LIFE PASTORALP

LIFE16 CCA/IT/000060

Pastures vulnerability and adaptation strategies to climate change impacts in the Alps

Deliverable C.3

Report on list of indicators and relevant thresholds

March, 2019

Acknowledgements

This report was produced under co-finance of the EC LIFE programme for the Environment and Climate Action (2014-2020), in the framework of Action C.3 "Environmental and socio-economic indicators" of the project LIFE PASTORALP (LIFE16 CCA/IT/000060) "Pastures vulnerability and adaptation strategies to climate change impacts in the Alps".

The project is being implemented by the following beneficiaries:

	University of Florence – UNIFI
	Agenzia Regionale Protezione Ambiente - Valle d'Aosta - ARPA VDA
	Centre National de la Recherche Scientifique - CNRS
	Institut Agricole Régional – IAR
	Institut National de la Recherche Agronomique – INRA
	National Research Institute of Science and Technology for Environment and Agriculture – IRSTEA
	Parc National des Ecrins – PNE
	Ente Parco Nazionale Gran Paradiso – PNGP

ACTION C.3: Environmental and socio-economic indicators

Deliverable: List of environmental and socio-economic indicators

Author(s)	Organisation(s)	E-mail(s)
Gianni Bellocchi	French National Institute for Agricultural Research (Clermont-Ferrand, France)	gianni.bellocchi@inra.fr
Lorenzo Brilli Giovanni Argenti Marco Moriondo Camilla Dibari	University of Florence (Italy)	giovanni.argenti@unifi.it
Stefano Targetti Claude Napoléone	French National Institute for Agricultural Research (Avignon, France)	stefano.targetti@inra.fr
Laura Poggio Paolo Varese Ramona Viterbi	PNGP	laura.poggio@pngp.it

Table of contents

List of figures

Executive summary

Climate change is expected to negatively affect semi-natural resources such as Alpine pastures, reducing their productivity and biodiversity, and their capacity to deliver ecosystem services such as protection from soil erosion, landscape maintenance for tourism and climate mitigation. The aim of this report was to indicate the modelling outcomes and socio-economic variables, as well as climatic and biodiversity indicators, which will be used for the vulnerability analysis. The model outcomes will be obtained using two distinct models. Pastures productivity and emissions will be estimated using two biogeochemical models (PaSim and DayCent), whilst shifts in distribution of pastures will be obtained using machine learning approach (Random Forest). List of socio-economic, climatic and biodiversity indicators are defined according to a variety of means including literature scanning, indicator classification, and local stakeholders' contribution by means of individual questionnaires. Model outcomes will be discussed coupled with climatic indicators (aridity index, hot and cold spells frequency index, etc.), and complemented with biodiversity indicators, in view of a socio-economic assessment. This will allow to create vulnerability indicators for the pastures located in the study area as well as to extrapolate information of the best timing for grazing under current and future climate. The socio-economic variables are ranked according to stakeholder questionnaires. For each variable, a range of potential indicators is defined. Data availability will steer the parameters (for instance "farm household gross margin" as a parameter to assess the revenue indicator) that can be used to calculate the indicators, and data collection will be scheduled to fill the information gaps (considering affordability of data collection).

1. How to read the document

The document consists of eight sections. Each section contains a complete description of sets of indicators of different nature, with the support of extended published sources where the topic is developed in more detail.

The sections are organized as follows:

- "Introduction" (Section 3) in which a description of the methodological basis of vulnerability analysis is reported
- "Outputs and indicators from pasture models" (section 4) where a model-based approaches are described to support vulnerability analysis
- "Biodiversity indicators" (section 5) where the process of developing biodiversity indicators is described
- "Climatic indicators" (section 6) where relevant climate indicators are reported
- "Socio-economic indicators" (section 7) where the process of developing indicators for socio-economic vulnerability analysis (with stakeholder involvement) is described
- "References" (Section 8) in which the relevant literature is reported

2. List of acronyms

GPP	Gross primary production
NPP	Net primary production
NEE	Net ecosystem exchange
RECO	Ecosystem respiration
CH_4	Methane
N_2O	Nitrous oxyde
Hw	Heat waves' frequency
B	De Martonne-Gottmann aridity index
P, PRCP	Precipitation
P_Y	Annual precipitation total
T_Y	Mean annual air temperature
p_a	Precipitation total of the driest month
t_a	Mean air temperature of the driest month
W	State variable
W_0	State variable's threshold
X	Climate driver
NDVI	Normalised Difference Vegetation Index
SLA	Specific leaf area

LDMC	Leaf dry matter content
LNC	Leaf nitrogen content
TX	Maximum air temperature
GSL	Growing Season Length - Number of days between snow melt and snow onset
GDD_ST	Growing Degree Days - Accumulated degree days above 0 °C (using soil temperature) between snow melt and snow onset
FDD_ST	Freezing Degree Days - Accumulated degree days below 0 °C (using soil temperature)
PDO	Protected Designation of Origin
PGI	Protected Geographical Indication
HACPP	Hazard Analysis and Critical Control Points

3. Introduction

Climate changes are expected to negatively affect natural resources such as pastures which, especially over Alpine regions, are acknowledged as very sensitive and vulnerable ecosystems to climate change. In this perspective, a crucial issue is the preservation of mountain pasture areas for their productivity and biodiversity, and for their ability to protect soils from erosion, maintain landscapes and open spaces useful for touristic activities. Moreover, properly managed pastoral farming is recognized to contribute to carbon sequestration and consequently safeguarding the crucial role of pasture ecosystems to mitigate the human greenhouse gas emissions. This function is also guaranteed by the high degree of plant and animal biodiversity deriving from a viable pastoral resource management.

On these basis, our objective is to provide model-based outcomes of productivity, emissions and biodiversity which, when coupled with climatic indicators (aridity index, hot and cold spells frequency index, etc.) and management/socio-economic dynamics changes, can provide indicators for assessing the vulnerability of pastures located in the study area under current and future conditions. Pasture models are meant to be up-scaled to the scale of the project territory using datasets and scenarios for climate, soil, land-use, and pasture management. Climate projections will be consistent with baseline and CO_2 stabilization scenarios produced for IPCC AR5. The climate is composed of both the mean climate signal (e.g. average annual temperature cycle) and its temporal variability, which also includes the occurrence and magnitude of extreme events (see Deliverable C.1). As climate change results in both changes in the mean climate signal (e.g. average annual temperature) and its temporal variability (including the occurrence and magnitude of extreme events), in a climate change context vulnerability is defined as “the extent to which a socio-ecological system is susceptible to sustaining damage from climate change”. Vulnerability is a function of the sensitivity of a system to changes in climate (the degree to which a system will respond to a given change in climate, including beneficial and harmful effects), adaptive capacity (the degree to which adjustments in practices, processes, or structures can moderate or offset the potential for damage or take advantage of opportunities created by a given change in climate), and the degree of exposure of the system to climatic hazards” (IPCC, 2001). Probabilistic measures and a set of indicators of vulnerability, accounting for sensitivity, exposure and adaptive capacity will be computed in (Action C.4) and assessed (Action C.5). The procedures for vulnerability assessment described in this report reflect the methodology outlined by Lardy et al. (2014, 2015), while the socio-economic vulnerability analysis relies on a framework from Marshall and Stokes (2014).

4. Outputs and indicators from pasture models

Modelling outputs target at three main factors: i) pastures productivity and its seasonal pattern; ii) pasture fluxes of greenhouse-gases; iii) pastures biodiversity. These outputs will be obtained using two distinct models. Pastures productivity and emissions will be estimated using two biogeochemical models (PaSim and DayCent), whilst biodiversity (changes in pastoral macro types distribution) will be obtained using machine learning approach (Random Forest).

Table 1. Model outputs to be assessed.

Main factor	Variable	Unit
Productivity	Aboveground biomass	g DM m^{-2}
	Belowground biomass	g DM m^{-2}
	Harvested biomass	g DM m^{-2}
	Animal intake	g DM m^{-2}
	Peak of productivity	g DM m^{-2}
Fluxes	GPP (gross primary production)	g C m^{-2}
	NPP (net primary production)	g C m^{-2}
	NEE (net ecosystem CO_2 exchange)	g C m^{-2}

	RECO (ecosystem respiration)	g C m^{-2}
	CH_4 emissions (methane)	g C m^{-2}
	N_2O (nitrous oxyde) emissions	g C m^{-2}

A vulnerability analysis may be virtually implemented based on any impact variable. Application in the project will be mostly focused on productivity outputs. Maps of vulnerability indices will be generated. Moreover, the comparison of multiple climate and impact models will provide an estimate of the uncertainty associated with using alternative modelling solutions.

Impact variables, indicators and metrics to be analysed will be defined in detail via an exchange with involved partners and stakeholders.

Outputs from a core of two pasture models (PaSim, DayCent) will be used to generate impact variables, as selected out of the list in Table 1, with primary focus on productivity. To characterize climate change hazards, an initial set of climatic hazard indicators will include the three indicators in Table 2.

Table 2. Short list of hazard indicators. *P*: daily precipitation (mm), T_{max}, maximum daily temperature (°C); P_Y, yearly precipitation total (mm); T_Y, mean annual temperature (°C); p_a, precipitation total of the driest month; T_a, mean temperature of the driest month (°C).

Indicator	Quantile	Metric	Reference
Dry spell length	25%	Maximum number of consecutive days in a year with P = 0	after Barnett et al. (2006)
Heat waves' frequency (*hw*)*	75%	Number of consecutive days (≥ 7) when the maximum temperature is higher than the average summer (June, July and August) maximum temperature of the baseline period +3 °C	after Barnett et al. (2006)
De Martonne-Gottmann aridity index (*b*)**	25%	$b = \frac{1}{2} \cdot \left(\frac{P_Y}{T_Y + 10} + 12 \cdot \frac{p_a}{T_a + 10} \right)$	De Martonne (1942)

* The range limits are: $b < 5$: extreme aridity; $5 \leq b \leq 14$: aridity; $15 \leq b \leq 19$: semi-aridity; $20 \leq b \leq 29$: sub-humidity; $30 \leq b \leq 59$: humidity; $b > 59$: strong humidity.

** The range limits are: $hw \leq 14$: extremely moderate frequency; $14 < hw \leq 28$: very moderate frequency; $28 < hw \leq 42$: moderate frequency; $42 < hw \leq 56$: high frequency; $56 < hw \leq 70$: very high frequency; $hw > 70$: extremely high frequency.

Dry spells, based on precipitation only, are indicative of prolonged periods of dry weather. However, they may not be as severe as a drought and may appear interspersed with occasional large rain events (> 100 mm). Heat waves address the issue of prolonged periods of excessively hot weather. The aridity index combines temperature and precipitation values.

Sensitivity will be assessed against low precipitation, high mean annual (or seasonal) temperatures and severe aridity (< 25^{th} or > 75^{th} percentiles). Synthetic measures (indices) for vulnerability assessment will also be provided as a complement to probabilistic assessment of sensitivity and exposure. This will help communicate the results of vulnerability assessment to stakeholders. As a basis, the index by Luers et al. (2003) will be calculated on 30-year time slices of future climate relative to baseline (>1, more vulnerability):

$$V_L = f\left(\frac{|\partial W/\partial X|}{W/W_0}\right)_{\text{future}} \Bigg/ V_L = f\left(\frac{|\partial W/\partial X|}{W/W_0}\right)_{\text{baseline}}$$

where W is the state variable (e.g. productivity), W_0 is a threshold and X is climate driver. It accounts for the sensitivity of the system to a stress factor (e.g. changes of pastoral production with aridity conditions), with respect to a given state. The coefficient of variation calculated over a series of states (e.g. a time series of agricultural production values) is adopted here to represent sensitivity ($\partial W/\partial X$), after Lardy et al. (2014, 2015).

The procedure will be first run without adaptation, and will be repeated by including adaptation options.

5. Biodiversity indicators

Biodiversity indicators are necessary in this framework, especially for protected areas, where sustainable management cannot avoid considering also animal/plant biodiversity conservation.

3.1 Floristic and vegetation indicators

3.1.1 Interactions between climate change and anthropogenic activities

Distinguishing the impacts of climate change on Alpine pastures from those of other anthropogenic drivers, such as type and intensity of pastoral management (Perotti et al., 2018), farming or grazing abandonment, and new species introduction, appears to be challenging. Some shepherds or farmers assign the development of the same undesirable species like *Cirsium eriophorum, Veratrum album* or *Rhinanthus alectorolophus* to drought periods, however these species typically come also after overgrazing or mowing drop-out. Similarly, in semi-natural grasslands of Europe, unpalatable late-succession tussock grasses are favored when hay cutting is abandoned or replaced by light grazing. These species include

Brachypodium rupestre, Brachypodium genuense or *Brachypodium caespitosum, Carex acutiformis*, *Nardus stricta*, *Festuca paniculata* among others. In the Alps, grazing drop-out facilitates the development of woody species (*Rhododendron ferrugineum* and other *Ericaceae, Alnus viridis* or conifer regeneration) and this fact is overlaid by several climate factors (heatwaves, earlier snow melt, seasonal droughts, vegetative period extension, etc.). In this regard Parco Gran Paradiso has begun monitoring activities in order to clarify some interactions between anthropogenic (pasture management) and climate change factors (Ghidotti, 2018). Entomological bio-indicators begin to give some partial information, while for floristic and vegetational observations, clear results need a longer analytical period.
For example, some protocols like GLORIA (Global Observation Research Initiative in Alpine Environments: Pauli et al., 2015) are focused on the long-term monitoring of the impacts of climate change on the biodiversity, hence they need to avoid direct human influences on the monitored vegetation (Rossi et al, 2004). Mountain areas frequently visited by tourists or located in an area of heavy grazing (either by livestock or wild ungulates) are not appropriate. The purpose of GLORIA's Multi-Summit Approach is to build globally usable indicators of the impacts of climate change on the biodiversity of natural to semi-natural environments and, more specifically, to assess regional to large-scale risks of biodiversity losses and the vulnerability of high mountain ecosystems under climate change pressures. A moderate traditional pastoralism, however, is less critical if land use practices remained quite the same over centuries concerning both type and intensity. Heavily overgrazed areas, where plant communities have obviously changed (grazing indicator plants), however, should not be used as GLORIA sites.
About 60 papers and reports (whose coming from European programs) have been examined in view of selecting useful indicators for PASTORALP (a preliminary draft). Plant indicators are regrouped in four categories:

- Phenology
- Alpine forest
- Indicative flora
- Plant functional traits

3.1.2 Phenology

Some European programs have allowed a decades-long experience in phenological indicators. In western alpine region, the following programs methodologies and protocols are the main

references in this context: PHENOALP (http://www.phenoalp.eu), PHENOCLIM (http://phenoclim.org), and e-PHENO (http://www.phenoalp.eu/index.php/it/pheno-net).
PHENOALP and e-PHENO programmes use a phenocamera network and a NDVI index database (Normalized Difference Vegetation Index) that quantifies vegetation changes with the difference between near-infrared and red light analysis; further insights are available by Busetto et al., 2010; Colombo et al., 2011; Cremonese and Henry, 2011; Migliavacca et al., 2011; Filippa et al., 2015; Cremonese et al., 2017. The PHENOCLIM programme, connected to the Centre de Recherches sur les Ecosystèmes d'Altitude (http://creamontblanc.org/fr), deals with a phenological observation network thanks to an app for smartphone in view of collecting observations data. According to previous programmes, three indicators are proposed for the PASTORALP context:

Category	Indicator type	Details	Notes
PHENOLOGY 1	Greening index (indice di inverdimento)	webcam + NDVI	E_PHENO, ARPA Piemonte, ARPA Valle d'Aosta
PHENOLOGY 2	Senescence phase (indice di ingiallimento)	webcam + NDVI	E_PHENO
PHENOLOGY 3	Start and duration of flowering of some wooden species	*Corylus avellana, Fraxinus excelsior, Betula pendula, Picea abies, Larix decidua, Sorbus aucuparia, Syringa vulgaris*	PHENOCLIM

3.1.3. Alpine forest

Alpine forest can give some general information concerning climate changes that can be useful also in pastoral activities like some inter-sectorial programmes, such as SECALP (Lavorel et al., 2011).

A parallel measure of forest decline concerning sensitive climate change species like *Picea abies* or *Abies alba* (Dullinger et al., 2004; Vieilledent, 2010; Lavorel et al., 2011; Vennetier et al., 2012; Csillery et al., 2017) shall provide important local and general information.

Others well-applied topics are the timberline changes in the time and the periodic fluctuations of forest species composition (Motta and Nola, 2001; Carrer and Urbinati, 2006). The woods progression over actually upper boundaries is frequently interpreted as a climate warming threat. Nevertheless, the increase of upwards natural regeneration of woody species does not necessarily appear like a climate change indicator, but in many cases it would be the effect of potential sites recolonization for woodlands in areas with decreased human activities (Wieser et al, 2009). Readers may refer to Didier and Brun (1998) for a critical methodological analysis.

In this context, two indicator types can be proposed for PASTORALP activity:

Category	Indicator type	Details	Notes
ALPINE-FOREST 1	TIMBER-LINE	Decametric periodic modifications of timber-line	with dendrochronological support
ALPINE-FOREST 2	FOREST DECLINE	Woodland areas concerned by decline	SECALP project

3.1.4 Indicative flora

Several studies (Vittoz et al., 2009; Fischer et al., 2011; Lavorel et al., 2011; Cremonese et al., 2017) have shown resilience of subalpine and alpine grazed grasslands to climate changes. In mountain pastures is therefore not easy to select species providing, in the short and medium term, clear and unequivocal direct climate and human change impacts on vegetation. Grazed vegetation appears from long time adapted to the cyclic annual variability of mountain climate, while it is only with extreme events' recurrence in a relatively short time that changes can become more important (Lavorel et al., 2011). However, as shown by some floristic researches (Steinbauer et al., 2018), it seems clear that wide-ranging species can better have a resilience capability than others: in the alpine range, *Poa alpina* is expanding to higher altitudes thanks to its adaptation capacity (Fischer et al., 2011), and high-mountain vegetation is enhanced by below-stage floristic elements. Steno-thermic species have an opposing trend (Parolo and Rossi, 2008), in particular arctic-alpine species (for example *Caricion bicoloris-atrofuscae* communities) or other species in peri-glacial and nival context (Luzzaro et al., 2005; Walther et al., 2005; Pauli et al., 2007; Matteodo et al., 2016).

It is useful to identify thermo-sensible species at local and regional level and monitoring their variations with specific protocols. Some experiences (Interreg ITA-CH "*Biodiversità: una ricchezza da conservare*": see Rivella et al., 2012) have used Landolt or Ellenberg autoecological indicative values (Ellenberg, 1992; Pignatti et al., 2001; Landolt, 2010) in specific plant communities, but locally meaningful numeric values shall be confirmed by a parallel sin-ecological approach. Statistical analysis showed that Ellenberg/Landolt (light, moisture, nitrogen) and climate indicator values (mean January temperature, mean July temperature and mean precipitation) could be used as environmental change indicators.

The micro-topographical variability of study areas shall be taken into account (Scherrer and Körner, 2010, 2011; Randin et al., 2017; Kulonen et al., 2018) because most sensible species can move not only upwards, but also use particular niches in which survive and arise again (Randin et al., 2017). Ecological niche modelling (Parolo et al., 2008) is an important opportunity for biodiversity conservation. In France, a research network called "Flore Sentinelle" (Bonnet et al., 2015) groups several conservation and management institutions (CBNA, ONF, national and regional parks, CEN, Natura 2000 managers) and this experience should be developed at trans-national level. Some specific studies have enabled the knowledge at local level of some target species adaptation attitude (C. Dentant-PNE, in litt.).

Finally lichens can be used like climate change bio-indicators (Aptroot, 2009; Wirth, 2010; Stapper and John, 2015); but we need to investigate how to apply at alpine level methodologies conceived for low altitude context.

Six indicator types are therefore proposed for PASTORALP (see table below):

Category	Indicator type	Details	Notes
INDICATIVE FLORA 1	Artic alpine communities	*Caricion bicoloris-atrofuscae*	see Rivella et al. (2012) notes
INDICATIVE FLORA 2	Nival and periglacial steno-thermic species	Population monitoring and/ or Landolt/Ellenberg T index in standard plots	see Rivella et al. (2012) notes or GLORIA manual
INDICATIVE FLORA 3	Other thermo-sensitive species (selection at local scale)	Population monitoring and/ or Landolt/Ellenberg T index in standard plots	see Rivella et al. (2012)
INDICATIVE FLORA 4	Peatland species sensitives to hydric level variations	areas with *Sphagnum, Cyperaceae,* peatland mosses (*Scheuchzerio-Caricetea* and *Oxycocco-*	see Rivella et al. (2012)

		Sphagnetea)	
INDICATIVE FLORA 5	Wide ranging species development in altitude	*Poa alpina* and other species	for alpine summits see GLORIA manual
INDICATIVE FLORA 6	Lichens	methodology adapted for alpine range	Aptroot (2009)

3.1.5 Plant Functional Traits (PFT)

Functional traits (Lavorel et al*.,* 1997) shall be used as environmental status indicators because ecosystem functioning is driven by the most abundant species traits. According to CSR model (Grime, 2001), species living in similar environments develop similar adaptation strategies. Consequently, it is possible to describe species through some characters called "key traits" (Cornelissen et al., 2003).

For example, Targetti et al. (2013, 2018) considered some grassland species as a useful guide for interpreting the dynamic of the plant communities as response to environmental and management changes (Díaz and Cabido, 1997; Grime, 2001). These key traits are the following:

- leaf functional traits: specific leaf area (SLA), leaf dry matter content (LDMC), leaf nitrogen content (LNC) (based on field survey);
- vegetation traits: life forms (therophytes, geophytes, hemicryptophytes, chamaephytes, nano-phanerophytes and phanerophytes), start and duration of flowering (based on existing database);
- characteristics of litter layer: dry weight, average weight per area, and density (based on field survey).

A strong field survey and accurate lab analysis are necessary to use adequately these indicators.

Category	*Indicator type*	*Details*	*Notes*
PFT 1	Specific leaf area (SLA)	-	-
PFT 2	Leaf dry matter content (LDMC)	-	-
PFT 3	Leaf nitrogen content (LNC)	-	-
PFT 4	Life forms (Raunkiaer)	therophytes,	-

		geophytes, hemicryptophytes, chamaephytes, nano-phanerophytes and phanerophytes	

3.1.6 Conclusion

In the alpine context, there is a large number of programmes, experiences, protocols and methodologies concerning monitoring and biological indicators of climate changes. It is necessary to harmonize them and develop operational partnerships focusing the researches at regional and local levels with specific implementing purposes.

6. Climatic indicators

Climatic indicators are useful for modelling pastures development, phenology and production along vegetative season (Li et al., 2019). During the activity of Action C3, a first list (with 65 different variables) of climatic indicators relevant for alpine pastures has been identified. The list encompasses different kind of climatic variables (concerning temperature, precipitation, wind, snow cover) that should represent, for a proper and reliable utilization, several characteristics as reported in literature:

- they are acknowledged to have a deep and direct effects on pasture vegetation activity and development (Pasho et al., 2011);
- they are easily found in public datasets or are easily accountable (Hijmans et al., 2005);
- they are projectable in the future to assess foreseen climatic scenarios by means of modelization methods (Randall et al., 2007).

For these reasons, some potentially useful indicators, such as those concerning evapotranspiration, have not been taken into account due to constraints in their availability.

The original list was then reduced, with a consensus evaluation among experts belonging to different PASTORALP partner beneficiaries, to the current one that contains 16 parameters in order to reduce redundancy of information and correlation among variables present in the original directory without losing a relevant amount of explanatory effect.

The definitive list is reported in the following table:

TEMPERATURE
Mean seasonal temperature
Heat waves frequency (number of consecutive days when TX is higher than the average summer)
GSL* (Growing Season Length) - Number of days between snow melt and snow onset
GDD_ST (Growing Degree Days) - Accumulated degree days above 0 °C (using soil temperature) between snow melt and snow onset
FDD_ST (Freezing Degree Days) - Accumulated degree days below 0 °C (using soil temperature) i.e. intensity and duration of winter frozen soil
Number and intensity of frost events in the first 30 days after snow melt, i.e. early frosts
Number and intensity of frost events in the 30 days before snow onset i.e. late (autumn) frosts
PRECIPITATION
Seasonal rainfall
Seasonal count inside GSL of days PRCP >10 mm
Start day of maximum dry spell (start of drought)
End day of maximum dry spell (end of drought)
Total amount of precipitation between snow melt and snow onset
WIND
Seasonal wind speed
SNOW
Date of snow onset
Date of snow melt
Maximum snow height during winter time

Temperature-based indicators ranging from very simple and easily achievable (e.g. seasonal average temperature, used over large scale, Dibari et al., 2016), to more complex ones, can be used as proxies of duration of vegetative season or to assess the occurrence of undesirable conditions for a proper grassland growth. In this context, extreme events like early or late frosts as extreme climatic events are among the drivers able to explain variability in plant biomass and productivity (Treharne et al., 2018). At the same time, indicators related to precipitation are intended to characterize a seasonal pattern (seasonal precipitation, precipitation during the growing season) but also critical periods (dry spell) with high effect on grassland development and production (Zeiter et al., 2016). Seasonal wind speed is a relevant and easily achievable (in combination with temperature and precipitation) to define evapotranspiration and its potential effects on pastures and grasslands production, by means also of satellite images (Pôças et al., 2013). Variables related to snow cover are mostly related to infer the beginning and the end of the growing season of pastures in mountain and alpine belt, which is expected to widen in the next future climate (Fuhrer et al., 2014).

7. Socio-economic indicators

In the context of the PASTORALP, the socio-economic vulnerability analysis will follow the general framework proposed by Marshall and Stokes (2014) (Fig. 1).

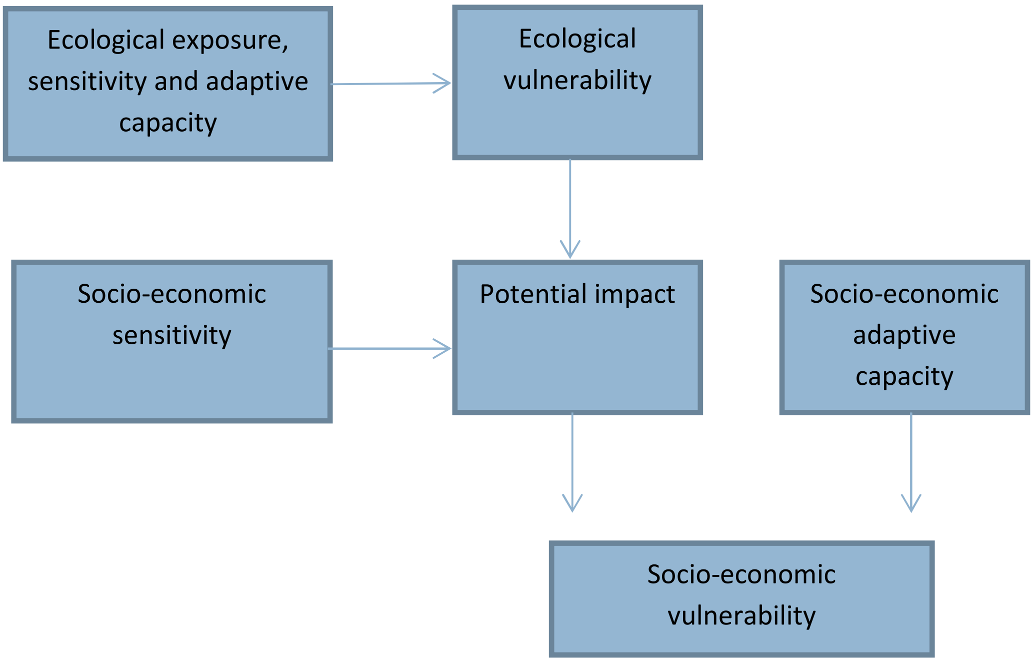

Fig. 1. Conceptual framework for the assessment of socio-economic vulnerability to climate change (adapted from Marshall and Stokes, 2014). Potential impacts depend on ecological vulnerability and socio-economic sensitivity, whereas socio-economic vulnerability may be reduced according to adaptive capacity.

Adaptive capacity is a property of a system, which is complex to assess with an objective "yardstick" (Metzger et al., 2006). For that reason, a mix of qualitative and quantitative indicators is usually employed. The four components of adaptive capacity proposed by Marshall et al. (2014) have been considered able to include the range of attributes and proxies reflecting the adaptation potential of livestock farmers in the case study areas:

Socio-economic adaptation components (Marshall et al., 2014):

- Perception of risks and uncertainties (e.g. climate change perception)
- Skills for planning, learning and experimenting (e.g. link with researchers or advisors, co-adaptive institutions)
- Capacity to cope with change (e.g. rate of changes adopted, financial capacity, training)
- Interest in changing (e.g. social and emotional flexibility)

According to explorative interviews with local experts, the identification of the components of **socio-economic sensitivity** in the local case study areas requires to develop further the framework proposed by Marshall et al. (2014). The selected analytical framework for the case study areas refers to sustainability as a valid framework for assessing socio-economic sensitivity. Indeed, if a change affecting a factor is expected to determine a relative change of sustainability, it also means that the system is sensitive in respect of changes of that factor. That interpretation widens the approach proposed by Marshall and Stokes (2014) and Marshall et al. (2014), where sensitivity was considered as a synonym of "local-resource dependency" (i.e. higher dependency of livestock farms on local hay or grasslands links to a higher dependency on climate impacts on local forage production). In our framework, dependency on local resources was not deemed as an accurate measure of sensitivity. Indeed, local resources are directly affected by climate change but the indirect impact of a wider range of issues on the pastoral system may concur to exacerbate or reduce the sensitivity of the system as a whole (Huber et al., 2013). Consequently, a wider range of issues was included in the evaluation of socio-economic sensitivity.

The first step aiming at the identification of indicators of climate change sensitivity regarded the identification of a set of socio-economic factors that are relevant for the pastoral system sustainability in the selected case study areas and the subsequent definition of indicators to take into account such factors in the analysis. The selection of socio-economic indicators was based on a literature-based classification that has provided a broad list of issues of concern such as profitability, autonomy, etc. The literature scan has also provided a range of potential indicators attributed to the different issues considering availability or affordability of data collection, sensitivity to change, usefulness for the local stakeholders, etc.

The selection process of socio-economic sensitivity indicators in the action C3 has followed four steps:

1. Literature scoping and database screening. In this step, indicators of sustainability proposed in available documents (both scientific literature and grey literature) were reviewed to find a range of indicators of sensitivity. In collaboration with the local units, existing database covering the case study areas were also identified.
2. Definition of socio economic dimensions relevant to the context. The preliminary list of indicators was classified according to socio-economic dimensions (social, economic, institutional) and the range of themes considered relevant in literature in Action E.2 (launching events).

3. Stakeholder validation and discussion to rank the relevance of the socio-economic issues in the local context. The range of socio-economic categories has been ranked by local stakeholders to identify the socio-economic issues considered more relevant in the case study areas and that, according to the stakeholders, drive the sustainability of the local pastoral systems (in Action E.2 first consultation workshops).
4. Screening of data availability, harmonization between the case study areas and planning for the data collection.

5.1 Results from the socio-economic indicator review and list of parameters able to describe the sustainability of the local pastoral systems

5.1.1 Economic dimension

- Autonomy
  - **Incentives** (dependency on subsidies and incentives e.g. rate of subsidies on gross margin, indebtedness e.g. interest rate on income)
  - **Autonomy** (dependency on external resources, e.g. forage sufficiency, manpower autonomy, rate of dependency on global/regional inputs, decision constraints e.g. via expert assessment of the negotiating power in the supply chain, collective action capacity)
- Profitability
  - **Efficiency** (e.g. livestock unit/working unit, kg milk/working unit, variable cost/working unit, gross margin/livestock unit, gross added value/working unit, income/working unit/year)
  - **Profit** (e.g. gross and net margin, variable and fixed costs, added value, price and input cost variability, productivity kg milk/ha, stocking rate, input and technological rate)
- Quality of products
  - **Local marketing** (e.g. organic label, PDO, PGI, price per unit of product compared to reference price, farmers' market, direct selling)
  - **Production quality** (e.g. certifications, HACPP)
- Structure
  - **Land tenure** (e.g. parcel size, farm size, farm ownership, rented land)
- Diversification
  - **Diversification** (e.g. off-farm income /total income, off-farm labour, non-farming activities such as agro-tourism, short supply chains such

as direct selling and farmers' market, agroforestry, functional diversity, tourism facilities, game hunting, social events, efforts in landscape maintenance such as area under stewardship agreement, hours spent in ecological structure maintenance)

5.1.2 Social dimension

- Durability
  - **Durability** (e.g. age of the decision maker, farm transmissibility, farm succession plan, age structure of family members, available farm income per worker compared with regional average, number of active farmers km^{-2}, historical trends, working time to reach minimal wage, second-home dwelling, urban sprawl)
  - **Sense of place** (e.g. rate of local/extra-regional farmers, traditions such as transhumance or pastoral-related public events, rate of grassland abandonment)
- Knowledge
  - **Training** (e.g. professional education, years of experience, workshop and training events, collaboration with research institutes, IT media access, perception of production variability and risk, traditional knowledge, local landraces, traditional events and demonstrations, popular-traditional customs, traditional infrastructures such as greenways, traditional products)
- Networking
  - **Social network** (e.g., participation in local elections, attendance to assemblies and other events, farmer groups and associations, cooperatives, joint use of equipment)
- Quality of life
  - **Quality of life** (e.g. free time availability, social-cultural facilities, isolation rate, Farmer identity and pride, rate of satisfaction, free days per week, holidays per year, housing-accommodation-equipment)

5.1.3 Institutional dimension

- Equity
  - **Equity** (e.g. access to public resources such as water and grazing lands, collective transformation facilities, historical institutions like e.g. "regole", formal/informal community institutions)

- **Conflicts** (e.g. wildlife, forest grazing, wolf management)
- Administration efficiency
  - **Legitimacy** (e.g. level of bureaucracy, decision-making process, public consultations)

5.2 Stakeholder ranking

The preliminary list of socio-economic issues has been evaluated by means of stakeholders' questionnaires where the range of socio-economic issues has been ranked according to local context (Fig. 2).

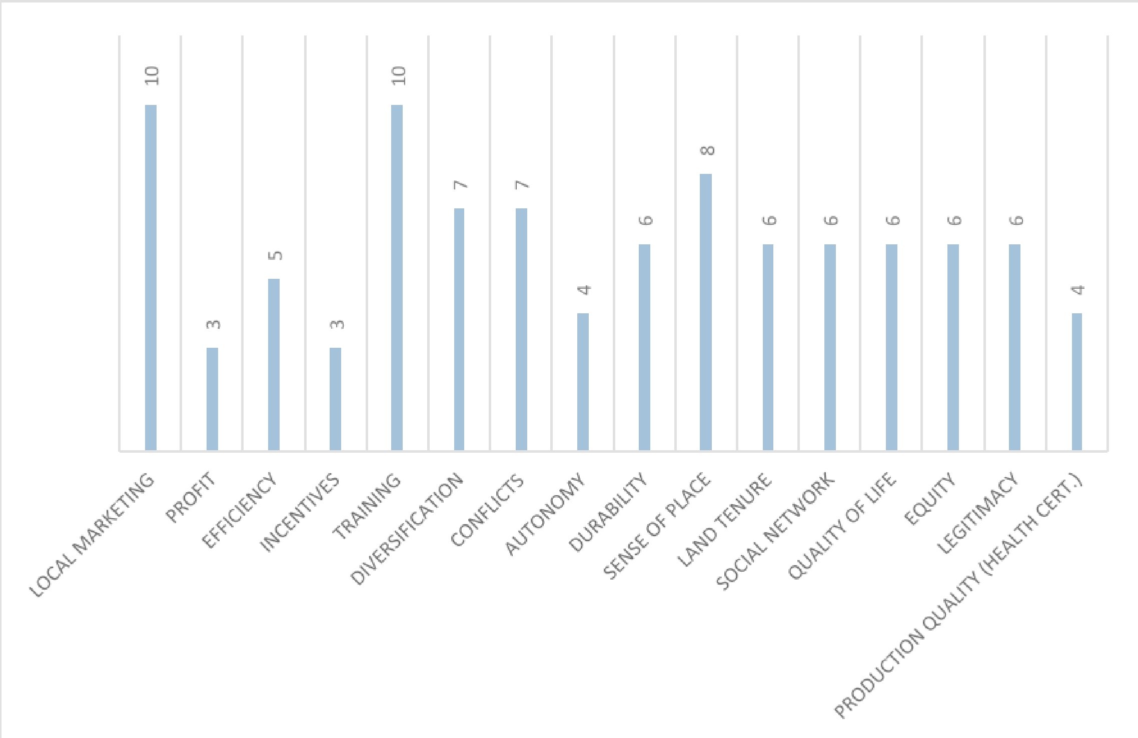

Fig. 2. Results from 20 questionnaires: Socio-economic issues rated by the local stakeholders in the two case study areas. Numbers on top of the histograms refer to the N. of stakeholders that rated the socio-economic variable as "very relevant".

The results from the questionnaires outline relevant importance for social aspects related to knowledge and expertise of the farmers ("training") and sense of place, which included aspects related to occupational identity. Besides this, economic issues related to profitability such as local marketing and diversification were also considered important. Conflicts concern a further issue, which is related to the problematic management of sheep predation by wolves (in particular in the French case).

5.3 Proposed set of potential indicators of socio-economic vulnerability in the case study areas

According to literature and the stakeholder survey, the socio-economic proxies that will be considered for the vulnerability assessment are as follows.

Sustainability variables and proxies selected for the case study regions, and links with the components of "socio-economic sensitivity" as proposed by Marshall et al. (2014):

	Socio-economic components	Expected impact on sensitivity reduction
Variables and proxies considered relevant by both Marshall et al. (2014) and local stakeholders	Diversification	+
	Sense of place	+ -
	Training, knowledge	+
Variables and proxies included in the assessment according to Marshall et al. (2014) but that were not considered relevant by the local stakeholders	Profit	+
	Efficiency	+ -
	Incentives	+ -
	Autonomy	+
	Social network	+
	Attachment to occupation	-
	Employability	+
	Off-farm family revenue	+
	Environmental awareness	+
Variables and proxies considered in the analysis as considered relevant by local stakeholders	Local marketing	+
	Conflicts	+ -

Indicators linked to diversification (income and input diversification), sense of place (attachment to traditions, perception of quality of life and landscape attributes) and training/knowledge (expertise, professional education, years of experience) will be considered the primary indicators of sensitivity to climate change. Nonetheless, indicators and proxies for the variables identified by local stakeholders, and proposed by Marshall et al. (2014), will be collected as secondary data to provide a more in-depth assessment.

Socio-economic components of "adaptation capacity" as proposed by Marshall et al. (2014):

	Rationale	Expected impact on adaptive capacity	Proposed indicators
Perceptions of risk	Perception of climate change uncertainty and risks facilitate to recognize and accept the need to anticipate climate impacts and identify opportunities.	+	Qualitative: reported changes and perception
Skills for planning and experimenting	Capacity to adapt is linked to skills for planning and experimenting new technologies or management options	+	Links with networks for adaptive management (e.g. Alpages Sentinelles), or research / advisors
Ability to cope with change	Capacity and experience to change increase the adaptive capacity.	+	Rate of practice change or adaptations
Interest in change	Several reasons may increase the interest in changing. For instance, social networks, information availability. Other issues may reduce the interest e.g. years to retirement	+	Qualitative: willingness to change practices

8. References

Aptroot, A., 2009. Lichens as an indicator of climate and global change. In: Letcher, T.M. (ed.) Climate change: Observed impacts on planet Earth. Oxford, Elsevier, p. 401-408.

Barnett, C., Hossel, J., Perry, M., Procter, C., Hughes, G., 2006. A handbook of climate trends across Scotland. Scotland and Northern Ireland Forum for Environmental Research, SNIFFER Project CC03, Edinburgh, United Kingdom.

Bonnet, V., Fort, N., Dentant, C., Bonet, R., Salomez, P., Till-Bottrau, I., 2015. Méthodologie de suivi des espèces végétales rares mise en place par un réseau d'acteurs de la conservation. Acta Botanica Gallica 162, 27-36. (in French)

Busetto, L., Colombo, R., Migliavacca, M., Cremonese, E., Meroni, M., Galvagno, M., Rossini, M., Siniscalco, C., Morra di Cella, U., Pari, E., 2010. Remote sensing of larch phenological cycle and analysis of relationships with climate in the Alpine region. Global Change Biology. Global Change Biology 16, 2504-2517.

Carrer, M., Urbinati, C., 2006. Long-term change in the sensitivity of tree-ring growth to climate forcing in *Larix decidua*. New Phytologist 170, 861-871

Colombo, R., Busetto, L., Fava, F., Di Mauro, B., Migliavacca, M., Cremonese, E., Galvagno, M., Rossini, M., Meroni, M., Cogliati, S., Panigada, C., Siniscalco, C., Morra di Cella, U., 2011. Phenological monitoring of grassland and larch in the Alps from Terra and Aqua MODIS images. Italian Journal of Remote Sensing 43, 83-96.

Cornelissen, J.H.C., Lavorel, S., Garnier, E., Díaz, S., Buchmann, N., Gurvich, D.E., Reich P.B., Steege, H. ter, Morgan, H.D., van der Heijden, M.G.A., Pausas, J.G., Poorter, H., 2003. A handbook of protocols for standardised and easy measurement of plant functional traits worldwide. Australian Journal of Botany 51, 335-380.

Cremonese, E, Filippa, G, Galvagno, M., Siniscalco, C., Oddi, L., Morra di Cella, U., Migliavacca, M., 2017. Heat wave hinders green wave: The impact of climate extreme on the phenology of a mountain grassland. Agricultural and Forest Meteorology 247, 320-330.

Cremonese, E., Henry, E., 2011. Protocol for phenological observations in alpine grasslands. Phenoalp Project Report, 10 pp.

Csillery, K., Bartalucci, A.-L., Seignobosc, M., Courbaud, B., 2017. Coupled effects of wind storms and drought on the mortality across 115 forest stands from Western Alps and the Jura mountains. Global Change Biology 23, 5092-5107.

De Martonne, E., 1942. Nouvelle carte mondiale de l'indice d'aridité. Annales de Géographie 51, 242-250. (in French)

Díaz, S., Cabido, M., 1997. Plant functional types and ecosystem function in relation to global change: a multiscale approach. Journal of Vegetation Science 8, 463-474.

Dibari C., Bindi M., Moriondo M., Staglianò N., Targetti S., Argenti G., 2016. Spatial data integration for the environmental characterization of pasture macrotypes in the Italian Alps. Grass and Forage Science 71, 219-234.

Didier, L., Brun, J.-J., 1998. Limite supraforestière et changements environnementaux : pour une approche pluriséculaire et spatialisée des écosystèmes d'altitude. Géographie physique et Quaternaire 52, 227-236. (in French)

Dullinger, S., Dirnböck, T., Grabherr, G., 2004. Modelling climate change-driven treeline shifts: relative effects of temperature increase, dispersal and invasibility. Journal of Ecology 92, 241-252.

Ellenberg, H., 1992. Zeigerwerte der Gefäßpflanzen Mitteleuropas [Indicator values of vascular plants in Central Europe]. Scripta Geobotanica 9 (third edition), Göttingen. (in German)

Filippa, G., Cremonese, E., Galvagno, M., Migliavacca, M., Morra di Cella, U., Petey, M., Siniscalco, C., 2015. Five years of phenological monitoring in a mountain grassland: inter-annual patterns and evaluation of the sampling protocol. International Journal of Biometeorology 59, 1927-1937.

Fischer, M., Weyand, A., Rudmann-Maurer, K., Stöcklin, J., 2011. Adaptation of *Poa alpina* to altitude and land use in the Swiss Alps. Alpine Botany 121, 91-105.

Fuhrer, J., Smith, P., Gobiet, A., 2014. Implications of climate change scenarios for agriculture in alpine regions - A case study in the Swiss Rhone catchment. Science of the Total Environment 493, 1232-1241.

Ghidotti, S., 2018. Esperienze di conservazione attiva nel parco nazionale gran paradiso. Federparchi Workshop "Monitoraggio e conservazione della biodiversità nelle aree protette. Parco Gran Paradiso, 21-22 June, Cogne (AO), Italy. (in Italian)

Grime, J.P., 2001. Plant strategies, vegetation processes, and ecosystem properties. John Wiley and Sons (second edition), Chichester, UK.

Hijmans R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25, 1965-1978.

Huber, R., 2013. Modeling social-ecological feedback effects in the implementation of payments for environmental services in pasture-woodlands. Ecology and Society 18, 41.

Kulonen, A., Imboden, R.A., Rixen, C., Maier, S.B., Wipf, S., 2018. Enough space in a warmer world? Microhabitat diversity and small-scale distribution of alpine plants on mountain summits. Diversity and Distributions 24, 252-261.

Landolt, E., 2010. Flora indicativa. Haupt Verlag, Bern. (in German)

Lavorel, S., Lamarque, F. Quetier, B. Courbaud, F. Véron, G,. Loucougaray, G,. Kunstler, Spiegelberger T., l. Dobremez b. - Nettier, 2011. Adaptation des territoires alpins à la recrudescence des sécheresses dans un contexte de changement global (projet SECALP), 58 pp. (in French)

Lavorel, S., McIntyre, S., Landsberg, J., Forbes, T.D.A., 1997. Plant functional classification: from general groups to specific groups based on response to disturbance. Trend in Ecology and Evolution 12, 474-478.

Lardy, R., Bachelet, B., Bellocchi, G., Hill, D.R.C., 2014. Towards vulnerability minimization of grassland soil organic matter using metamodels. Environmental Modelling & Software 52, 38-50.

Lardy, R., Bellocchi, G., Martin, R., 2015. Vuln-Indices: Software to assess vulnerability to climate change. Computers and Electronics in Agriculture 114, 53-57.

Li, Z., Wang, Z., Liu, X., Fath, B.D., Liu, X., Xu, Y., Hutjes, R., Kroeze, C., 2019. Causal relationship in the interaction between land cover change and underlying surface climate in the grassland ecosystems in China. Science of the Total Environment 647, 1080-1087.

Luzzaro, A., Cerabolini, B., Caccianiga, M., Pierce, S., Andreis, C., 2005. Strategie delle piante e tipi funzionali nello studio della dinamica di vegetazione in ambiente periglaciale. Informatore Botanico Italiano 37, 224- 225. (in Italian)

Marshall, N., Stokes, C.J., 2014. Identifying thresholds and barriers to adaptation through measuring climate sensitivity and capacity to change in an Australian primary industry. Climatic Change 126, 399-411.

Marshall, N.A., Stokes, C.J., Webb, N.P., Marshall, P.A., Lankester, 2014. Social vulnerability to climate change in primary producers: A typology approach. Agriculture, Ecosystems and Environment 186, 86-93.

Matteodo, M., Amman, K., Verrechhia, E.P., Vittoz P., 2016. Snowbeds are more affected than other subalpine–alpine plant communities by climate change in the Swiss Alps. Ecological Evolution 6, 6969-6982.

Metzger, M.J., Rounsevell, M.D.A., Acosta-Michlik, L., Leemans, R., Schröter, D., 2014. The vulnerability of ecosystem services to land use change. Agriculture, Ecosystems and Environment 114, 69-85.

Migliavacca, M., Galvagno, M., Cremonese, E., Rossini, M., Cogliati, S., Manca, G., Diotri, F., Busetto, L., Colombo, R., Fava, F., Pari, E., Siniscalco, C., Morra di Cella, U., Richardson, A.D., 2011. Using webcam images for monitoring and modeling phenological and functional dynamics of a subalpine grassland. Agricultural and Forest Meteorology 151, 1325-1337.

Motta, R., Nola, P., 2001. Growth trends and dynamics in subalpine forest stands in the Varaita valley (Piedmont, Italy) and their relationship with human activity and global change. Journal of Vegetation Science 12, 219-230.

Parolo, G., Rossi, G., 2008. Upward migration of vascular plants following a climate warming trend in the Alps. Basic and Applied Ecology 9, 100-107.

Parolo G., Rossi, G., Ferrarini, A., 2008. A. Toward improved species niche modelling: Arnica montana in the Alps as a case study. Journal of Applied Ecology 45, 1410-1418.

Pasho, E., Papanastasis, V.P., Pelz, D., Lako, T., 2011. Inventory and evaluation of grasslands in Albania. Grass and Forage Science 66, 123-137.

Pauli, H., Gottfried, M., Reiter, K., Klettner, C., Grabherr, G. 2007. Signals of range expansions and contractions of vascular plants in the high Alps: observations (1994-2004) at the GLORIA master site Schrankogel, Tyrol, Austria. Global Change Biology 13, 147-156

Pauli, H., Gottfried, M., Lamprecht, A., Niessner, S., Rumpf, S., Winkler, M., Steinbauer, K., Grabherr, G., 2015. The GLORIA field manual – standard Multi-Summit approach, supplementary methods and extra approaches. 5th edition. GLORIA-Coordination, Austrian Academy of Sciences & University of Natural Resources and Life Sciences, Vienna.

Perotti, E., Probo, M., Pittarello, M., Lonati, M., Lombardi, G.P., 2018. A five-year rotational grazing changes the botanical composition of sub-alpine and alpine grasslands. Applied Vegetation Science 21, 647-657.

Pignatti, S., Bianco, P., Fanelli, G., Paglia, S., Pietrosanti, S., Tesacarollo, P., 2001. Le piante come indicatori ambientali. Manuale tecnico-scientifico. ANPA Report, 108 pp. (in Italian).

Pôças, I., Cunha, M., Pereira, L.S., Allen, R.G., 2013. Using remote sensing energy balance and evapotranspiration to characterize montane landscape vegetation with focus on grass and pasture lands. International Journal of Applied Earth Observation and Geoinformation 21, 159-172.

Randall, D.A., Wood, R.A., Bony, S., Colman, R., Fichefet, T., Fyfe, J., Kattsov, V., Pitman, A., Shukla, J., Srinivasan, J., Stouffer, R.J., Sumi, A., Taylor, K.E., 2007. Climate models and their evaluation. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (eds.) Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Randin, C.F., Pellissier, L., Guisan, A., Nakhutsrishvili, G., 2017. A comparison of climatic niches of the same Alpine plant species in the Central Caucasus and the Alps. In: Nakhutsrishvili, G., Abdaladze, O., Batsatsashvili, K., Spehn, E., Körner, C. (eds.) Plant diversity in the Central Great Caucasus: A quantitative assessment. Springer International Publishing, pp. 133-144.

Rivella E., Converso C., Nappi P., 2012. Clima e biodiversità. Esperienze di monitoraggio in ambiente alpino. Brochure ARPA Piemonte, 69 pp. (in Italian)

Rossi, G., Parolo, G., Della Vedova, R., 2004. Gli organismi vegetali come bioindicatori dei cambiamenti climatici, il progetto GLORIA. Atti del convegno "Acque a Cremona" - Museo civico di Storia Naturale di Cremona, pp. 81-94. (in Italian)

Scherrer, D., Körner, C., 2010. Infra-red thermometry of alpine landscapes challenges climatic warming projections. Global Change Biology 16, 2602-2613.

Scherrer, D., Körner, C., 2011. Topographically controlled thermal-habitat differentiation buffers alpine plant diversity against climate warming. Journal of Biogeography 38, 406-416.

Stapper, N.J., John, V., 2015. Monitoring climate change with lichens as bioindicators. Pollution Atmosphérique 226, 12 pp.

Steinbauer, M.J., 2018. Accelerated increase in plant species richness on mountain summits linked to climate warming. Nature 556, 231-234

Targetti, S., Messeri, A., Argenti, G., Staglianò N., 2018. A comparative analysis of functional traits in semi-natural grasslands under different grazing intensities. Agronomy Research 16, 2179-2196.

Targetti, S., Messeri, A., Staglianò, N., Argenti, G., 2013. Leaf functional traits for the assessment of succession following management in semi-natural grasslands: a case study in the North Apennines, Italy. Applied Vegetation Science 16, 325-332.

Treharne, R., Bjerke, J.W., Tømmervik, H., Stendardi, L., Phoenix, G.K., 2019. Arctic browning: Impacts of extreme climatic events on heathland ecosystem CO_2 fluxes. Global Change Biology 25, 489-503.

Vennetier, M., 2012. Advances in climate change and global warming research and application. Scholarly ed., Atlanta, GA, USA, 3053 pp.

Vieilledent, G., Courbaud, B., Kunstler, G., Dhôte, J.F., 2010. Mortality of Silver fir and Norway spruce in the western Alps - a semi-parametric approach combining size-dependent and growth-dependent mortality. Annals of Forest Sciences 67, 305-305.

Vittoz, P., Randin C., Dutoit A., Bonnet F., Hegg O., 2009. Low impact of climate change on subalpine grasslands in the Swiss Northern Alps. Global Change Biology 15, 209-220.

Walther, G.-R., Bessner, S., Burga, C. 2005. Trends in the upward shift of alpine plants. Journal of Vegetation Science 16, 541-548.

Wieser, G., Matyssek, R., Luzian, R., Zwerger, P., Pindur, P., Oberhuber, W., Gruber, A., 2009. Effects of atmospheric and climate change at the timberline of the Central European Alps. Annals of Forest Science 66, 402.

Wirth, V., 2010. Ökologische Zeigerwerte von Flechten – erweiterte und aktualisierte Artenliste [Ecological indicator values of lichens - enlarged and updated species list]. Herzogia 23, 229-248. (in German).

Zeiter, M., Schärrer, S., Zweifel, R., Newbery, D.M., Stampfli, A., 2016. Timing of extreme drought modifies reproductive output in semi-natural grassland. Journal of Vegetation Science 27, 238-248.