



Human–environment dynamics in European treeline ecosystems: a synthesis based on the DPSIR framework

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ABSTRACT: The state of, and changes to, altitudinal and polar treeline ecosystems and their services in selected mountain regions in Europe were analyzed using the drivers–pressures–state–impacts–responses (DPSIR) framework. The analysis was based on 45 responses of experts from 19 countries to 2 semi-structured questionnaires on treeline ecosystem services (ESs), stakeholders and the DPSIR factors, and 11 case study descriptions of best management practices. The experts recognized climate and land-use changes as the main drivers, resulting in various pressures that contrasted among the regions. The impacts of the pressures were mainly considered as negative (e.g. loss of biodiversity, root rot diseases, moth and bark beetle outbreaks, wild fires, decrease of (sub)alpine grasslands, browsing), but also as positive (e.g. increase in forested area). The influence of climate warming, altered precipitation regimes, a longer growing season, annual variation in winter climate and increased ground-level ozone concentrations were considered less critical for recent treeline dynamics than land abandonment, increased tourism and livestock pressure. Current policy responses to emerging pressures and stakeholder demands were considered insufficient and incoherent. Mitigation, adaptation and restoration actions were rare and with no evident long-term impact. We conclude that (1) locally-specific human–environment interactions have greater influence on treeline dynamics than global warming; (2) ecological and social sustainability of the treeline areas can be enhanced by simultaneously promoting traditional land use and regulating tourism development; (3) ES users should look for new opportunities arising from environmental change rather than trying to sustain current levels of ESs indefinitely; and (4) to safeguard the unique ecological and social values of treeline areas, more coherent and proactive policies are needed.

KEY WORDS: Mountain forests · DPSIR framework · Climate change · Land-use change · Ecosystem services · Disturbances · Biodiversity

1. INTRODUCTION

Mountain forest ecosystems are among the most endangered ecosystems in the world (Broll & Keplin

2005). In Europe and elsewhere, climate change (Theurillat & Guisan 2001, Grace et al. 2002, Skre et al. 2002, Kullman & Öberg 2009, Smith et al. 2009), and land-use change (Bryn & Daugstad 2001,

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Gehrig-Fasel et al. 2007, Hofgaard et al. 2013, Ameztegui et al. 2016) are 2 important drivers of environmental change. The treeline ecotone (Holtmeier 2009) can be particularly useful as an early indicator of environmental change (Kupfer & Cairns 1996). Altitudinal and polar treeline ecotones are primarily controlled by climate, as seasonal mean temperature decreases with increasing elevation and latitude. The isotherm theory for natural treeline formation has been confirmed in several empirical studies and modelling exercises (Paulsen & Körner 2014). However, centuries of human disturbances have altered the climatic position of treelines. To capture the complexity of factors influencing the dynamics of treeline ecotones, the ecological definition of a treeline as an ecotone should be extended to include 'treeline-related administrative areas, and associated landscapes and ecosystems' (Sarkki et al. 2016a, p. 2020).

The contributions that ecosystems make to human well-being arising from the interaction of biotic and abiotic processes (Grunewald & Bastian 2015) have been described as ecosystem services (ESs). To systematically arrange the benefits that humans receive from nature, several ES classifications have been proposed (e.g. Boyd & Banzhaf 2007, Luck et al. 2009) and used in studying the treelines (e.g. Sarkki et al. 2016a), such as classification into provisioning, regulation and maintenance, and cultural services.

The subalpine and subarctic forests close to the treeline provide a number of resources for local communities with traditionally low land-use intensity. They provide regulating ESs, such as erosion and flood control and reduction of environmental risks such as avalanches and forest fires. Access to exclusive and non-exclusive ESs may potentially cause conflicts among stakeholders due to overuse of some ESs by some stakeholders. Treeline ESs have been analyzed in small areas at or near the treeline and for certain ESs in mountainous regions (e.g. Grabherr 2009, Hastik et al. 2015). However, there is little information regarding Europe-wide mapping of ESs combined with stakeholder and governance analysis. Sarkki et al. (2016a), for instance, identified key ESs in European treeline areas, along with treeline-relevant stakeholders and the threats they pose to, and benefits they receive from, ESs. They found context- and treeline-specific behavior of stakeholders and governance structures that insufficiently addressed the sustainability of these areas. A similar finding was obtained by Sarvašová et al. (2014). However, to be able to understand the pressures on treeline ESs and adaptive responses, a holistic framework is

required for studying cause–effect relationships in treeline areas (see Sarkki et al. 2017a, this Special).

In this context, the drivers–pressures–state–impacts–responses (DPSIR) framework (see Section 2.1 below) is useful for describing the interactions between society and the environment. It has been adopted by the European Environment Agency (EEA 2016) to show how social–ecological systems function in a dynamic way and what the interactions are among different factors. The 'drivers' (e.g. climate and land-use change) create 'pressures' that are causing social–ecological changes in treeline areas. The resulting change in the 'state' of the social–ecological system has 'impacts' on the functioning of the system, but societal 'responses' may restore the desired state or reduce pressure, trying to make the social–ecological system resilient to change (cf. Fig. A1 in the Appendix)

This study examines factors influencing human–environment dynamics at or near European treelines by synthesizing various results of the SENSFOR project ('Enhancing the resilience capacity of SENSitive mountain FORest ecosystems under environmental change'). Empirical results summarized in this paper have been previously published as technical reports, but with no overall synthesis. In this study, pressures to treeline ESs (Kyriazopoulos et al. 2014), the state of ESs in treeline areas (Sarkki et al. 2013) and potential policy responses (Sarkki et al. 2015, 2016a,b, 2017b, this Special) are synthesized under the DPSIR framework for the first time. We summarize the most important DPSIR factors and their threats to, and benefits for, the coupled human–environmental system and ESs. This synthesis allows us to draw conclusions about the relationships between ecological and social sustainability in European treeline areas and their relationships to governance responses.

2. METHODOLOGY

2.1. The DPSIR framework

The DPSIR framework is a well-established causal framework for describing the interplay between the environment and socio-economic activities (EEA 2016) that has its roots in the stress–response environmental statistical system (S-RESS) proposed by Friend (1979). The basic logic behind the DPSIR framework is that any status or change in a social–ecological system is related to its driving forces and pressures through a number of feedbacks. Humans play a determinant role in steering the social–ecological system and structuring its state.

The DPSIR framework belongs to the family of systems analysis frameworks. It shares many similarities with the Framework for the Development of Environment Statistics (FDES), the Pressure-State-Response (PSR) framework, the Pressure-State-Response/Effect (PSR/E) framework, the Pressure-State-Impact-Responses (PSIR) framework and the Driver-Pressure-State-Welfare-Response (DPSWR) framework (see Cooper 2013 for a review).

Applications of the DPSIR framework in practice differ with regard to the interpretation of DPSIR factors, and may include a number of modifications. We used an interpretation that closely follows the original definition by the EEA (2016). For each of the categories in the DPSIR framework, we present the most important factors and issues as reported by the respondents and discuss how these categories link to each other. Responses were grouped into restoration practices, adaptation practices and mitigation measures.

2.2. Surveys

To identify the DPSIR factors, we used the multiple case study analysis, which is a qualitative technique of data gathering when representative sampling is difficult to conduct. The multiple case study analysis enabled us to generalize causalities between the drivers, pressures, state, impact and responses based on similarities in patterns and processes.

We sent 2 questionnaires and a call for detailed case study descriptions to more than 100 experts from 20 European countries to obtain the widest possible assessment on the state of altitudinal and polar treelines in Europe. The aims of these surveys were to (1) analyze the present state of, and potential changes in, ecosystems with a particular focus on identifying DPSIR factors in each case study region; (2) map the drivers and pressures of ecosystem change; (3) analyze the history and present state of ecosystems and their services for different land uses and management practices, including the identification of trends in ES delivery capacity and socio-political adaptation; (4) identify current societal responses to ES-related challenges; and (5) generate a holistic understanding of treeline ecotone ecosystems and their services, based on the DPSIR framework.

The first questionnaire consisted of mainly closed-ended questions on the relevance of ESs, stakeholder benefits from, and threats to, ESs, and governance and science–society relationships. The questionnaire was sent in 2013 to approximately 100 SENSFOR con-

sortium members (Sarkki et al. 2013, 2016a, Table 1). The assessment of ESs was based on the Common International Classification of Ecosystem Services using 5-point Likert scale (Sarkki et al. 2016a). Altogether, 22 treeline case study descriptions from 15 countries were received, describing 20 different treeline areas in Europe (see Sarkki et al. 2013, 2016a for detailed description of the methodology and the questionnaire). Stakeholder benefits from, and threats to, treeline ESs were then cross-tabulated with pressures identified in the second questionnaire.

The second questionnaire was distributed to more than 100 experts in late 2013 using the SENSFOR and Mountain Research Initiative (MRI) network. This mostly open-ended questionnaire (see Kyriazopoulos et al. 2014 for the questions) used the DPSIR framework, and also included a request for a detailed description of the size, altitude, latitude, climate, geology, dominant tree species and the major wild, semi-domestic and domestic herbivores in the area. The questionnaire included several questions regarding land-use change and climate change trends to estimate possible effects of these 2 drivers (see Table A1 in the Appendix). A total of 26 responses from different European treeline case study regions were received. A follow-up questionnaire was distributed in mid-2014 to all who responded to this questionnaire, focusing on the state and responses in the treeline areas. Eight responses from different treeline areas were received in the second round (Kyriazopoulos et al. 2014).

A call for detailed case study descriptions was sent in 2015 to SENSFOR consortium members asking them to describe best management practices in European treeline areas and to suggest proposals for enhanced governance of treeline areas. Eleven descriptions of successful and failed practices were received, identifying 75 proposals for enhanced governance. These proposals were inductively clustered into several groups (Sarkki et al. 2015, 2017b).

3. RESULTS AND DISCUSSION

3.1. Drivers

Climate change and land-use change were recognized as the main drivers of treeline ecotone dynamics (cf. Kyriazopoulos et al. 2014). Although high-resolution spatio-temporal data indicating directional impact of climate or land-use change were not provided, both drivers were unanimously suggested as being of major importance for all case study regions.

Table 1. Case study areas used for the assessment of human–environment dynamics in European treeline areas (adapted from Kyriazopoulos et al. 2014, Sarkki et al. 2015, 2016a, 2017b). ES: ecosystem services; DPSIR: drivers–pressures–state–impacts–responses framework, NP: National Park

Country	Case study area	Type	Questionnaire on:		
			ES, stakeholders and governance	The DPSIR	Good environmental management
Iceland	Almenningar, Southern Iceland	Polar	✓	✓	
Ireland	Burrishoole	Non-climatic	✓		
Spain	Cantabrian range, Iberian peninsula	Altitudinal		✓	
Slovakia	Carpathian Mts.	Altitudinal		✓	
Russia	Caucasus Mts.	Altitudinal		✓	
Italy	Central Alps	Altitudinal		✓	
Spain	Central Pyrenees	Altitudinal	✓		✓
Slovenia	Dinaric Mts, Sneznik Mt.	Altitudinal	✓		
Serbia	Dinaric Mts., Tara NP	Altitudinal		✓	
Norway	Dovre Mt., Central Norway	Altitudinal		✓	
Czech Republic	Hercynian Mts.	Altitudinal		✓	
Ukraine	Khust and Rachiv regions, villages Nyzhniy Bystry and Bohdan, Carpathians	Altitudinal			✓
Russia	Khibini Mts., Kola Peninsula	Polar		✓	
Finland	Kilpisjärvi-Käsivarsi region, NW Finnish Lapland	Altitudinal	✓		✓
Sweden	Lake Torneträsk Catchment (Abisko)	Altitudinal	✓		
UK	Lochaber Forest District, North Western Scotland	Non-climatic			✓
Ukraine	Lviv, Chernivtsi and Ivano-Frankivsk regions, Carpathians	Altitudinal			✓
Italy	Majella NP, central Apennines	Altitudinal	✓	✓	
Spain	Montseny, NE Spain	Altitudinal		✓	
UK	Moray, Aberdeenshire and the Dee river catchment, Cairngorms NP	Non-climatic	✓	✓	✓
Greece	Mount Parnon, South Greece	Altitudinal		✓	
Finland	Muonio, North western Lapland	Altitudinal			✓
Finland / Norway	Northern Fennoscandia	Polar		✓	
Norway	Northern Norway	Polar		✓	
Spain	Northern Pyrenees	Altitudinal		✓	
Sweden / Norway	Northern Scandinavia	Polar	✓		
Germany	Berchtesgaden-Alps NP	Altitudinal	✓		
Bulgaria	Central Balkan NP	Altitudinal	✓		
Romania	Piatra Craiului NP	Altitudinal	✓		
Italy	Paneveggio-Pale di San Martino NP, Eastern Alps	Altitudinal	✓	✓	
Portugal	Peneda do Geres NP	Altitudinal		✓	✓
Greece	Pindos Mts.	Altitudinal	✓	✓	✓
Greece	Psiloritis, Crete	Altitudinal		✓	
Bulgaria	Rila and Pirin Mts.	Altitudinal	✓	✓	✓
Spain	Sierra Nevada	Altitudinal		✓	
Slovenia	South-Eastern Alps	Altitudinal		✓	
Norway	Southern Norway (Hardangervidda)	Altitudinal	✓		
Spain	Southern Pyrenees	Altitudinal		✓	
Bulgaria	Stara Planina	Altitudinal		✓	
Czech Republic	Sudeten Mts.	Altitudinal	✓		
Slovakia	Tatra NP, Dolina Parichvost	Altitudinal			✓
Slovakia	West Carpathians	Altitudinal	✓	✓	
Slovakia	Západné Tatry Mts. (Western Tatras)	Altitudinal	✓		

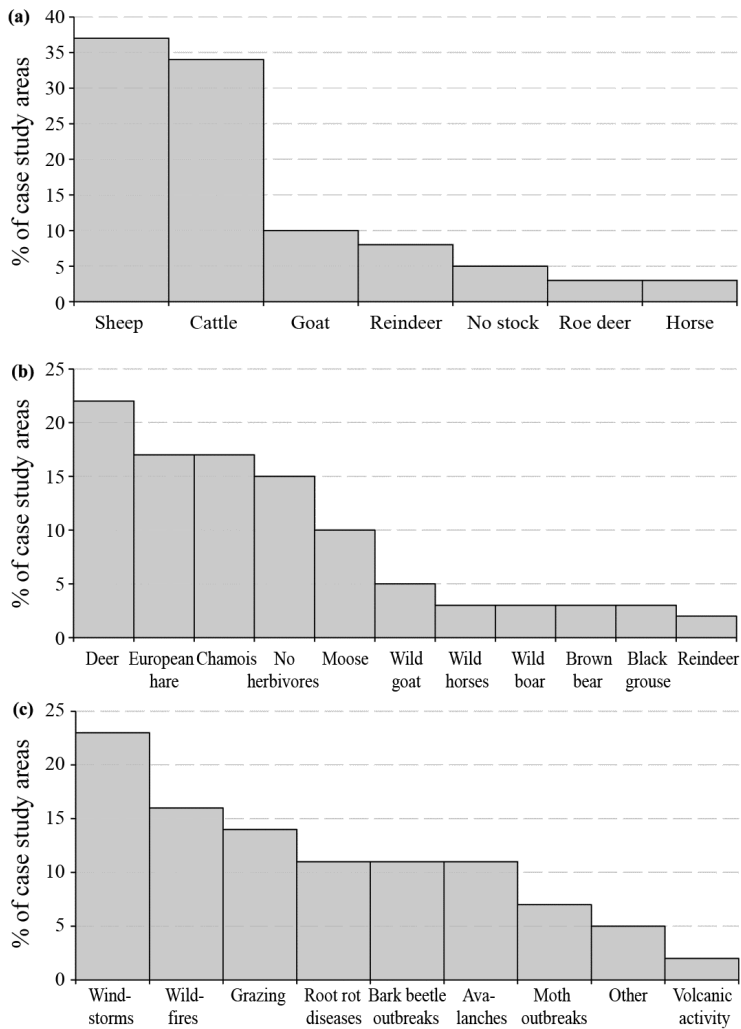


Fig. 1. (a) Main grazing stock, (b) wild herbivores and (c) main disturbances at and near treeline ecotones in Europe (based on Kyriazopoulos et al. 2014)

It is well-documented that treeline ecotones are sensitive to climatic fluctuations and, consequently, are useful indicators of climate change (Theurillat & Guisan 2001, Grace et al. 2002, Smith et al. 2009, Kullman & Öberg 2009). However, Kupfer & Cairns (1996), among others, warned against the limitations of using treelines as climate change indicators in highly altered anthropogenic landscapes. Firstly, the response of an ecotone to changing climate is at a timescale of several decades, in which these impacts may be difficult to disentangle from impacts of more short-term duration. Moreover, although tree growth in general becomes more and more constrained by the harsher environmental conditions associated with increasing altitude or latitude (Körner 2012), the altitudinal or latitudinal forest- and tree-limits may show

different responses to climate change (Hofgaard et al. 2013), mostly due to differences in upslope edaphic limitations and competitive interactions with established canopy and subcanopy individuals (Kupfer & Cairns 1996).

The main changes that can counteract climate-driven forest expansion, especially at the local level (Debussche et al. 1999), are land-use changes. Land-use changes in treeline areas have been strongly linked to the dynamics of the socio-economic systems in Europe over the last century (e.g. reduced summer farming in Scandinavia; Bryn & Daugstad 2001). Locally-specific impacts of land-use changes are described in detail in Section 3.2. In Iceland, volcanic activity was identified as a driver causing specific natural disturbances. Other disturbances, such as insect attacks, wildfires and windthrows were classified as pressures related mostly to climate change.

3.2. Pressures

The pressures acting on the treeline ecotones were divided into 3 categories according to the forces driving them: (1) climate change, (2) land-use changes and (3) volcanic activity. Our findings suggest that in the past decades, land-use changes have been more critical for treeline dynamics than climate change.

According to the respondents, the main pressure related to climate change was climate warming, which was sometimes accompanied with increased precipitation, resulting in a longer growing season, summer drought, and inter-annual variation in winter climate as well as increased ground-level ozone concentrations (cf. Kyriazopoulos et al. 2014). A longer growing season was reported as a positive result of the warmer climate in most of the northern and the central European study areas. The predicted warmer climate could potentially move the treeline ecotone toward more northern latitudes. Kullman (2004) reported that seedlings of white birch *Betula pubescens*, Norway spruce *Picea abies* and Scots pine *Pinus sylvestris* have recently become established 500–700 m above their recent tree limits. However, occurrence of tree seedlings above the tree limit may also be interpreted as part of the natural dynamics of the zone,

with largely ephemeral seedling populations (Hofgaard et al. 2013). An advance of the treeline ecotone will probably cause an increase in forest cover and create the potential for development of local forestry-dependent economies, but this process could take decades or centuries (Skre et al. 2002, Van Bogaert et al. 2011, De Wit et al. 2014). In contrast, inter-annual variation in winter climate and summer drought was reported as a negative result of climate change, particularly in the southern European regions (cf. Kyriazopoulos et al. 2014).

Land abandonment was identified as the major pressure arising from land-use change. This pressure manifests through abandonment of traditional pastoral activities mirroring the socio-economic changes in mountainous areas. The most common pressure was abandonment of pastures due to a decrease in livestock (54 % of cases). The impact of this change was considered positive in all cases except in the southern part of the Balkan Peninsula and some parts of the Carpathian Mountains. Some respondents reported land abandonment in general (13 %) and an increase in grazing (11 %), the latter reported only from northern Europe and in Crete, Greece. Increased livestock farming was related to an increasing demand for high-quality reindeer and goat products, and local livestock farming traditions (Kyriazopoulos et al. 2014). Our results confirmed the conclusions of several studies, that the current treeline position mostly occurs well below its potential location due to the long history of anthropogenic disturbances such as clear-cutting, burning and grazing (e.g. Gehrig-Fasel et al. 2007, Palombo et al. 2013, Ameztegui et al. 2016).

Populations of grazing livestock were found to be decreasing in 67 % of the study regions, increasing in 12 % and stable in 17 %; there was no data for the rest of the cases. The most important grazing stocks in European treeline areas (Fig. 1) include cattle and sheep (34 and 37 %, respectively), goats (10 %) and semi-domestic reindeer (8 %). Horses and roe deer were considered less important pressures (3 % each).

Livestock grazing was recognized as a positive pressure, since high grazing intensity reduces or prevents tree establishment (Potthoff 2009). In some cases in Spain and Greece, the abandonment of grazing in treeline ecosystems was recognized as unfavorable due to shrub encroachment, which could pose a serious threat to forage productivity and biodiversity of the subalpine grasslands. In these regions, grazing was recognized as an ecological tool to restore or conserve these habitats (Papanastasis 2009). Using similar justification, some respondents described increased livestock grazing as negative because of

disturbances to vegetation dynamics and an increase in soil erosion. However, a negative effect of livestock grazing was highlighted in only a few case study areas in northern Europe and Crete, Greece.

Wild herbivores were described as a pressure in 90 % of the case studies (Fig. 1b); Cervidae (deer family), European hare *Lepus europaeus* and chamois *Rupicapra* spp. were among the main species in 22, 17 and 17 % of the case studies, respectively. Additionally, elk *Alces alces* was listed as a pressure in 10 % of the cases, but in certain areas (e.g. Scandinavia) it occurs along with wild reindeer *Rangifer tarandus*. Wild goat *Capra aegagrus*, brown bear *Ursus arctos*, wild boar *Sus scrofa* and black grouse *Tetrao tetrix* were reported at lower percentages (3–5 % of the cases).

For some areas in Europe, i.e. Scotland and northern Fennoscandia (Danell et al. 1991, Oksanen et al. 1995, Hester et al. 2004) the impact of wild and semi-domestic herbivorous species on treeline vegetation is well-documented. In addition to the negative effect of grazing on treeline vegetation, large ungulates may also contribute to local livelihood through income obtained from hunting and tourism (e.g. Hester et al. 1996, Tolvanen et al. 2005, Sarkki et al. 2013). Furthermore, environmental policies may multiply pressures on treeline ES and stakeholders by applying strict conservation guidelines for predators (*U. arctos*, grey wolf *Canis lupus*, Eurasian lynx *Lynx lynx*, eagles) and support for tourism development.

Intensive tourist activity was considered as a negative pressure in 19 % of the cases. Although increased numbers of tourists may financially benefit local communities, it can also negatively impact sensitive ecosystems and species, mainly due to the construction of infrastructure. Furthermore, in some cases industrial development (including mining, and the construction of hydropower plants and windmills) was recognized as a pressure. A majority of the respondents identified limited or no logging activities in the treeline ecotones. The only exception was reported from Caucasus, and was considered a negative effect. Pressures related to volcanic activity were identified only in Iceland. They were reported as negative, as lava and ash can destroy the treeline vegetation.

3.3. State

The state of treeline ecosystems varies greatly by country and region. Here, we describe exemplary states of treelines in 8 case studies (Kyriazopoulos et

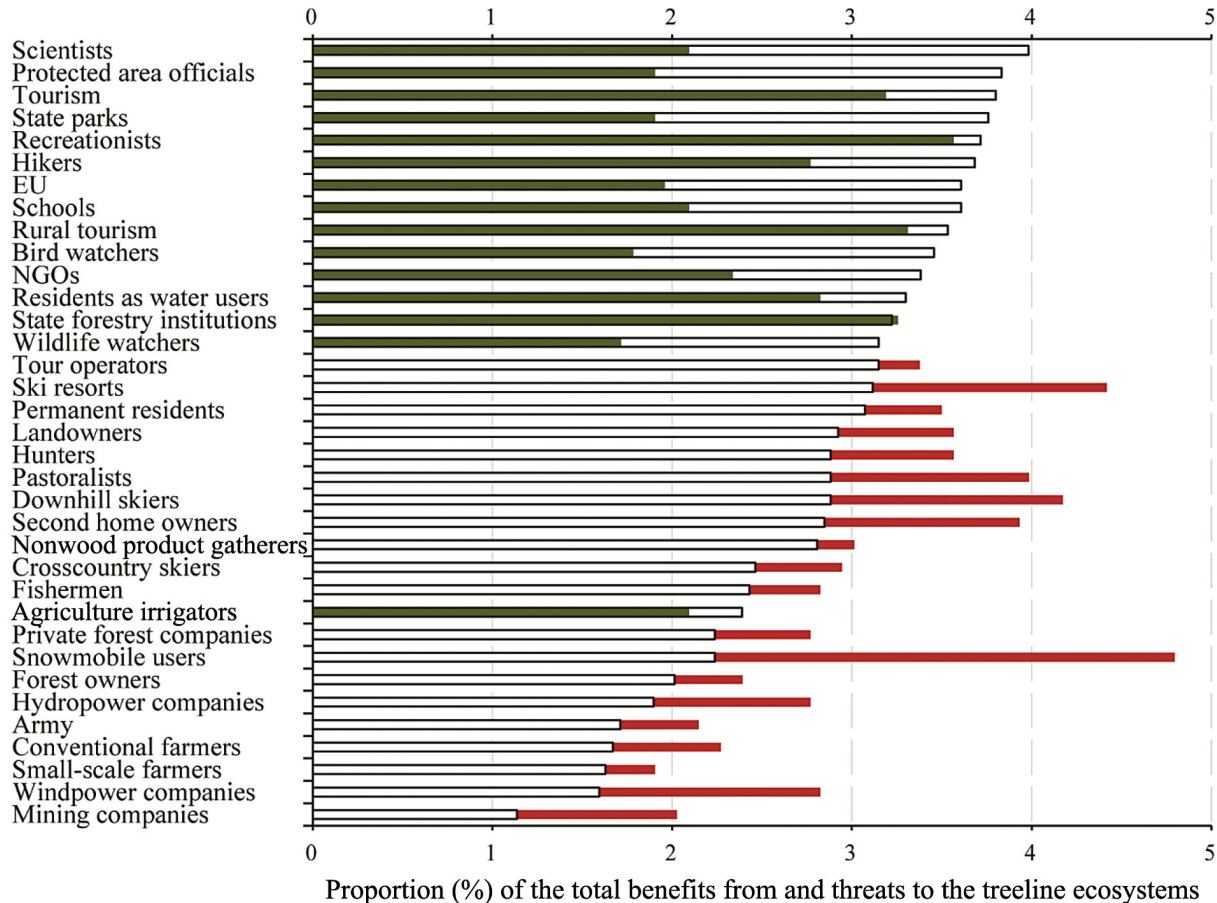


Fig. 2. Main stakeholders in European treeline areas sorted top-down on a scale from 0 to 5 by the benefits they obtain from tree-line ecosystems (white bars: the degree a stakeholder gets of the total benefits produced by tree-line ecosystems). Colored bars (green or red): degree of the total threats to the tree-line ecosystems that is attributable to a certain stakeholder. If this percentage is lower than the percentage the stakeholder gets of the total benefits produced by tree-line ecosystems, the bar is colored green (net receivers), else red (net-givers). 'Ski resort business', 'Downhill skiers' and 'Tour operators' are different forms of the tourism industry. 'Recreationists', 'Hikers', 'Bird watchers' and 'Crosscountry skiers' are different forms of nature-based tourism

al. 2014) to illustrate the diversity of the pressures in different parts of Europe.

Most of the Pyrenean treeline ecotones (Spain) were severely disturbed by humans in the past (e.g. grazing and logging), but in the period from the 1930s until 1980, sheep densities decreased in concert with a 61% decrease in the human population (Alados et al. 2014). As a result, 24% of the subalpine grasslands under 2100 m a.s.l. in the Central Pyrenees reverted to forest between the 1980s and 2000s (Gartzia et al. 2014). Since 1960, industrial development, the intensification of agriculture and development of the skiing industry have been the prevailing human activities. Several areas show destruction of the vegetation due to overgrazing and extreme erosion, which is usually conditioned by local topography and disturbances such as snow avalanches (Cudlín et al. 2017, this Special). Elsewhere, encroaching scrublands (horrible broom *Echinopar-*

tum horridum, snow rose *Rhododendron ferrugineum*) dominate former grassland above the current treeline (Camarero et al. 2015). The expansion of woody plants has affected biodiversity and the goods and services provided by grasslands. It has also altered the spatial distribution of wild animals. *S. scrofa*, for instance, is now found to be feeding on grasslands, which rarely happened before.

In the Central Stara Planina Mountains (Bulgaria), burning and grazing in areas near the treeline has resulted in the replacement of conifers by European beech *Fagus sylvatica* and reduced soil carbon storage capacity (Grunewald & Scheithauer 2011). Forest conversion has also decreased soil organic matter. However, climate warming is expected to contribute to upslope advance of conifers as well as *F. sylvatica* (Dakov et al. 1980). Land-use intensity also influenced the quality and composition of soil humus in mountain grasslands. The alteration of natural vege-

tation was mostly due to fire and grazing (Cudlín et al. 2017). Today, only few cattle graze on Bulgarian high-altitude pastures. In the last few decades, changes to the timberline have mainly been caused by winter sport facilities (Grunewald & Scheithauer 2011).

The current state of Pindos Mountain treeline ecotones (northern Greece) indicates intense human activities in the past, which have since been strongly reduced. As a result, soil erosion risk is being minimized. As a result of land abandonment, shrub encroachment by junipers *Juniperus* spp. in formerly grazed grasslands is common. Further decreases in livestock grazing may negatively affect both floristic and faunistic diversity, especially populations of raptors (Bakaloudis 2016). Conversely, in Psiloritis (Crete), decades of overgrazing have contributed to severe soil erosion. Desertification has become a serious problem, particularly due to fires set by the shepherds to combat unpalatable species, followed by continuous, heavy grazing. However, pastoral activities have positively influenced biodiversity. There is still a relatively high population of raptors in Crete (Xirouchakis 2004). Reduced tree regeneration due to overgrazing has also been reported in North Caucasus (Ukraine). The threat of soil erosion is huge as a result of the overexploitation of forests, fire and intense grazing (Kyriazopoulos et al. 2014).

In some areas of the Carpathians (Czech Republic) the treeline ecotone was subjected to several disturbances, particularly originating from the construction or enlargement of ski resorts, recreation facilities and infrastructure (Cudlín et al. 2013). On the other hand, large tracts of the treeline ecotone are regenerating well via secondary succession due to a reduction in sheep and cattle grazing. (cf. Cudlín et al. 2017). Large-scale windfalls and bark beetle outbreaks in forests below the treeline represent constant pressure on treeline ecosystems resulting in a decrease in the aesthetic qualities of the cultural landscapes and possibly distracting tourists and hikers. These areas are at risk of fire due to forest operations such as road construction and burning wood residuals from salvage logging.

In alpine space, conflicts between stakeholders about ES are common (von der Dunk et al. 2011). In the treelines of the Central Alps (Switzerland) there has been a strong impact from grazing by sheep and cattle, and to some extent, goats (Bebi 1999), followed by a treeline advance as a result of warmer climate and abandonment of cottage farming. In the south-eastern Alps, livestock grazing was historically high at the beginning of the 19th century but decreased after World War II, while pressures from

large wild ungulates (mostly red deer *Cervus elaphus*) remained noticeable in most of the central European mountain forests (e.g. Ficko et al. 2016). One of the most important ES provided by the tree-line forests in the Alps is avalanche protection (Bebi et al. 2009), often combined with erosion control (Brang et al. 2006, Huber et al. 2013).

In the northern Scandes on the subarctic mountain plateau Finnmarksvidda and adjoining areas in Finnish Lapland (Kevo), birch forest covers a 300 km wide zone north of and above the conifer treeline. In contrast to most treeline areas in Europe, these birch forests have been partly overgrazed by domestic reindeer over the last 50 yr (Tømmervik et al. 2005, Cudlín et al. 2017). Since *Cladonia* lichen is the preferred winter food for reindeer, this overgrazing has dramatically reduced the lichen cover throughout northern Fennoscandia (Helle 2001, Lempa et al. 2005). Because of the warming climate, birch forests are increasingly subjected to attacks by various moth species, particularly *Epirrita autumnata* (Neuvonen et al. 2005, Skre et al. 2017, this Special), because more insect eggs can survive in milder winters (Tenow et al. 2005).

3.4. Impacts

Climate warming has led to increased occurrences of tree diseases (root rot diseases) and insect outbreaks (e.g. moths, bark beetles), which are considered particularly problematic for the northern and central European regions. Several projections have indicated that climate warming is likely to affect the frequency, geographical extent and intensity of insect population outbreaks, with potentially severe consequences for the affected ecosystems (Neuvonen et al. 1999, Ayres & Lombardero 2000, Volney & Fleming 2000, Logan et al. 2003, Battisti et al. 2006). However, some disturbances (e.g. insect outbreaks, forest fires on cold soils) may also be beneficial because they could increase recycling of nutrients and production in the long-term.

Increasing risk of wildfires was interpreted mainly as a consequence of summer drought, which was considered particularly critical for the treeline ecosystems during drought years in southern European regions (Hoff 2013) and in central Europe. Such fires strongly impact tourism in the affected areas.

An upward shift of the treeline ecotone and consequently a potential increase in forested area were associated with both warmer climate and abandonment of traditional agricultural and pastoral activities

in mountainous areas. The majority of the respondents interpreted the upward shift of the ecotone positively, while in a few study cases (e.g. Norway, Spain and Greece) an increase in forest cover was recognized as negative as it would result in a decrease in grassland area, loss of biodiversity and possibly negative influences on tourism.

Loss of biodiversity was interpreted as a negative impact in the treeline ecosystems as a result of intense human activities such as overgrazing and massive tourism. Moreover, climate change might also have negative impacts on biodiversity, as it affects ecosystems and the ability of species to adapt (Gitay et al. 2002).

Among the impacts of climate and land-use changes, wind (23% of the cases), wildfires (16%) and grazing (14%) were mentioned as significant (Fig. 1a–c). Avalanches, root rot diseases and bark beetle outbreaks were considered important in 11% of case studies. Moth outbreaks were identified as a major disturbance, especially in northern Fennoscandia and southern Norway. In Iceland, volcanic activity was identified as causing changes to vegetation assemblages. In all cases, except for the Carpathian Mountains, the impacts of natural disturbances were identified as a negative. Direct human activity by logging was nearly absent in most of the study regions (84%) but was recognized in the Caucasus Mountains (4%).

Pressures in treeline areas may also be induced by stakeholders and ES users. While using the ES, stakeholders pose threats to ecosystems and could potentially change their state (Fig. 2). The strongest beneficiaries of ESs are scientists, who were considered to be the least threatening stakeholders. Much of the benefit also goes to protected area officials, tourism, state parks, hikers and recreationists. Several stakeholders were considered as net beneficiaries, meaning that the benefits they receive from treeline ecosystems are higher relative to the threats. Stakeholders posing relatively high threats were snowmobile users, ski resorts and windmill companies. However, the negative impact of most of the stakeholders was rather low, and the vast majority of stakeholders in the treeline area operate in a sustainable way (Sarkki et al. 2016a).

3.5. Responses

Linkages between human responses to the outlined drivers, pressures, and their impacts on the current state of treeline ecosystems and their services

(Table 2) are based on the practices used in the same regions as outlined in Section 3.3.

Mitigation measures were rarely practiced. Among the mitigation measures, adaptations of silvicultural practices as well as re-zoning and re-assessment of the Natura 2000 sites were mentioned. These measures mostly targeted specific objects, and were operating at the local level, such as prescribed fires near National Parks in Spain. The locally or regionally focused actions were not really mitigation measures based on a precautionary principle, but rather were risk-reduction activities taking place after the occurrence of a large windfall event or bark beetle outbreak (e.g. Slovakia, Slovenia, Spain). Moreover, the effectiveness of mitigation measures was considered to be very limited. Most of the mitigation measures resulted from international or national commitments on nature protection or national legislation on reserves and national park territories. Current mitigation measures are focused on improvement and maintenance of the regulating and supporting ESs, but without a systematic approach. No specific mitigation measures at any level were reported from Russia, Norway, Greece and the Kola Peninsula.

Adaptation practices were extremely rare and of limited effectiveness, and they took place mainly at the local level with no evident long-term impact. The general problem of adaptation was that the adaptation measures tried to alleviate the maintenance of all ESs, which is in contradiction to ecosystem functioning. The trade-offs between different ESs may not always be resolved at the same place and same time, which should be accounted for in the projections of future ES portfolios (Sarkki et al. 2016a). No adaptation practices at any level were reported from Russia, Norway, Slovenia, Greece and the Kola Peninsula.

Restoration was also seldom practiced. Soil erosion was recognized as the main problem that required restoration. However, information on the successfulness of the restoration was missing. This is partly due to the limited data about the changes near the treeline ecotone. GIS and remote sensing methods will be helpful to address this issue. Future monitoring of ecosystem changes will answer the question of whether restoration actions are feasible in a highly dynamic social–ecological system such as the treeline.

Governance and political instruments specifically designed for treeline ecosystem restoration or adaptation to changes were not common either. Detailed case study descriptions on best management practices highlighted various methods for land-use planning (Sarkki et al. 2015, 2017b). Many of the

Table 2. Adaptive measures applied in treeline areas for maintaining ecosystem services (ES). LSU: livestock unit

Pressures	State	Impact	Responses
Local climate fluctuations	Reduced number of days with snow cover	Fewer positive impacts (benefits) for skiing resorts due to shorter ski season	Use of artificial snow
Large predator conservation policies	Increased number of predators in the treeline areas	Predation on herds has negative impacts on pastoralism	Intensive herding practices (e.g. shepherd dogs, electric fences), state compensation to cover losses
Building ski slopes	Erosion	Negative impact on aesthetic value	Land-use zoning, priority areas
Use of motorized vehicles	Trampling effects; experience of nature disturbed	Ecotourists dislike this, attractiveness of the area decreases	Rules on how protected areas can be accessed
Land abandonment	Encroachment, nitrification in the areas with excess LSUs	Decreasing proportion of pastures	Agri-environmental schemes, e.g. management of low-intensity pasture systems, min.–max. LSU load control, <i>Rumex alpinus</i> control in nitrate-rich environments
Warming climate	Insect attacks	Negative impact on economic and aesthetic value, higher CO ₂ emissions More rapid succession and faster recycling of nutrients (positive impact)	Adapted silviculture, climate-smart forestry
Industrial forestry	Treeline shift downwards	Negative impact on aesthetic value; impacts on pastures	Collaborative land-use planning, promoting the principles of continuous-cover forestry
Less precipitation	Summer droughts	Increased risk of wildfires; deteriorating pastures and deteriorating aesthetic value	Hazardous fuels reduction programs, vulnerability zoning, simulation models for wildfire risk assessment

European treeline areas include protected areas. The management planning in these areas is not sufficiently linked to other land-use planning and often suffers from inadequate participation of local actors and government sectors, e.g. in municipal zoning to control infrastructure building, forest planning, environmental impact assessment processes linked to industrial developments.

4. CONCLUSIONS

Based on 45 case studies, we have come to several conclusions about the social and ecological sustainability of European treeline areas. Firstly, climate change and land-use change represent the 2 most significant drivers in treeline areas. However, unlike most previous analyses of treeline dynamics, our synthesis suggests that land-use change is a more immediate threat to the social and ecological sustainability of European treeline areas than climate change. This

calls for paying more attention to human and local-specific pressures instead of fine-tuning climate change scenarios. Secondly, examples from different parts of Europe have evidenced that maintaining traditional pastoral practices in treeline areas in combination with sustainable tourism could enhance social and ecological sustainability. Thirdly, in analyzing the social–ecological systems with the DPSIR framework, it is crucial to be aware that the state dimension should be regarded as a state of a social–ecological system, not as a state of an ecological system (cf. Sarkki et al. 2017a). This distinction is not entirely academic, and has implications for the sustainability of ESs, which are not solely the benefits that ecosystems provide to human well-being, but benefits co-evolved through centuries of human–environment coexistence. Consequently, society must adapt to the changing nature of treeline ESs and look also for new opportunities arising from environmental change, rather than trying to sustain the current level of ESs indefinitely. Finally, policy and governance systems

that have so far been incoherent and not specifically focused on treeline areas should be proactive without being bureaucratic (Heikkinen et al. 2010). More emphasis should be given to local stakeholder participation in decision making, enhancing local acceptability of decisions. The results from this study indicate that without proactive response to changes, some ESs may be lost in the following decades, changing historical landscapes, reducing financial and other benefits, decreasing biodiversity and consequently, reducing the opportunity to maintain ESs in the future.

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Appendix

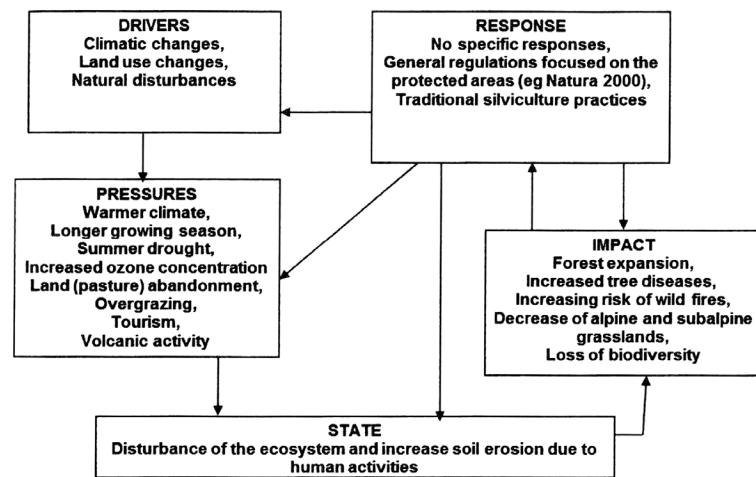


Fig. A1. Application of the drivers-pressures-state-impacts-responses (DPSIR) framework for treeline ecotones in Europe (Kyriazopoulos et al. 2014)

Table A1. Example of the description protocol for drivers, pressures, state, impacts and responses in the second survey (Kyriazopoulos et al. 2014). Colour shading—grey: location, climate and species; green: land use types; blue: climate change types; red: DPSIR factors

Location	Western Carpathian Mts N 48° 48' to 49° 35', E 19° 18' to 21° 00' Elevation >1200 to 1850 m
Climate	Mountainous
Dominant tree species	<i>Pinus mugo</i> , <i>Pinus cembra</i> , <i>Picea abies</i> , <i>Fagus sylvatica</i>
Wild herbivores	<i>Cervus elaphus</i> , <i>Rupicapra rupicapra</i> , <i>Ursus arctos</i>
Land use changes	Pasture abandonment
Grazing / livestock	Decreased / sheep and cattle
Logging pressure	No
Climatic changes	Climate warming
Temperature trend	Increase
Precipitation trend	Slightly increase
Driving forces	Climatic changes, land-use changes
Pressure	Climate warming, decreased grazing
State	Treeline is being increasingly disturbed, particularly by construction/enlargement of ski resorts and other recreation facilities. Regeneration via secondary succession due to abandonment of grazing
Impact	Longer growing season, bark beetle outbreaks
Responses	Creation of nature protection zones, or specific parts of Rural Development Programme dedicated to treeline ecosystems. Silviculture measures