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REPORT

Climate Warming and the Recent Treeline Shift in the European Alps: The Role of Geomorphological Factors in High-Altitude Sites

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Abstract Global warming and the stronger regional temperature trends recently recorded over the European Alps have triggered several biological and physical dynamics in high-altitude environments. We defined the present treeline altitude in three valleys of a region in the western Italian Alps and reconstructed the past treeline position for the last three centuries in a nearly undisturbed site by means of a dendrochronological approach. We found that the treeline altitude in this region is mainly controlled by human impacts and geomorphological factors. The reconstruction of the altitudinal dynamics at the study site reveals that the treeline shifted upwards of 115 m over the period 1901–2000, reaching the altitude of 2505 m in 2000 and 2515 m in 2008. The recent treeline shift and the acceleration of tree colonization rates in the alpine belt can be mainly ascribed to the climatic input. However, we point out the increasing role of geomorphological factors in controlling the future treeline position and colonization patterns in high mountains.

Keywords Climate change · Treeline · Geomorphology · Tree rings · *Larix decidua* · European Alps

INTRODUCTION

The recent global warming of the atmosphere is driving several dynamics, especially in temperature-limited environments, which may undergo rapid changes in their physical and biological components. In high-altitude environments the responses to climate change are proved by rapid changes in the landscape and especially glacierized areas and the upper portions of the valley slopes are involved. The European Alps are experiencing a temperature increase that is stronger than the global mean of about +0.7°C for the last century (e.g. Hansen et al. 2006). In particular, a strong increase in the mean temperature of about +1.7°C was recorded in Switzerland for the 30-year period 1975–2004 (Rebetez and Reinhard 2008), potentially inducing strong impacts on high-altitude ecosystems. Glacier retreat and disintegration (Paul et al. 2004), permafrost degradation and correlated rockfalls (Haeberli and Gruber 2009) and changes in snow-cover duration (Hantel and Hirtl-Wielke 2007) are only a few examples of the marked effects of temperature changes on glacial and periglacial environments. On the other hand, the biological components have also been strongly involved and the ongoing climatic trends are inducing changes in the vegetation structure and biodiversity of high-altitude environments. Within the most evident responses, longer growing seasons and warmer temperature conditions have in fact induced an upward shift of vegetation belts (Theurillat and Guisan 2001) and changes in species compositions, especially in the alpine and nival belt (Pauli et al. 2003). The responses of treelines to climate change are more complex and slower since the interaction between the highest portion of the forest and the alpine grasslands or the unfavourable substrates involves many factors that at the site scale may even mask the climatic input. Within the main factors controlling the treeline altitude, low-temperature conditions are recognized as strongly limiting tree growth and survival (Tranquillini 1979; Stevens and Fox 1991; Körner 2003; Holtmeier 2009). In particular, the soil temperature has recently been found to be the most important factor in controlling the treeline position at the global scale (Körner and Paulsen 2004). In the European Alps (but not at the global scale), a good approximation of the potential treeline altitude is given by the altitude at which the air temperature exceeds 5°C for at least 100 days (Ellenberg 1963). Other factors influencing the treeline responses to climate depend on the dominant species and its colonization rates, the kind of reproduction and the seed-dispersal strategy and vitality (Holtmeier 2009). All these factors interact directly and continuously with climatic conditions, substrate quality and geomorphologic processes, thus resulting in different responses to the climatic input. Considering a mountain range, in general trees take advantage of the mass–elevation effect (e.g. Brockmann-Jerosch 1919; Ellenberg 1978; Barry 1981; Holtmeier 2009) and of the more continental, warmer and drier, climate of the inner regions. As a result, treelines are found at higher elevations in the inner regions but also generally at greater distances from mountain peaks and geomorphological constraints than in the peripheral zones (Leonelli et al. 2009). Under warmer temperature conditions tree colonization patterns and treeline shifts are therefore expected to be more evident in the inner regions since there the treelines are potentially freer to shift upward into the alpine grasslands.

Under the warmer conditions established since the end of the Little Ice Age (the coolest period of the whole Holocene, also corresponding to a generalized maximum glacier advance in the Alps) an altitudinal upward shift has been observed in several treelines (Luckman and Kavanagh 2000; Kullman and Kjallgren 2006; Gehrig-Fasel et al. 2007; Vittoz et al. 2008; Kullman and Öberg 2009). In other studies, the treeline responses to climate were recorded mostly as an increase in forest density at the treeline (Klasner 2002; Mazepa 2005; Shiyatov et al. 2005). In both cases, in the European Alps the forest dynamics at the treeline have also been influenced by the constant decline of pastoralism and the related human activities due to the land abandonment since the Industrial Revolution (1850), making it difficult to disentangle climate influence and human impacts (Motta and Nola 2001). Recent findings have demonstrated that the most important changes at the treeline in the Swiss Alps are given by forest ingrowth (90% of new forest areas), whereas a treeline shift (10%) was found to be related to climate change only in 4% of the cases and to land abandonment in most cases (Gehrig-Fasel et al. 2007). Other studies have found human impact changes to be the main factor causing a treeline upward shift (Chauchard et al. 2010).

Our objective was the reconstruction of the past treeline altitude during the last 300 years in a semi-natural site and the comparison with climatic trends over the last 150 years. We define as ‘natural’ those sites where the human impact on the treeline is negligible and only climatic or geomorphological factors are the most important factors. In particular, we wanted to evaluate the present and future role of geomorphological factors in determining the treeline altitude under the ongoing climatic inputs. The study area is in the western Italian Alps, an area where the Alpine mountain range represents a barrier to the warmer and wetter air masses coming from the Atlantic Ocean carried by the western winds. Here the climate is semi-continental and treelines grow at higher altitudes than in areas characterized by more oceanic conditions (Caccianiga et al. 2008). In this region, the treelines are mainly constituted by the European larch (*Larix decidua* L.), a widespread species in the European Alps adapted to poor and shallow soils, which has a wind-dispersed strategy for seeds. Together with *Pinus cembra* L., the European larch is the most widespread species at the treeline in the European Alps (Bernetti 1998) and it is sporadically associated with *Pinus uncinata* Miller in the western Alps and with *Picea abies* (L.) Karst. in the Eastern Alps. Since it is a deciduous species with a light crown, the European larch is often also associated with high-altitude pastures. Our hypotheses were: (1) where geomorphological factors are spatially discontinuous or absent, under the present climatic conditions, natural treelines show an upward shift over time; (2) over the past 30 years (the period covered by daily temperature data), the trees growing at the treeline were subject to more limiting temperature conditions than the trees at the present treeline; (3) the recent treeline shift in natural sites is still mainly driven by climate but it is going to be more limited by geomorphological and edaphic factors in the future.

STUDY AREA AND GEOMORPHOLOGICAL CHARACTERIZATION

We analyzed European larch treelines in the Valle d’Aosta region, in the inner portion of the western Italian Alps. Analyses were conducted at two spatial scales: at the regional scale to depict the present-day treeline altitude and at the site scale to reconstruct the treeline position over time (Fig. 1). The Valle d’Aosta region is surrounded by the highest peaks in the European Alps and the climate in the region has a semi-continental temperature regime, with a monthly temperature range of about 20°C. Precipitation is scarce (about 680 mm in the main valley) with 70% of the land receiving less than 1000 mm per year (Mercalli et al. 2003). The site for the past treeline altitude reconstruction was selected on the SW-facing slope of the Becca di Viou Mountain (45°47′36″N; 7°21′44″E), an area characterized by 1.5 km of treeline with the presence of extensive talus slopes and rockfall deposits above the forest line. Here, despite the unfavourable substrate that strongly limits tree establishment, up to high altitudes there are several sparse portions of alpine grassland where trees may easily establish and grow (Fig. 2a).

The study area is mainly dominated by mass wasting and gravity processes (Fig. 3). Glaciers are absent in the present day and deposits due to mass wasting dominate the landscape. In the upper part, rock faces of the Arolla

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Gneiss formation (fine-grain gneiss and schists derived from granite) dominate the landscape. Detachment zones related to rockfalls and rock avalanches are present on the higher slope. Unconsolidated and coarse deposits characterize the whole site. The debris cover is represented by many debris cones and, in the central belt, by a continuous talus slope. Several debris-flow channels and deposits cross this talus slope. Between the talus area and the rocky area the debris is partially stabilized, while below the talus area, the soil slopes are more stable.

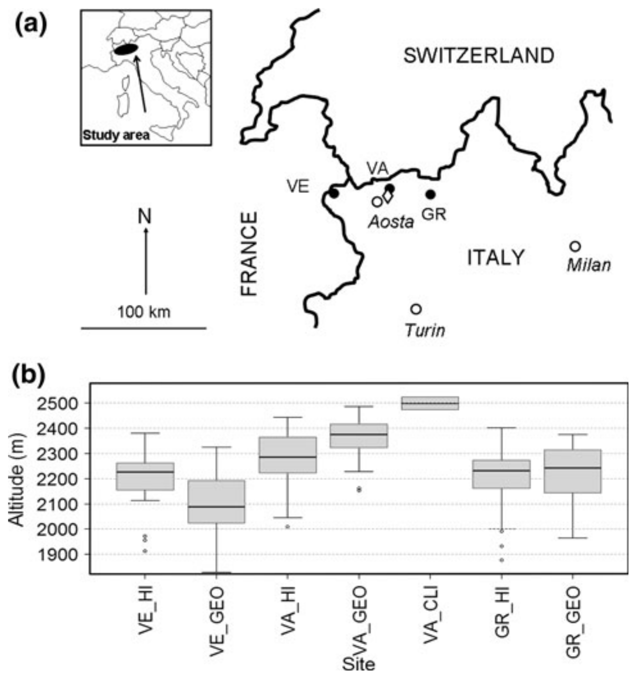

Fig. 1 Sketch map of the study area. **a** Treeline altitudes were assessed at the regional scale for three valleys in the Valle d'Aosta region, western Italian Alps: *VE* Veny, *VA* Vallpelline–Etroubles, *GR* Gressoney (*black spots*). The *rhombus* indicates the position of the study site Becca di Viou. b Boxplot of the treeline altitude in the three valleys. The treeline altitude was assessed over 240 km by considering the trees growing at the highest altitudes and the most important factor limiting a treeline potential upward shift in the three study valleys by considering human impacts (HI), geomorphologic constraints (GEO) and climate (CLI)

The irregular conditions of the surface also prevented an intensive exploitation of the area in the past centuries. South-west of the study area, about 200 m below the forest-treeline boundary, instead, there is barn (at 2080 m) and an alpine pasture where cows graze during summertime. Past timber harvesting may have altered the distribution of trees, especially on the southernmost side of the area (closer to the barn). However, the forest in its highest portion and at the treeline ecotone presents semi-natural conditions, with some old trees in the open forest at the lower treeline and progressively younger trees at the upper treeline (defined by the upper limit of 2 m tree growth forms). Some small trees, stunted and deformed trees (krummholz), dead trees and saplings are sparsely present at the species line.

MATERIALS AND METHODS

Regional-Scale Analysis

At the regional scale, we assessed the treeline altitude by means of a GIS-based approach, detecting on ortophotos the trees growing at the highest altitudes in three valleys of the Valle d'Aosta region. The trees were selected about every 600 m for about 240 km along the valleys' slopes and for each tree we also established the factors that could hamper or exclude a potential future treeline upward shift, distinguishing between human impacts (cattle grazing, logging, ski resorts, etc.), geomorphological factors and related landforms (screes, talus slopes, rock outcrops, etc.)

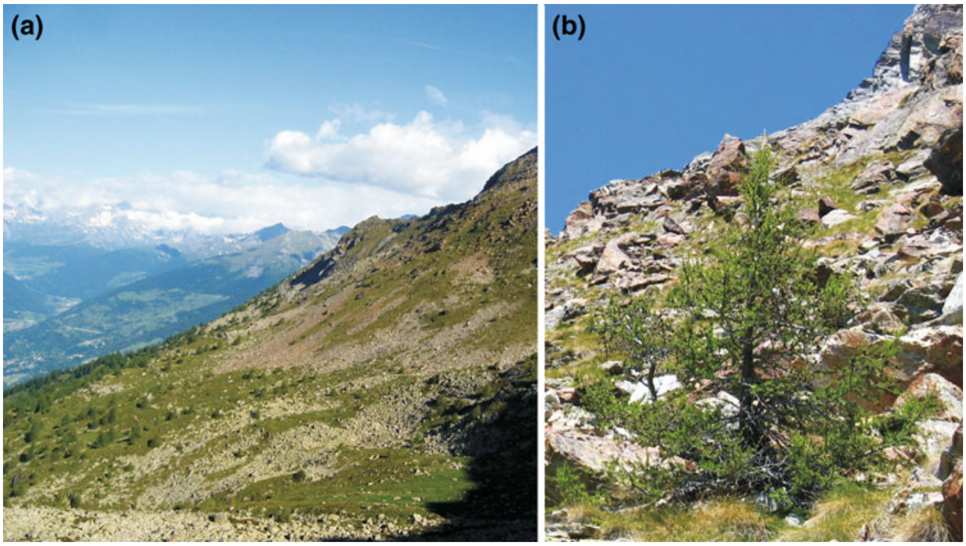

Fig. 2 **a** The treeline at the Becca di Viou site (summer 2008). Geomorphological factors prevent the forest growth and the treeline from moving uniformly upward, driven by the recent climatically induced trend. **b** At some positions treeline trees at the highest altitude already grow close to exposed rock faces and in a very poor, rocky substrate

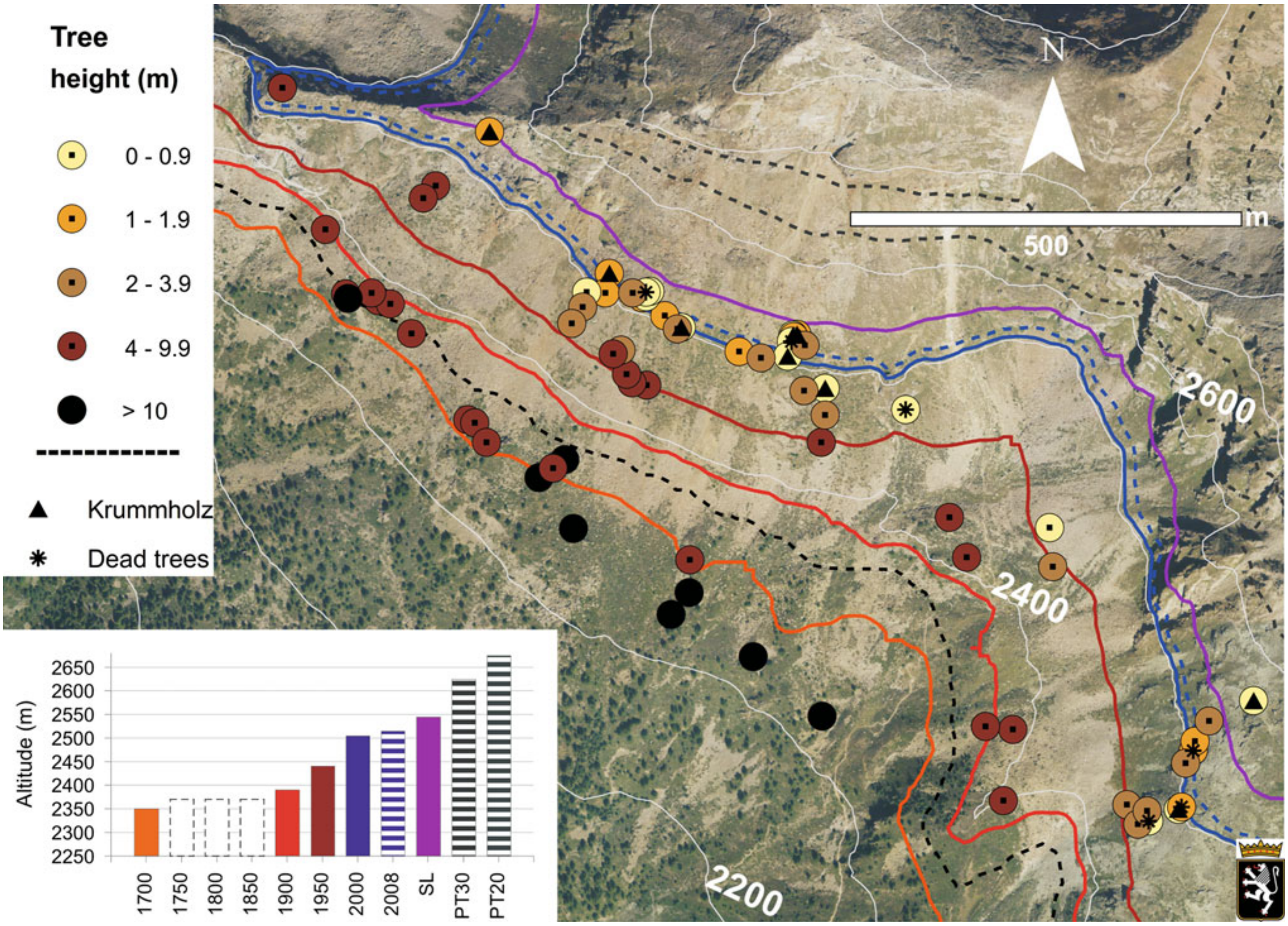

Fig. 3 Distribution of the sampled trees at the treeline in the study site and their height in 2008 (and 2009 for some trees >10 m). The figure also reports the treeline positions over 1700–2000 for 50-year time periods and the treeline and species line (SL) in 2008. The treeline altitude for the 50-year periods ending in 1750, 1800 and 1850 (*black-dashed line*) was estimated as the average between the 1700 and 1900 treelines since no trees 2 m tall were found in these periods. Potential treelines (*grey-dashed lines*) PT30 and PT20 were defined by the altitude with more than 100 days per year with a temperature over 5°C over the periods 1975–2004 (30 years) and 1985–2004 (20 years). The orthophoto is courtesy of the Regione Autonoma Valle d'Aosta, Assessorato Territorio, Ambiente e Opere Pubbliche, Edition 2006–Aut. n. 1156 of 28.08.2007

and climate (Leonelli et al. 2009). The climate's strongest influence was assessed only for the highest treeline in the region (Körner and Paulsen 2004), where trees are growing on a regular slope, in continuity with the forest beneath. The regional approach helped in selecting an appropriate site located at the altitude of the climatic treeline in the region, where we reconstructed the treeline position over time by means of a tree-ring-based approach.

Site-Scale Analysis

Tree Sampling

Overall, at the study site we sampled 62 trees of European larch (in summer 2008, and 2009 for some trees taller than 10 m), selecting the biggest and oldest-looking trees at the different altitudes by evaluating their heights, stem diameters and crown shapes. We selected the trees in the treeline ecotone and up to the tree species line (19 trees at the lower treeline, 28 at the upper treeline and 15 at the species line); another 10 specimens of dead trees, krummholz and saplings at the species line were only described and positioned. Sampling was performed at the lower and upper treelines by extracting one core at breast height (1.3 m) and a lower core either at 50 cm, 30 cm or root-collar level (depending on the tree size and field conditions). At the highest altitudes (at the species line) we described some specimens of dead trees, krummholz and saplings. We recorded the coordinates of all the trees that were analyzed by means of a GPS and we measured their heights and diameters.

Tree-Ring Approach to Age Estimation

For each sample we determined the cambial age by counting the rings from bark to pith. In the case of missing pith, we estimated the number of missing rings between the last visible ring and the pith based on the curvature of the last available rings, supposing constant growth (Applequist 1958). The tree age at 2 m height (and consequently the year in which the tree was 2 m tall) was estimated for each tree by calculating a linear regression of cambial age versus different heights between 3 points: the cambial age of the lower core, the cambial age of the core at 1.3 m and age 0 at the present tree height. The relationships between tree age and tree height may not be linear, especially in extreme environments, but this is the best approximation when not performing a stem analysis, which, moreover, requires a tree fall. The trees were grouped into 50-year periods over the period 1650–2008 according to the year in which the tree reached 2 m in height. For each of these 50-year groups we determined a mean treeline position by averaging the altitude only of those trees (maximum 5 per group) growing at the highest altitudes, above the previous treeline position. The treeline altitudes were then approximated to the nearest 5 m.

GIS-based Approach to Geomorphological Characterization

All of the study area has been analyzed by means of photointerpretation with the objective of quantifying the surface cover of debris and rocks every 100 m belt of altitude above 2300 m. We distinguished between unconsolidated debris (mainly from active taluses and rockfall deposits), consolidated debris (partially covered by vegetation) and rock faces.

Treeline Temperature Estimation

Daily temperature series (1974–2004) from eight weather stations at an altitude comprised between 1320 m and 2530 m a.s.l. were selected in the surroundings of the study site. By means of a linear regression we established an altitudinal temperature lapse rate for the months from April to September to avoid problems related to temperature inversions during wintertime. After standardizing each temperature series, we calculated a mean series that together with the found lapse rate was used to estimate the air temperature at different altitudes at the study site. In particular, we estimated the potential treeline altitude by using a thermal index defined by the number of days over 100 with a temperature above 5°C (Ellenberg 1963). The altitude with 100 days exceeding 5°C approximately fits the treeline position in the European Alps passing from 1850 m (peripheral regions) to 2200 m in the inner region (Ellenberg 1963). The yearly data were averaged over the periods 1975–2004 (30 years; potential treeline PT30) and 1985–2004 (20 years; PT20).

RESULTS

The treeline altitude assessed by means of photointerpretation in the three selected valleys was mainly influenced by human impacts and geomorphological factors (Table 1). Apart from the Veny Valley, strongly influenced on the left slope by the presence of the Mt Blanc massif, human impact determines the treeline in the region for about 70% of the cases. A climatic treeline was found at the Valpelline–Etroubles Valley, where trees are growing undisturbed by human activities or geomorphological factors, ranging between 2470 m and 2520 m a.s.l. (Fig. 1). Both human impacts and geomorphological factors are lowering the treelines in the region up to 400 m (Veny Valley) from the present-day climatic treeline. In this valley, in particular, geomorphological factors limit the natural treeline altitude below the anthropogenic treelines; at the Valpelline–Etroubles Valley, geomorphologic treelines were found at an altitude between the anthropogenic and the climatic ones; at the Gressoney Valley, geomorphological treelines were at a comparable altitude to the anthropogenic ones.

The reconstruction of the past treeline position reveals the presence of an ongoing trend of tree establishment towards higher altitudes (Fig. 3). The tree height decreased with altitude as well as mean age at breast height, which passed from a mean of 116 years (max. 340 years) at the lower treeline to 40 years (max. 115 years) at the upper treeline and to 28 years (max. 49 years) at the species line. Even if data are missing for the 50-year periods ending in

Table 1 Percentage of trees growing at the highest altitudes in the three selected valleys, according to the main factors limiting a treeline potential upward shift. Only at the Veny valley geomorphological factors are more important than human impacts in determining the treeline altitude. Here, on the left side of the valley, trees are growing on the southern flanks of Mt Blanc, also resulting in a strongly lowered treeline (VE_GEO in Fig. 1)

	Human impact	Geomorphological factors	Climate	Total nr. of trees
Veny	47.4	52.6	–	38
Valpelline–Etroubles	68.5	30.3	1.1	178
Gressoney	75.8	24.2	–	157

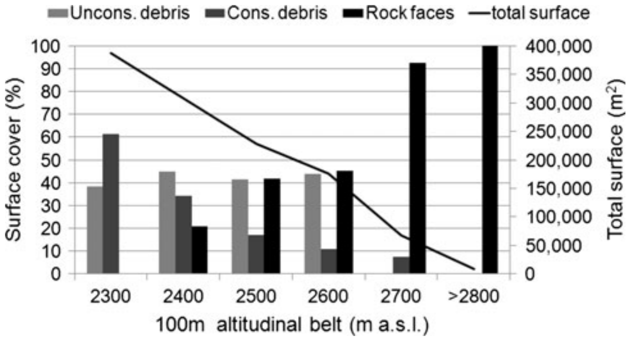

Fig. 4 Surface cover percentages of debris and rock faces at the study site along 100 m altitudinal belts above 2300 m. Unconsolidated debris (mainly from active talus slopes and rockfall deposits) and rock faces are typically unvegetated, whereas consolidated debris is partially covered by herbaceous vegetation. For each altitudinal belt the total surface is reported

1750, 1800 and 1850 our data show that the treeline shifted upward only by 40 m between 1700 and 1900. In the next period, 1901–1950, the treeline shifted by 50 m, and another 65 m up to the year 2000. In 2008, the treeline (at 2515 m a.s.l.) was 10 m higher than in 2000. The species line for the European larch at this site, determined by living specimens, was found at 2545 m.

Considering the geomorphological factors at the study site, we found that unconsolidated debris from active talus slopes, rockfalls and debris flows averages about 40% of the total surface at all the altitudinal bands considered up to 2600–2700 m (Fig. 4). Consolidated debris partially covered by herbaceous vegetation shows decreasing cover, ranging from about 60% (2300–2400 m) up to less than 10% (2700–2800 m). On the contrary, the percentage of total cover due to rock faces increases with increasing altitude (from 20% at 2400–2500 m up to 100 at <2800 m).

The calculation of the temperature lapse rate with increasing altitude from the daily data of eight weather stations revealed a gradient of −0.44°C/100 m for the months from April to September over the period 1974–2004 (Fig. 5a). With this gradient applied to the mean series derived from the daily data of the eight weather stations (see methods), we could estimate the elevation of the potential climatic treeline over the periods 1975–2004 (30 years) and 1985–2004 (20 years), resulting in 2625 m (PT30) and 2675 m (PT20), respectively (Fig. 3). The number of days with a temperature above 5°C has markedly increased from 87 days in 1974 up to 112 days at the altitude of PT30 (values related to the regression line; Fig. 5b). Considering the treeline altitudes in 1974 (2465 m) and 2004 (2510 m) as derived from the precedent analyses, we estimated that the number of days with a temperature >5°C at the treeline changed from 98 in 1974 to 119 in 2004: 21 days more.

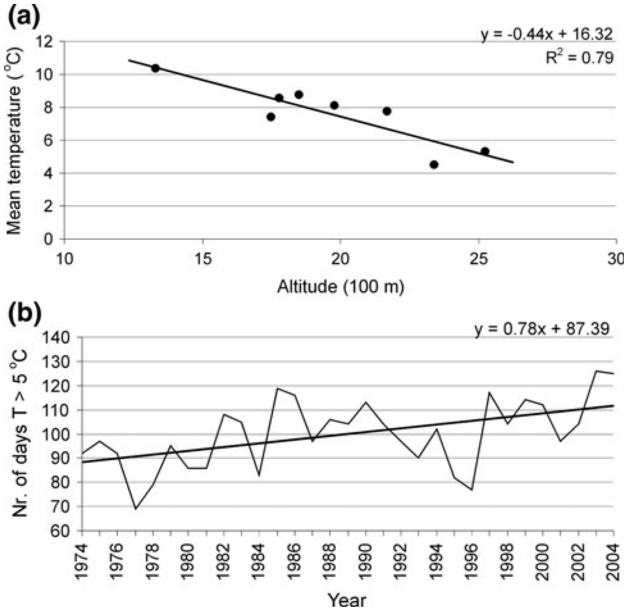

Fig. 5 **a** Mean air temperature versus altitude for eight stations at >1000 m a.s.l. in the surroundings of the study site, derived from the daily temperature from April to September 1974–2004. The linear regression indicates an altitudinal lapse rate of −0.44°C/100 m. **b** The number of days with an air temperature >5°C at 2625 m a.s.l. (at the altitude of the potential treeline PT30)

DISCUSSION

Our analysis revealed that the climate is the main driver of the natural treelines' upward shifts in the studied region and that geomorphological factors play a fundamental role in modulating the treeline responses to the climate. Under the ongoing climatic trend the importance of geomorphological factors in determining tree establishment and treeline dynamics will increase in the near future in the studied region. Geomorphological factors should always be taken into account in studies on climate change impacts on treeline dynamics. The temperature trend based on daily temperature data since 1975 is consistent with the generally constant trend of increasing mean temperatures recorded in the historical homogenized time series of Aosta (Brunetti et al. 2006) and in the temperature anomaly series HISTALP of the grid point 45°N 7°E (Böhm et al. 2010) (Fig. 6). It is also evident that over the last century, the minimum temperatures of Aosta present a stronger positive trend than the maximum temperatures. The precipitation of Aosta since the mid 1800s presents a negative trend that is not present in the considered series of the selected grid point of the HISTALP data set (this series, however, starts at the beginning of the 1900s).

The results show that the treelines are mainly influenced by human impacts and by geomorphological factors. At the study site, where trees grow at the same altitude as the

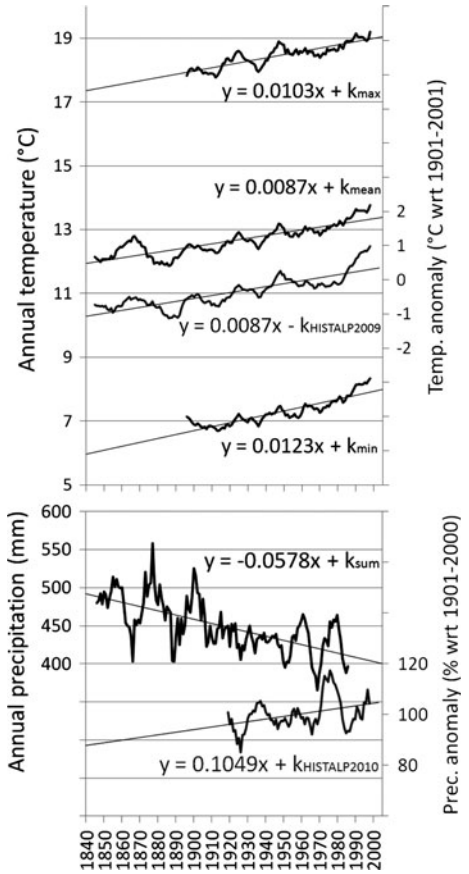

Fig. 6 The mean annual temperature and annual precipitation sum presented as 11-year running means for Aosta (*black*) and for the grid point 45°N 7°E (*grey*); the original series are courtesy of the Società Meteorologica Italiana (Mercalli et al. 2003) and of the HISTALP project (Böhm et al. 2010; http://www.zamg.ac.at/histalp/), respectively. The regression lines for the mean temperatures are calculated on data referring to the common period 1840–2003

climatic treeline in the region, the presence of unfavourable substrates for cattle grazing prevented the treeline from being intensely exploited in the past and left the site in semi-natural conditions. Moreover, since the geomorphological constraints were spatially discontinuous, trees could freely colonize the portions of land covered by alpine grassland, with a consequent treeline upward shift (Figs. 2, 3). The reconstruction of the past treeline position is especially valid and driven by the ongoing climatic trends for the most recent period (up to the last 150 years), whereas the absence of trees from 1700 to 1850 (which comprises the maximum cooling period of the Little Ice Age) either indicates that treeline trees were climatically limited and tree establishment was suppressed or that the site has been disturbed by human activities in its lower portion. However, between 1700 and 1900 the treeline shifted upward not more than 40 m. What we found for the most recent period is evidence of an acceleration of the upward treeline shift strongly driven by the ongoing climatic trends and not related to land-use changes or past disturbances. The marked response is probably linked to the reproduction strategy of the European larch. Its seed-dispersal strategy leads to a massive diffusion of seeds from the forest beneath, and to a faster treeline response than treelines constituted by e.g. *Pinus cembra*, a treeline-dominating species in the central and western Alps, a species with heavy zoochorous seeds. The comparison of the past temperature condition at the treeline in 1974 (i.e. at 2465 m) with the temperature condition at the treeline in 2004 (i.e. at 2510 m) revealed that in recent years the trees at the treeline had about 20 days more with a temperature >5°C. Five degrees is a key temperature for modulating European larch photosynthetic activity and growth (Friedel 1967); the tree growth at the treeline was more limited by temperature conditions in the 1970s. The present-day treeline is therefore in a stronger disequilibrium with climatic factors than in the 1970s, and it is now about 110 m below the potential treeline (PT30; Fig. 3).

Comparing the mean annual temperatures from the two considered data sets (Fig. 6) it is evident that the temperature increase from the 1970s up to the recent decades is almost continuous in the series of Aosta, whereas it shows a period of constant annual temperature in the HISTALP series. A period of generally stable annual temperature (below the general trend) and higher precipitation is known in the European Alps for the late 1970s–1980s, and has also been recorded in the Alpine environment by an increase in glacier advances (Wood 1988; Santilli et al. 2002). However, the reconstructions of the past treeline temperature (for the 1970s and the 2000s) and the potential treeline altitude estimation, based only on daily data from stations close to Aosta (hence holding a similar climatic signal), are consistent with the general trend recorded in the studied region.

After the 1980s, climatically driven dynamics due to a temperature increase have been particularly strong in the Alpine environment: accelerating glacier retreat (Paul et al. 2004), changes in growth periods and phyto-phenological trends (Defila and Clot 2005), altitudinal shifts of vegetation belts and changes in vegetation composition at high-altitude sites (Theurillat and Guisan 2001; Walther et al. 2005). According to Kullman and Öberg (2009), treeline positions in the Swedish Scandes have reached their pre-Little Ice Age position and the current treeline shift is an ‘anomalous event in Holocene vegetation history’, especially for its unique trend break. During the Holocene however, treeline position on the western Alps was at higher altitudes than present days. In the southwestern European Alps, the maximum treeline position during the Holocene, established by means of macro remains and dating 9800cal. year BP was at least 2200 m a.s.l., about 200 m above the current treeline (Ali et al. 2003). Pollen sequences from bogs and lake sediments indicate past altitudes similar to present potential climatic treelines (in the Vanoise massif; David 1995) or about 100 m above it (in the Thabor-Galibier massif; Wegmüller 1977). In the Valle d'Aosta region, the analysis of pollen in a peat bog at 2510 m (in the proglacial area of the Rutor Glacier) showed that between 6735 and 6055 cal. year BP (a period included in the optimal phase of dry and warm climate of the Older Atlantic) the treeline was 200–300 m higher than in the 1990s and that the July temperature was higher by 1.5–3°C (Porter and Orombelli 1985; Burga 1991).

Since all future scenarios depict a surface air temperature rise for the next decades (Hansen et al. 2006) and the Alps already record stronger temperature increases with respect to global trends, according to our findings natural treelines will accelerate their colonization rates, becoming closer to mountain peaks and geomorphologic constraints. This fact has implications both for modelling treeline responses to climate change and as evidence of the potential biodiversity loss that likely will involve the treeless alpine belt vegetation in mountain environments because of fragmentation and habitat loss (Theurillat and Guisan 2001; Dirnböck et al. 2003; Kullman 2010). A treeline upward advance by 200–600 m has been estimated for the next 100 years in the Swedish mountain region: a climatically driven change that could cause a 75–85% of reduction of the alpine areas, with most of the remaining area being constituted by scree slopes and boulder fields (Moen et al. 2004). At the study site, the role of geomorphological factors in controlling the upward treeline shift is becoming more important than the climatic input. The potential climatic treeline is already in an altitudinal belt (2600–2700 m) where the consolidated rock cover (presenting herbaceous vegetation and shallow soils) is already only about 10% of the total cover (Fig. 4). The rest of the surface is dominated by unconsolidated debris and rock faces. In the next altitudinal belt (2700–2800 m) rock faces dominate the landscape, whereas the consolidated debris cover is restricted to less than 10%. Hence, under the ongoing climatic trends, the role of geomorphological factors in controlling the treeline position will increase in the near future. The treelines will advance to the areas closer to the mountain tops or crests than today. Here geomorphological processes are more intense (e.g. rockfalls, landslides, debris flows, etc.) and unstable landforms (talus slopes, screes, rock faces, etc.) are markedly and extensively distributed, becoming 'disturbance factors' able to slow down altitudinal shifts and maintain the treeline below the potential climatic treeline (Butler et al. 2009). Therefore, in the future, the treeline dynamics in the region will be hampered or stopped, as is already the case of many geomorphologic treelines detected in the region, where climatic factors have little influence on the treeline altitude (Fig. 2b). The evidence of a natural treeline already at a lower altitude with respect to anthropogenic treelines and about 400 m below the climatic treeline of the region (GEO_VENY, on the southern flanks of the Mt Blanc massif; Fig. 1) indicates the strong role that geomorphological factors may have in blocking any possible treeline response to climate. Anthropogenic treelines represent the most widespread treelines in the region and were found about 200–300 m below the climatic treeline. The responses of these treelines to climate change are more difficult to predict because of the different site histories that may induce different dynamics; at these sites, the disequilibrium with climate conditions will be likely to persist for the next centuries.

CONCLUSION

We found that the treelines in the studied region are mainly limited in altitude by human impacts and geomorphological factors. At the study site, the recent dramatic air temperature increase has caused a treeline upward shift of 115 m over the period 1901–2000. This treeline advance was mainly driven by the climate. We also found a recent acceleration of tree colonization rates of higher altitudinal belts, formerly colonized by the alpine grassland vegetation, also resulting in a risk of biodiversity loss. Even if the recent temperature rise is the main driver of the treeline shift, we emphasize the increasing role of geomorphological factors in controlling future treeline positions and colonization patterns in high mountains, due to increasing land-mass wasting and gravity processes as well as unfavourable substrates at higher altitudes. We emphasize the importance of taking geomorphological factors into account for the predictions of future responses of natural treelines to climate change.

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