Then, the mean ± one standard error of each ES indicator was calculated for each inventory at the forest level. This information allowed us to derive historical trends in ES provision, based on both the inventory data and the FM information. In addition, a correlation analysis was carried out in each CSA to identify trade-offs among ES. The indicators used here are described in more detail below (cf. also D2.2).

### 2.2.1 Wood production

Wood production is described by three indicators: timber volume harvested, forest stocking, and forest productivity.

(i) Timber volume harvested ($m^3ha^{-1}yr^{-1}$) denotes the total annual volume of timber harvested from a stand (*TVH*).
(ii) Stocking ($m^3ha^{-1}$) denotes stocking volume of living trees per hectare (*V*).
(iii) Productivity ($m^3ha^{-1}yr^{-1}$) was calculated by current annual volume increment per hectare (*VI*), following the description in D2.2:
*Annually produced stem wood volume = [(stem wood of trees alive at time (i+1) + stem wood of harvested trees in that period + stem wood of trees which died in that period and were not harvested] - stem wood of trees alive at time (i)].*
Since not all information was available from the historical forest inventories of some CSAs, VI on the compartment level was also estimated using equation (1).

$$VI_{Y\_Y+1} = \left[V_{Y+1} - V_Y + \sum_{i=Y}^{Y+1} TVH_i\right]/[(Y+1) - Y] \qquad \text{[eq. 1]}$$

where *VI* is annual volume increment per ha, *V* is stocking volume per ha, *TVH* is total annual timber volume harvested per ha, and *Y* is the year of the forest inventory.

### 2.2.2 Carbon Storage

Carbon storage was computed by means of two indicators: (i) aboveground carbon storage and (ii) belowground carbon storage, both referring to living tree biomass, and both expressed as $t \cdot ha^{-1}$. They are defined as the dry mass of carbon contained in above- and belowground living tree biomass, respectively.

Among the methods presented in D 2.2 to compute aboveground carbon storage, the Wood Volume method was chosen, due to its applicability to all CSAs considered here. Carbon storage in deadwood and soil organic matter was not analyzed due to a lack of data.

### 2.2.3 Biodiversity conservation

Biodiversity conservation was assessed using the following indicators: (i) tree species diversity, (ii) tree size diversity, and (iii) abundance of large living trees.

(i) Tree species diversity was computed using the Shannon index, H (Neuman & Starlinger, 2001), which takes into account the number of species in the stand and their relative abundance (by number of trees, basal area, biomass, volume, etc.). However, in the present analysis the diversity index $D$ ($D$=exp $H$) was employed. It can be interpreted as an "equivalent number of species" as it equals to tree species richness when all species in the stand share the same abundance. Otherwise, it is always lower than tree species richness (and superior or equal to 1).

(ii) Tree size diversity was computed by means of the post-hoc index by Staudhammer & LeMay (2001) without the species diversity component, which is already represented by another index (see (i)). The post-hoc index corresponds to the mean of the Shannon entropy indices applied to diameter classes and height classes instead of species. If data on tree heights were not available in the historical records, the Shannon index $H_{dbh}$ applied to diameter classes (i.e., number of trees per diameter class was used as a proxy of tree size diversity.

(iii) Abundance of large living trees *LLTN* was defined as the number of trees per hectare with a *dbh* above *dbh* thresholds $D_{LLC}$ for conifers (i.e., 70 cm) and $D_{LLB}$ for broadleaves (i.e., 50 cm). *LLTN* denotes the index at the stand scale.

# 3 Results of the historic analysis

As it has been presented in the Introduction, data from the different forest inventories include two types of information: (a) quantitative information: the number of trees per species and diameter classes at the compartment level, as well as the removals carried out in each compartment, thus enabling the identification of forest evolution over time, and (b) qualitative information obtained from the Management Plans: not only the type of forest management but also the silvicultural treatment carried out in each compartment during each period.

For each compartment in the represented forests, the provision of the main ES is analyzed by means of their indicators. This analysis will be combined with the qualitative information on FM provided by each CSA and effects of forest management on ES provisioning will be derived.

## 3.1 CSA1 – Montes Valsain, Iberian Mountains, Spain

It is worth noting that until 1984, the cuttings performed in the compartments were much lower than the prescriptions in the Forest Management Plan. In 1984, the aim was formulated to increase the cuttings to reach the planned values.

**(i) Wood production**

*a. Timber volume harvested ($m^3ha^{-1}yr^{-1}$)*

According to the data available for Valsaín, timber harvests mainly comprised timber from thinnings, regeneration cuttings and sanitary fellings.

According to the data available for Valsaín, timber harvests mainly comprised timber from thinnings, regeneration cuttings and sanitary fellings. According to the Management Plans, since 1965 forest management in Valsaín introduced other uses different to timber. This effect is shown in Figure 3.1-1. that shows that a decrease in the timber volume harvested from 1965 coinciding with the adoption of more conservative-oriented practices. From 1984, the TVH started to increase slightly with the aim of bringing up-to-date the cuttings prescribed in former periods.

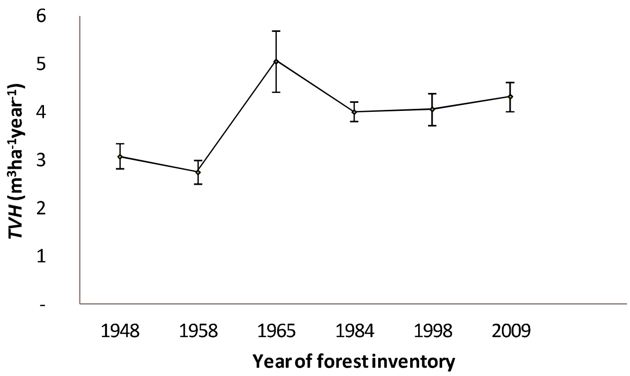



**Figure 3.1-1.** Timber volume harvested ($m^3ha^{-1}yr^{-1}$± standard error of the mean) in CSA1-Valsaín during the period 1941-2012.

*b. Productivity ($m^3ha^{-1}yr^{-1}$)*

The results show a decreasing trend from 1948 until 1965, when a minimum is reached (0.61 $m^3ha^{-1}year^{-1}$). However, from 1965 the productivity increases until 2009 where a maximum value of 4.33 $m^3ha^{-1}year^{-1}$is reached (Fig. 3.1-2).

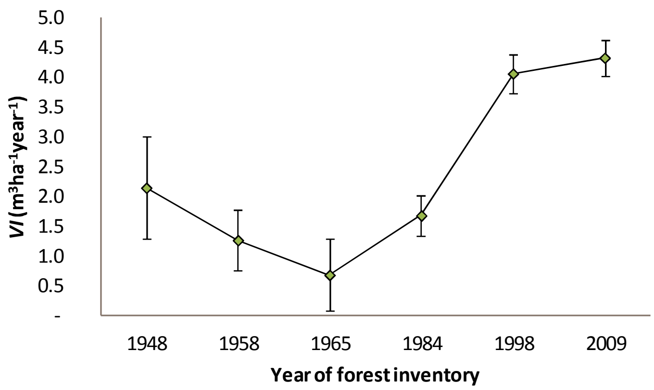



**Figure 3.1-2.** Productivity ($m^3ha^{-1}yr^{-1}$; mean ± standard error of the mean) presented by the different compartments analyzed in CSA1-Valsaín for the period 1941-1998.

*c. Stocking ($m^3ha^{-1}$)*

The data (Figure 3.1-3) show that stocking increased over time, from 266.4$m^3ha^{-1}$ in 1941 to 359.4 $m^3ha^{-1}$ in 2009, meaning an increase of 35%. According to the results, this increasing trend is stressed in 1965 when more conservative-oriented schedules were performed with the consequent increase in standing volume.

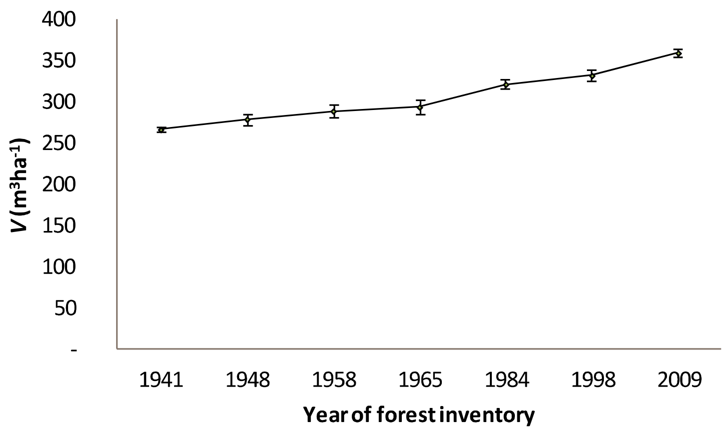



**Figure 3.1-3.** Stocking ($m^3ha^{-1}$; mean ± standard error of the mean) presented by the different compartments analyzed in CSA1-Valsaín for the period 1941-1998.

### (ii) Carbon storage

Carbon storage was computed from carbon sequestered above- and belowground, using the "wood volume method" (Cordonnier et al., 2013). The value of carbon storage, both above- and belowground (Figure 3.1-4), showed the same trend as the stocking.

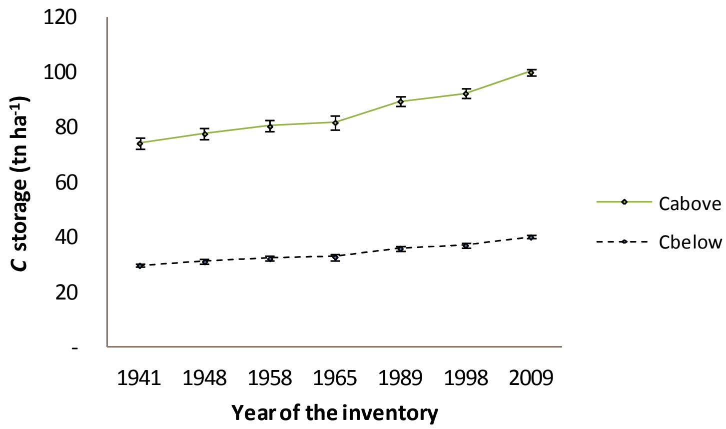



**Figure 3.1-4.** Carbon storage ($t.ha^{-1}$; mean ± standard error of the mean) above and below ground presented by the different compartments analyzed in CSA1-Valsaín for the period 1941-1998.

### (iii) Nature conservation

Regarding nature conservation, only two indices could be computed: Tree size diversity and abundance of large living trees. Tree size diversity was approximated only with *Hdbh* and not with the *post-hoc* index. The tree species diversity was not computed since the inventories only included *Pinus sylvestris*.

Despite of presenting an increasing trend during the analysed period, the values for $H_{dbh}$ remained relatively constant between 1941 and 1965, ranging from 1.52 in 1941 to 1.56 in 1965. However, the increasing trend is stressed a bit in 1965 reaching a value of 1.62 in 1984 with a subsequent decrease in 1998 until 1.51 in 1998. The increase in 1984 may be due to the adoption of more conservative-oriented practices while the decrease occurred in the period 1984-1998 could be caused by the adoption of group selection system instead of uniform shelterwood system. The abundance of large living trees (*LLTN; dbh50 cm*) increased from 23 in 1941 to 42 in 1998 (compare Fig. 3.1-5).

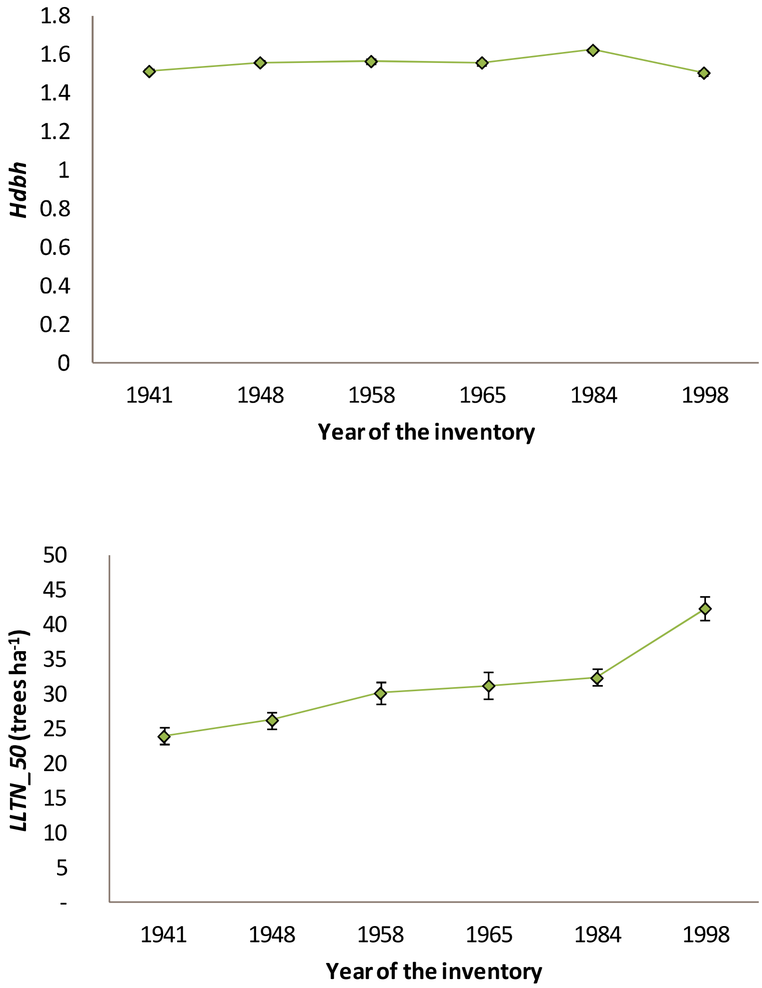



**Figure 3.1-5** Nature conservation indices (mean ± standard error of the mean) observed in the different compartments analyzed in CSA1-Valsaín for the period 1941-1998. Top: tree size diversity; Bottom: Abundance of large living trees.

### (iv) Correlation analysis

It is interesting to analyze how the different indicators of ES provisioning show significant correlations (Table 3.1-1). This is the case of stocking that shows a synergetic relationship with productivity and carbon stored above and below ground. Moreover, the stocking volume also shows a positive correlation with the nature conservation index *LLTN*. The nature conservation indices also seemed to present a synergetic relationship between them. Regarding the trade-off among ES, according to our results there are no trade-off relations (i.e. negative correlation coefficient) in this CSA.

**Table 3.1-1.** Spearman's correlation coefficients between indicators of ES provisioning in the CSA1-Valsaín

| Indicator | ***TVH*** | $C_{above}$ | $C_{below}$ | $H_{dbh}$ | ***LLTN*** |
|---|---|---|---|---|---|
| ***V*** | -0.054 | 1.000** | 1.000** | -0.099** | 0.543** |
| ***TVH*** | - | -0.054* | -0.054* | -0.055* | -0.052 |
| $C_{above}$ | | - | 1.000** | -0.099** | 0.542** |
| $C_{below}$ | | | - | -0.099** | 0.542** |
| $H_{dbh}$ | | | | - | 0.434** |
| ***LLTN*** | | | | | - |

## 3.2 CSA2 – Vercors, Western Alps, France

In this study case, the forest is composed of uneven-aged stands. These stands started to be managed as uneven-aged in 1895, with a theoretical cutting interval of 10-12 years, although the current cutting records for the different compartments revealed some variation in these cutting intervals.

**(i) Wood production**

*a. Timber volume harvested (m$^3$ha$^{-1}$yr$^{-1}$)*

The timber volume harvested provided shows some peculiarities. First, the values seemed too low (Figure 3.2-1), given the stocking in the different compartments (compare results with Figure 3.2-3). Second, there is no information about the distribution of the harvested volume over diameter classes which would indicate what type of cuttings were performed.

Nevertheless, when looking at the *TVH* for a given compartment in different cutting operations, it is noteworthy that it is constant over the years, indicating that the stands had reached the ideal uneven-aged structure (steady-state structure).

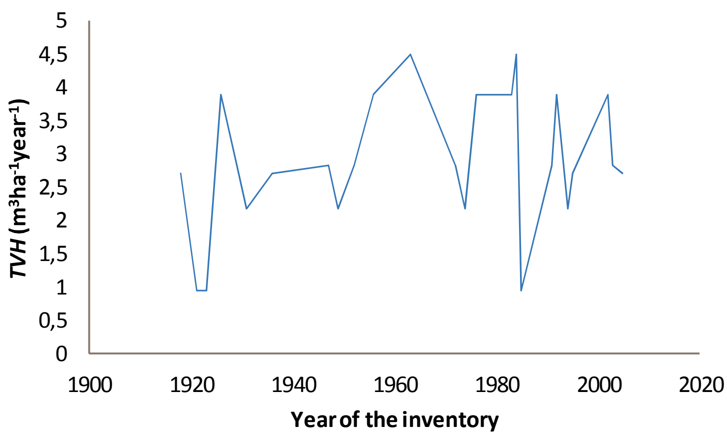



**Figure 3.2-1.** Timber harvested (m$^3$ha$^{-1}$yr$^{-1}$) presented by the different compartments analyzed in CSA2-Vercors for the period 1909-1993.

*b. Productivity (m$^3$ha$^{-1}$yr$^{-1}$)*

Productivity of forest stands was estimated according to the equation 1 described in the section 2.3. The observed results (Figure 3.2-2) show that productivity decreased from 1.25 m$^3$ha$^{-1}$yr$^{-1}$ in the period 1909-1927 to 0.89 m$^3$ha$^{-1}$yr$^{-1}$ in the period 1928-1954, to increase again until a maximum of 2.80 m$^3$ha$^{-1}$yr$^{-1}$ in the period 1955-1993.

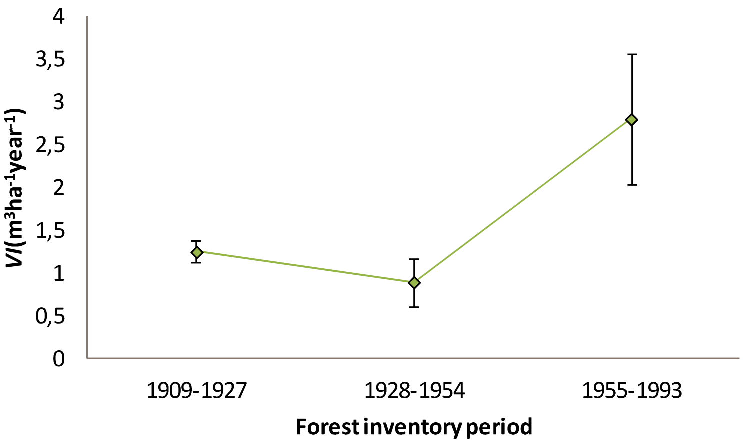



**Figure 3.2-2.** Productivity ($m^3ha^{-1}yr^{-1}$; mean ± standard error of the mean) shown by the different compartments analyzed in CSA2-Vercors for the period 1909-1993.

*c. Stocking ($m^3ha^{-1}$)*

The data shows that the stocking volume increases drastically, from 48.72 $m^3ha^{-1}$ in 1909 to 162.96 $m^3ha^{-1}yr^{-1}$ in 1993, meaning an increase of 235% in stocking volume along the period analyzed. This result is interesting since, according to the information provided by the CSR, the compartments are supposed to have reached the ideal uneven-age structure. The reason might be that actually the "ideal structure" had not been reached yet and therefore the cutting operations (which are defined as constant for the whole period analyzed) have not been properly defined (Fig. 3.2-3).

Moreover, inventories performed at the beginning of the century targeted coniferous species (spruce and fir). As an example, there are 40% of broadleaves (not taken into account) in one of the management units of Engins. This fact can explain the low level of stocking found in some management units.

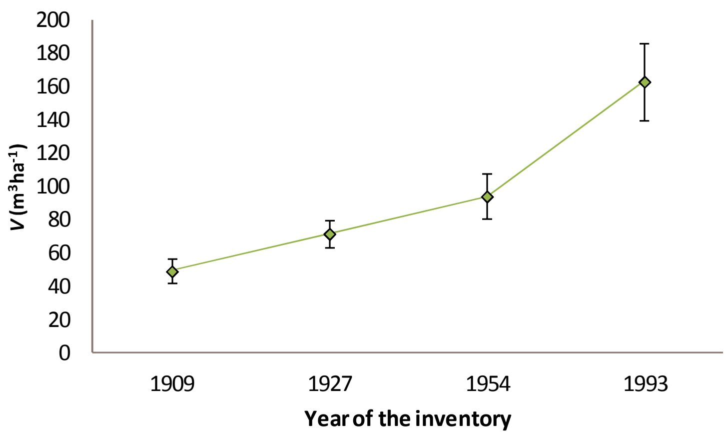



**Figure 3.2-3.** Stocking ($m^3ha^{-1}$; mean ± standard error of the mean) shown by the different compartments analyzed in CSA2-Vercors for the period 1909-1993.

### (ii) Carbon storage

The method employed to compute carbon storage above- and belowground is based on the standing volume of the stand as a predictor; therefore it seems logical that both the carbon above- and belowground follow the same trend as the stocking (Figure 3.2-4).

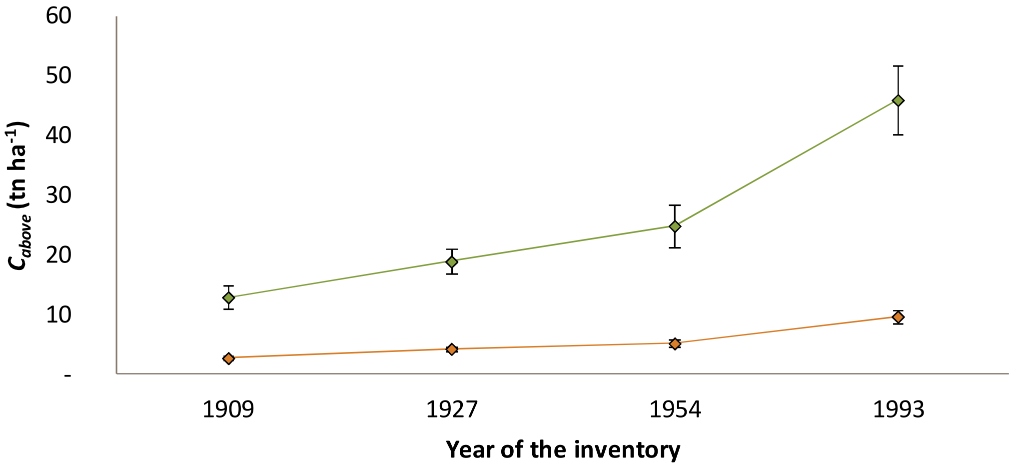



**Figure 3.2-4.** Carbon storage (t.ha$^{-1}$ ; mean ± standard error of the mean) above and below ground presented by the different compartments analyzed in CSA2-Vercors for the period 1909-1993.

### (iii) Nature conservation

Regarding nature conservation, three indicators were computed: $D$, $H_{dbh}$ and $LLTN$ (Figure 3.2-5). In the first case, the tree species diversity index ($D$) indicates an increase in the value of this index over the time period analyzed. However, taking into account that the broadleaves species were not considered in the inventories at the beginning of the century, the value of the indicator loses reliability since the true indicator value at the beginning of the analysis period was obviously systematically underestimated.

For the tree size diversity (computed by $H_{dbh}$), the increase over time is clear. This fact joined to the former considerations regarding the trend found in the stocking, lead us to the conclusion that the uneven-aged stands were not at the steady-state at the beginning of the analyzed period.

The third indicator is the abundance of large living trees ($LLTN$), which can be computed separately for conifer and broadleaves species, although broadleaves were not big enough (dbh<50 cm). For the conifer species, the index increases over time, strengthening the assumption that the steady state has not been achieved in the stands.

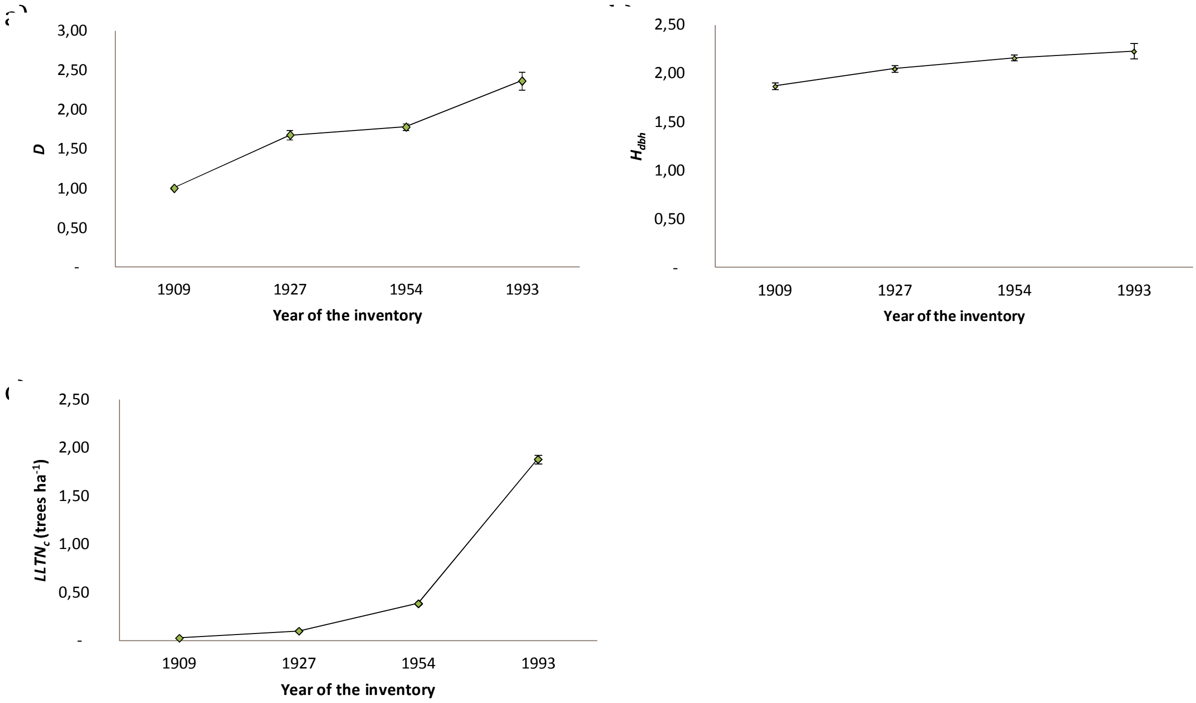



**Figure 3.2-5.** Dynamics of nature conservation indices in the case study area during the observation period: a) species diversity index D, b) tree size diversity index H, c number of large living conifers (with dbh≥70 cm).

### (iv) Correlation analysis

The correlation analysis performed in this CSA does not show a clear trade-off among any ES (Table 3.2-1), but some synergies can be found. Firstly, wood production is positively correlated with carbon stored. Secondly, also carbon stored presents positive correlation with nature conservation indices, although this relationship is not significant in the case of LLTN for conifer species. Moreover, this trend is also shared by stocking volume although the productivity is only correlated with the LLTN for broadleaves species.

TVH was not included in this correlation analysis. For some years there was a unique value of the variable, and therefore it was treated as a constant, enabling its inclusion in the analysis.

**Table 3.2-1.** Spearman's correlation coefficients between indicators of ES provisioning in the CSA2-Vercors

| Indicator | *VI* | $C_{above}$ | $C_{below}$ | *D* | $H_{dbh}$ | $LLTN_c$ | $LLTN_b$ |
|---|---|---|---|---|---|---|---|
| *V* | 0.736** | 0.992** | 0.966** | 0.519** | 0.428* | 0.090 | 0.907** |
| *VI* | - | 0.738** | 0.756** | 0.289 | -0.038 | -0.28 | 0.667** |
| $C_{above}$ | | - | 0.984** | 0.573 ** | 0.422** | 0.082 | 0.885** |
| $C_{below}$ | | | - | 0.622 ** | 0.433** | 0.092 | 0.865** |
| *D* | | | | - | 0.079 | 0.178 | 0.372* |
| $H_{dbh}$ | | | | | - | -0.083 | 0.552** |
| $LLTN_c$ | | | | | | - | 0.063 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $\boldsymbol{LLTN_b}$ | | | | | | | - |

## 3.3 CSA4 – Sneznik, Dinaric Mountains, Slovenia

In the Slovenian case study, mixed uneven-aged stands prevail and were created with the single-tree selection ('plenter') system used until the 1970s and afterwards with a combination of different silvicultural systems and techniques.

**(i) Wood production**

*a. Timber volume harvested ($m^3ha^{-1}yr^{-1}$):*

In the case study area, timber harvesting was generally performed each year during the observation period (Figure 3.3-1). On average, 6.65 $m^3ha^{-1}$ of timber were harvested annually, with conifers representing 70.9% and broadleaves 29.1%.

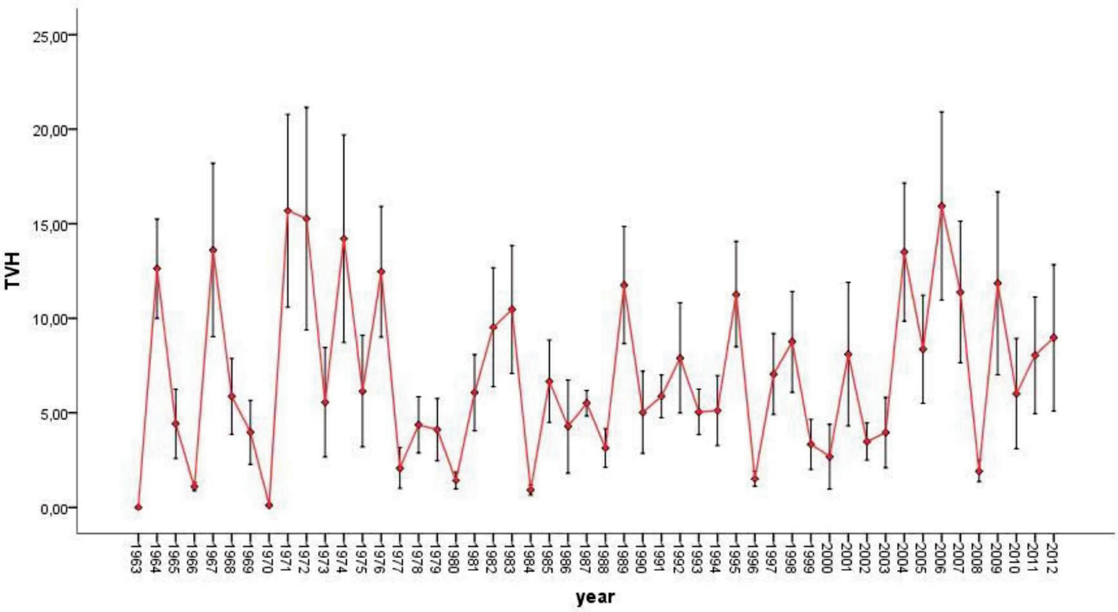



**Figure 3.3-1.** Timber volume harvested TVH ($m^3ha^{-1}yr^{-1}$)±SE in the case study area (179 ha).

Five main types of harvests were recognized in the analyzed forest area: regeneration harvests, thinning, sanitary harvests, selection harvests, and harvest due to a construction of forest roads (Figure 3.3-2). On average, the largest amount of timber was harvested in regeneration harvests (59.5 $m^3ha^{-1}yr^{-1}$), followed by selection harvests (48.1 $m^3ha^{-1}$ $yr^{-1}$) performed only before 1970s, thinnings (28.2 $m^3ha^{-1}$ $yr^{-1}$), sanitary fellings (4.8 $m^3ha^{-1}$ $yr^{-1}$), and harvests for forest roads (3.6 $m^3ha^{-1}$ $yr^{-1}$). After the 1970s and the introduction of a combination of "uneven-aged" silvicultural systems it was impossible to delineate between the selection and regeneration harvests, therefore they were joint into the category of regeneration harvests. In the first decades after this introduction, the intensity of regeneration harvests decreased, but after 2000 it increased again. Thinnings were not registered regularly, since they were mainly executed together with regeneration and/or selection harvests. Sanitary harvests were carried out through the entire observation period with no significant peaks.

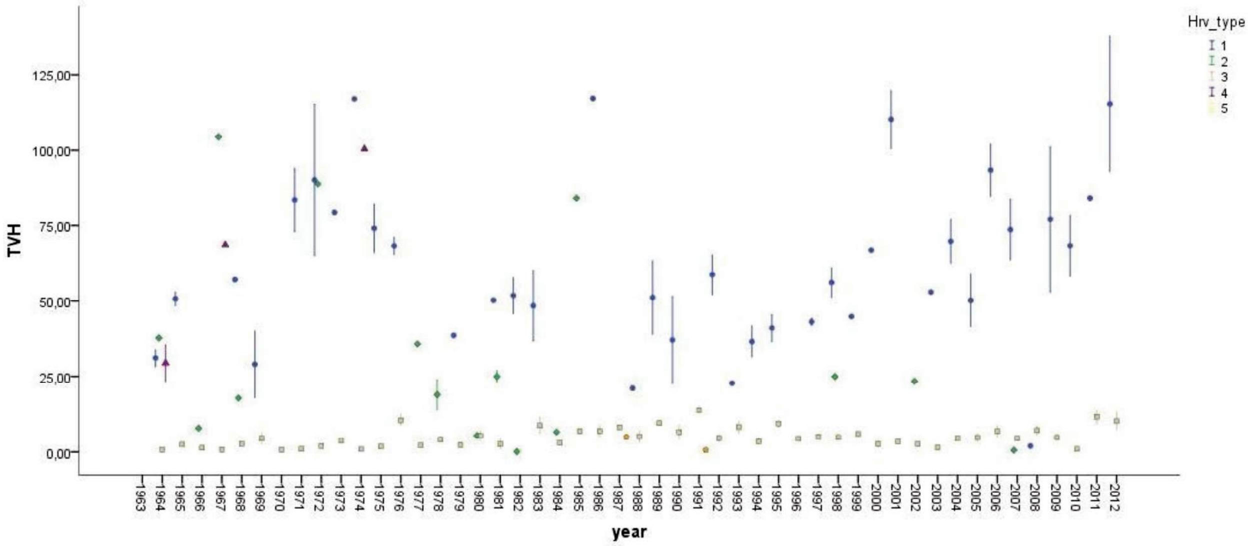



**Figure 3.3-2.** Dynamics of timber volume harvested TVH ($m^3ha^{-1}yr^{-1}$) ±SE per harvesting type (Hrv_type: 1, regeneration felling; 2, thinning; 3, sanitary felling; 4, selection harvest; 5, harvest for forest roads construction).

*b. Productivity ($m^3ha^{-1}yr^{-1}$):*

Productivity of forest stands was estimated according to equation 1 described in the section 2.3. The observed general trend was that productivity increased during the observation period (Figure 3.3-3) – from 5.8 $m^3ha^{-1}yr^{-1}$ in the period 1963-1973 to 11.6 $m^3ha^{-1}yr^{-1}$ in the period 1993-2003.

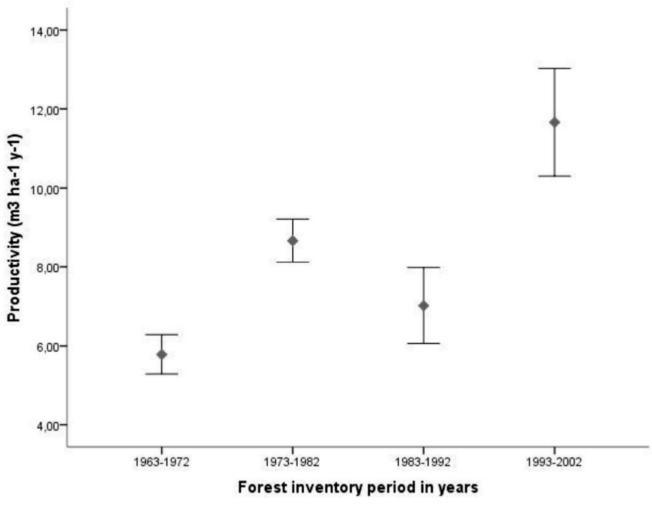



**Figure 3.3-3.** Productivity ($m^3ha^{-1}yr^{-1}$; mean ± standard error of mean) of the analyzed forest stands in CSA4 – Sneznik for the period 1963-2002.

However, some problems and systematic errors may be incorporated in these results. The first was the noise in estimated stand volume in compartments since the forest inventory methodology changed in 1993 – from full callipering to permanent sampling plots. This can be a reason for a drop in productivity in the period 1983-1992 (underestimated stand volume in 1993) and the following high increase in the period 1993-2002 when the new methodology was already fully adopted and enhanced, giving much more accurate results.

c. *Stocking ($m^3ha^{-1}$):*

The dynamics of stocking in stands was presented by changes in stand volume. The analysis revealed the increasing trend in stand volume (Figure 3.3-4). From the first forest inventory in 1912 to the last forest inventory analyzed in 2003 the average stand volume increased for 116% (from 214 $m^3ha^{-1}$ to 462 $m^3ha^{-1}$).

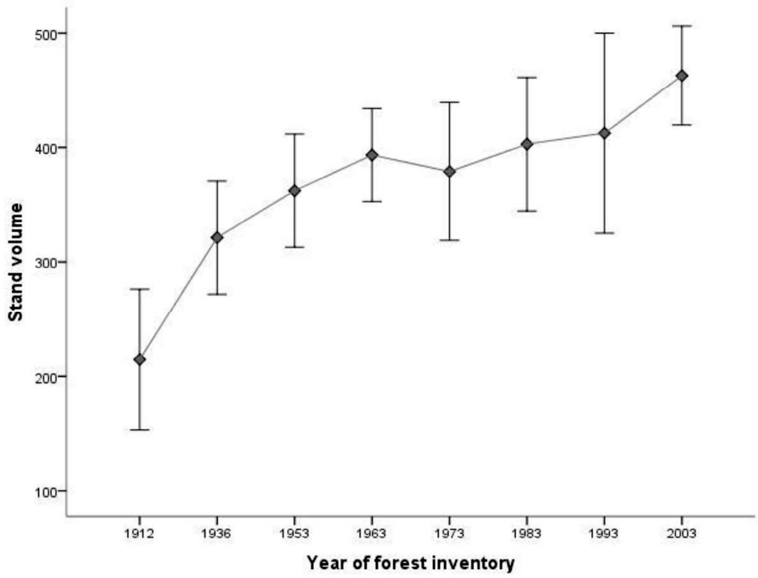



**Figure 3.3-4.** Dynamics of stand volume ($m^3ha^{-1}$) ±SE in CSA4 – Sneznik in the observation period 1912-2003.

The effect of forest management in the observed dynamics of stand volume cannot be unambiguously determined and explained. In general, uneven-aged forest management promotes high stand volumes. According to our results we can conclude that stands in the case study area were reaching an equilibrium stocking of 400-500 $m^3ha^{-1}$ (Schütz, 2001), since the range of stand volume in 2003 was 391-563 $m^3ha^{-1}$.

**(ii) Carbon storage**

Carbon storage was computed by means of the carbon sequestered above- and belowground, using the "wood volume method" (Cordonnier et al., 2013). The results are closely related to the ones obtained for the stocking. The observed general trend was an obvious increase in the amounts of both the aboveground and belowground carbon storage, but the intensities of the increase were slightly different. Between 1953 and 2003 the amount of aboveground carbon increased for 33.4%, while the same increase in belowground carbon was 43.7% (Fig. 3.3-5).

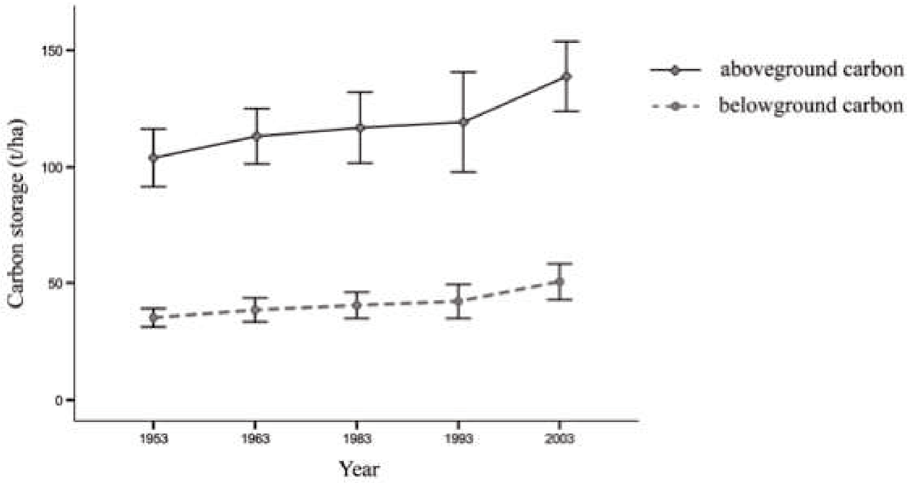



**Figure 3.3-5.** Aboveground and belowground carbon storage (t ha$^{-1}$; mean ± standard deviation) ±SE in the case study area for the period 1953-2003.

When analyzing the trends disaggregated into the tree species, we observed a significant relation to the dynamics of tree species composition. Increases in *Fagus sylvatica* and *Picea abies* carbon storage and in contrary a decrease in *Abies alba* carbon storage were noticed during the observation period (Fig. 3.3-6).

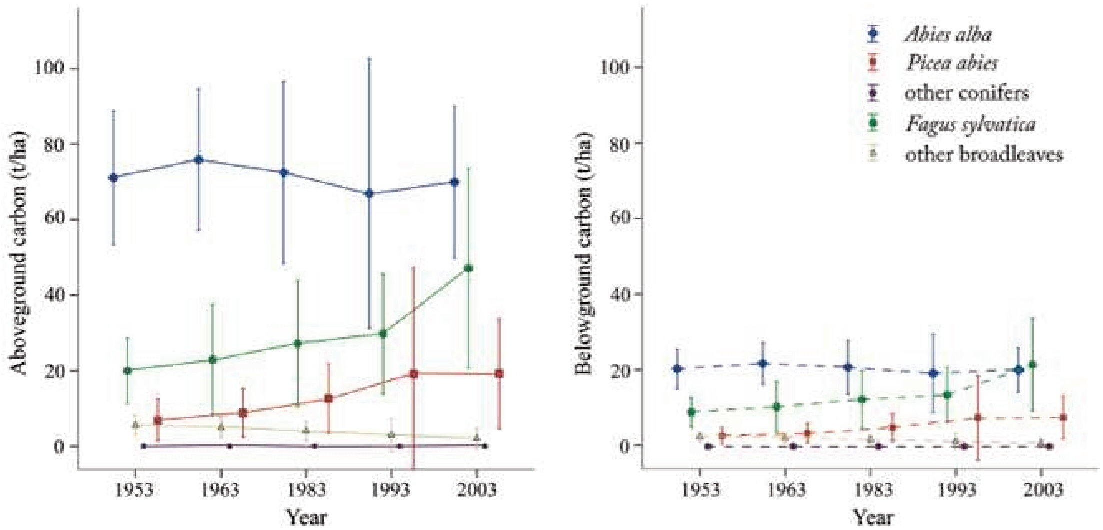



**Figure 3.3-6.** Aboveground (left) and belowground (right) carbon storage (t ha$^{-1}$; mean ± standard error of the mean) in CSA4 – Sneznik by tree species.

**(iii) Nature conservation**

In the CSA, the analysis of all three nature conservation indicators used in the study was performed; however, tree size diversity was approximated only by $H_{DBH}$ and not by the *post-hoc* index.

Species diversity was relatively constant throughout the entire observation period (Figure 3.3-7a), being the highest in the last forest inventory (*D*=2.5). The applied uneven-aged forest management in the case study area has obviously been maintaining a relatively constant mixture of tree species, and the change in the silvicultural system in the 1970s obviously did not have a significant influence in species diversity.

Tree size diversity index *Hdbh* increased in the period 1953-1983, but decreased afterwards (Figure 3.3-7b). Two reasons for that could be exposed. The first one is forest management with high harvests in the 1970s. The intensive harvesting in the 1970s resulted in less uneven-sized stands and decreased tree size diversity. The second reason is a changed forest inventory method. Forests in the case study area are characterized as a mosaic of irregular-sized patches of both even-aged (even-sized) and uneven-aged (uneven-sized) structure, being the result of forest management system applied in the area (the combination of different uneven-aged silvicultural systems). Patch size can range from a few hundred square meters to a few hectares (Boncina, 2011). Since the area surveyed by a permanent sampling plot is small (500 $m^2$), the entire plot can be placed into one (even-sized) patch, resulting in lower tree size diversity on a plot and consequently also on a landscape spatial level.

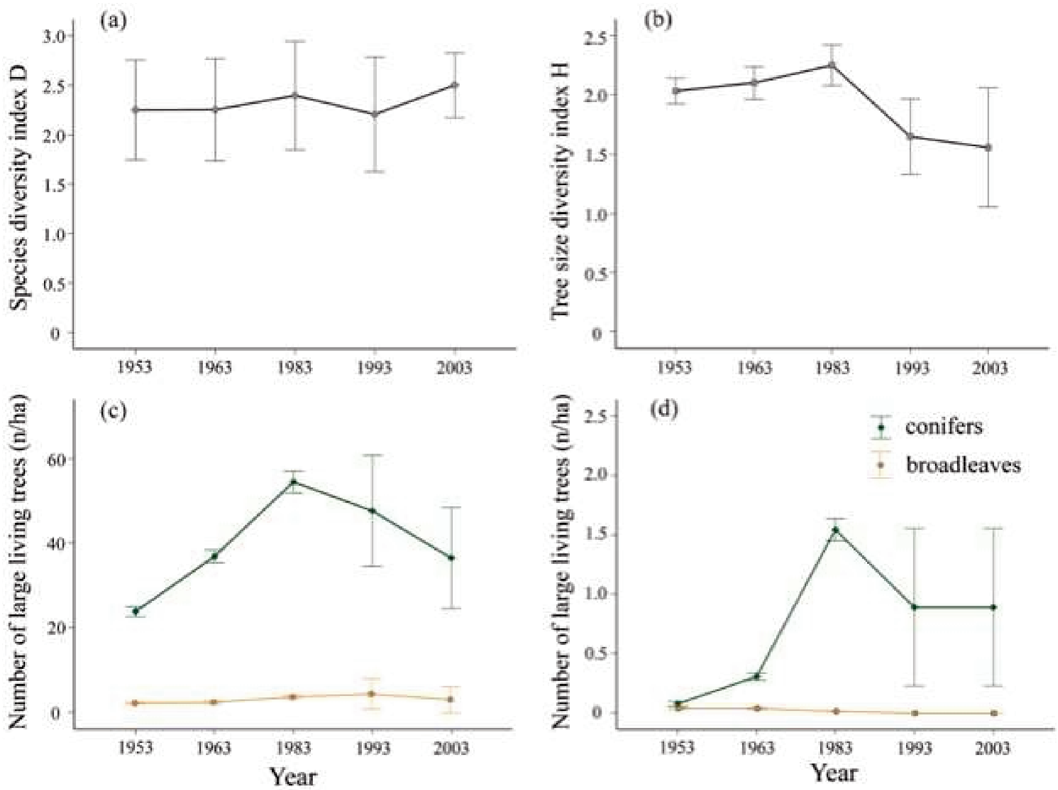



**Figure 3.3-7.** Dynamics of nature conservation indices in the case study area during the observation period: (a) species diversity index *D*; (b) tree size diversity index $H_{dbh}$; (c) number of large living trees with dbh≥50 cm; and (d) number of large living trees with dbh≥70 cm.

The amount of large living trees in the case study area was sufficient throughout the observation period if trees above 50 cm in dbh were considered (Figure 3.3-7c); their number was much lower if trees above 70 cm in dbh were considered (Figure 3.3-7d). However there were much more coniferous large sized trees than broadleaved ones (at trees of dbh≥50 cm by the ratio of 10.6 in 1953, 14.5 in 1983, and 11.7 in 2003). The decrease in the number of large living trees after 1983 could be explained by two reasons, forest management and forest inventory methods.

After 1983 some intensive regeneration (and selection) harvests were carried out, resulting also in reduction of large living trees since these trees are usually the first chosen to be cut (especially if of low vitality). The second reason is the survey method of permanent sampling plots since the small plot area minimizes a possibility of large living trees being registered.

Nature conservation status of forests in the case study area was relatively good during the entire observation period. All studied indicators showed that all diversities were on a high level resulting in high quality habitats for wildlife flora and fauna. Forests (and meadows) in the entire CSA4 Sneznik are included into Natura 2000 network (Natura 2000, 2014) and represent a habitat for many, also endangered, species: all three large carnivores present in Europe: brown bear (*Ursus arctos*), grey wolf (*Canis lupus*) and European lynx (*Lynx lynx*), several ungulate species (red deer *Cervus elaphus*, roe deer *Capreolus capreolus*, chamois *Rupicapra rupicapra*) and other endangered mammals (e.g. bats *Barbastella barbastellus*, *Myotis emarginatus* and *Rhinolophus hipposideros*), birds (e.g. *Strix uralensis, Aegolius funereus, Aquila chrysaetos*, *Picoides tridactilus, Dendrocopos leucotos*, *Dryocopus martius*, *Tetrao urogallus*, Bonasa bonasia*,* Lullula arborea and many others), amphibians (e.g. *Triturus carnifex*), butterflies (e.g. *Callimorpha quadripunctaria*, *Euphydryas aurinia*, *Maculinea teleius* and *Lycaena dispar*), beetles (e.g. *Morimus funereus*, *Rosalia alpine* and *Leptodirus hochenwarti*), and many endangered or even relict floristic species (e.g. *Cerastium dinaricum*, *Arabis scopoliana*).

### (iv) Correlation analysis

Several indicators of ES provisioning correlated significantly (Table 3.3-1). In general, no trade-off relation between studied ES was found, however some trade-off relations (i.e. negative correlation coefficient) between individual indicators were found.

Among indicators of timber production, the correlation analysis revealed significant positive relations between stand volume and several indicators of carbon storage and biodiversity conservation ES, but not between indicators of timber production themselves (Table 3.3-1). For the stand volume $V$ significant positive correlations were found with carbon storage $C_{above}$ and $C_{below}$, tree size diversity $H_{dbh}$ and abundance of large living trees $LLTN$, and only one significant trade-off relation with species diversity $D$.

Carbon storage ($C_{above}$ and $C_{below}$) was highly positively related to abundance of large living trees $LLTN$, $C_{above}$ also with tree size diversity index $H_{DBH}$. Since $C_{below}$ was calculated directly from $C_{above}$ a very high positive relation between them was expected.

All three indicators of biodiversity conservation were significantly correlated, however species diversity $D$ correlated negatively to both, tree size diversity $H_{DBH}$ and abundance of large living trees $LLTN$. The abundance of large living trees $LLTN$, however, was strongly positively correlated to tree size diversity $H_{dbh}$.

**Table 3.3-1.** Spearman's correlation coefficients between indicators of ES provisioning in CSA4 – Sneznik.

| Indicator | ***TVH*** | ***VI*** | $C_{above}$ | $C_{below}$ | ***D*** | $H_{dbh}$ | ***LLTN*** |
|---|---|---|---|---|---|---|---|
| ***V*** | -0.018 | -0.027 | 0.963** | 0.792** | -0.272* | 0.411* | 0.624** |
| ***TVH*** | - | -0.084 | 0.006 | -0.080 | -0.218 | 0.061 | 0.053 |
| ***VI*** | | - | -0.026 | -0.050 | -0.144 | 0.410* | 0.558** |
| $C_{above}$ | | | - | 0.911** | -0.125 | 0.361* | 0.592* |
| $C_{below}$ | | | | - | 0.184 | 0.201 | 0.432* |
| ***D*** | | | | | - | -0.333* | -0.349* |
| $H_{dbh}$ | | | | | | - | 0.720** |
| ***LLTN*** | | | | | | | - |

## 3.4 CSA5 – Vilhelmina, Scandinavian Mountains, Sweden

The Swedish case differs from the other case study areas. In this CSA the data from the inventories comes from the National Forest Inventory (NFI), consisting of a series of plots located following a grid. Although the number of plots is high, the problem with these inventories lays in the fact that the aggregation of the plots is not possible since we do not have the information of the type of stands inventoried in each plot. Therefore the type of analysis that can be carried out using these plots is too general and very descriptive. Moreover, the time period analyzed is not long enough to allow the derivation of any significant results.

The Swedish case differs from the other case study areas. In this CSA the data from the inventories comes from the National Forest Inventory (NFI). The design of Swedish NFI is made for producing results at the county and country level, and not for an area as Vilhelmina, or smaller. Moreover, the time period analyzed is not long enough to allow the derivation of any significant results.

Nevertheless, the analyses were carried out for the plots that were inventoried in the same years with the aim of depicting a general trend.

**(i) Wood production**

*a. Timber volume harvested ($m^3ha^{-1}yr^{-1}$)*

No data are available at the plot level.

*b. Productivity ($m^3ha^{-1}yr^{-1}$)*

In this CSA, productivity was not computed using Eq. 1 because the values of VI were provided by the CSR. The trend (Figure 3.4-1) shows that productivity increases in the analyzed period with the exception of a slight decrease between the 1988 and 1994 inventories.


**Figure 3.4-1.** Productivity ($m^3ha^{-1}yr^{-1}$; mean ± standard error of the mean) presented by the different compartments analyzed in CSA5 – Vilhelmina for the period 1983-2008.

*c. Stocking ($m^3ha^{-1}$)*

Results of the stocking volume show an increase (24%) during the analyzed period, from 70 $m^3ha^{-1}$ to 87 $m^3ha^{-1}$ (Figure 3.4-2).

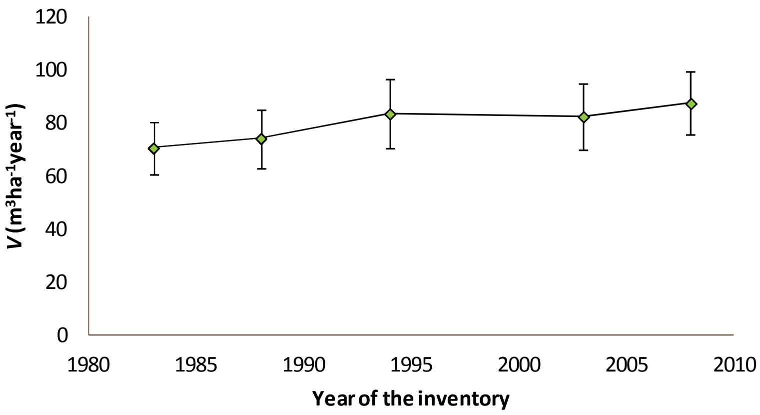



**Figure 3.4-2.** Stocking ($m^3ha^{-1}$; mean ± standard error of the mean) presented by the different compartments analyzed in CSA5 – Vilhelmina for the period 1983-2008.

**(ii) Carbon storage**

Carbon storage follows the same trend as stocking volume (cf. above and Figure 3.4-3).

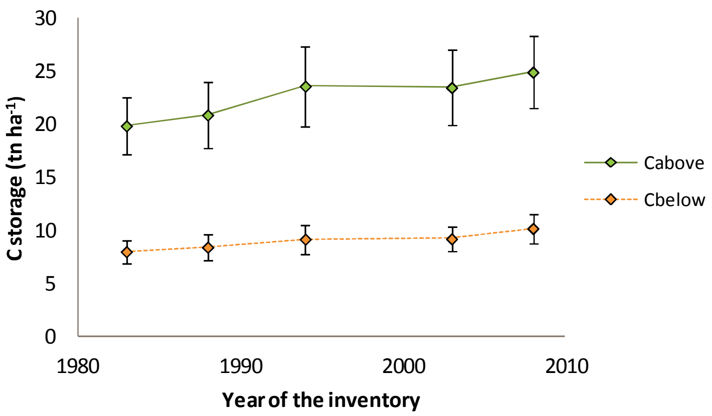
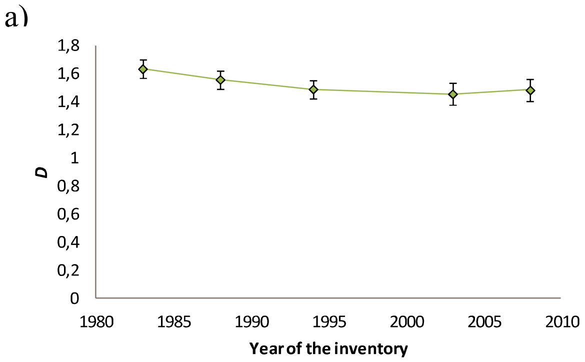



**Figure 3.4-3.** Carbon storage ($t.ha^{-1}$ ; mean ± standard error of the mean) above and below ground presented by the different compartments analyzed in CSA5 – Vilhelmina for the period 1983-2008.

**(iii) Nature conservation**

The results show that the nature conservation indices slightly decrease during the analyzed period, which is very interesting considering that even though the adoption of nature–conservation practises since the 1980's, the nature conservation values as measured here have decreased (Figure 3.4-4).



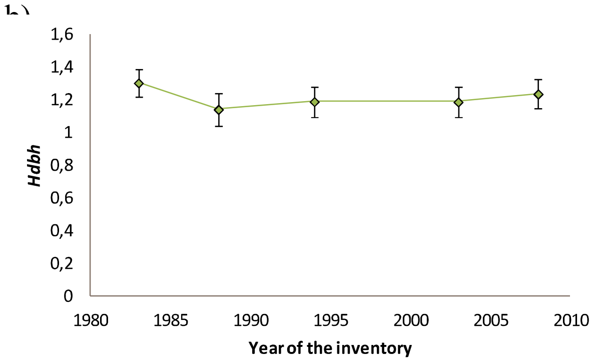




**Figure 3.4-4.** Dynamics of nature conservation indices in the case study area during the observation period: a) species diversity index D, b) tree size diversity index $H_{dbh}$.

### (iv) Correlation analysis

When analyzing the potential trade-offs among the different ES, the results (Table 3.4-1) do not show any trade-off among them but there are some significant synergies between some of them. This is the case with wood production and carbon storage. Moreover these ES also show a significant positive correlation with the structural diversity. This synergy may be due to the fact that since the 1980´s nature conservation objectives were included in FM practices. The effects of this policy are depicted by the trend followed by *Hdbh*.

**Table 3.4-1.** Spearman's correlation coefficients between indicators of ES provisioning in CSA5 – Vilhelmina.

| Indicator | *VI* | $C_{above}$ | $C_{below}$ | *D* | $H_{dbh}$ |
|---|---|---|---|---|---|
| *V* | 0.607** | 0.999** | 0.967** | -0.025 | 0.283** |
| *VI* | - | 0.616** | 0.607** | -0.034 | 0.181* |
| $C_{above}$ | | - | 0.984** | -0.024 | 0.284** |
| $C_{below}$ | | | - | -0.015 | 0.290** |
| *D* | | | | - | -0.020 |
| $H_{dbh}$ | | | | | - |

## 3.5 CSA6 – Kozie Chrbty, Western Carpathians, Slovakia

In the Slovakian CSA, the majority of the information comes from the records of the Forest Management Plans (FMPs). The used FMPs refer to periods 1977-1986, 1987-1996, 1996-2005 and 2006-2015. The FMPs contain information on stand functional category, stand area, applied rotation and regeneration periods, stand age and stocking volume for each tree species, species proportion, dimensions of mean stem (diameter, height, volume), yield class and growing stock. Planned silviculture and harvesting operations are specified as well. Information from the FMPs was complemented in 2012 by more detailed inventory. In the inventory, circular plots (25 m in diameter) distributed equally within a stand and covering a ca 5% of stand area were surveyed. Number of living tress for each tree species, tree diameters in a 1 cm class and heights in each diameter class, were measured. Share of dead trees was estimated as well. In addition, sanitary felling data for the period 1998-2011 were available.

**(i) Wood production**

*a. Timber volume harvested ($m^3ha^{-1}yr^{-1}$):*

In order to analyze the evolution of the different ES along the years, the first analysis carried out consisted in characterizing the type of cuttings that took place along the life of the different stands. For this analysis, the harvested volume was employed as an indicator. Figure 33.20 shows the evolution of the type of thinning. At the beginning of the planning period a regeneration cutting took place; after this, thinnings were the most common practise, but since 1999 only sanitary felling took place. Analysing this indicator from the point of view of stand age we can conclude that, in general terms, sanitary fellings were replacing thinning and regeneration fellings. This trend is particularly important for spruce.

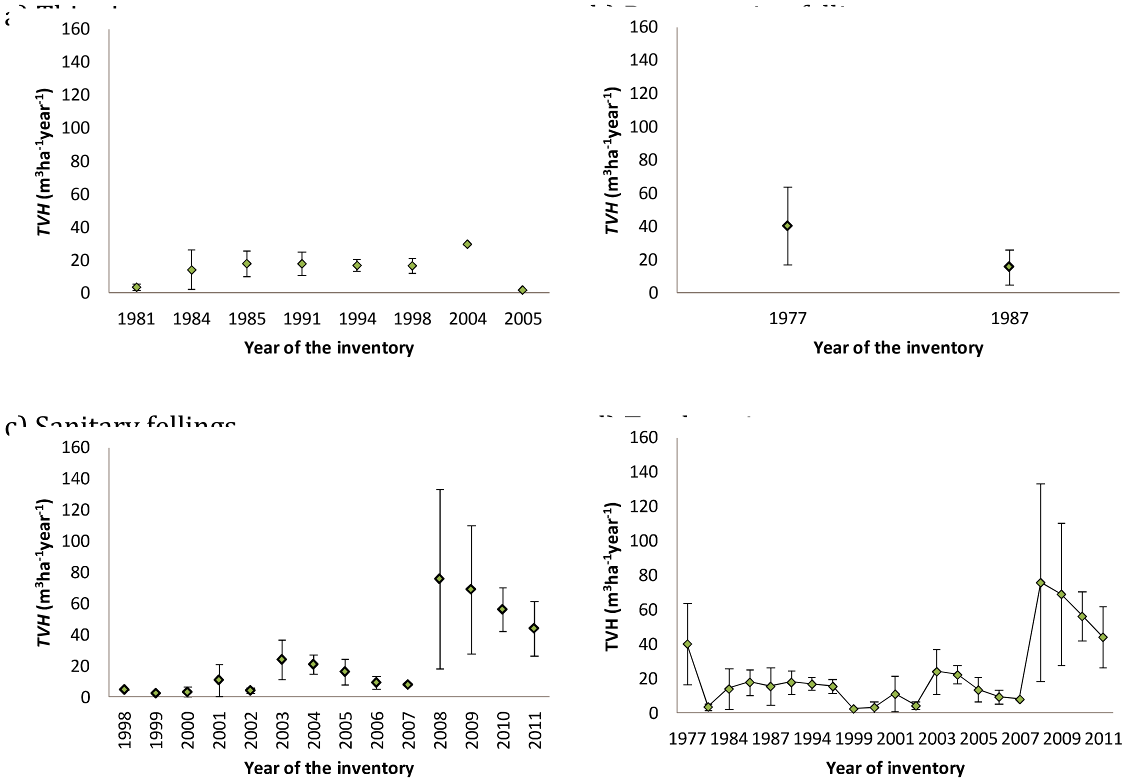



**Figure 3.20.** Timber harvested (m$^3$ha$^{-1}$yr$^{-1}$; mean ± standard error of mean) in CSA6 – Kozie Chrbty in the analyzed period, according to the different type of cuttings performed.

*b. Productivity (m$^3$ha$^{-1}$yr$^{-1}$):*

According to the results (Figure 3.21), the productivity of the stands increased over time, from a mean value of 6 m$^3$ha$^{-1}$year$^{-1}$ in 1987 to 21.5 m$^3$ ha$^{-1}$year$^{-1}$ in 2012, implying an increase of 250% along the analyzed period.

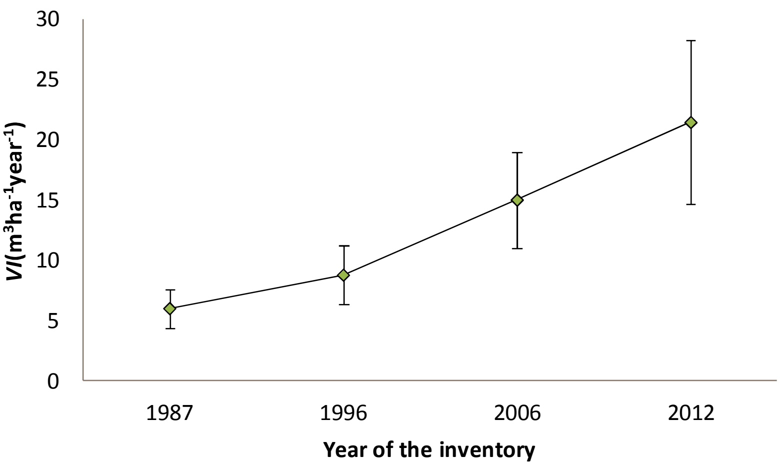



**Figure 3.21.** Productivity (m$^3$ha$^{-1}$yr$^{-1}$) presented by the different compartments presented in CSA6 – Kozie Chrbty in the analyzed period.

*c. Stocking ($m^3ha^{-1}$):*

The stocking of the stands increased all over the analyzed period.


**Figure 3.22.** Stocking ($m^3ha^{-1}$) presented by the different compartments presented in CSA6 – Kozie Chrbty in the analyzed period.

**(ii) Carbon storage**

Carbon storage is computed by means of the carbon sequestered above- and belowground. Since these indicators are computed using the "wood volume method", the results are closely related to those obtained for the stocking (Fig. 3.23).

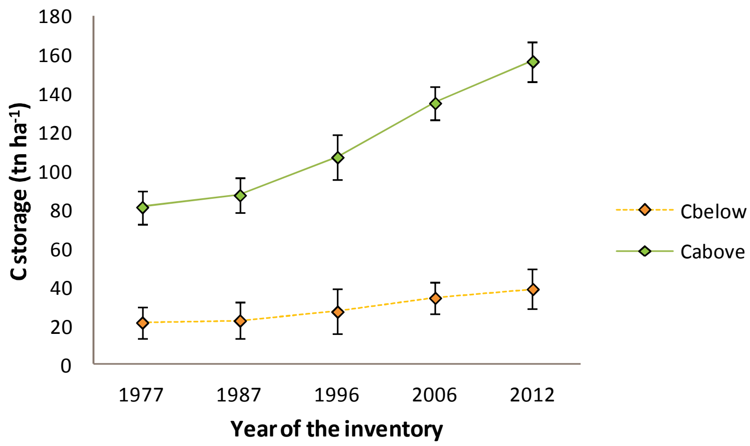



**Figure 3.23.** Carbon storage ($t.ha^{-1}$) above and below ground by the different compartments presented in CSA6 – Kozie Chrbty in the analyzed period.

### (iii) Nature conservation

*a. Tree species diversity*

According to the results obtained when computing the diversity index *D*, it seems that the diversity decreases over the analyzed period.

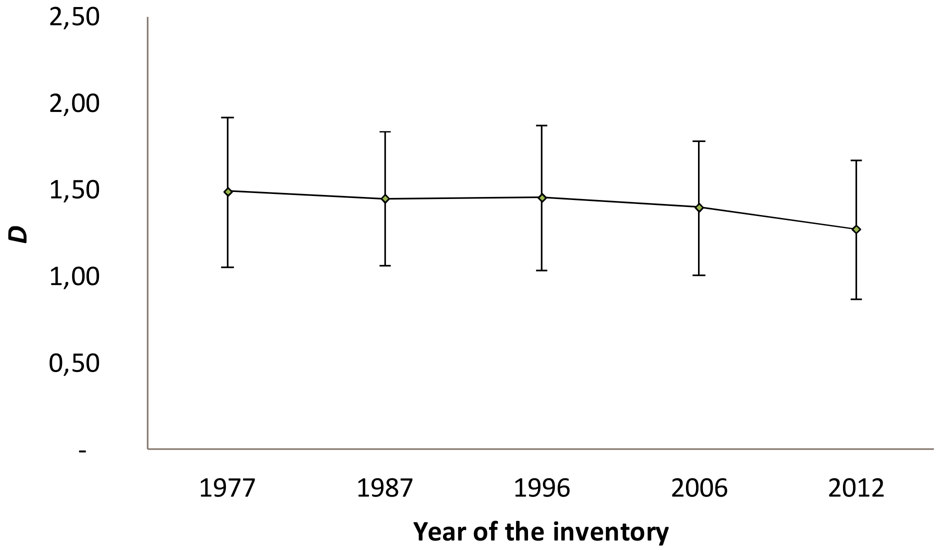



**Figure 3.24.** Tree species diversity index ±SE observed in the different compartments presented in CSA6 – Kozie Chrbty in the analyzed period.

The *D* and *LLTN* indices were not computed in this CSA because the diameter distributions were available for the inventory carried out in 2012 only.

### (iv) Correlation analysis

Analysing the performance of the different ES along the historic series, it can be seen (Table 3.5) that, again, there are no clear trade-offs among ES themselves but there are among some individual indicators of those ES. For instance, the only one indicator of nature conservation (*D*) computed for this CSA presents a negative relationship with stocking volume. At the same time, the species diversity index is also positively correlated with *TVH*. These relationships give an idea of how FM affects nature conservation, in the Slovakian CSA the increase in *TVH*, and the consequent decrease in *V*, leads to an increase in the *D.* This might be because the fellings are more concentrated in spruce, so when the fellings take place the “proportion” of other species increase.. Regarding carbon storage, it presents a synergetic relationship with both stocking volume and productivity.

**Table 3.5.** Spearman's correlation coefficients between indicators of ES provisioning in CSA6 – Kozie Chrbty.

| **Indicator** | ***TVH*** | ***VI*** | $C_{above}$ | $C_{below}$ | ***D*** |
|---|---|---|---|---|---|
| ***V*** | -0.294 | 0.569** | 0.983** | 0.941** | -0.283* |
| ***TVH*** | - | -0.815** | -0.293 | -0.319 | 0.833 |
| ***VI*** | | - | 0.499** | 0.492** | -0.278 |
| $C_{above}$ | | | - | 0.964** | -0.268* |
| $C_{below}$ | | | | - | -0.112 |
| ***D*** | | | | | - |

The interest of these results lays in the fact that, theoretically, the main objective in European forest was timber production and this trend was supposed to shift towards the multiple use of the mountain forests where nature conservation had an important role. The results show that this was not the case in the Slovakian case study.

## 3.6 Provisioning of ES across the case study areas

Timber production indicators generally increased during the observation periods in the CSA (Table 3.6-1). In the French and Slovenian CSA, TVH remained relatively constant throughout the observation period (87 years in the first and 49 years in the later CSA, respectively). This can be a consequence of the application of uneven-aged silvicultural systems in both CSA – single tree selection system in the French CSA and a combination of several "uneven-aged" systems in the Slovenian CSA – which should permanently and continuously provide constant timber yields over a long period of time on a relatively small forest area (Schütz, 2001). Standing volume increased in all CSAs over the observation period, as was the case with productivity.

Following the trend in stocking, the provisioning of carbon storage ES increased during the observation period in all CSAs.

Biodiversity conservation was the only ES which differed significantly between the CSAs. Biodiversity indicators increased in the Spanish and French CSA, remained rather constant in the Slovenian CSA, and decreased in the Swedish and Slovakian CSA. If we compare this result to silvicultural systems and/or prevailing types of harvests in the CSA, we find that systems creating even-aged stands (i.e. clear cutting system, uniform shelterwood system) decreased provisioning of biodiversity conservation ES, especially in combination with intensive sanitary harvests (the case of Slovakian CSA).

**Table 3.6-1.** Summary of the historical trends of ES provisioning found in the CSA (↑- an increasing trend; ↓ - a decreasing trend; ↑↓ - an increasing trend in a certain period, but a decreasing trend in the last period; ↓↑- a decreasing trend in a certain period, but an increasing trend in the last period; ↔ - a stagnating trend of ES; - - not available or not applicable.

| CSA | Valsain | France | Slovenia | Sweden | Slovakia |
|---|---|---|---|---|---|
| **Stand type** | Pure stands,<br><br>Even-aged | Mixed stands<br><br>Uneven-aged | Mixed uneven-aged stands | Mixed stands<br><br>Even-aged | Mixed stands<br><br>Even-aged |
| **FM** | Uniform shelterwood (before Group system) | Individual tree selection | Single tree selection system, changed in the 1970s to an irregular shelterwood system in combination with group selection and single tree selection systems | Clear cutting (before selection cutting) | Uniform shelterwood |
| **ES / indicators** | | | | | |
| **Timber production** | ↑ | ↑ | ↑ | ↑ | ↑ |
| TVH | ↑ | ↔ | ↔ | - not available | ↑ |
| Productivity | ↓↑ | ↑ | ↑ | ↑ | ↑ |
| Stocking | ↑ | ↑ | ↑ | ↑ | ↑ |
| **Carbon storage** | ↑ | ↑ | ↑ | ↑ | ↑ |
| **Biodiversity conservation** | ↑ | ↑ | ↔ | ↓ | ↓ |
| Species diversity | - not applicable | ↑ | ↔ | ↓ | ↓ |
| Tree size diversity | ↔ | ↑ | ↑↓ | ↓ | - not available |
| Abundance of large living trees | ↑ | ↑ | ↑↓ | - not applicable | - not available |

# 4 Business-As-Usual management and its implications in the Case Study Areas

## 4.1 Case Study Area CSA1 (Valsain)

### 4.1.1 Simulation setup

Three different forest management (FM) systems are being used in CSA1: even-aged, coppice and no management. Even-aged FM is applied in *Pinus sylvestris* stands, coppice in the *Quercus pyrenaica* stands and no management in the *Quercus ilex* stands. In the pure *Pinus sylvestris* even-aged stands, the regeneration method is the group shelterwood system, with a rotation period of 120 years and initial density between 3250 and 6500 seedlings/ha (natural regeneration). One tending (at t=20 years), three thinnings (at t= 40, 60 and 80 years; removal of 15-30% of standing volume) and 3-4 regeneration fellings (at t=100, 110, [115] and 120 years) are applied. In the pure coppice *Quercus pyrenaica* stands, clearcutting is the regeneration method, with a rotation period of 70 years, and an initial stand density of 3600 to 4000 shoots/ha (natural regeneration). One tending (at t=20 years) and three or four thinnings (at t= 30, 40, [50] and 60 years; removal of 30-45% of standing volume) are applied. In the mixed *Pinus sylvestris-Quercus pyrenaica* stands, as both species are mixed in small patches, single-species groups are managed as pure stands, although some practices are simplified and/or matched on time.

All simulations were conducted for 1 ha areas and run for 100 years under 6 climate scenarios (current climate baseline and 5 climate change scenarios). Operations included in tending, thinning and regeneration fellings were applied following the description of D1.3, Annex 2. Pure *Quercus pyrenaica* stands were simulated as coppice forests and the regeneration from sprouting is achieved by clearcutting. The simulations with the model were done separately for gap areas and for the rest of the area. The results were subsequently aggregated using the area shares of both implemented simulations (60% gap area, 40% other forest area). In the mixed RSTs the two tree species (*Pinus sylvestris* and *Quercus pyrenaica*) are distributed in patches. Furthermore the treatments differ and do not occur simultaneously, so the simulations were run separately and then the results were aggregated.

All indicators included in D1.5 were calculated, except for *2.3 Dead wood carbon* (*C_dw*), *2.4 Soil carbon* (*C_soil*), *4.3.1 Abundance of dead wood* (*DWV*) and *3.1 Above ground wood energy biomass harvest* (*BMH*). Additionally, *Standing dead wood volume* (*SDWV*) and *Bird habitat quality* (*BHQ*) were included.

### 4.1.2 Simulation results

Results of simulations over the 100 years are shown for the three main stand types: pure *P. sylvestris* stands (examples are shown for RST 11.4; Fig. 4-1), pure *Q. pyrenaica* stands (examples are shown for RST 7.1; Fig. 4-2) and mixed stands of both species (examples are shown for RST 6.3; Fig. 4-3). The values of the stocking volume over the 100-years simulation period for a pure high quality, over-mature *Pinus sylvestris* stand (RTS 11.4: 1500 m, SI 26 m) follow the silviculture applied, with maximum volumes between 420 and 560 $m^3 \cdot ha^{-1}$, and average values between 195 and 236 $m^3 \cdot ha^{-1}$, depending on the climate scenario (Fig. 4-1). Similar trends are shown for above- (average between 54 and 62 $t \cdot ha^{-1}$) and belowground carbon and basal area (average between 25 and 28 $m^2 \cdot ha^{-1}$). All these ES decreased for climate scenarios C4 and C5, while they are similar for the other scenarios.

The BAU management maintained a maximum canopy cover between 80-90% for all climate scenarios, i.e, there is a good cover of the space. The standing dead wood volume (SDWV) has average values between 12 and 20 $m^3 \cdot ha^{-1}$, and it is higher for climate scenario C1. Average current annual volume increment (VI) is highest between the years 60 and 80 of the simulation, which corresponds to the ages 40 to 60 of the stand. For climate scenarios C4 and C5, VI is delayed, i.e, growth is slowed down. Total volume harvested (TVH) over the 100-year simulation varied between 354 and 411 $m^3 \cdot ha^{-1}$. Again, climate scenarios C4 and C5 decreased TVH. For this RST (highly productive pure *P. sylvestris* stands at 1500 m), climates C4 and C5 will negatively affect the provision of all measured ES, while the response in terms of productivity to the other climate scenarios is quite similar. In addition, climate scenario C3 is the best for TVH, while with the current climate SDWV shows the higher average values.

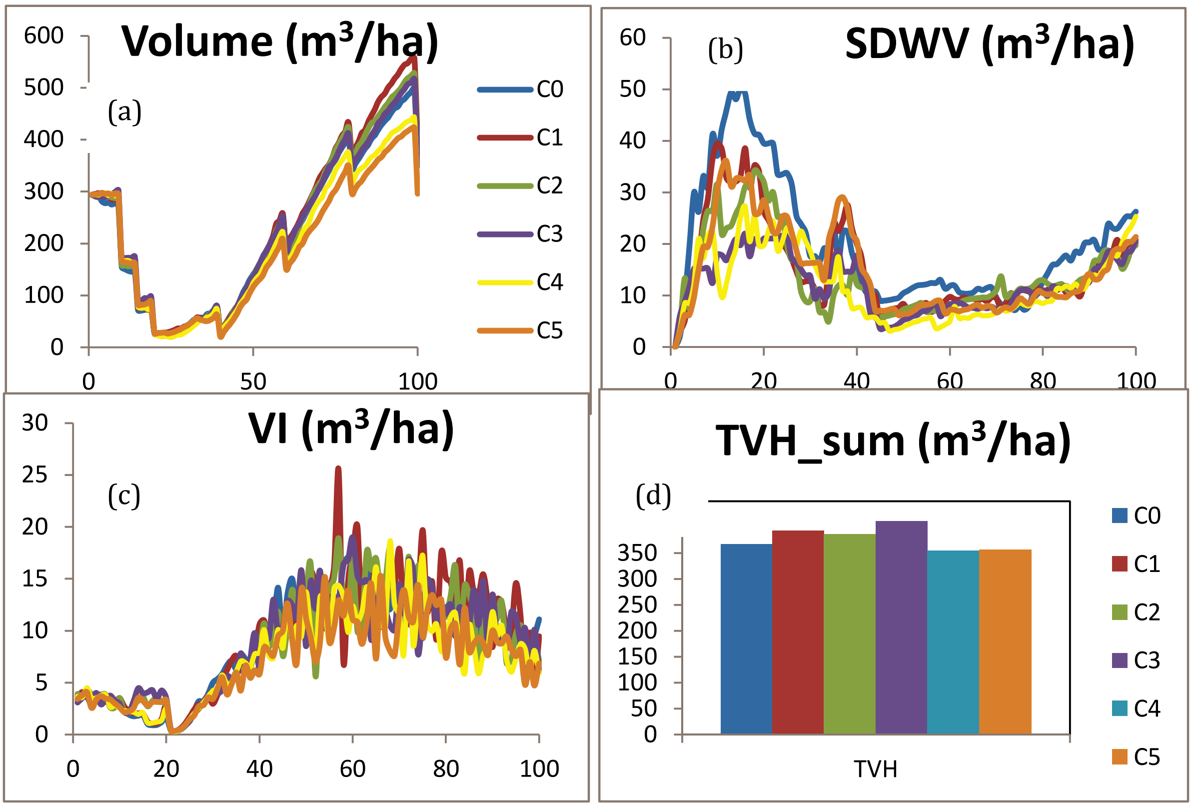



Fig. 4-1. (a) Stocking volume (V, m³/ha), (b) standing dead wood volume (SDWV, m³/ha) and (c) current annual volume increment (VI, m³/ha) over the 100-year simulation period; and (d) total volume harvested (TVH, m³/ha) at the end of the 100-year simulation for the baseline climate and five climate scenarios in RST 11.4 (pure *Pinus sylvestris* 120 years old stands, SI=26 m, 1500 m).

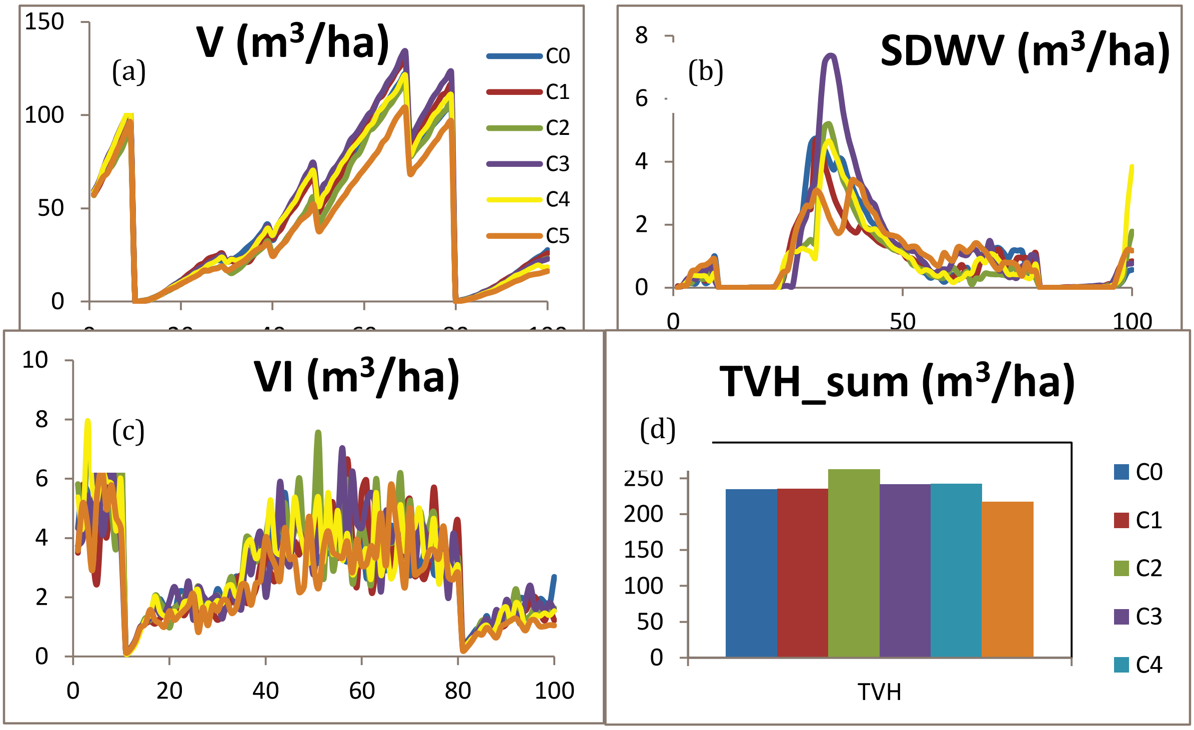



Fig. 4-2. (a) Stocking volume ( m³/ha), (b) standing dead wood volume (SDWV, m³/ha) and (c) current annual volume increment (VI, m³/ha) over the 100 years simulation period; and (d) total volume harvested (TVH, m³/ha) at the end of the 100 years simulation for the baseline climate and five different climate scenarios, in RST 7.1 (pure dense *Quercus pyrenaica* stands at 1250m, SI=17 m)

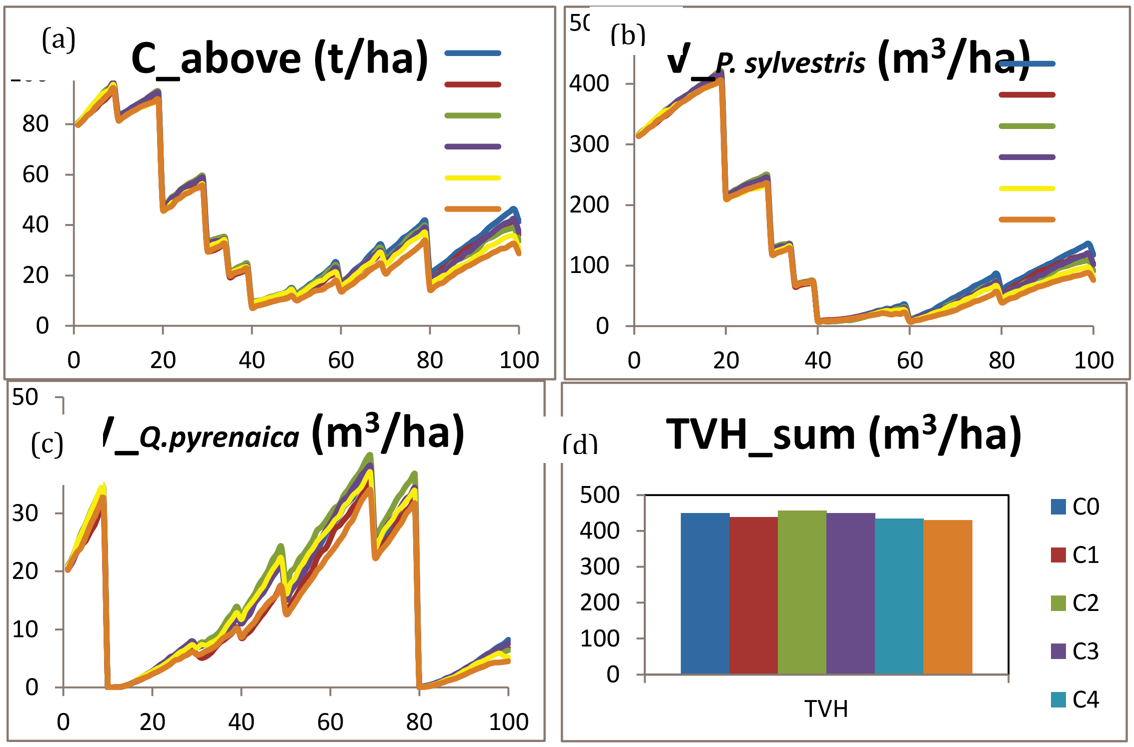



Fig. 4-3. (a) Carbon storage above (C_above, t/ha), (b) stocking volume for *P. sylvestris* (V, m³/ha) and (c) stocking volume for *Q. pyrenaica* (V, m³/ha) over the 100 years simulation period; and (d) total volume harvested (TVH, m³/ha) at the end of the 100-year simulation for the baseline climate and five different climate scenarios, in RST 6.3 (mixed *P. sylvestris*(70%, SI=19) – *Quercus pyrenaica* (30%, SI=17) stands at 1250 m).

Maximum values of stocking volume (V) in RST 7.1 (pure coppice dense *Q. pyrenaica* stands, 1250 m, SI=17 m) varied between 104 and 130 m³·ha⁻¹, while average values varied between 39 and 50 m³·ha⁻1, according to the climate scenario. Similar trends to V, over the 100-year simulation period, were evident for carbon storage (average between 19 and 24 t·ha-1) and basal area (average between 7.5 and 9.2 m²·ha⁻¹). Maximum VI values are shown at the age of 30 to 50 (that correspond to years 40 to 60 of the simulation). As in *P. sylvestris*, VI is delayed under climate scenarios C4 and C5. The standing dead wood volume (SDWV) has average values between 0.83 and 1.2 m³·ha⁻¹, and it is higher for climate scenario C3. Total volume harvested (TVH) over the 100-year simulation varied between 217 and 262 m³·ha⁻¹. In these stands, climate scenarios C1 and C5 (the driest and hotter) showed the lowest values for the ES analyzed, while the response of the ES to climate scenarios C2 and C3 were usually the best (Fig. 4-4).

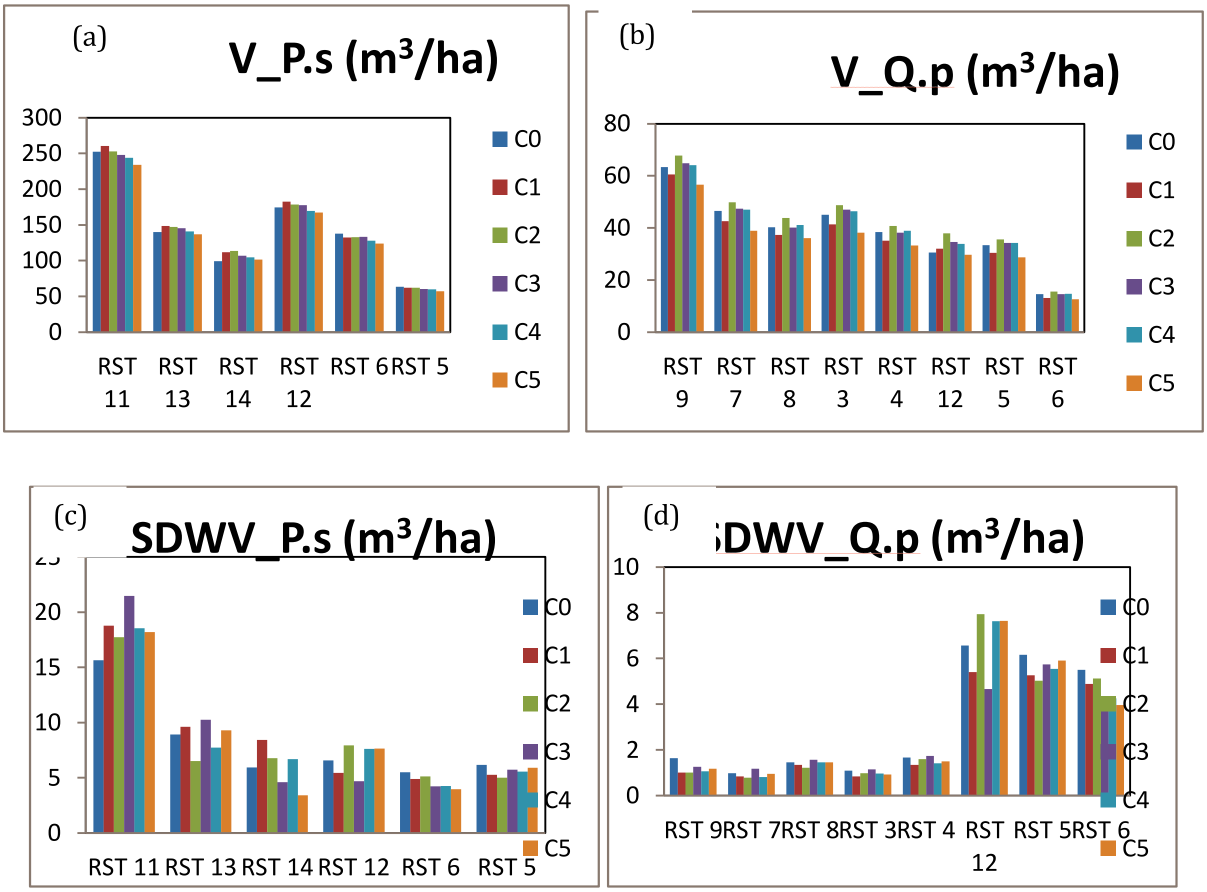



Fig. 4-4. Stocking volume (V, m³/ha) and standing dead wood volume (SDWV, m³/ha) for all *P. sylvestris* ((a) and (c)) and *Q. pyrenaica* ((b) and (d)) stands at the end of the 100-year simulation for the baseline climate and five scenarios of climate change.

In *P. sylvestris* (70%) – *Q. pyrenaica* (30%) mixed stands at 1250 m (RST 6.3, *P. sylvestris* 80 years, SI 29 m and *Q. pyrenaica* coppice SI 17 m) average aboveground carbon varies between 38 and 41 t·ha⁻¹. Canopy cover is maintained between 60-70% for all climate scenarios, and standing dead wood volume (SDWV) has average values between 4.0 and 5.5 m³·ha⁻¹. Productivity in *P. sylvestris* is reduced over the 100-year simulation period for all climate scenarios, although stocking volume (V) at the beginning of the simulation was similar to V in the pure *P. sylvestris* stands. Under climate scenario C5 all the ES decreased. Productivity of *Q. pyrenaica* in mixed stands at 1250 m also decreased under climate scenario C1, which is the driest after climate scenario C5, while *P. sylvestris* is more negatively affected by climate scenario C4.

The comparison of the three RSTs with pure *P. sylvestris* stands (RST 11, 13 and 14) show that stocking volume (V) (and related ES) decreases with higher altitude and lower site index (SI). In addition, under climate scenarios C4 and C5, productivity decreases. However, in the stands located at higher altitudes (RST 14) the decrease is not so evident. In mixed stands (RST 12, 6 and 5), *P. sylvestris* productivity decreases with lower shares (30%), lower altitudes (1250 m) and under climate scenarios C4 and C5. In summary, under the hotter climate scenarios (C4 and C5) *P. sylvestris* stands show a poor performance at lower altitudes; while the effect of climate scenarios C4 and C5 is not so negative as the altitude increases. Differences in SDWV are mainly related to RST, while the effect of the climate scenarios does not follow a similar trend for all RSTs.

Productivity in the six RSTs with pure *Q. pyrenaica* (RST 3, 4, 7, 8, 9 and 10, all located at 1250 m) decreases according to site type and with lower densities. In mixed stands (RST 12, 6 and 5), productivity decreases according to site type, with lower shares (30%) and lower altitudes. In all *Q. pyrenaica* stands, productivity decreases under climate scenarios C1 and C5, which are the hotter and drier scenarios, while the best results are shown for climate scenarios C2 and C3. There are no differences in SDWV between the RSTs with pure *Q. pyrenaica*, while SDWV decreases similarly to the productivity in the mixed stands.

### 4.1.3 Discussion

ES related with volume and carbon storage are satisfied both in pure *P. sylvestris* stands and in mixed stands where *P. sylvestris* is the dominant species, for altitudes over 1500m. However, volume and carbon storage are defective in those RST with pure coppice *Q. pyrenaica* stands or in mixed stands where *Q. pyrenaica* is the dominant species. Even under the baseline climate, a reduction in the productivity of *P. sylvestris* mixed stands located in the lower parts (RST 5 and 6) is expected. The BAU guarantees a continuous canopy cover in the pure *P. sylvestris* stands. SDWV and LSDTV are guaranteed by BAU.

*P. sylvestris* is more sensitive to the climate scenarios with increasing temperature (C4 and C5) than to those that reduce precipitation. At higher altitude *P. sylvestris* is favored by higher temperatures, i.e. the climate scenarios with a moderate temperature increment (C1 and C2) can lead to higher productivity in *P. sylvestris* stands over 1500m. The proposed scenarios that reduce precipitation do not affect *P. sylvestris* when compared to the baseline climate, except in the lower parts of the forest (1250m). *Q. pyrenaica* is more sensitive to the reduction in precipitation (climate scenarios C1 and C5), while the increases in volume and carbon storage are related to climate scenarios with moderate temperature increase and moderate precipitation reduction (climate scenarios C2 and C3). Current climate (C0) may not fully represent the historic climate in the region as a productivity deacrease is simulated, particularly at low elevation sites. To make these results concrete enough so as to be able to derive guidelines for forest practive, there is a need to adapt the management in pure and mixed *Q. pyrenaica* stands to increase the stocking volume and the canopy cover, i.e., we need less density, but larger trees. Furthermore, there is a need for a specific management in mixed *P. sylvestris* stands in the lower areas (1250 m) because even the baseline climate has led to a significant decrease in the productivity. The Adaptive Management (AM) simulations will be an important next step towards this goal.

## 4.2 Case Study Area 2: Vercors

### 4.2.1 Simulation setup

Nineteen representative stands have been simulated for CSA2.

Forest management has evolved in the study site over the past century from an even-aged management, focused on mountain conifers with the elimination of beech in the young stages, towards a single tree selection uneven-aged management with a goal of producing balanced uneven-aged stands with a mixed composition of spruce, fir, beech and other broadleaves. All forest stand types in the study site are now managed with single-tree selection uneven-aged management, but most stands do not show balanced structures yet. Both harvesting and thinning are conducted together at each management operation. Stands are renewed continuously through a moderate flux of saplings. Management guidelines consider two levels of site productivity: in high productivity sites, harvesting interval is 10 years and harvesting dbh is 52.5 cm, whereas in low productivity sites, the harvesting interval is 15 years and harvesting dbh is 57.5 cm. Cuts comprised between 3 and 8 $m^2$/ha (5 $m^2$/ha in average) at each stand entry, depending on the basal area of trees above harvesting dbh. If there are few big trees in the stand, harvest is complemented by thinning, usually limited to a maximum of 30% of the basal area of medium size trees. The management strategy is then adaptive: it takes into account both stand stocking and tree size distribution. Tending can be neglected in these stands as the selection system allows intermediate irradiance under canopy and a moderate quantity of saplings.

Simulations were made with the model Samsara.2. BAU was implemented using a management algorithm based on 14 management parameters described in Lafond *et al.* (2013). As the algorithm adapts each cut to stand structure, cuts change progressively along stand dynamics. Differences of harvested quantities appear between representative stands, in agreement to important differences of initial stocking and dbh distributions. Only the baseline climate has been simulated with Samsara2, as this model is not able to take climate into account.

Standard Ecosystem Service indicators were calculated for ARANGE:

- Structure: Stocking volume, Basal area by species and by diameter classes
- Carbon: Above ground, below ground and dead wood Carbon
- Biodiversity: Tree species diversity, dead wood, large standing dead trees, large living trees, canopy cover
- Protection: Protection against rockfall, avalanches and landslides.

### 4.2.2 Simulation results

Initial stand structure

The nineteen representative stands of CSA2 are mostly composed of *Abies alba*, *Picea abies* and *Fagus sylvatica* in different proportions. Other broadleaved species are also present in some stands, but usually in small proportions. Standing stocks are highly variable, with basal area between 11 and 56 m²/ha (Fig. 4-6 & 4-7).

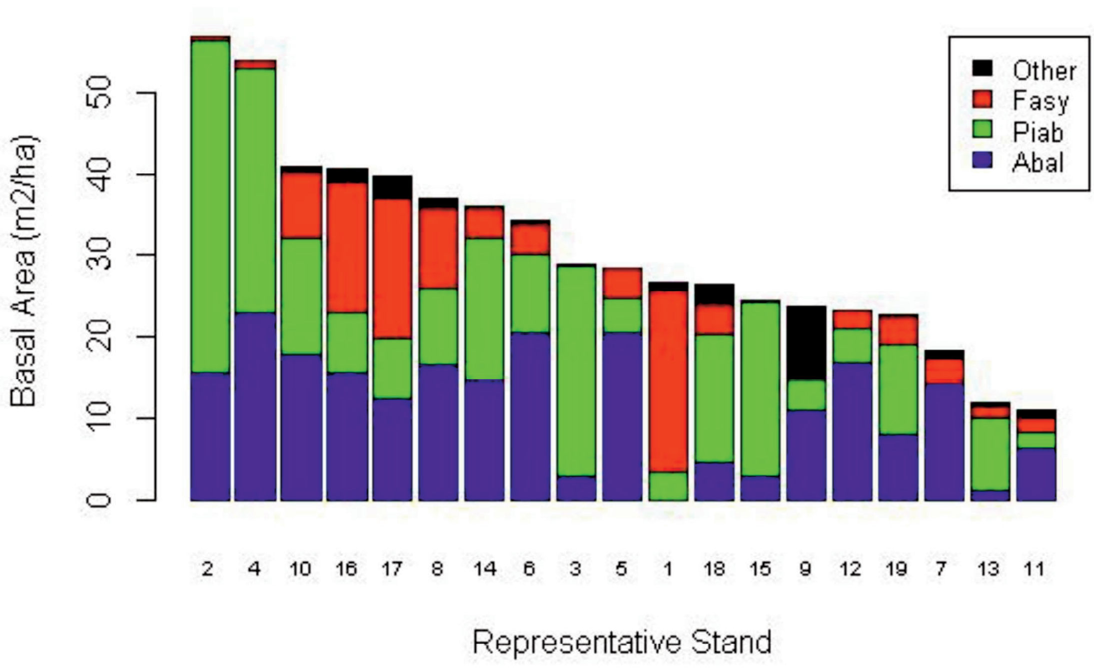



Fig. 4-6: Initial composition and stocks of the 19 representative stands.

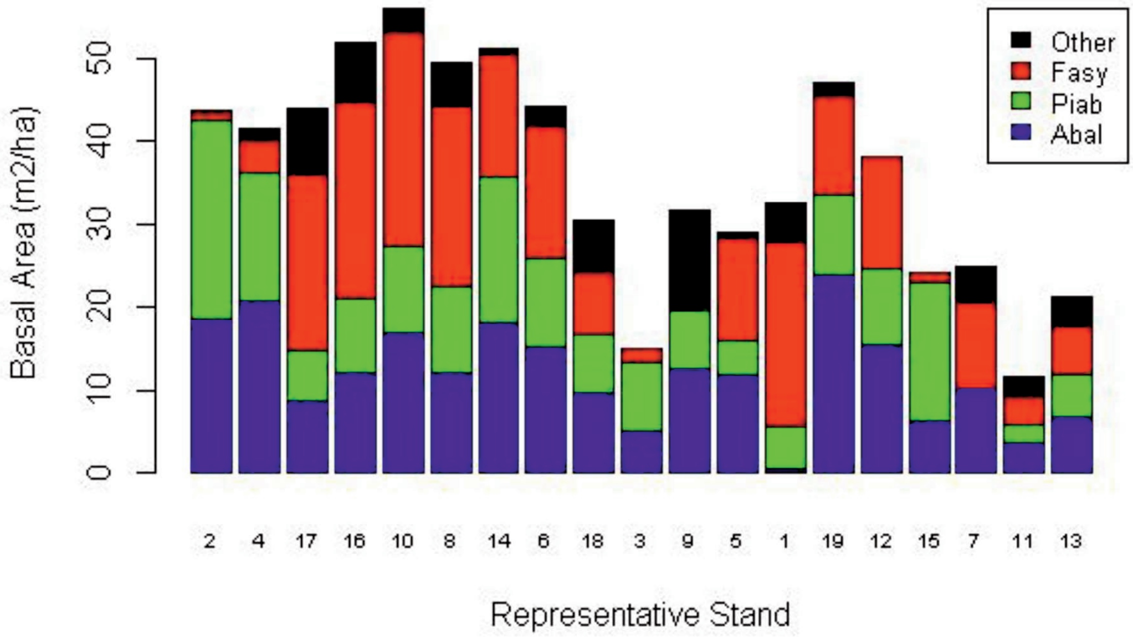



Fig. 4-7: Composition and stocks of the 19 representative stands after 100 years.

Development of stand structure over 100 years

Business-As-Usual management consists of a single-tree selection system in all stands. Over 100 years, standing stocks increased in most stands to reach basal areas between 25 and 50 $m^2$/ha, a value to compare to the target of 30 $m^2$/ha proposed in current forest management guidelines. This can be explained by the fact that the target harvest diameters (57.5 cm in high productivity sites, 52.5 cm in low productivity sites) were relatively high and the amount of trees bigger than this diameter was small at the beginning of the simulation. However, harvest was complemented by thinning up to a maximum of 30% of the basal area. Stand structure had not stabilized yet after 100 years. Longer simulations indicate indeed that stocks reach a peak after 100 years and decreased afterwards. *Fagus sylvatica* and other broadleaved species increased in most stands, in relation to a BAU strategy of avoiding cuts of low-abundance species (i.e., species with a basal area <30% of the total) (Fig. 4-7).

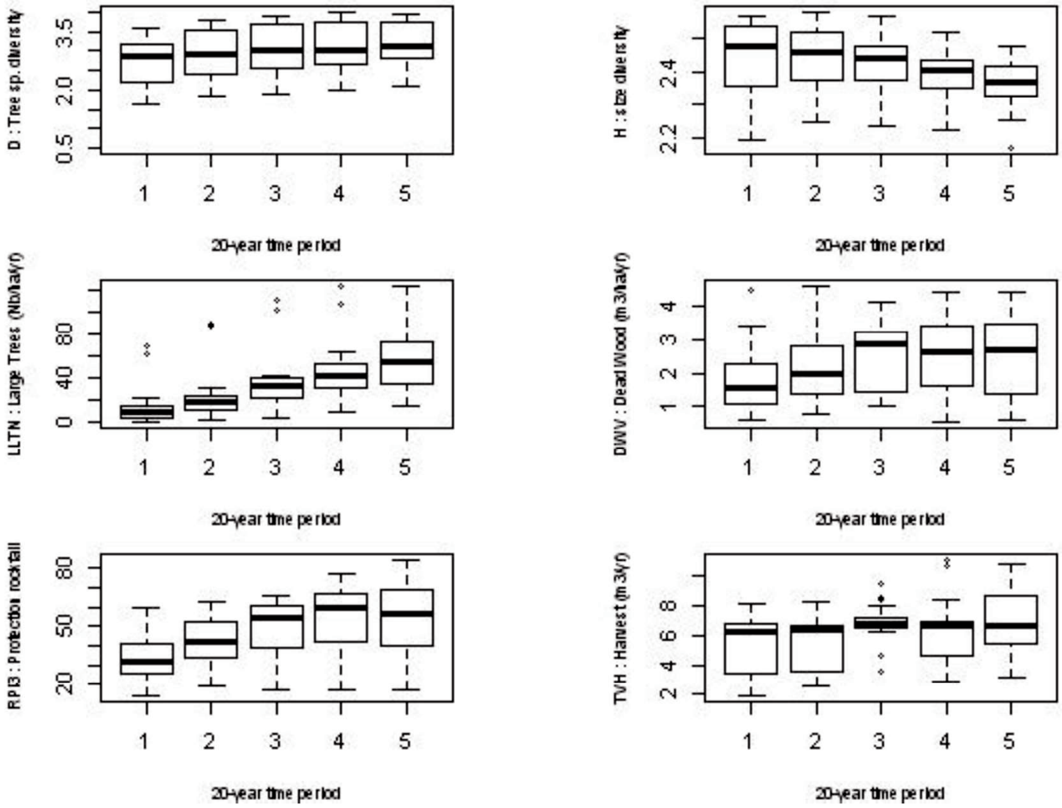



Fig. 4-7: Dynamics of Ecosystem Services over 20 year time periods in the CSA. Box-plots represent the distribution of ES values among the 19 RSTs.

<u>Ecosystem Service Provision</u>

*Biodiversity* – Tree species diversity increased smoothly in most stands during 100 years, in agreement with the increase of Fagus sylvatica and other broadleaves and the strategy of avoiding cutting species representing less than 30% of the basal area. The number of large trees also increased in average in relation to high harvest limit diameters. Differences among stands increased and were huge after 100 years with a number of large trees varying from 20 to 100/ha, depending on the stand. However tree size diversity diminished in most stands, because of a reduction of small trees. Dead wood stabilized at low values, in relation to the BAU strategy where 90% of the dead wood was harvested.

*Production* – The volumes harvested were relatively stable during 100 years, around a value of 6 $m^3$/ha/year. However, harvests were highly variable among stands (from 1 to 11 $m^3$/ha/year during the last 20 years) in relation to high differences of initial standing stocks. Log diameters increased progressively during the simulation, in line with the evolution of stand structure towards bigger diameters and a shift from thinning to harvesting in several stands.

*Protection* – In the Case Study Area, protection against natural hazards was relevant only in very small areas with a slope higher than 40°. In these areas, forest protection efficiency increased in relation to the increase of standing stocks.

### 4.2.3 Discussion

Biodiversity and protection against natural hazards increased in most stands during the simulation period, indicating that the single-tree selection system adopted as Business-As-Usual management is relatively efficient for the provision of Ecosystem Services. Production was stable in volume, with a progressive shift towards bigger wood products. This point should be examined in detail as the optimum wood product size for the industry is for logs of about 55 cm of diameter but not more. In addition, biodiversity could be largely improved by the conservation of dead wood in the stands, a conservation measure that does not reduce incomes much.

Regarding adaptation to climate change, the BAU strategy appeared as positive as it increased the resilience of forest stands through enhanced species and size diversity. In the diverse uneven-aged forests obtained, seedlings and saplings of different species are always present and can close very rapidly openings created by disturbances of different types (wind-throws, bark-beetle attacks, droughts…). However this strategy translated also in huge standing stocks and an increased number of big trees. These two points can be viewed as negative in a context of climate change because they mean that trees are exposed to risks during a long period of time.

Current management practices seem rather satisfying both regarding ecosystem services and climate change. However axes of improvement are discussed by forest managers and will be tested in ARANGE: first, managers would like to decrease harvesting diameters to produce mainly logs around 55 cm of diameter, in agreement to industrial demand, and this evolution is expected to impact negatively biodiversity. The question is whether it can be compensated by an increase of the retention of attributes specifically interesting for biodiversity, such as standing dead trees. Moreover, a reduction of harvesting diameters can be also seen as an adaptation to climate change, in order to limit the duration of risk exposure. Second, managers would like to introduce group selection in order to reduce harvest and exploitation damage and the impact of this new practice both on production, biodiversity and protection has to be evaluated.

## 4.3 Case Study Area 3: Montafon

### 4.3.1 Simulation setup

The Montafon valley is situated in an Alpine landscape, with the largest share of the forest located at altitudes >1200 m a.s.l., in steep mountainous terrain, which makes management difficult and cost intensive. Management objectives are primarily timber production and providing protection against landslides and soil erosion. The silvicultural aim is to create a mosaic of uneven-aged forest structures. Timber harvesting relies mainly on long distance skyline systems. Along the skyline tracks irregular shaped patch cuts are implemented, where all trees >20cm DBH are harvested. Regeneration is only of natural origin and no tending or thinning activities are done. If current management practices are extrapolated in time 40-50 year harvesting intervals with 15-20% of area cut in each entry results in a theoretical rotation of more than 200 years. For the stand-level analysis of BAU management, 21 stands were chosen to represent the gradient of site and species mixtures. For the BAU simulations the focus was set on the landscape Rellstal, because it provides higher species and stand diversity than the landscape Silbertal. RST description of Silbertal is very similar to the north exposed RSTs in Rellstal (site types 3, 4, 6 and 14). Furthermore, for simulations at the landscape scale, both Silbertal and Rellstal will be covered.

For stand level simulations in PICUS, generic stands with a size of 2 ha (100 m x 200 m) were created. In 42-year intervals, a skyline track was set up and all trees taller than 10 m where harvested on the 5 m wide track. Then, on 2 irregular patches of size 1500 m² all trees >20 cm DBH were harvested (see Fig. 1). In a 100-year simulation period, 3 harvesting operations are implemented. External seed input (i.e. from outside the 2 ha simulated forest) was considered for *Acer pseudoplatanus*, *Alnus viridis*, *Alnus incana* and *Sorbus aucuparia*. For *Picea abies*, *Abies alba* and *Fagus sylvatica*, however, only on-site seed production was simulated. See Fig. 4-8 for details on cutting pattern.

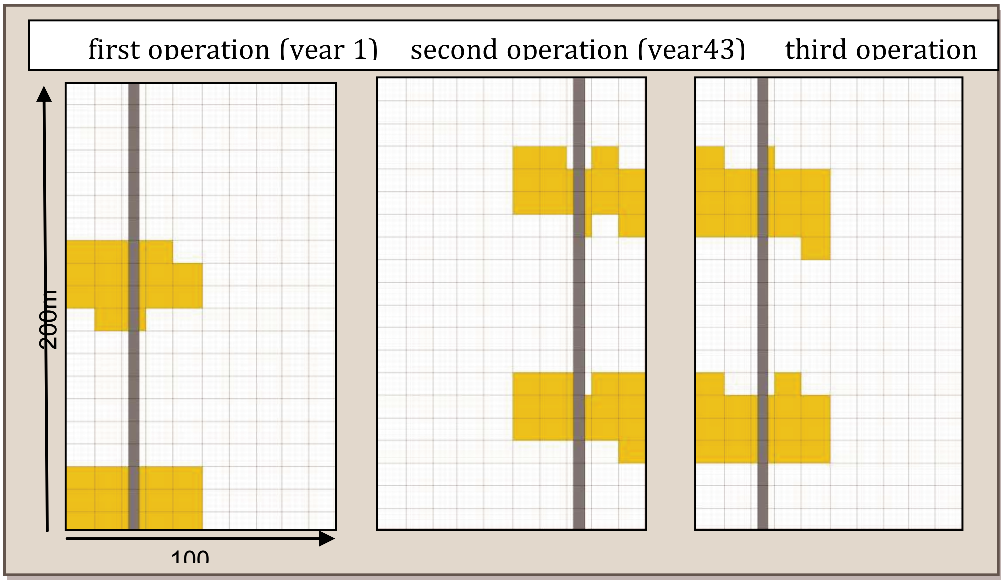



**Fig. 4-8:** layout of management activities for stand level simulations, grey= skyline track, orange = regeneration patches

Table 4-1: Output variables according to D1.5 for CSA3 as used in BAU simulations.

| | ID | Variable name | Aggregation level |
|---|---|---|---|
| **Timber production** | 1.1 | Timber volume harvested | Stand, Species, Diameter class |
| | 1.3 | Current annual volume increment | Stand, Species |
| | 1.4 | Stocking Volume (living trees) | Stand, Species, Diameter class |
| | 1.5 | harvested timber by assortment | Species x assortment class |
| **Carbon storage** | 2.1 | Above ground carbon | Stand |
| | 2.2 | Below Ground carbon | Stand |
| | 2.3 | Dead wood carbon | Stand |
| | 2.4 | Soil carbon | Stand |
| **Wood-energy** | 3.1 | Wood energy biomass | Stand |
| | 3.2 | Wood energy biomass (th) | Stand |
| **Biodiversity Conservation** | 4.1 | Tree species diversity | Stand |
| | 4.2 | Tree size diversity | Stand |
| | 4.3.1 | Abundance of dead wood | Stand (as deadwood carbon) |
| | 4.3.2 | Abundance of large standing dead trees | Stand |
| | 4.4 | Abundance of large living trees | Stand |
| | 6.1 | Basal area by species | Species |
| | 6.2 | Basal area in diameter class | Diameter class |
| | 6.3 | Basal area in height class | Height class |
| **Bird habitat quality** | 4.5.1 | Volume of large standing dead trees | Stand |
| | 4.5.2 | Unmanaged forest | Stand |
| | 4.5.3 | Abundance of large living trees | Stand |
| | 4.5.4 | Canopy cover | Stand |
| | 4.5.5 | Alien tree species | Stand |
| **Protection against natural hazards** | 5.1 | Protection against rock-falls (RPI) | Stand |
| | 5.2 | Protection against avalanches (API) | Stand |
| | 5.3 | Protection against landslides (LPI) | Stand |

### 4.3.2 Simulation results

#### 4.3.2.1 Wood production

The productivity of forest stands is predicted to increase under business as usual management and current climate. This is a result of a changing forest structure with developing regeneration in the harvested patches instead of over-mature initial stands and therefore higher growth rates. On top of these changes, climate scenarios show divergent impacts: under more moderate scenarios (C1, C3, C4) annual volume increments increase by about 10% due to the warmer climate. Comparing the mean precipitation in the period 2070-2100 to current climate, in scenario C2 the mean summer precipitation (July-Sept) decreases by 37%, in C5 by 52%. As a result those scenarios show more drought events during summer, causing average increment to decrease in the C5 scenario by -13% and staying constant despite higher temperature in the C2 scenario.

Under current climatic conditions European spruce bark beetle (*Ips typographus*) causes, on average, tree mortality of about 7% of annual increment. With changing climatic conditions, bark beetle damage increases to 70% under the most severe climate scenario (C5).

Harvested volume per year is rising under current management and current climate (C0), but under climate change scenarios, the volumes harvested are decreasing, because of bark beetle caused disturbances.

#### 4.3.2.2 Carbon storage

Looking at the resulting carbon storage, we simulated an increase in aboveground carbon and increasing carbon deadwood levels under current climate. Increase in deadwood is an expected result, because no deadwood was initiated at the start of the simulation. In total (sum of carbon aboveground, belowground, deadwood and soil) mean values for carbon in the stands was 260 t/ha (average for first 33 year period). Under current climate simulation results showed an increase of 5% for the last period. Under climate change, stable conditions where simulated for scenarios C1 and C3, while the other scenarios show a decrease in carbon storage (see Fig. 2).

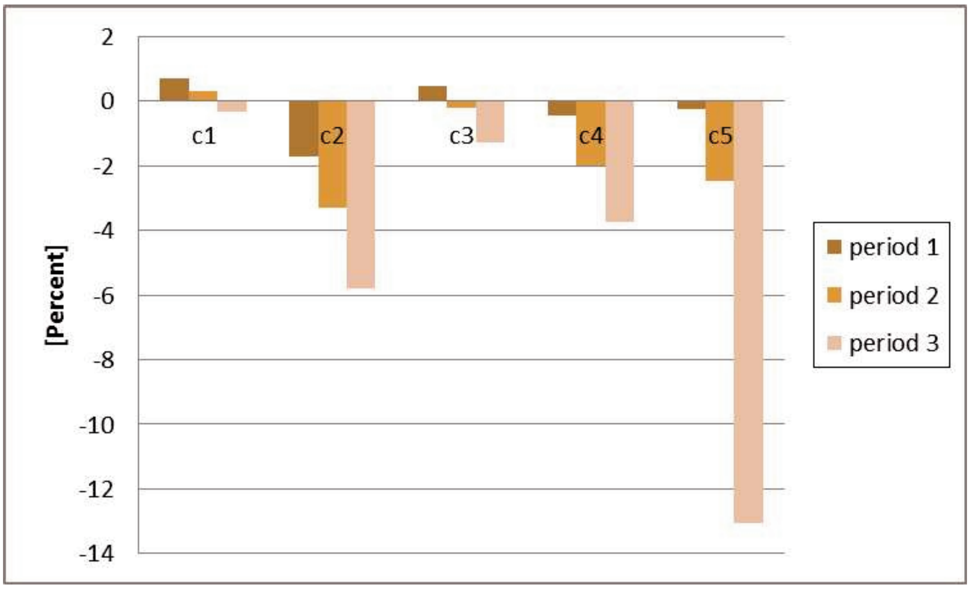



**Fig. 4-9:** Mean sum of carbon in simulated stands for three 33-year periods. Relative development for climate change scenarios (C1-C5) to current climate (C0)

#### 4.3.2.3 Biodiversity

Business as usual management has manifold consequences on biodiversity in the simulated stands. Under current climate species diversity is decreasing as a result of the selective browsing of fir regeneration. Climate change partly counteracts this development because more species appear during the regeneration processes and beech and fir profit from warmer temperature regimes.

Height diversity on the other hand shows an increasing trend under current climate, but is not influenced by climate change scenarios, indicating high relevance of management.

Due to bark beetle caused mortality and over mature trees dying from senescence the quantity of large standing deadwood increases.

#### 4.3.2.4 Protective Function

Protection against landslide is currently rated as "medium" (90% of RSTs according to LPI) but would improve under Business-As-Usual management and current climate. Considering the more severe climate change scenarios (C4 and C5), landslide protection effects will be lower than under current climate.

Regarding rockfall protection, typical rocks expected would have a diameter smaller than 1 m and a density of approximate 2500 kg/m$^3$. Therefore RPI1 and RPI2 were chosen, with a threshold value of 0.95 for good protective functionality. Throughout the 100 years of simulation, 19 out of 21 stands fulfil these criteria under Business-As-Usual management. Under climate change, only minor changes are visible for small rocks (RPI1 and RPI2), whereas for bigger rocks a decreasing protective functionality is expected under the scenarios C2, C4 and C5 (see Fig. 4-9).

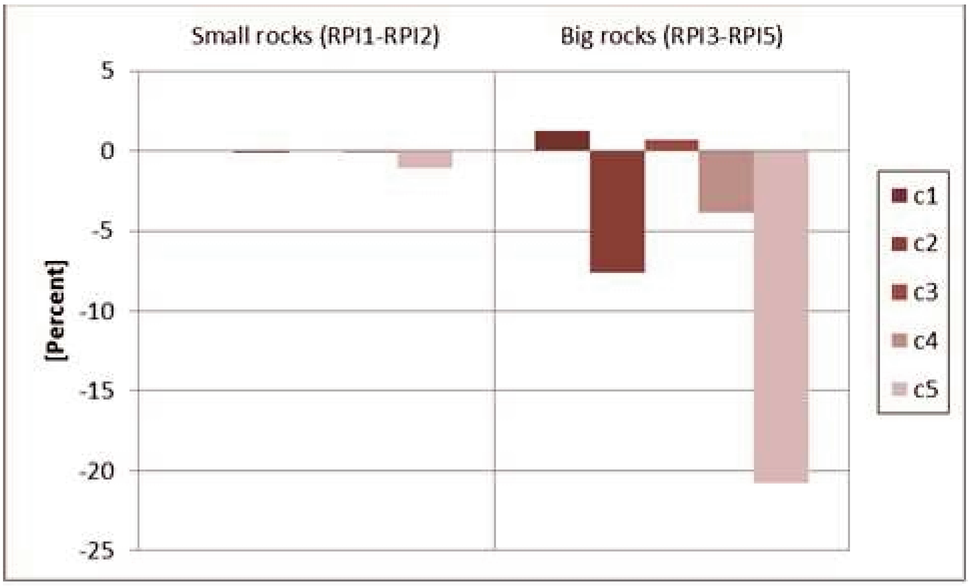



**Fig. 4-9:** Mean change in rockfall protection in last 33 year period for climate scenarios (C1-C5) compared to current climate (C0). "Small rocks" is calculated as mean value of RPI1 and RPI2, "Big rocks" as mean of RPI3, RPI4 and RPI5.

Protection against avalanche release is always evaluated as optimal on stand level in all climate scenarios as the stands are dominated by evergreen species and basal area is never below the limit of 15 m$^2$/ha due to small scaled harvesting activities.

### 4.3.3 Discussion

Main ecosystem services in the CSA Montafon are protective functions and timber harvest. One question that is prevalent in management decisions is how much timber can be harvested while ensuring good protective functionality. BAU scenarios have a very low area turnover rate of 250 years with harvests well below expected increment rates in the stands. Most decisive for future management decisions will be the development of tree mortality caused by bark beetles, as in steep terrain sanitary management is very cost intensive. Furthermore, bark beetle damage is posing a threat to landslide and rockfall protection. Intensification of management could therefore decrease the vulnerability to bark beetle infestations and utilize the increasing productivity of the stands with climate change.

In stands with more emphasis on biodiversity and less need for protective function, BAU management seems rather suitable, as long turnover rates increase the habitat quality for birds due to more large standing trees and standing deadwood. However, increasing bark beetle damage under climate change conditions indicates the risk of uncontrolled tree mortality.

## 4.4 Case Study Area 4: Dinaric Mountains (Sneznik)

### 4.4.1 Simulation setup

In CSA4, Dinaric Mountains, three BAU FM approaches were determined: small-scale even-aged FM, uneven-aged FM, and no FM; although the latter was excluded from the modeling simulations. Even-aged FM was applied in form of irregular shelterwood silvicultural system. The rotation periods were determined in the range of 130-140 years. During this period 4 thinning operations and 2-3 regeneration felling operations (regeneration period lasts 2-3 decades) were commonly applied with different time intervals between them. Uneven-aged FM combined small-scale irregular-shelterwood and a group selection silvicultural system. Due to the model constraints and the impossibility to explicitly simulate tree position, the uneven-aged FM was applied as single tree selection. The average harvesting intensity was 15 % of stand BA, the harvesting time interval was 10 years. For a more detailed description see deliverable D1.3, p. 26-29 and 382-437.

The management sub-model (Rasche et al., 2011) was specifically enhanced for implementing correctly BAU FM in ForClim. A detailed routine allows simulating harvesting at any year within a defined management phase. Each operation is quantified with a total amount of relative basal area (or volume) to be removed. Within this quantity, a species-specific amount of relative basal area (or volume) to be removed is defined. The model calculates the boundaries of five Relative diameter classes (RDC) from the diameter distribution for each species over all model runs. Harvesting is then distributed accordingly to different percentages that must be specified in an additional RDC list for each species. In addition, it is possible to choose a species-specific minimum diameter that acts as a threshold for the calculation of RDC that determines the lowest measure of stems still harvested.

RSTs characterized by even-aged structure and FM were initialized separately depending on their stand development stage. The stand age at a certain dominant DBH was provided by the CSR for setting the time reference of every harvesting operation. Regeneration type in the CSA is always natural; therefore the planting routine in ForClim was never activated. If an operation is quantified with 100% of the total amount of relative basal area the model simulates a clear cut, which is typically executed at the end of each regeneration phase. Since ForClim does not explicitly consider tree seedlings, tending operations in young stand development stages described by height classes were not executed. In uneven-aged RSTs, the time reference of each operation was defined in regular harvest intervals as specified in the BAU prescriptions.

In the CSA four main ES were determined: timber production (TP), carbon storage (CS), nature conservation (NC) and protection against hazards (PH); game management (GM) is another important ES, but was not addressed through indicators. According to the high intensity of timber exploitation, TP seem to be the most important ES. TP was described and analyzed using several indicators: timber volume harvested TVH, above ground wood energy biomass harvest BMEH, volume increment VI, volume of living trees V, wood energy biomass BME, and technically harvestable wood energy biomass BME_th. CS was evaluated by the above ground carbon C_above and below ground carbon C_below. NC was addressed by the tree species diversity index D, tree size diversity index H, abundance of dead wood DWV, abundance of large standing dead trees LSDTN, abundance of large living trees LLTN, and birds' habitat quality score, while PH was evaluated through the RPI, API, and LPI indices. For detailed descriptions of the given indicators see the deliverable D2.2.

### 4.4.2 Simulation results

The BAU simulations using ForClim indicated stand dynamics similar to the expected one. Using the baseline climate scenario, the final stocking of even-aged RSTs (i.e., final stand basal area BA or stand volume V = stand parameter value just before a stand is being regenerated) remained rather the same as it is currently, while in the uneven-aged RSTs it dropped in the first decades of simulations and then increased to the level of the current value or even higher (see right panel in Fig. 4-10). The main reason for the obtained stocking dynamics in uneven-aged RSTs was the BAU FM prescription in D1.3, which cannot adapt to changed characteristics of RSTs during the simulation period. The removals per tree species are prescribed as fixed percentages of total removals and as such could not be adapted to a tree species composition in a certain point of time during the simulation run. For example, when the proportion of a certain tree species becomes very low, the removals of this species should be adapted to such development (i.e., lowered) so as to not remove it completely.

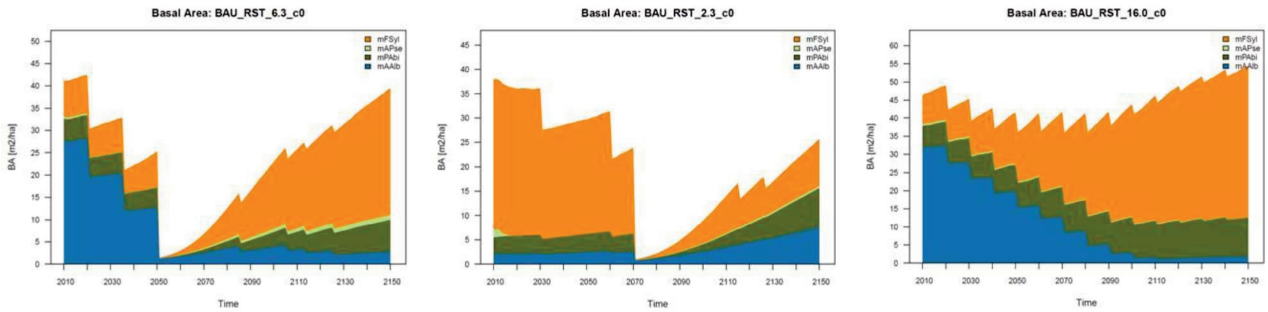



Fig. 4-10: Model simulations of stand basal area (BA) and tree species composition in two even-aged (left and center) and one uneven-aged (right) RSTs.

Simulated development of tree species composition indicated significant changes if compared to the current state of RSTs (Fig. 1). *Fagus sylvatica* will become the dominant species in all RSTs irrespectively of its current proportion in a stand stocking. This will happen due to its very abundant regeneration, its vitality and vigorous growth, but also due to a lower browsing rate if compared to some other tree species, such as *Abies alba* or *Acer pseudoplatanus* (Klopcic and Boncina, 2011). An interesting feature occurred in some RSTs (e.g., RST 2.3, 2.4, 12.0, 23.0) at the beginning of the simulation period – a (small) drop in *Acer pseudoplatanus* and/or *Fagus sylvatica* proportion was registered, most probably due to a discordantly initialized h/d relationship between field data and the model (see the center panel in Fig. 1). In contrary, a significant decrease of *Abies alba* proportion in stand stocking was simulated in the majority of RSTs. The BAU FM prescription of preserving *Abies alba* thinner than 25 cm DBH maintained silver fir in almost all RSTs, but in a very low proportion. Preservation of *Abies alba*, and *Picea abies* as well, is more likely at higher altitudes (≈1100-1300 m) and/or on north-facing sites (RSTs 2, 12, 23). *Acer pseudoplatanus* was simulated to remain in all RSTs, but in higher proportions in the even-aged RSTs, especially those at lower altitudes (RSTs 4, 5, 7, 9). Changes in tree species composition were also likely influenced by the methodological problem of removals not being adapted to tree species composition in a certain point in time during the simulation run described above.

The application of different climate change scenarios resulted in similar stand dynamics compared to the baseline climate scenario. The main differences were 1) lower final stand stocking (or even a decreasing one in the final decades) in some RSTs when c2 and c5 climate change scenarios were considered in the simulation, 2) larger decrease in *Abies alba* proportion under all climate change scenarios, 3) slight increase in *Acer pseudoplatanus* proportion, but not in uneven-aged RSTs.

Considering the baseline climate scenario, forests managed according to the BAU FM successfully provided all four main ESs. Timber production, measured by TVH (and BMEH), reached a reasonable level, resulting also in reasonable forest productivity (VI) and stocking (V, BA). The aboveground (Fig. 4-11) and belowground carbon storage (CS) followed the dynamics of TVH and V; it generally showed higher values at the end of the simulation period compared to current values.

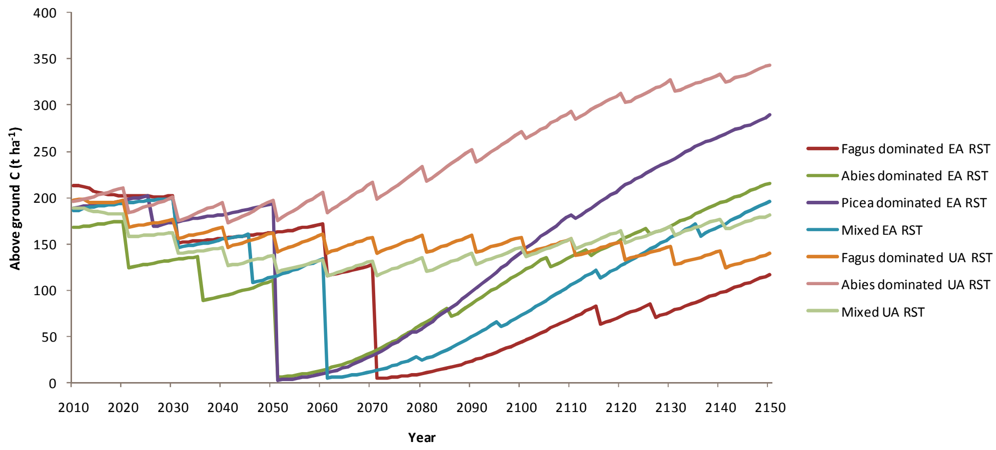



Fig. 4-11: Dynamics of the above ground carbon storage in living tree biomass in some representative RSTs.

Indicators of nature conservation generally pointed to forest stand characteristics that enable the successful provision of this ES. Index D indicated poorer tree species diversity in most RSTs due to a simulated increased dominance of *Fagus sylvatica*, although some exceptions with an increasing D were observed (e.g., RSTs 1.3, 2.3, 5.3, 12.0). Tree size diversity H only slightly changed in uneven-aged RSTs, while it showed expected dynamics in even-aged RSTs (a large drop due to a regeneration process). In even-aged RSTs H reached a reasonably high level during the simulation period as well. Volume of dead wood (DWV) and the abundance (LSDTN) and volume of large standing dead trees (LSDTV) showed a significant increase during the simulation period, which was mainly due to the absence of adequate data on these parameters on a RST level at the simulation starting point (year 2010). The analysis of bird habitat quality (Fig. 4-12) indicated a change from a low to medium quality in the first simulation decades to a medium to high quality in the second half of simulation period. The main reasons for lower quality were poor abundance of dead wood and veteran trees and intensive forest management resulting in frequent harvest operations.

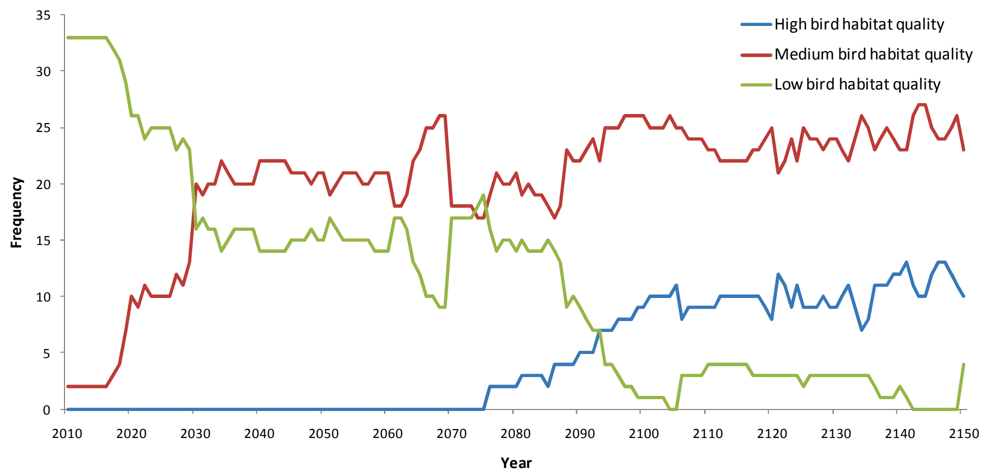



Fig. 4-12: Dynamics in frequencies of bird habitat quality in RSTs of the CSA4.

According to simulation, all indicators of PH showed satisfying protection against rockfall (RPI), avalanches (API) and landslides and erosion (LPI).

When the various climate change scenarios were considered, the provision of ESs was not significantly affected. In some RSTs (e.g., RSTs 4.3, 4.4, 8.3, 9.2, 9.3, 9.4), mainly at lower altitudes, timber production decreased when the c2 and c5 scenarios were applied (an example is shown in Fig. 4-13). In these RSTs, forest stand stocking decreased due to a higher tree mortality, which increased the abundance of standing dead trees (LSDTN) and the volume of dead wood (DWV). On the other hand, this positively influenced the nature conservation ESs and bird habitat quality.

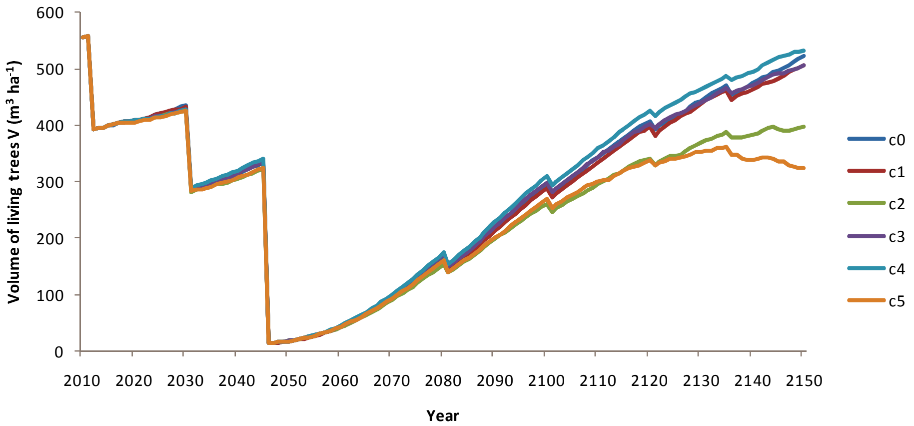



Fig. 4-13: Development of stand volume in RST 4.3 according to five climate change scenarios (c0 – baseline climate scenario, c1 – optimistic scenario, c5 – pessimistic scenario).

## 4.4.3 Discussion

According to the simulation results in mixed montane Dinaric forests, the supply of all important ESs will be satisfying. The most pessimistic climate change scenario(s), however, lowered the provision of timber production (due to a higher mortality rate of trees), but on the other hand it positively influenced indicators of nature conservation.

The simulated dynamics of tree species composition confirmed the expectations on changes towards the future dominance of *Fagus sylvatica*. Although it is a rather undesired scenario, it may be the most likely one to appear. The least desirable results for the nature conservation are the decreasing tree species diversity and the decreasing proportion of *Abies alba* as one of the main tree species of this forest type (important also from the TP perspective). The current high proportion of *Abies alba* in some RSTs is mainly a result of past forest management promoting *Abies alba* due to its economic value, but other factors may be relevant as well (Klopcic et al., 2010). Reasons for simulated decreasing proportion of *Abies alba* in the future still need to be discovered, but high browsing rate and consequently low recruitment rate are probably the most crucial factors. These results are important for local forest experts for the awareness on (possible) future forest stand development if BAU FM is applied, to rethink on appropriate management strategies, and consequently to adapt forest management goals and guidelines.

Some indicators obtained from the model simulation do not indicate the actual state of a certain indicator since no adequate input data were available for the simulation. For example, indicators of dead wood are constantly underestimated since no data on dead wood were used when initializing current RSTs' state. This influenced also other indicators such as lowering the bird habitat quality.

Since the simulated forest stand development is a rather undesired scenario from the local foresters' perspective, the simulations of alternative FM strategies, including also the adapted version of BAU FM prescription, will be an important task in the frame of ARANGE. Appropriate adaptations of FM strategies, goals and guidelines could be elaborated only based on all simulation results.

## 4.5 Case Study Area 5: Vilhelmina

### 4.5.1 Simulation setup

The forest in Vilhelmina is represented by fifteen stand types depending on species (pine, spruce, contorta, or mixed conifers ≥65%, and birch ≥35%) and site index (poor $H_{dom}$ ≤14 m, medium, and relatively high ≥18 m). More than two thirds of the area is dominated by spruce (Picea abies), 41% on medium sites, 13% on poor, and 18% on high sites. BAU is even-aged forest management with clear felling. Regeneration is done with soil preparation and planting of spruce (pine or contorta are exemptions). In most cases cleaning operations (or pre-commercial thinning) are needed at the stand height of 3-5 m. Commercial thinning may also be done at stand height 13-16 m if stand density is ca. 25 $m^2$/ha or above. Details can be found in D1.3, Annex 2.

Simulations of stand development and management are made at the stand level for spruce stands with the Heureka decision support system. Pre-commercial and commercial thinning are made in the simulations if motivated by the state of the forest (number of stems or basal area), otherwise not. Two climate scenarios are used, today's climate C0, and C1 with higher temperature and higher precipitation (ECHAM5_A1B).

These BAU regimes have been used since ca. 1950, and more extensively since 1970. Before that continuous cover forestry systems – or some kind of – were used. Thus, stands younger than 40 years, covering 31% of the area, are a result of the clear cutting system, whilst generally speaking old stands have been formed by another forest management system. To describe the effect of BAU simulations, simulations are made for three site conditions and for stands 121-140 years old.

Standard Ecosystem Service indicators were calculated for ARANGE:
- Structure: Stocking volume, Basal area by species and by diameter classes
- Carbon: Above ground, below ground and dead wood Carbon
- Biodiversity: Tree species diversity, dead wood, large standing dead trees, large living trees, canopy cover
- Protection: Protection against rockfall, avalanches and landslides.

### 4.5.2 Simulation results

The results of the simulations are shown in Fig. 4-14. All variables are shown after cut at respective time. The results show three spruce stands that initially feature old forest. They are clearcut during the first year, giving 160 $m^3ha^{-1}$, 118 and 59 respectively, for each RST. Fig.4-1 thus shows the stand development during one rotation (or a little longer) after regeneration.

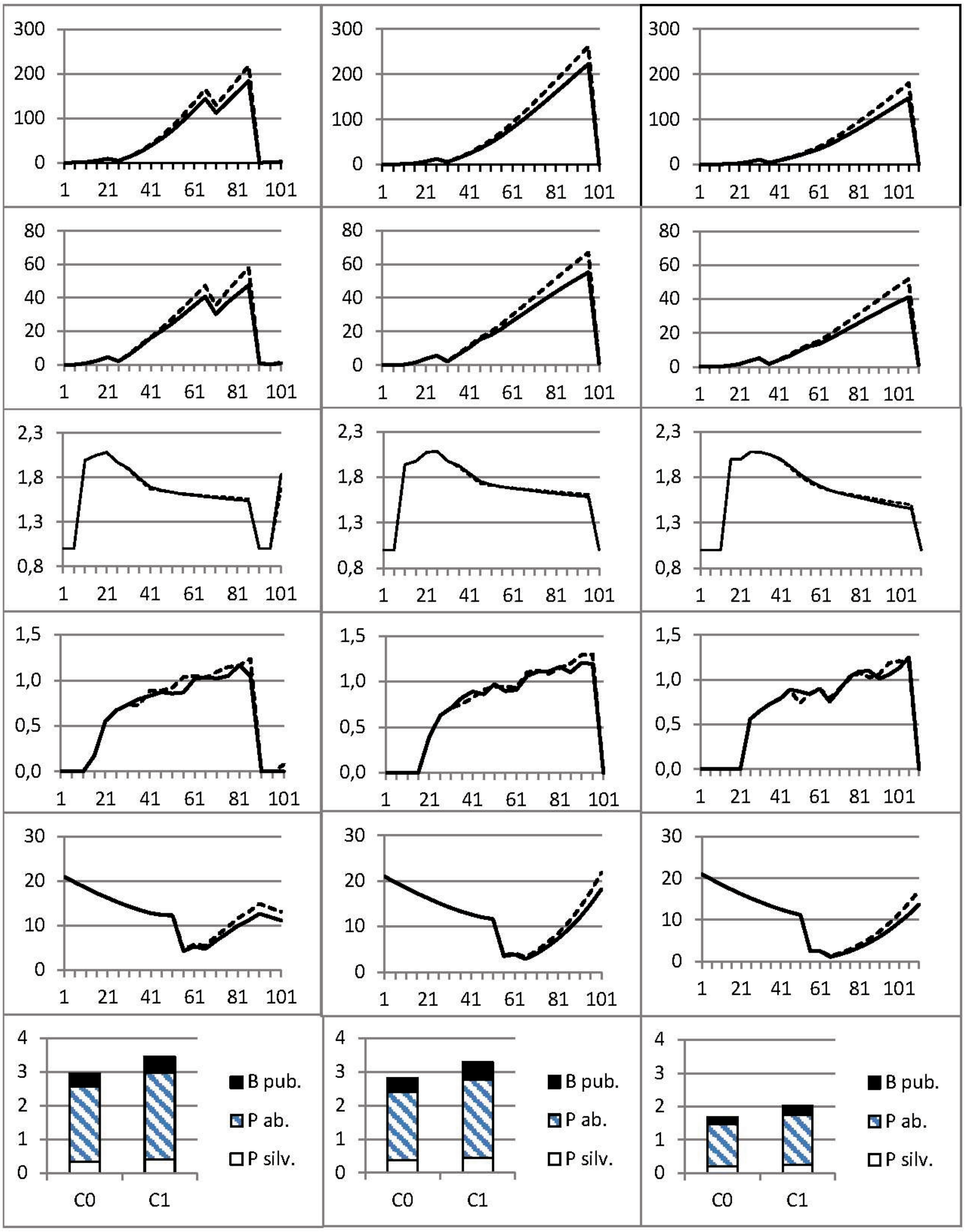



Fig. 4-14. Model simulation for spruce dominated stands with high (left column), medium (center column) and low (right column) site index (SI18, 16 and 13) (RST4.8, 5.8 and 6.8) for current climate (C0, solid line) and alternative climate (C1, dotted line) (ECHAM5_A1B). The variables are from above a) stand volume ($m^3ha^{-1}$), b) carbon stock in standing trees above ground ($tonnes^1ha^{-1}$), c) D-index for species diversity, d) H-index for tree height diversity, e) volume of dead wood ($m^3ha^{-1}$), f) average timber production ($m^3ha^{-1}yr^{-1}$) during a rotation.

The new stands develop well from the timber production and thus also the carbon storage perspective, and the alternative climate has a positive effect. The average annual net timber growth for a whole rotation is 3,0, 2,8 and 1,7 $m^3ha^{-1}yr^{-1}$, of which app. one quarter comes from naturally regenerated Pinus silvestris and Betula pubescens. An unknown proportion of the Picea abies also comes from natural regeneration. The simulated growth is higher than the current net annual growth for the old stands which are simulated to 2,2, 1,9 and 1,2 $m^3ha^{-1}yr^{-1}$. Climate change increases the growth with 17-21 per cent to 3,5, 3,3 and 2,0 $m^3ha^{-1}yr^{-1}$, and the increase is most significant for Betula pubescens (26-36 per cent). Thus, the clearcut volume at the end of the rotation period is higher than in the existing stands (today's forests). The cut volume is simulated to 211, 242 and 155 $m^3ha^{-1}yr^{-1}$ (are not shown explicitely in Fig 4-1.), and after climate alternative C1 254, 289 and 194 $m^3ha^{-1}yr^{-1}$. Thinning in RST with relatively high SI takes out 55 and 65 $m^3ha^{-1}yr^{-1}$ for C0 and C1.

The tree species diversity index (D) decreases during the early age phase because of cleaning and stand development. The alternative climate has a very low effect on this index. The tree height diversity index (H) increases during the rotation period. The alternative climate has a very small positive effect.

The volume of dead wood decreases during the first fifty years to almost half, and then decreases rapidly because the density of the dead wood falls below the limit that is default in the Heureka system. During the last decades trees in the new stand start to die and the dead wood volume increases almost to up to the initial level except in the RST with highest site index where a thinning is done which decreases the dead wood volume. The alternative climate is positive for the dead wood volume during the last decades.

The different RST show quite similar result for the variables shown here, but the rotation period is longer on poorer sites. RST on site index 18 are thinned once which of cause influence both the standing volume and the carbon stock. But the thinning also reduces the growth and makes the difference to medium sites smaller than what one might expect.

### 4.5.3 Discussion

The analysis of the ecosystem services supply has to be done at the landscape scale and can not be answered based on these standwise simulations. Anyhow, the results of the simulations at stand level described here, are generally positive for timber production. Artificial regeneration with site preparation and planting gives a more productive forest and higher carbon storage over 100 years or more. But of course the clear cut at the start takes away the existing carbon storage above ground.

The climate change has a high positive effect on both timber production and carbon storage in the forest if the stands are managed according to BAU. Increased production is also positive for dead wood. The climate change has almost no effect on tree species diversity, and only a little positive effect on tree height diversity. Climate change is so far positive, but there are many effects we have not studied, such as occurrence of fungies and insects, and risks for storm felling.

It is obvious that data about the effect of other management alternatives are necessary if we should be able to make any recommendations about forest management in the future. The Arange project can provide some of these data and will give information to managers and other people concerned or affected. Whether it will be possible to draw more precise conclusions about how to balance management alternatives and output on the landscape level is still unclear.

## 4.6 Case Study Area 6: Kozie Chrbty

### 4.6.1 Simulation setup

**BAU management description**

Even-aged management with a rotation length of 95-140 years is applied in the entire CSA. Combined natural and artificial regeneration is applied, depending on tree species composition. Weeding and regeneration protection against ungulates is applied in most of the stands. Tending is applied at thicket stage so as a canopy closure is reduced to 0.9 after each tending operation. From 2 to 4 thinning operations with variable intensity are applied. Regeneration system is the uniform shelterwood system in stands with fir and/or beech admixtures, which is implemented in 3-4 felling cycles. A small-scale clearcutting system (strip cuts) is applied in spruce monocultures.

Because of high amounts of sanitary felling due to wind damages and bark beetles, stabilization of forest stand by increasing the proportion of species other that Norway spruce (*Fagus sylvatica, Abies alba, Larix decidua ….*) is an important part of the current management scheme. Applied sanitary measures contain standard measures such as early identification and removal of infested and mechanically damaged trees, debarking, etc.

**BAU management implementation in the model**

Even-aged BAU management according to D1.3 is implemented in the Sibyla model in the form of time series that prescribe tree removal and planting with 5-year periods (forest growth is simulated in one-year time steps). Both natural and artificial regeneration is simulated. While the natural regeneration module is implemented in the Sibyla model, artificial regeneration module is under development now. Therefore, we introduced the artificially regenerated trees into the stands semi-manually. As Sibyla simulates growth of trees higher that 1.3 m only, we generated artificially regenerated trees with age of ca 10 years in pre-defined positions ca 10 years after the planting year. Tending is implemented as a reduction of stocking when an actual stocking exceeds the value prescribed by the management plan. Thinning of different types is implemented (from above, from below, neutral) using selection of trees by database queries according to D1.3. To mimic the harvesting procedure that is currently applied in the CSA, the harvesting is simulated in strips with width based on the yield class. A time lag between harvest cycles is 5-10 years in each stand. One third of stand is harvested in each cycle. In case of stands with beech or fir admixtures, two phase harvesting is implemented: firstly, a stocking is reduced to 0.5 to support the regeneration; then, the rest of trees in a strip is harvest after a ten-year period.

**List of evaluated ES**

The following *state* variables were evaluated: Stocking volume, Above ground carbon, Below ground carbon, Dead wood carbon, Tree species diversity, Tree size diversity, Abundance of dead wood, Abundance of large standing dead trees, Volume of large standing dead trees, Unmanaged forest, Abundance of large living trees, Canopy cover, Protection against rockfall, Protection against avalanches, Protection against landslides and erosion, Basal area by species, Basal area in diameter classes, Basal area in height classes.

The following *flow* variables were evaluated: Total annual volume of timber harvested by species and diameter class, Current annual volume increment by species, Harvested timber by assortments and species, Aboveground wood energy biomass harvest by species.

### 4.6.2 Simulation results

We evaluated the simulation outputs from the view of the differential response to four climate change scenarios compared to current climate (i); response in three elevation zones in the CSA for which climate change scenarios were developed (< 650, 650-950, and >950 m a.s.l.) (ii); response of main tree species occurring in the CSA (iii); and differential response in four time periods (2000-2025, 2030-2050, 2055-2075, 2080-2100) (iv). The hypotheses leading us to such a design are that response of state and flow variables as well as respective ES indicators will increase along the range of climate change scenarios used, from c1 to c5 (i); that potential water scarcity may limit tree growth in lower elevations, while in high elevations the growth may improve (ii); that differences in climatic sensitivity of tree species in the CSA induce a differential response to climate change (iii), and that forest development and provision of some ES may substantially differ between the time periods addressed, being a consequence of the ongoing forest conversion, which is a part of the BAU management as well as of the progressive changes in climate (iv).

To allow for the evaluation of changes in the above-listed variables, we calculated absolute and relative (%) change between the baseline climate and all climate change scenarios for each variable. We present the response of three main species in the CSA: Norway spruce, European beech and Silver fir, as well as the response of some stand-level indictors, such as diversity indices.

For the case of forest growth, production and aboveground carbon indicators, a generic response of decline in lower elevations and increase in higher elevations was observed. The response is typical of all investigated tree species, though the magnitude of change differs depending on species climatic sensitivity (Hlásny et al. 2011). To exemplify these effects, we present in Fig. 1 the response of stocking volume of living trees (V variable) for Norway spruce, European beech and Silver fir (mean % change of simulations under a scenario and the baseline climate). In the lowest elevation zone (>650 m a.s.l.), the stocking volume of all three species was projected to decline significantly by the end of the century, which is the fact that may generate concern about the sustainability of the current forests in these elevations of the CSA (however, the inter-scenario variability of responses is high, as we present below). European beech was projected to preserve its growth performance under climate change in medium elevations, and the species may even benefit from climate change in highest elevations. Norway spruce can be expected to perform poorly in the future in extensive areas of the CSA except for highest elevations; however, as the species persistence in Central Europe is determined by wind and insect damages rather than by climate directly (Hlásny and Turčáni 2013), consequences of our findings for the CSA should be formulated cautiously (see Figure 4-15).

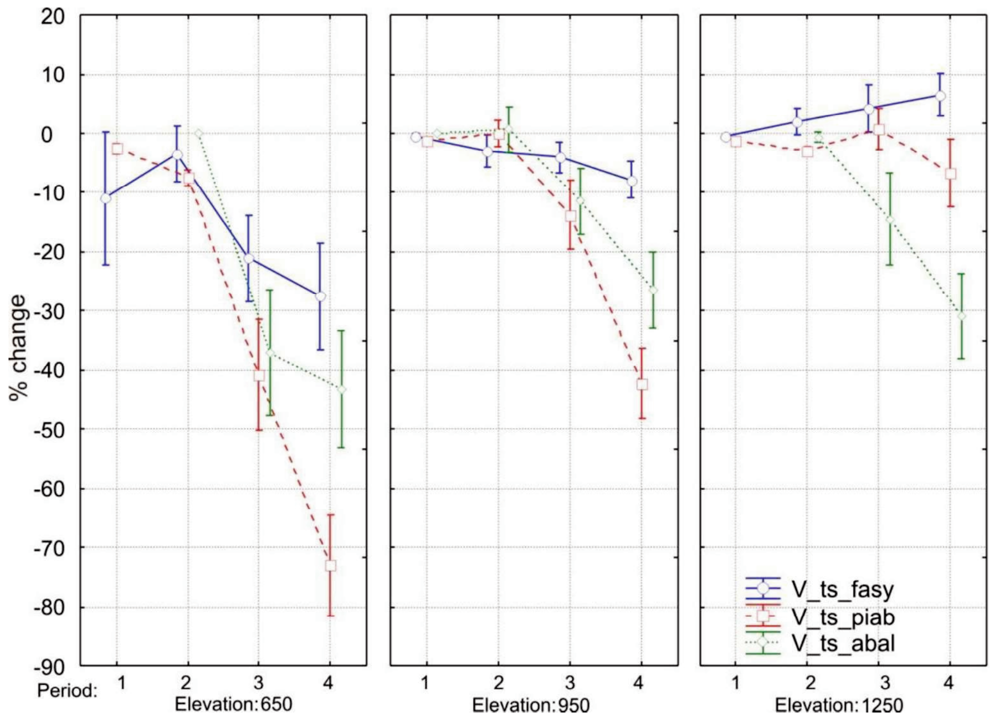



Fig. 4-15. Effect of climate change (ratio of mean simulation under four climate change scenarios and the baseline) on the stocking volume of living trees in three elevation zones and four time periods. Blue – European beech, Red – Silver fir, Green – Norway spruce; Period: 1 – 2000-2025, 2 – 2030-2050, 3 – 2055-2075, 4 – 2080-2100.

In case biodiversity indicators, we present here the response of species diversity index (D) and tree size diversity index (H) (see Deliverable 2.2) (Fig. 4-16). Our simulations indicate that species diversity gradually increases during the simulation period, potentially leading to increased forest resilience. The pattern of increase is similar in all elevations of the CSA. This effect is induced almost exclusively by forest management; the effect of climate change was found to be negligible (not presented here). A response of tree size diversity index (H) was not as pronounced as that of D. The index slightly decreases in time in the lowest elevation zone, while it remains more or less stable in medium to high elevations.

Gravitation hazard indices were found to slightly decrease in the future; the decrease was however highest in lower elevations, where risk of rockfall is marginal. In contrast, in highest elevations, where protective forests currently occur, all indices remained high (>0.95) (Fig. 4-17). These facts indicate that risk of rockfall cannot be expected to increase in the future.

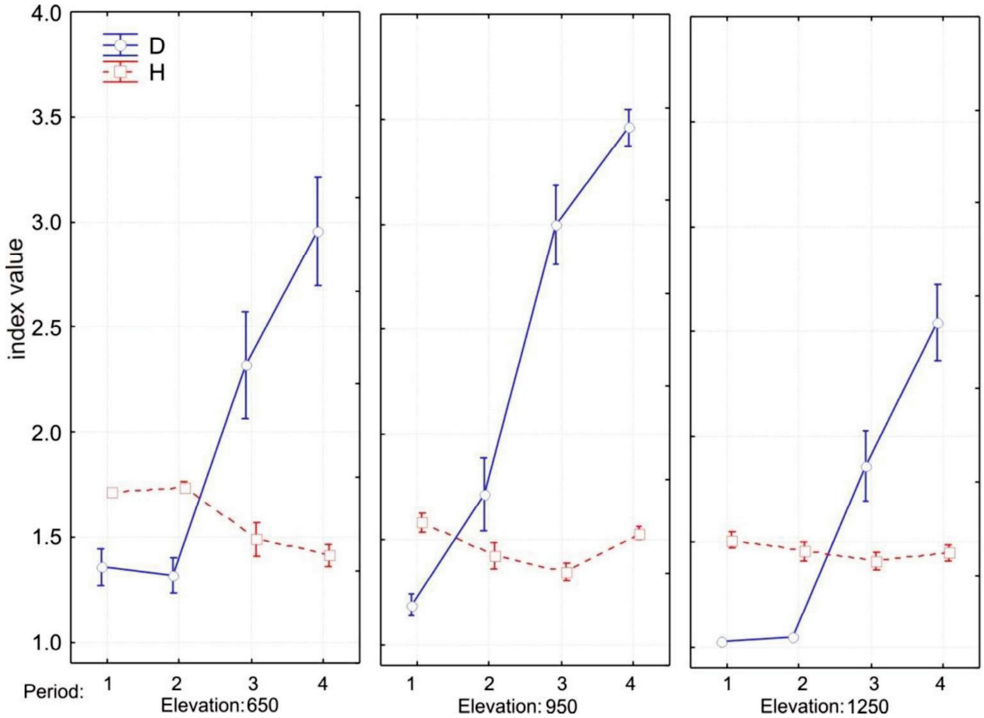



Fig. 4-16. Effect of climate change on tree species diversity index (D) and tree size diversity index (H) (difference of mean simulation under four climate change scenarios and the baseline) in three elevation zones and four time periods. Period: 1 – 2000-2025, 2 – 2030-2050, 3 – 2055-2075, 4 – 2080-2100.

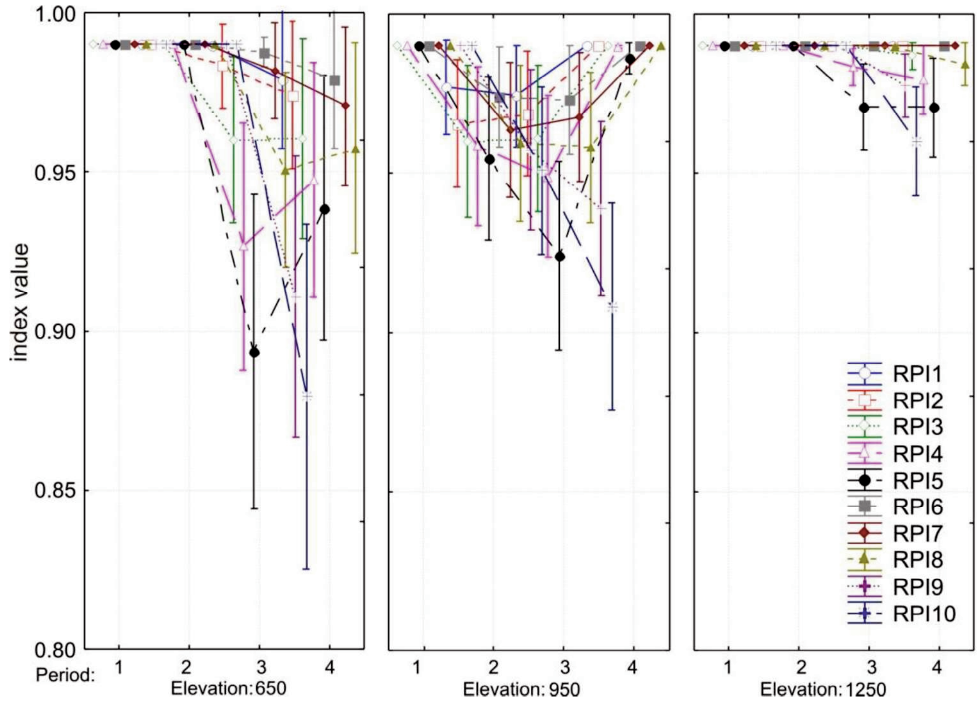



Fig. 4-17. Effect of climate change on 10 rockfall protection indices in three elevation zones of the CSA and for time periods. Mean simulation under 5 climate change scenarios are given. Period: 1 – 2000-2025, 2 – 2030-2050, 3 – 2055-2075, 4 – 2080-2100.

The effect of differences in the climate change scenarios on the variability of simulated variables was found to gradually increase to the future. Variability differed significantly between tree species, altitudinal zones and simulated variables. Generally, the response of most indicators was proportional to the differences in used climate change scenarios (ranked from c1 to c5), though not being a rule. To exemplify these effects, Fig. 4-18 shows the response of stocking volume of living trees (i.e., the V variable) for Norway spruce and European beech (% change of simulations under a scenario and the baseline climate). The c5 scenario induced the most intensive decrease in both species, inter-scenario variability was however large. While in beech, the c1-c3 scenarios induced almost no change, the c4-c5 scenarios induced a change of 20-30% by the end of the century. In spruce, balanced V was preserved only under the c1 scenario, while a decline up to 80% decline of the current V by the end of the century was found under the c5 scenario. A more detailed exploration shows that the most extreme responses relate to the low-elevation stands, where the effects of drought can become critical.

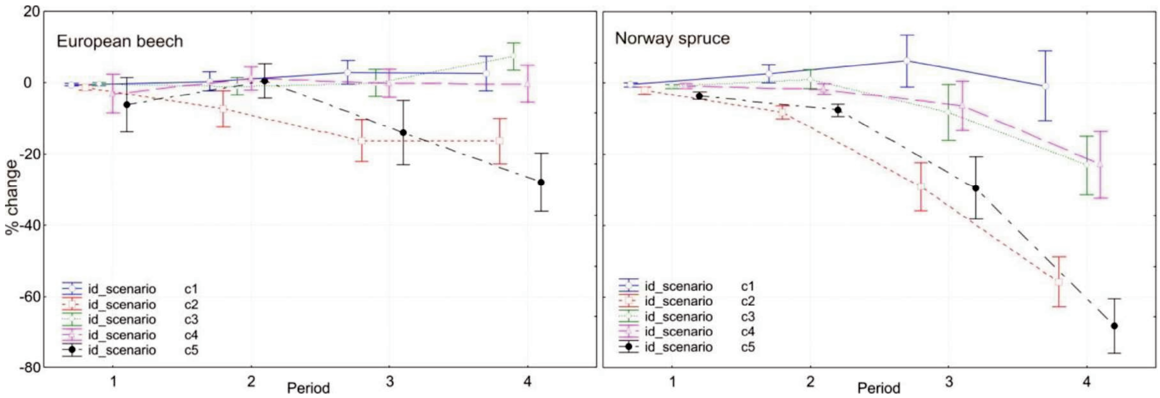



Fig. 4-18. Inter-scenario variability of relative changes in Stocking volume of living trees for European beech and Norway spruce in four time periods in the entire CSA. Five climate change scenarios are considered. Period: 1 – 2000-2025, 2 – 2030-2050, 3 – 2055-2075, 4 – 2080-2100.

### 4.6.3 Discussion

The implications of BAU and the interaction with climate change conditions for the main groups of ES can be summarized as follows:

- *Timber production*: Several growth and yield indicators were found to decline under climate change, which implies potential decline of timber production mainly in the second half of the century, at low and medium elevations. However, as the current demands on timber are satisfied, and current production even exceeds the capacity of timber processing industry, we do not expect that the projected production decline could affect the satisfaction of the current demands critically. Moreover, stable or improved production in higher elevations may provide opportunity, which can be utilized in the future.
- *Biomass for energy purposes*: Forest biomass production should be actively fostered as current demands of private households on fuel wood are not satisfied, and are increasing. Demand on biomass production for powerplants can be expected to increase as well. Projected decline of several growth and yield indicators may adversely affect the biomass supply in the future and thus the demand on this service can become increasingly unsatisfied. Therefore,

change of the current management towards promoting biomass production rather than timber can be considered as an opportunity to meet biomass demands in the future.

- *Biodiversity*: As forests in the CSA are mostly commercial, and timber and biomass production have key importance, biodiversity provided by forests has not been an important issue in the CSA so far. However, importance of the recreational function, and of game management and hunting indirectly imply a potential interest in increased biodiversity. As has been described in this report, the BAU management can be thought of as supporting species diversity and thus satisfying potentially increasing demands.
- *Rockfall protection*: Gravitational hazards are generally not thought of as an important issue in this CSA, hence there is no benchmark that could be related to the simulation outputs. The fact that the BAU simulations indicated a balanced development of the rockfall protection indices in at elevations, where such hazards are more likely to occur, suggests that the risk of gravitational hazards should not increase in the future, and demands for such service should be satisfied. However, such services are highly susceptible to increasing disturbance intensity.

The simulated impacts of climate change were highly variable and differed in relation to climate change scenarios, elevation, tree species, state and flow variables and ES indicator. Generally, forest production and carbon sequestration are projected to decline under the BAU management, despite the fact that the current management contains some adaptive elements recommended for the Central European region (e.g., Hlásny et al. 2014b). Improvement can be expected at the highest elevations, which agrees with carbon cycle simulations performed in a neighboring mountain range, i.e. the High Tatras Mts. (Hlásny et al. 2014a). Species diversity was found to increase in the course of stand development. This response was however due to the effect of management rather than climate change; the effect of climate change can be expected to be marginal.

These results can be thought of as concrete enough to warrant the guidelines for forest practice. However, the use of only a single model and high inter-scenario variability of some simulation outputs may question the soundness of our findings, and potentially limit their transfer to forest management.

High inter-scenario variability of responses may generate concern about the robustness of our conclusions. Estimation of the most important indicators by at least one additional model would be desired to feature a more comprehensive set of potential developments. Conclusions and recommendation could be more trustworthy once derived using a multi-model approach.

## 4.7 Case Study Area 7: Shiroka Laka

### 4.7.1 Simulation setup

#### BAU management description

Two main approaches were determined regarding BAU forest management in the CSA: (*i*) small-scale even-aged forest management; and (*ii*) no forest management. Even-aged FM was applied in rotation periods of 120 and 130 years. Three thinning operations were applied during the first 70 years of the rotation. Regeneration felling operations started at age of 90 or 100 years and regeneration period lasted three decades. Regeneration type in the CSA was always natural. Advanced regeneration was released in patches by removing the mature stand in two successive fellings (seed and final felling of the shelterwood system). Under the assumption of no advance regeneration, preparatory cutting of the shelterwood system was performed over the entire area before the implementation of the seed regeneration felling. Initial regeneration patches were between 0.15 and 0.20 ha in area in pure and mixed stands, composed by shade tolerant species (spruce, fir and beech), and between 0.20 and 0.30 ha in stands with participation of black and Scots pines. Pines were favored during the harvest operations in mixed stands. No management forest concept was applied in three RSTs (for a more detailed description of the RSTs see deliverable D1.3) due to steep and stony terrains, impeding harvest operations, and to assure the important protective function of stands.

#### BAU management implementation in the model

For stand level simulations in PICUS v1.5, generic stands sized 1ha (100 m x 100 m) where created. Thinning operations were carried out very close to the description in D1.3: Trees in the stands where sorted by species and relative diameter class and removed by random selection until prescribed removal volume was reached. For the third thinning operation a dbh threshold of 5 cm was included, to exclude regenerated trees from harvesting operations. The preparatory cut (regeneration felling, operation 1) for RST 3, 4 and 5 was included in a stepwise manner: First the management goal for pine was followed (management from below until desired volume share of pine or total removal volume limit is reached), then management goal for spruce was pursued with the same routine until removal volume is reached.

According to BAU description 2 regeneration patches (size 0.18 ha in stands with shade tolerant species, size 0.25ha for pine stands) where set up inside the simulated area of 1 ha.

External seed input was included according to local expert knowledge: RST1: *Fagus sylvatica*; RST2-4: *Pinus nigra*, *Picea abies*, *Fagus sylvatica*; RST5: *Pinus nigra*, *Pinus sylvestris*, *Picea abies*, *Fagus sylvatica*; RST6-8: *Picea abies*, *Abies alba*, *Fagus sylvatica*; RST9-10 *Picea abies*.

Regeneration was always natural and resulted from both on site seed production of trees and external seed input as described above. Tending operations were not included in a relative way, as described in D1.3, but as a reduction of seedlings to reach a number of about 4000 stems/ha at age 30 when the first thinning operation was done.

**List of evaluated ES**

In Shiroka Laka CSA three main ES were determined by the stakeholder panel: (i) timber production (TP); (ii) carbon storage (CS); and (iii) Nature protection and maintenance of biodiversity (NPMB). Non-wood forest products (e.g. fruits, herbs and mushrooms), recreation (e.g. tourism, hiking and biking) and air/water quality maintenance were other important ES, but were not addressed through indicators. Both forest managers and other stakeholders in the CSA considered TP as most important ES. TP was evaluated by using the following indicators: Stocking volume of living trees (V) and Current annual volume increment (VI). CS was described by aboveground carbon (C_above). The following parameters were employed in assessing NPMB: Volume of large standing dead trees (LSDTV), Abundance of large living trees (LLTN) and Basal area by species (BA_SP).

## 4.7.2 Simulation results

The BAU simulations under baseline climate change scenario (c0) showed stand dynamics similar to the expected one. Under c0, simulated stocking volume of the mature stands was reasonably comparable to the one from the previous rotation (Fig. 4-19). However, simulated development of stocking volume under climate change indicated significant alterations (decrease) in all selected RSTs in three (c2, c3 and c5) out of five climate change scenarios, especially during the last thirty years of the 100 year simulated period (Fig. 4-19). Similar trends with climate change were observed in the three RSTs in the dynamics of current annual volume increment, the relative decrease of increment being greater in RST1 under c2, c3 and c5.

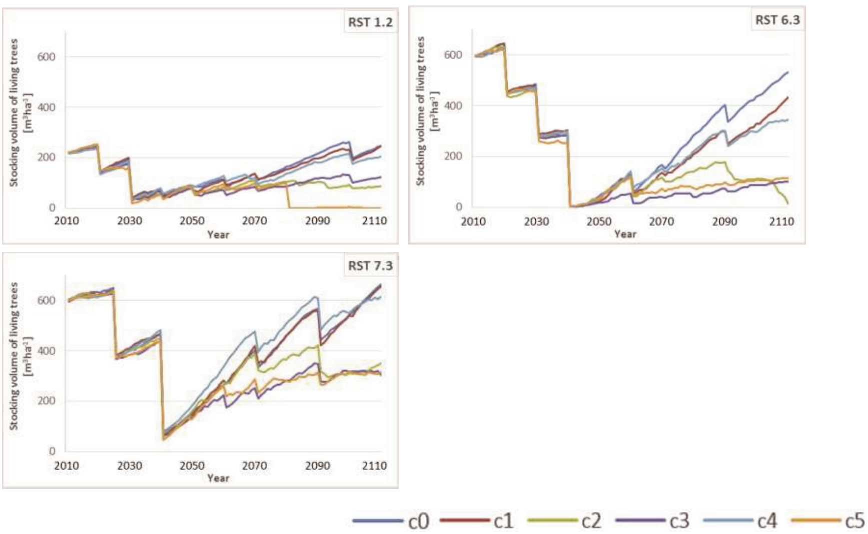



Fig. 4-19. Dynamics of stocking volume of living trees in RSTs 1.2 (beech forests, final harvest 2030), 6.3 (mixed coniferous forests on Cambisols, final harvest 2040) and 7.3 (mountainous spruce forests on permesotrophic soils, final harvest 2040) under baseline climate and the five climate change scenarios.

The most productive RSTs (6.3 in landscape 1 and 7.3 in Landscape2) and the least productive RST in the landscape 2 (RST 8.1) were selected to show how carbon sequestration potential (in situ) would change under different climate. In all selected RSTs, simulated values of carbon stored were significantly lower in c2, c3 and c5 climate change scenarios. The relative decrease of carbon stored was greater in RST6 (Fig. 4-20).

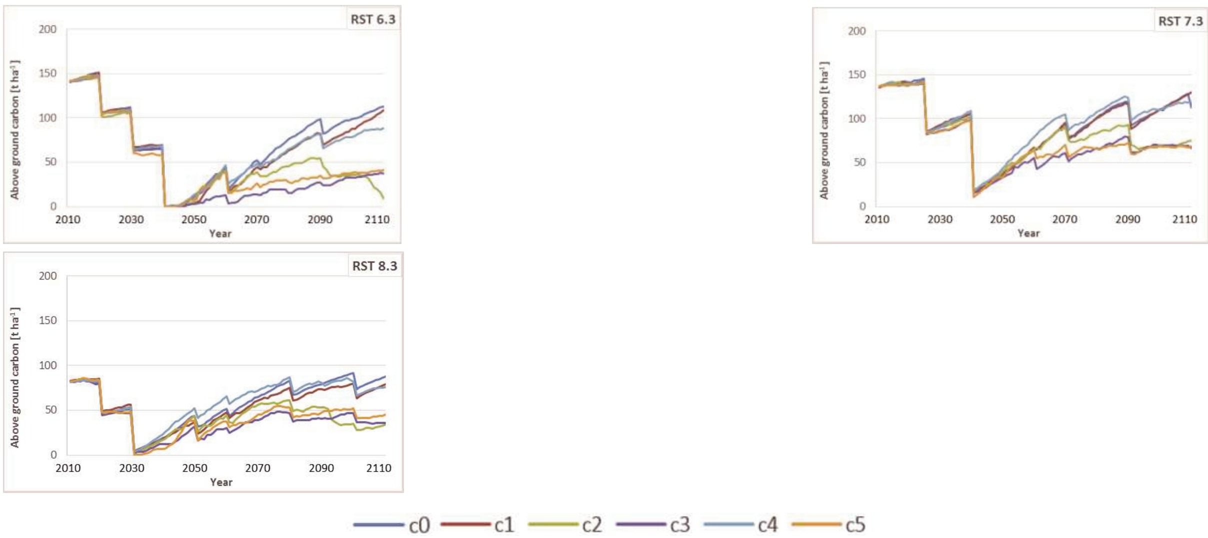
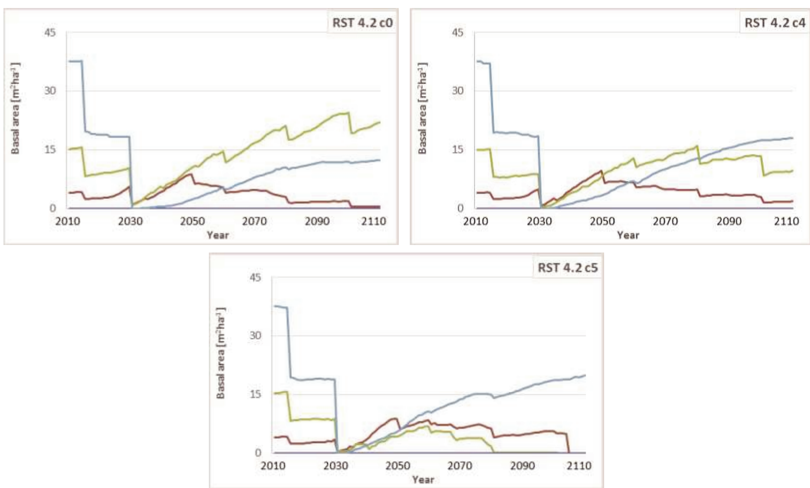



Fig. 4-20. Carbon sequestration dynamics in RSTs 6.3, 7.3 and 8.3 (mountainous spruce forests on submesotrophic soils, final harvest 2040) under baseline climate and five climate change scenarios.

Simulated development of the tree species composition under baseline climate did not indicate significant changes when compared to the current state of RSTs (Fig. 4-21). Lower share of spruce in RST 4.2 c0 was due to more intensive harvest of spruce during thinnings and especially during the first regeneration felling at age of 90 (60% of volume removed was from spruce). However, both the "optimistic" (c4) and the "pessimistic" (c5) climate change scenarios induced changes in species dominance in RST 4.2 and RST 6.3, the black pine and the fir outcompeting the spruce. Beech disappeared in the last simulated years in RST 5.2 under c4 climate and in both RSTs 4.2 and 5.2 under c5. On the other side, climate change led to increase in the share of beech in RST 6.3.



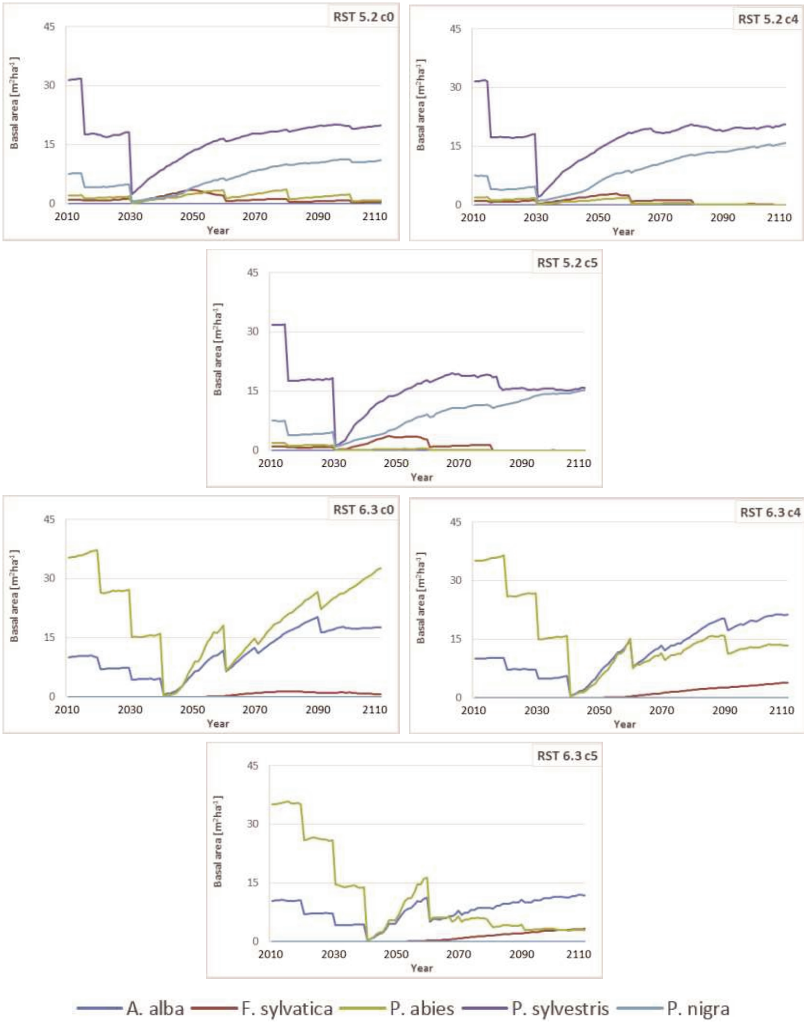



Fig. 4-21. Simulations of stand basal area (BA) by tree species in three mixed RSTs under three climate scenarios: Mixed forests on Cambisols (RST 4.3); Scots pine dominated forests on Cambisols (RST 5.2); and RST 6.3.

The potential of stands to develop LLT and LSDT (both parameters are described in the ARRANGE Deliverable 2.2) varied across different RSTs. For example, density of LLT at the time of stand maturity (>80 years) is expected to exceed 40/ha in RSTs 6.1 and 7.1 (both RSTs are among the most productive in the CSA) and 20/ha in RST 8.1 (Fig. 4-22). In the case of all three RSTs, the abundance of LLT at maturity is considered as "good" in terms of the bird habitat quality criteria (see also ARRANGE deliverable 2.2). It is expected that climate change will cause significant decrease in the abundance of LLT. Even under the optimistic climate change scenarios (c1 and c4), density of LLT is expected to decrease by 50% at maturity. In both RST 6.1 and RST 8.1, no trees are expected to cover the criterion of LLT under the three pessimistic climate change scenarios until age of 100. As depicted in Fig. 4-22, there is no straightforward correlation between the potential of RST to produce LLT and the simulated LSDT values. LSDT values at stand maturity are highest under c2 (the second most pronounced pessimistic cc scenario regarding the growth and survival of spruce in the CSA. Under BAU management, the potential of the three RSTs to meet the "good" criterion for LSDTV in terms of bird habitat quality is not high (Fig. 4-22).

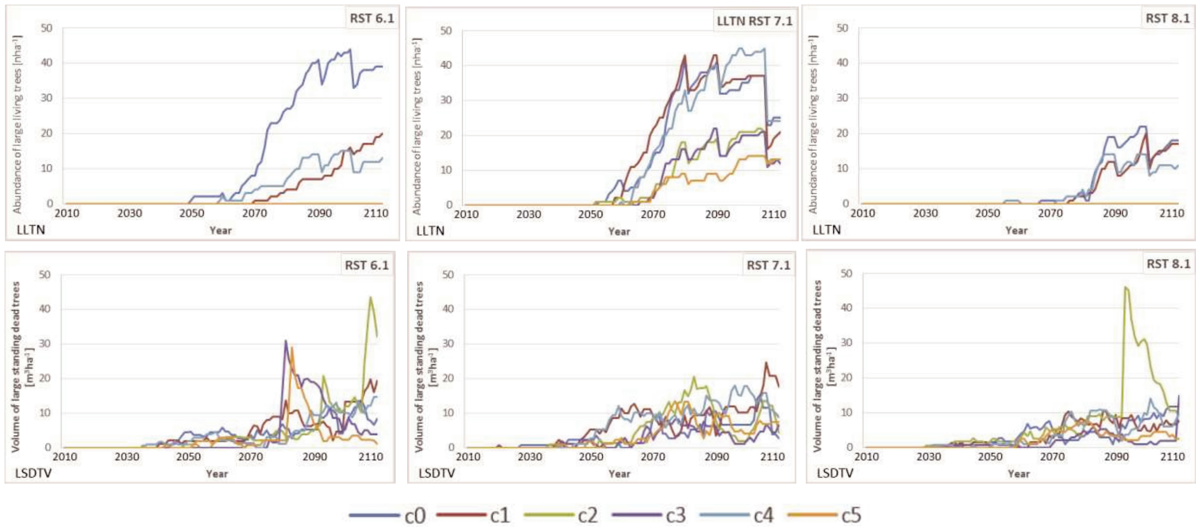



Fig. 4-22. Simulated abundance of large living trees (LLTN) and volume of large standing dead trees (LSDTV) in RSTs 6.1, 7.3 and 8.3, all aged 20 in the beginning of stand simulation (2010).

### 4.7.3 Discussion

According to the simulation results, under BAU management the pure and mixed mountain forests in Shiroka Laka CSA have a good potential to supply all main ecosystem services under optimistic climate change scenarios (e.g. c1 and c4). Some ES are expected to be supplied well under BAU management, such as timber production and carbon sequestration, while others might depend on further adjustments of the management regime. BAU management would likely assure little loss of habitat area (as seen in Fig. 4-21) but would only partially assure coverage of all requirements needed for achieving favorable conservation status of forest bird habitats at stand scale (as defined by the Natura 2000 criteria). For example, adequate availability of large living trees or dead wood during the whole rotation period is required, not only at maturity, as it is the case of the current simulations. This points at the need to adjust BAU management and add explicitely other ES than timber in the management scheme.

The simulations under pessimistic climate change scenarios (c2, c3, and c5), however, depict significantly lowered potential of all RSTs, even of those located at higher elevations, to provide timber production and carbon sequestration. In some RSTs in landscape 1, tree species composition is expected to drastically change. Under the most extreme climate change scenario (c5), beach decline is simulated in RST 1, 4 and 5 and a significant decrease of share or decline of spruce is simulated in RST 4 and 6, where Norway spruce is a dominant species at present. The simulated increase of LSDTV in some RSTs under severe climate change might be beneficial for some endangered bird species but the lack of LLT is likely to be a more influential limiting factor. The uncertainty brought by the climate change is reinforced by the pronounced separation of optimistic and pessimistic climate change scenarios, e.g. simulation results are usually clustered in two groups, the one under climate scenarios c1 and c4 and the other under c2, c3 and c5, with no climate change scenario showing intermediate results. All this might require significant changes of current forest regimes, albeit not comprehended yet by the local communities.

# 5 Conclusions

## 5.1 Analysis of historic data

Historic inventory data as well as management records from five CSAs (Spain, France, Slovenia, Sweden and Slovakia) were available to study the development of ES indicators over several decades. For those two CSAs (Spain and Slovenia) where the management regime had changed during the historic period, it is particularly interesting to analyze if there is a response of the ES indicators related to management. Over time, several changes in forest properties or management occurred that, in some cases, led to variations in the provision of ES.

For instance, in the Spanish CSA the management system changed in 1984 from a uniform shelterwood system to a group selection system. However, the effect of this change was overwhelmed by the increase in regeneration cuttings that have taken place since 1984 in these stands with the aim of bringing up-to-date the cuttings that had not been performed in the past according to the Management Plans. The reasons for the delay in regeneration cuttings were the adoption of more conservation-oriented practices since 1965 that resulted in a drastic decrease in the timber harvested in the period 1965-1984, but also an increase in the structural diversity and number of large living trees. In contrast, since 1984 the volume of timber harvested has increased, but has led to a decrease in the structural diversity and an increase in the number of large living trees. Thus, the changes in management that occurred in these stands over a relatively short period of time do not permit to draw general conclusions.

The Slovenian CSA also experienced a change in forest management practices in 1970 from single-tree selection systems to an irregular shelterwood system in combination with group selection and single-tree selection. This change did not influence the indicators related to timber production or carbon sequestration, but it had a noticeable effect on nature conservation indices. The structural diversity and the number of large living trees have decreased since 1970 although no effect was found in species diversity. Nevertheless, the decrease in these conservation indices can be explained by (1) the change in the management system and (2) the inventory method, which decreased the area surveyed by a permanent sampling plot, leading to the placement of the inventory plot (500 m$^2$) into one (even-sized) patch.

In summary, the results for these two CSA show that over a few decades it is quite difficult to isolate the effect of changes in the management regime on the provision of ES because multiple factors are involved.

Focusing the attention on the provision of ES over time in each CSA, the results showed that the timber production indicators increased in all CSAs, in terms of both timber stocking and productivity. For stocking volume, the increases ranged from 23% in Sweden to 234% in France, although in France the data indicate that the inventory data of 1909 did not account for all tree species present in the stands. Spain, Slovenia and Slovakia showed an increase in stocking volume of 35%, 116% and 96%, respectively. Regarding productivity, a positive trend was found in all CSAs with an increase of 67% in Sweden, around 100% in Spain and Slovenia, 124% in France and up to 256% in Slovakia. Harvesting levels were quite constant in the CSA, while in the Slovakian CSA the harvest trend was clearly positive.

Following the trend in stand stocking, carbon storage increased during the analysed period in all CSAs.

Biodiversity conservation indicators differed significantly across CSAs. Systems creating even-aged stands (i.e. clear-cutting system, uniform shelterwood system) featured lower indicators, especially in combination with intensive sanitary harvests (e.g., Slovakian CSA). In the Spanish CSA structural diversity increased at the beginning of the analysed period with a subsequent decrease, thus maintaining nearly constant average values. In the Swedish CSA, structural diversity decreased by 5%, whereas both Sweden and Slovakia featured a decrease of 10 and 15%, respectively.

The analysis of the historic series of forest inventories and management practices proved to be useful to analyze and understand the development of the provision of ES over time. However, this methodology also has limitations. First, the difficulty of finding accurate and reliable historic information that can be used for this type of analysis is the main issue (for two CSAs, this was not possible at all). Second, the raw data need to be quality-checked and homogenized, since they usually refer to different management units (i.e., the management or inventory units may have changed over time). Third, in some occasions the management information refers to what was theoretically planned in the Management Plans, rather than what was executed in reality. Nevertheless, the information provided and analyzed in the present Deliverable represents an important piece of knowledge regarding the provision of forest ES over time.

## 5.2 Analysis of BAU management

There is a broad spectrum of silvicultural systems used as BAU management in the seven CSAs. In three CSAs, uneven-aged management regimes are in use, in the Spanish CSA coppice system is also an element of current management. There is no obvious relationship between the management objectives (i.e., demanded ES) in the CSAs and the BAU approaches. However, it seems that even-aged systems based on small- to medium-scale clear-cutting is the favoured silvicultural system when timber production is the dominant ES demand. To some extent tradition also plays a role in determining the management regime. The fact that just in one CSA (Montafon, Austria, i.e. in the steep-slope central European Alps) protection against gravitational hazards was a high priority ES partly explained the high share of even-aged systems based on homogeneous shelterwood and strip-clear cut approaches in the other CSAs. When evaluating BAU management for its performance regarding current ES demands (timber, carbon storage, biodiversity maintenance), in most CSAs the result was satisfactory. However, there are limitations with regard to species and structural diversity as well as deadwood abundance.

An issue not fully represented in the simulation setup are the impacts of disturbances such as bark beetles and windstorms. Just in CSA3 (Montafon) bark beetle damages were considered explicitly in the simulations. However, it can be assumed that bark beetle disturbances in conifer forests are a similar threat to ES provisioning in CSA2, CSA4 and CSA6. Thus, it is fair to assume that the simulation results are rather too optimistic.

When BAU management was simulated under a set of climate change scenarios the results indicated substantial variation regarding ES provision among climate scenarios. Furthermore, we found the typical altitudinal gradient in mountain regions, with mainly negative impacts on forest growth at low elevations due to increasing summer drought and species change from conifers to broadleaved species, while at higher altitudes growth benefits from longer vegetation periods and more favourable thermal regimes. This is a consistent finding across all CSAs. However, it is important to note that scenario simulations that do not consider disturbance regimes are very likely too optimistic. Intensifying disturbance regimes bear the potential to severely impact ES provisioning such as timber production, carbon storage and protection against gravitational hazards. Table 5-1 summarizes these findings across all CSAs.

Table 5-1. Summary of BAU simulation results in all ARANGE case Study Areas (CSAs). CSA1 = Spain, CSA2 = France, CSA3 = Austria, CSA4 = Slovenia, CSA5 = Sweden, CSA6 = Slovakia, CSA7 = Bulgaria.

| CSA | BAU management regime | current ES provision | climate change impact on ES |
|---|---|---|---|
| 1 | EAHF [group shelterwood]<br>coppice [Qu. pyrenaica]<br>*noMgt* *[marginal sites]* | TP<br>Pinus sylv. 🟢 Quercus pyr. 🔴<br>NC & PH 🟡 | TP & CS 🟢 🔴 |
| 2 | UAHF [single tree selection]<br>*[10-15 year intervals]* | TP 🟡 reduce target DBH<br>PH & NC 🟢 | TP & CS 🟡 🔴<br>PH & NC 🟡 |
| 3 | UAHF [group selection]<br>*[20-30year intervals]* | TP & CS & PH 🟢 🟡<br>NC 🟡 (browsing) | TP & CS & PH 🟡 🔴<br>NC 🟢 🟡 |
| 4 | EAHF [irregular shelterwood]<br>UAHF [group selection]<br>*[10 year intervals]* | TP & NC 🟡<br>Abies alba ↓<br>Fagus sylvatica ↑ | TP & CS 🟢 🔴 |
| 5 | EAHF [clear cut & plant]<br>*[in transition from UAHF]* | TP & CS 🟢<br>NC 🟡 | TP & CS 🟢 |
| 6 | EAHF [small clear cuts & plant]<br>[stripwise shelterwood] | TP 🟢 (but: bark beetles]<br>NC 🔴 | TP & CS 🟡 🔴 |
| 7 | EAHF [shelterwood (patches)]<br>*noMgt* *[marginal sites]* | TP & CS & PH 🟢<br>NC 🟡 | TP & CS 🟢 🔴<br>PH 🟡 |

The regional ES portfolios that are requested by human societies typically include conflicting objectives, and it is likely that such conflicts will intensify in the future. There is a clear contrast in policy objectives to intensify timber and biomass production and to mobilize biomass potentials to support industries and the feedstock demand of biomass power plants on the one hand, and the increasing interest to increase the area of protected forests for conservation purposes.

Another potential conflict exists in small-scale ownership structures, where the demand for timber production (usually the primary interest of forest owners) and the need to protect against rockfall, snow avalanches and erosion and landslides meet. No segregative approaches are possible when ownership size is too small to disentangle ES. However, approaches to balance (i.e., integrate) ES such as timber and protection by fine-grained small-scale silviculture may be severely hampered by technical and economic constraints regarding feasible harvesting technologies.

Overall, our results call for the design of ES portfolios that feature no or low conflict potential and a partial segregation of ES provisioning at the landscape scale. From the BAU simulations, we further conclude that setting aside larger areas in coniferous mountain forests for conservation purposes may not be a viable option due to intensifying disturbance regimes, which are likely to jeopardize key ES such as protective services.

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