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Physiognomic and physiologic changes in mountain grasslands in response to environmental and anthropogenic factors

Maite Gartzia [a, *], Fernando Pérez-Cabello [b], C. Guillermo Bueno [c], Concepción L. Alados [d]

[a] Instituto Pirenaico de Ecología (CSIC), Avda de Nuestra Señora de la Victoria 16, P.O. Box 64, Jaca, E-22700 Huesca, Spain
[b] Department of Geography and Spatial Management, University of Zaragoza, Pedro Cerbuna, 12, E-5009 Zaragoza, Spain
[c] Department of Biological Sciences, CW 405, Biological Sciences Bldg, University of Alberta, Edmonton, Alberta T6G 2E9, Canada
[d] Instituto Pirenaico de Ecología (CSIC), Avda Montañana 1005, P.O. Box 13034, E-50192 Zaragoza, Spain

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A B S T R A C T

Mountain grasslands provide valuable ecosystem services for sustainable development and human wellbeing. These habitats have suffered important changes related with their physiognomic (biomass) and physiologic (greenness) properties. Some of these changes received significant attention i.e. woody encroachment, while others, like the changes in biomass and greenness of those grasslands that have not experienced woody encroachment are almost unknown. We calculated physiognomic and physiologic properties for dense grasslands not affected by woody encroachment through the Normalized Difference Vegetation Index (NDVI) and Normalized Difference Infrared Index (NDII) from Landsat-5 Thematic Mapper. Imagery taken in the late-1980s and late-2000s in the Spanish Pyrenees were analyzed with multi-temporal vectors to detect increases or decreases of biomass and greenness. To understand the source of these changes, we modeled them with anthropogenic (land use, i.e. grazing, ski resorts, and related infrastructures) and environmental factors (topographic, lithologic and climatic). Anthropogenic factors were most strongly correlated with decrease in the biomass and greenness, showing degradation patterns of the grasslands at localized patches. Nonetheless, environmental factors were most strongly correlated with positive changes in both indices, detecting a continuous pattern in the increase in biomass and greenness. In areas that had high livestock stocking rates, grasslands biomass and greenness decrease, while in areas that had low stocking rates, biomass and greenness increases. Grasslands at low elevation showing decrease in biomass and greenness were either on gentle slopes and largely affected by human activities, or on steep slopes locally affected by ski resorts. In areas that have been disturbed by anthropogenic factors, the increase of rain in early summer trigger erosion processes, enhancing the negative effect of anthropic pressure on grassland greenness and biomass. In contrast, grasslands at high elevations, on steep slopes, and those that had north or west aspects and that had an acidic lithology, with less continentality, and that received more rain, had the most increase in biomass and greenness. Those results suggest that changes in mountain grasslands, apart from woody encroachment, are deeply altering their physiology and physiognomy, pointing out direct relationships with current management practices and climate trends.

1. Introduction

For centuries, mountain grasslands have provided valuable ecosystem services, such as high quality forage for traditional livestock grazing (Chan, Shaw, Cameron, Underwood, & Daily, 2006; Millennium Ecosystem Assessment, 2005). These services are fundamental for sustainable development and human well-being, including the preservation of biodiversity and unique landscapes, which have become highly valuable by tourism (Fillat, Aguirre, Pauné, & Fondevilla, 2012; Millennium Ecosystem Assessment, 2005). Directly or indirectly, those grasslands have sustained and diversified local economies in mountain areas; however, the extent and structure of mountain grasslands has changed rapidly (Barrio et al., 2013; Gautam, Webb, Shivakoti, &

* Corresponding author.
E-mail addresses: maitegartzia@yahoo.es (M. Gartzia), fcabello@unizar.es (F. Pérez-Cabello), cgbuenog@gmail.com (C.G. Bueno), alados@ipe.csic.es (C.L. Alados).

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Zoebisch, 2003; Millennium Ecosystem Assessment, 2005). The nature and extent of the loss of grasslands has been studied in many mountain systems, especially, the effects of woody plant encroachment (Brandt, Haynes, Kuemmerle, Waller, & Radeloff, 2013; Gartzia, Alados, & Pérez-Cabello, 2014; Matson & Bart, 2013; Wehn, Pedersen, & Hanssen, 2011); however, other changes have occurred in these grasslands that have had a significant effect on their structure and composition because of changes in land management and stocking rates (Bradley & O'sullivan, 2011; Wehn et al., 2011), climate change (Neuwirth & Hofer, 2013; Wipf & Rixen, 2010; Xu et al., 2009; Zhao et al., 2015), and the development of constructions (Barni, Freppaz, & Siniscalco, 2007; Gros, Monrozier, Bartoli, Chotte, & Faivre, 2004). Yet, few studies have measured the physiognomic (biomass production) and physiologic (greenness) changes in mountain grasslands that have not experienced woody encroachment.

Changes in the type of grazing livestock can have significant effects on mountain grasslands because livestock species graze differently depending on their diet, body size, behavior, and mobility (Aldezabal, Laskurain, & Mandaluniz, 2012; Rose, Hertel, & Leuschner, 2013; Wehn et al., 2011). In the Pyrenees, cattle have replaced most of the sheep (García-Ruiz et al., 1996; IAE, 2014; Lasanta-Martínez, Vicente-Serrano, & Cuadrat-Prats, 2005), which has changed the distribution and intensity of grazing. Consequently, some areas have been grazed intensively, but others have been abandoned (MacDonald et al., 2000; Wehn et al., 2011). Changes in the type of grazing livestock have other negative effects, such as an increase in wild boar disturbances in areas grazed by cattle (Bueno, Barrio, García-González, Alados, & Gómez-García, 2010), which have a negative effect on mountain grasslands because boars can turn over large areas of dense grasslands as they forage for food below-ground (Barrios-Garcia & Ballari, 2012; Massei & Genov, 2004). Rooting reduces plant cover substantially, alters soil properties (Bueno, Azorín, Gómez-García, Alados, & Badía, 2013; Massei & Genov, 2004; Mohr, Cohnstaedt, & Topp, 2005) and plant communities (Bueno, Alados, Gómez-García, Barrio, & García-González, 2009; Kotanen, 1997), which affects the pastoral and ecological values of those grasslands (Bueno, Barrio, García-González, Alados, & Gómez-García, 2011).

Climate warming has a significant influence on the biomass production and greenness of mountain grasslands (Li et al., 2014; Vicente-Serrano, Lasanta, & Romo, 2005). In recent decades, annual precipitation (López-Moreno, Vicente-Serrano, Angulo-Martínez, Beguería, & Kenawy, 2010; Vea, Duran, & Aguilar, 2012) and snow accumulation (Krasting, Broccoli, Dixon, & Lanzante, 2013; López-Moreno, 2005; Zhou, Aizen, & Aizen, 2013) in mountainous areas highly correlated with grasslands productivity (Choler, 2015; Liu, Wu, Wu, & Liu, 2013; Smit, Metzger, & Ewert, 2008) have decreased, and temperature and potential evapotranspiration have increased significantly (Krishnaswamy, John, & Joseph, 2014; Vicente-Serrano et al., 2005; Zeng & Yang, 2008). Snow depth in spring (April and May) mainly depends on the snow that has accumulated in the previous months and with air temperature in April (López-Moreno, 2005). Therefore, in a context of climate warming, we can expect earlier snow melting, longer growing seasons, and increased grassland productivities (Choler, 2015; Neuwirth & Hofer, 2013; Panday & Ghimire, 2012; Vicente-Serrano et al., 2005). In mountainous areas of Siberia, however, biomass productivity increased after deep snow cover and a late snowmelt (Grippa et al., 2005), which suggests that factors other than climatic have also played a role.

Remote sensing can be used to quantify changes in terms of the physiognomic and physiologic properties (e.g., biomass, greenness) of mountain grasslands across large areas (Karnieli et al., 2013; Numata et al., 2007; Paudel & Andersen, 2010; Zeng & Yang, 2008). A combination of Normalized Difference Vegetation Index (NDVI) (Rouse, Haas, Schell, & Deering, 1974) and Normalized Difference Infrared Index (NDII) (Hardisky, Klemas, & Smart, 1983) derived from Landsat-5 TM imagery taken on different dates can be used to detect changes in those properties (Numata et al., 2007) based on multi-temporal vectors (Pérez-Cabello, 2011). Negative changes in both indices between periods reflect grassland degradation, understood as decreases in biomass and greenness (Numata et al., 2007). Conversely, positive changes in both indices will reflect an increase grassland biomass and greenness.

The primary objective of this study was to quantify and explain the vegetation changes in terms of the physiognomy (biomass) and physiology (greenness) of the dense grasslands of the summer mountain pastures in the Central Pyrenees, Spain. For this purpose we use two vegetation indices, NDVI and NDII, derived from remote sensing data for late-1980s and late-2000s. The specific objectives were to (i) detect and understand a) decreases (negative changes in both indices) and b) increases (positive changes in both indices) in biomass and greenness in the grasslands and (ii) to test the relative importance of environmental and anthropogenic factors in those changes through explicative regression models.

2. Materials and methods

2.1. Study area

The 21,880 ha study area encompassed the dense grasslands of the administrative units of summer mountain pastures, named "summer pasture units", which derived from the traditional partitioning of the grazing summer pastures. This area covers 11 municipalities within the Central Pyrenees, Aragón, Spain (42° 36′ N, 0° 00′E) (Fig. 1) (Gartzia et al., 2014). The study was restricted to the dense grasslands between 1270 m 2850 m a.s.l. Dense grasslands have high plant cover (>50%), they are located on gentle slopes, deep soils, and have high productivity and pastoral values (García-González & Marinas, 2008; Gómez, 2008). In the study area, the main dense grasslands have been classified in four phytosociological alliances depending on their dominant species; *Nardion strictae* (dominated by *Nardus stricta*), *Bromion erecti* (at low elevation and non-dominated by a single species), *Primulion intricatae* (at high elevation, and non-dominated by a single species) and *Festucion eskiae* (dominated by *Festuca eskia* or *Festuca paniculata*). From these grasslands; 10% are montane grasslands (below 1700 m), 86% are subalpine grasslands (between 1700 m and 2450 m) and 4% are alpine grasslands (above 2450 m) (Badía & Fillat, 2008). The dense grassland extension was estimated on previous studies based in the supervised classification of the Landsat-5 TM imagery taken in the mid-2000s (Gartzia et al., 2014).

The region has principally autumn and spring precipitation, an annual average of 1688 mm, and daily maximum and minimum average temperatures of 8.7°C and 1.5°C, respectively, at 2200 m a.s.l. (data from the Goriz meteorological station, 1982–2012, Fig. 1) (AEMET, 2014). Those grasslands are covered by snow for several months a year. Elevation (north–south gradient) and the Cantabric sea and Continental-Mediterranean influence (west–east gradient) have a strong influence on climatic factors (López-Moreno, 2005). In the southern portion of the study area, where the elevation is lowest, the climate is warmer and drier. In contrast the area closer to the Cantabric sea (western site) receive more rain. Those climatic gradients, topography, and land use have direct effects on plant communities.

To assess the dynamics of the climatic factors in the study area, we used the data from the Goriz Meteorological Station as ancillary data. Two periods were analyzed: period 1 (the 1980s, based on monthly mean values from 1982 to 1991) and period 2 (the 2000s,

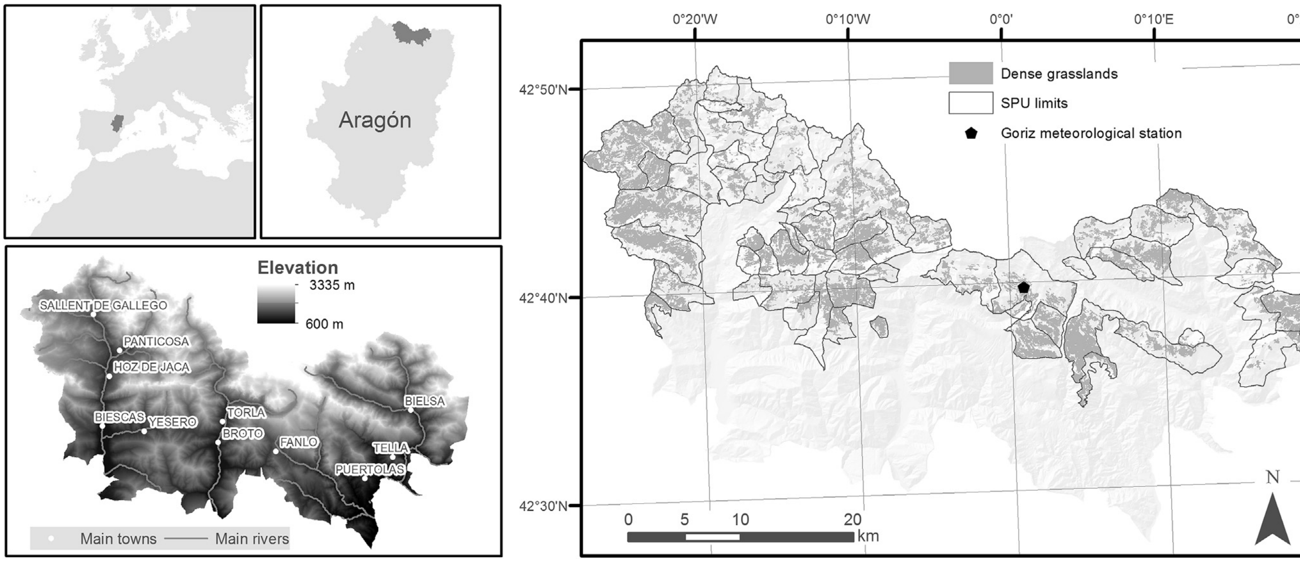

Fig. 1. The study area within the Central Pyrenees, Aragón, Spain. The study was restricted to the dense grasslands of the summer pasture units (SPU), which were grasslands that had high productivity and high pastoral value.

based on monthly mean values from 2002 to 2011). Between those periods, minimum and maximum temperatures increased, and snow accumulation decreased, particularly, in late spring (see Fig. 2, dotted box).

In the last decades grassland management has changed in our study area. Until the 1930s, mountain grasslands were grazed mainly by sheep and goat (Fig. 3), which were managed by shepherds, and stocking rates were high. Between the 1930s and the 1980s, rural depopulation reached almost 60% (Fig. 3) and sheep and goat heads had decreased 80% (Fig. 3). Since the 1960s, however, cattle stocking rates have increased 243% by the 2000s (Fig. 3), primarily, because of subsidies associated with the European Union

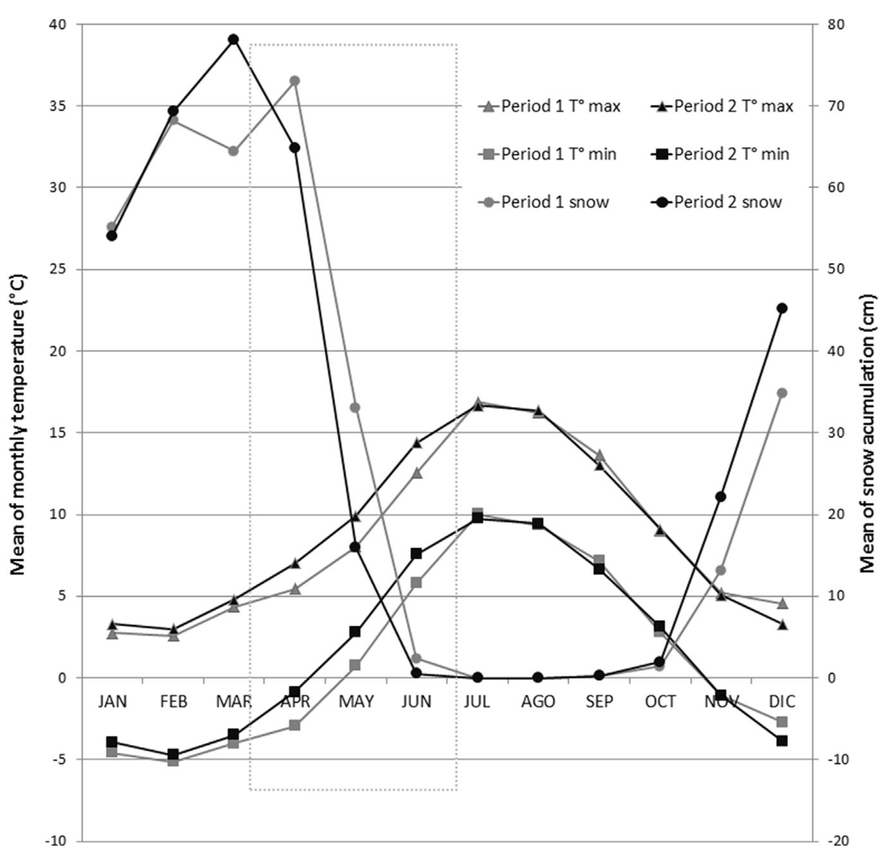

Fig. 2. Mean monthly maximum and minimum temperatures (T° max and T° min), and snow accumulation in period 1 (1980s:1982–1991) and period 2 (2000s:2002–2011) at the Goriz meteorological station (2200 m a.s.l.), Fanlo, Aragón, Spain (AEMET, 2014).

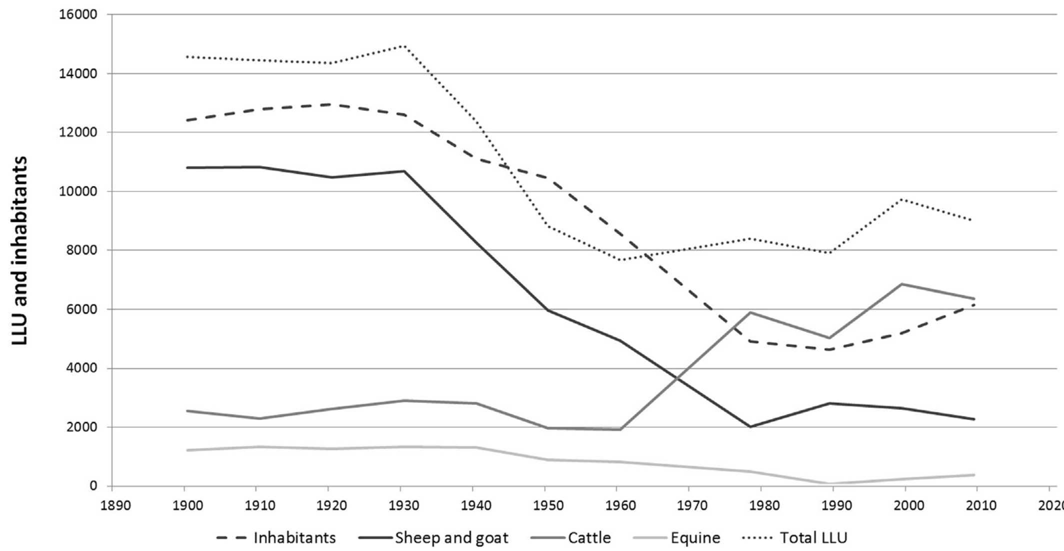

Fig. 3. Large livestock units (LLU) and inhabitants in 11 municipalities in the Central Pyrenees, Spain, since 1900 ((IAE, 2014), Historic Archive of Huesca Province in Aragón).

Common Agricultural Policies. With the exception of a few locations within the summer mountain pastures, shepherds no longer lead and care for livestock in situ; rather, livestock graze the pasture units with little or no hands-on control.

2.2. Quantifying physiognomic and physiologic changes

2.2.1. Remote-sensing imagery

To identify the physiognomic and physiologic changes in dense grasslands, we used ortho-rectified and cloud-free Landsat 5-TM imagery provided by the United States Geological Survey and the European Space Agency, and the digital values were converted into reflectance. ATCOR module was used in the process for atmospheric compensation and topographic correction of imagery with semi-empirical model to correct DEM illumination effects, very significant in mountainous areas (Balthazar, Vanacker, & Lambin, 2012; Schläpfer, Richter, & Kellenberger, 2012). This method was developed mainly for high spatial resolution satellite sensors with a small swath angle (e.g. Landsat) by Geosystems GmbH for ERDAS (Richter, 2009). The algorithm performs the atmospheric correction by inverting results of a radiative transfer code (Berk et al., 1998). This correction method guarantees the comparison of multi-temporal scenes recorded under different atmospheric conditions because the influence of the atmosphere path radiance and the solar illuminations is removed.

To detect changes in the dense grasslands at different phenological stages of the vegetation, and to quantify temporal and spatial changes, the analyses were based on eight imagery (Table 1): four each from the late-1980s (period 1) and the late-2000s (period 2). In each period, two time series were used: early summer and late summer. To eliminate the effects of climatic variations and phenological discrepancies in each time series and period, two imagery were combined (Coppin, Jonckheere, Nackaerts, Muys, & Lambin, 2004).

2.2.2. Vegetation indices used to assess grassland properties

To identify the physiognomic and physiologic changes in dense grasslands, the following two vegetation indices, which quantify vegetation biomass and greenness, derived from Landsat-5 TM imagery were used: Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1974) and Normalized Difference Infrared Index (NDII) (Hardisky et al., 1983). The combination of the two indices is better than either index alone because the NDVI is best suited to detecting variation in greenness in wet seasons and the NDII is best suited in dry and grazed conditions, which it is better at detecting senesced grass (Numata et al., 2007). Thus, the combination of the two indices was appropriate in our study because the analyses were based on imagery taken in early summer and late summer, when the grasslands were at different phenological stages.

The NDVI is based on the difference between the reflectance of solar radiation in the red band (R) of the visible spectrum and the reflectance in the near infrared (NIR) band (Equation (1)). The NDII is based on the difference between the NIR and the short wave infrared (SWIR) band (Equation (2)). We used the fifth band of the SWIR spectrum in the Landsat-5 TM imagery because it is best

Table 1
Landsat-5 TM imagery used to measure the physiognomic and physiologic properties of the dense grasslands in the Central Pyrenees, Spain. Data of the imagery taken in each period (the late-1980s and late-2000s) and time series (early summer -ES- and late summer -LS-), composite indices (cNDVI and cNDII) measured as the mean of the indices of each pair of imagery, and the difference between periods (dNDVI and dNDII).

Time series	Period (P)						Difference (P2–P1)	
	Late-1980s (P1)			Late-2000s (P2)				
	Imagery date	NDVI	NDII	Imagery date	NDVI	NDII	NDVI	NDII
ES	13 Aug 87 02 Aug 89	cNDVI (P1ES)	cNDII (P1ES)	04 Aug 07 27 Jul 10	cNDVI (P2ES)	cNDII (P22ES)	dNDVI (ES)	dNDII (ES)
LS	14 Sep 87 06 Sep 90	cNDVI (P1LS)	cNDII (P1LS)	05 Sep 07 10 Sep 09	cNDVI (P2LS)	cNDII (P2LS)	dNDVI (LS)	dNDII (LS)

suited for measuring aboveground biomass (Numata et al., 2007; Tucker, 1980).

$$NDVI = (NIR - R)/(NIR + R) \quad (1)$$

$$NDII = (NIR - SWIR)/(NIR + SWIR) \quad (2)$$

We combined the indices data of the two imagery from each period and time series to calculate the mean for the NDVI (cNDVI) and for the NDII (cNDII) (Table 1). Differences in each index between the two periods were calculated using the indices for the late-2000s as the reference (dNDVI and dNDII) (Table 1).

2.2.3. Intensity and direction of change in grassland properties: multi-temporal vectors

To measure the intensity and direction of the physiognomic and physiologic changes in the dense grasslands between the late-1980s and late-2000s, we calculated multi-temporal vectors based on the NDVI and the NDII (Fig. 4) (González & Bosque, 2008; Julien, Sobrino, & Jiménez-Muñoz, 2011; Pérez-Cabello, 2011). The intensity of the changes was based on the absolute difference of the two indices between the two periods (Fig. 4). To detect significant temporal changes, we created a buffer centered at zero intensity and based on the first standard deviation (Jensen, 1986; Volcani, Karnieli, & Svoray, 2005). If the intensity was within the boundaries of the buffer, changes were not significant; otherwise, the changes were significant. Significant changes between the late-1980s and late-2000s were either positive or negative depending on the direction of the change in the NDVI and the NDII. If both indices increased (quadrant I in Fig. 4), changes were positive, if they decreased, changes were negative (quadrant III in Fig. 4). The few instances in which one index was negative and the other was positive were excluded from the analyses.

To identify the spatial patterns of the changes, we created Moran's Index correlograms of the distributions of the negative changes and the positive changes in both indices. The shapes of the correlogram curves reflect the differences in the spatial patterns. If the changes are patchily distributed, the correlogram will have a curvilinear decrease toward zero; if the changes are homogeneously distributed, the correlogram will exhibit a continuous linear decrease that goes below zero (Fortin & Dale, 2005).

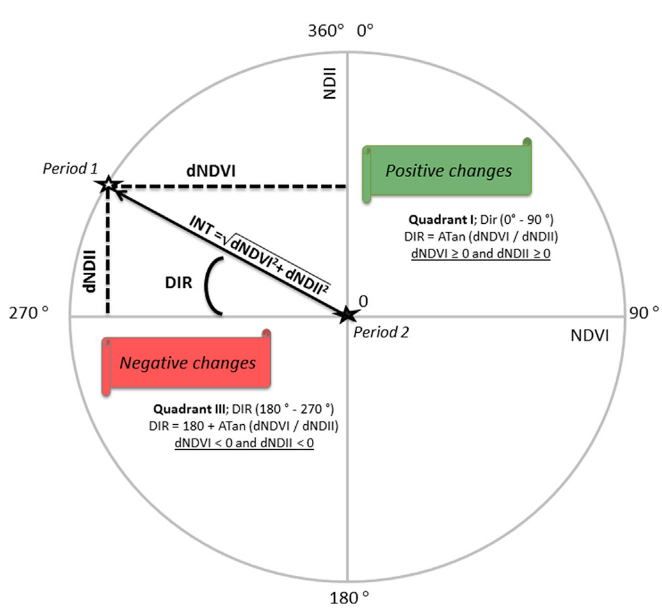

Fig. 4. Multi-temporal vectors used to measure the physiognomic and physiologic changes in the mountain grasslands in the Central Pyrenees, Spain, based on differences in NDVI (dNDVI) and NDII (dNDII) between the late-1980s (Period 1) and the late-2000s (Period 2). The intensity and direction (positive or negative) of the changes in the indices are measured. INT: intensity of dNDVI and dNDII; DIR: direction of the changes for the dNDVI and dNDII to detect the sign (positive or negative) of the changes depending on the quadrant to which each pixel was assigned; ATan: arctangent function used to calculate the direction of the changes in the indices.

2.3. Statistical analyses

2.3.1. Environmental and anthropogenic factors

To identify the causes of changes in the dense grasslands, the following environmental and anthropogenic factors were assessed:

- The environmental factors (see Appendix A) included (a) topographical factors derived from the digital elevation model of 30 m resolution (SITAR, 2014): elevation (m) (Fig. 1), slope (°), north−south aspect (cosine of the aspect), east−west aspect (sine of the aspect), (b) climatic factors: continentality (30 m resolution, measured as the distance from the Cantabric sea), annual mean precipitation and annual mean of the minimum temperatures (Cuadrat, Saz, & Vicente-Serrano, 2007), (c) distance to the nearest river based on 1:25,000 scale river map (IGN, 2014), and (d) lithology based on 1:50,000 scale map (basic, acidic, or quaternary period materials) (SITAR, 2014).
- The anthropogenic factors (see Appendix B) included (a) administrative boundaries that can influence land management: county, presence of nature protected areas or ski resort areas, (b) factors correlated with anthropogenic pressure: distances to nearest building and passable roads (IGN, 2014; SITAR, 2014), depopulation in each historical municipality between the 1930s and the 1980s (IAE, 2014), land ownership (private or public) (SITAR, 2014), and livestock stocking rates, all of them based on 1:25,000 scale topographic map (SITAR, 2014).

To quantify the livestock pressure in each of the summer pasture unit, in the summers of 2010, 2011 and 2012, face to face semi-structured interviews were held with each of the farmers that had grazing livestock in the study area (Wehn et al., 2011). The information gathered included the numbers of heads of sheep and goat, cattle, and equines, and the number of days per year that the livestock spent within each unit. Number of livestock was converted to large livestock units by multiplying the number of sheep and goat heads by 0.125, the number of cattle by 0.8, and the number of mares by 1.25 (Aldezábal et al., 1992). The large livestock unit values were multiplied by the number of months that the livestock spends in each summer pasture unit, which was divided by the hectare of the grassland in which they grazed. To estimate the extent of the grasslands used by livestock, we assumed that sheep and goats grazed the dense and the sparse grasslands, and cattle and mares used the dense grasslands only (Garcia-Gonzalez, Hidalgo, & Montserrrat, 1990). The size of the dense and the sparse grasslands was estimated in previous studies based on a supervised classification of the Landsat-5 TM imagery taken in the mid-2000s (Gartzia et al., 2014).

2.3.2. Generalized additive models

Generalized Additive Models (GAM) were used to identify the factors that were significantly correlated with the physiognomic and physiologic changes in the dense grasslands. The choice of GAM models was influenced by the non-linearity in the data (Zuur, Leno, Walker, Saveliev, & Smith, 2009). To correct for the spatial autocorrelation in each of the models, we used a spatial eigenvectors procedure (Dray, Legendre, & Peres-Neto, 2006) and spline smoothing of the x and y coordinates (Bivand, Pebesma, & Gómez-Rubio, 2008). Those vectors were added to the models, which accounted for all of the spatial autocorrelation in the residuals of each of the models. The residuals from the GAMs indicated that the assumptions (normality, independence, and heteroscedasticity of the variance of the residuals) of the models were met (Zuur et al., 2009). To select the optimal model, we choose the one that had the lowest AIC (Akaike Information Criterion). Only factors that had low collinearity (Pearson r < 0.7 (Schulz, Cayuela, Rey-Benayas, & Schröder, 2011)) were included in the models. All of the analyses were run using R software (R Development Core Team, 2011). GAMs were run using the mgcv package (Wood, 2011), and the tests for spatial autocorrelation were within the ncf, packfor, apacemakeR, spdep, and tripack R packages. Four GAM models were performed, one each for the positive and the negative changes of both indices in early and late summer. Each model included 1000 randomly selected pixels for no significant change areas and another 1000 for negative or positive change areas.

3. Results

3.1. Changes detected in mountain grassland properties

Data from early and late summer indicated the same trend for the two time-series in the physiognomic and physiologic changes at mountain grasslands of the Central Pyrenees, Spain (Fig. 5). The negative changes occurred in localized patches (Fig. 6(a) and (b)), which is of great concern because they indicate degraded grasslands that have lost biomass and or greenness even if this occur only in 3% of the dense grasslands in early summer and 4% in late summer. The distribution of the positive changes in both indices were spread over large areas (Fig. 6(a) and (c)) indicated an increase in grassland biomass and greenness that were most extensive in early summer, with 15,000 ha (68%), compared with 12,700 ha (58%) in late summer.

3.2. Main factors correlated with changes in mountain grasslands properties

The environmental factors were most strongly correlated with increases in biomass and greenness and the anthropogenic factors were most strongly correlated with decreases in biomass and greenness (Table 2). More factors were correlated with the two types of changes in late summer than they were in early summer. Factors such as elevation, lithology, precipitation and stocking rate were correlated with both types of changes, but generally in the opposite direction.

Increases in biomass and greenness (Table 2) were most extensive at high elevations (Fig. 7(a)), on steep slopes, in areas that had a north or west aspect, had an acidic lithology (Fig. 7(b)), and in areas that had lowest continentality and received more rain. In contrast, decreases in biomass and greenness (Table 2) occurred at

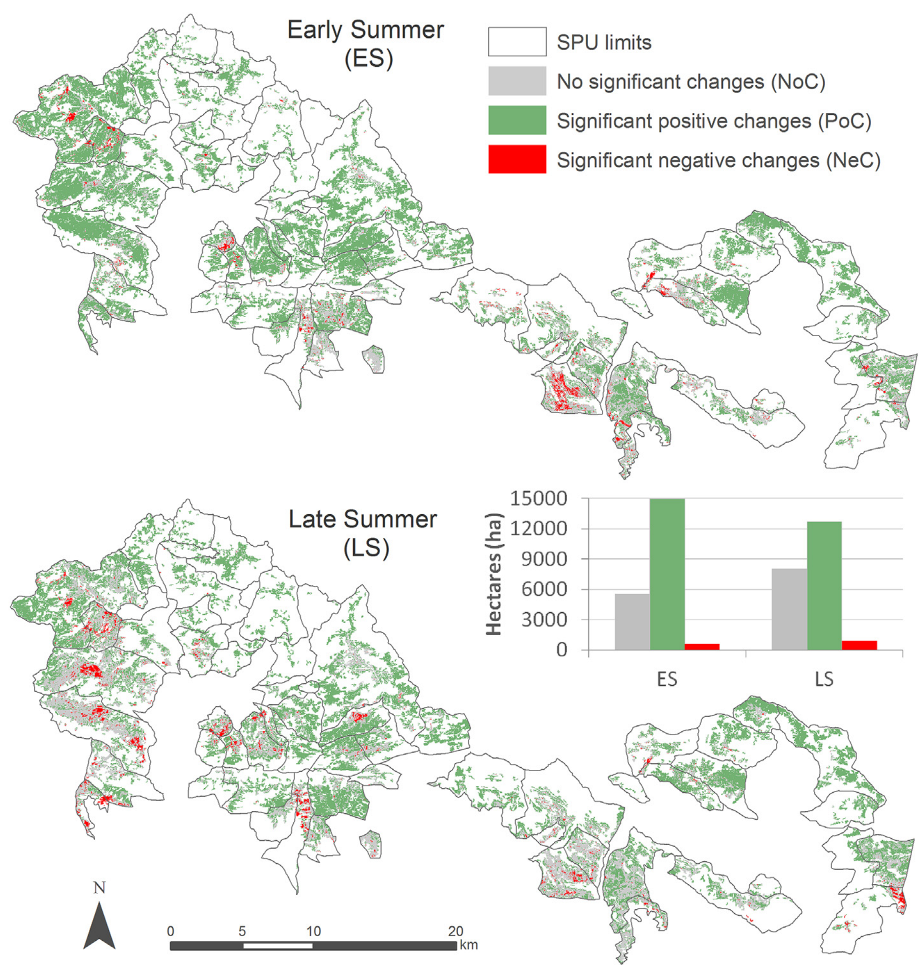

Fig. 5. Physiognomic and physiologic changes between the late-1980s and the late-2000s in the dense grasslands of the summer pasture units (SPU) of Central Pyrenees, Spain, detected by the multi-temporal vectors based on the NDVI and the NDII indices. Significant positive changes in the indices indicate increases in the biomass and greenness of the grasslands and significant negative changes indicate decreases in biomass and greenness.

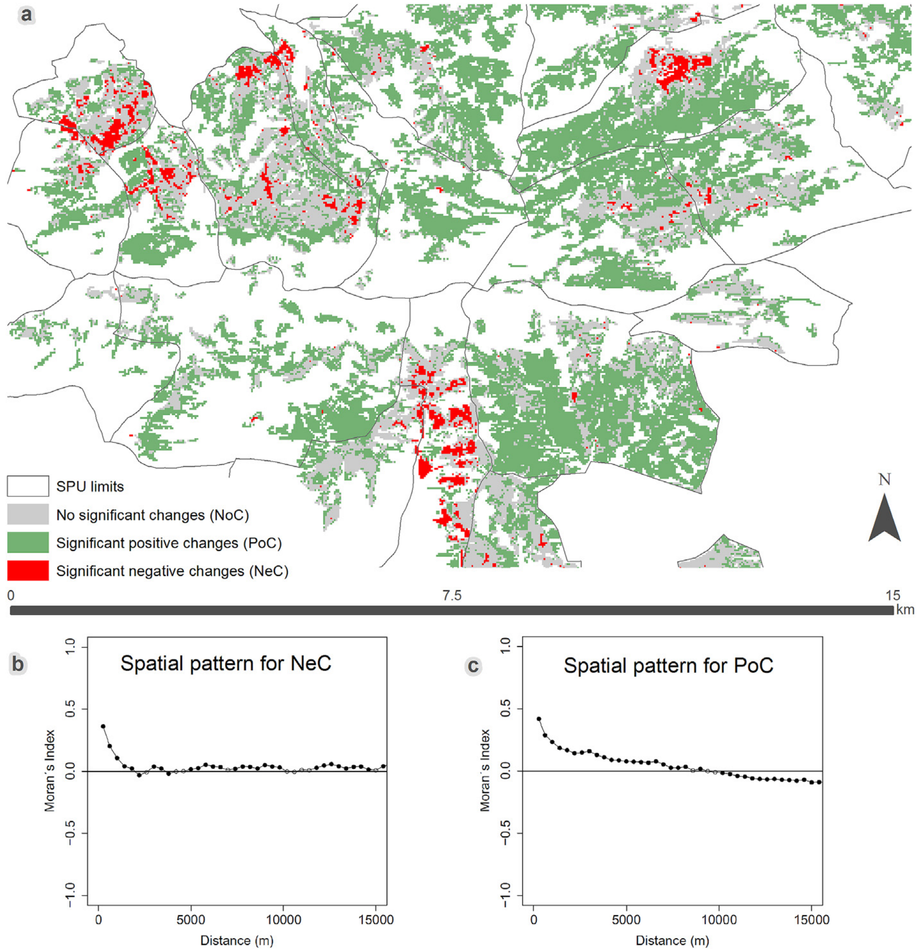

Fig. 6. Spatial pattern of the changes in the physiognomic and physiologic properties in the dense grasslands of the summer pasture units (SPU) of Central Pyrenees, Spain. (a) Portion of the study area showing the spatial distribution of the changes identified in the imagery taken in late summer, (b) correlogram reflecting the spatial pattern for negative and (c) positive changes in the indices.

Table 2
GAMs of the environmental and anthropogenic factors correlated with negative and positive changes in the indices in the physiognomic and physiologic properties of the grasslands in early and late summer in the Central Pyrenees, Spain. BM: basic material, CM: quaternary material, Publ: public land, Ski: within ski-resort area, AlGa: Alto Gállego county.

Factor	Type[a]	Negative changes		Positive changes	
		Early summer	Late summer	Early summer	Late summer
Environmental					
Elevation	CON		–		+
Slope	CON				+
North–south aspect	CON			+	+
East–west aspect	CON			–	–
Lithology	CAT	BM+/CM+		BM-/CM-	
Distance to sea (Continentality)	s()			–	–
Precipitation	s()	+	–	+	+
Anthropogenic					
Distance to the buildings	s()/CON	–	–		
Distance to passable road	CON	–	–		
Owner type of the land	CAT		Publ+		
Ski resorts area	CAT	Ski+	Ski+		
County boundary	CAT		AlGa+		
Large livestock units (LLU)	s()/CON		+		–
Interactions					
Ski*slope			+		

Significant factors $p < 0.05$, significant positive (+) or negative (–) effect.
(grey = not significant factors).
[a] CAT = categorical factor; CON = continuous factor; s() = continuous factor using splines.

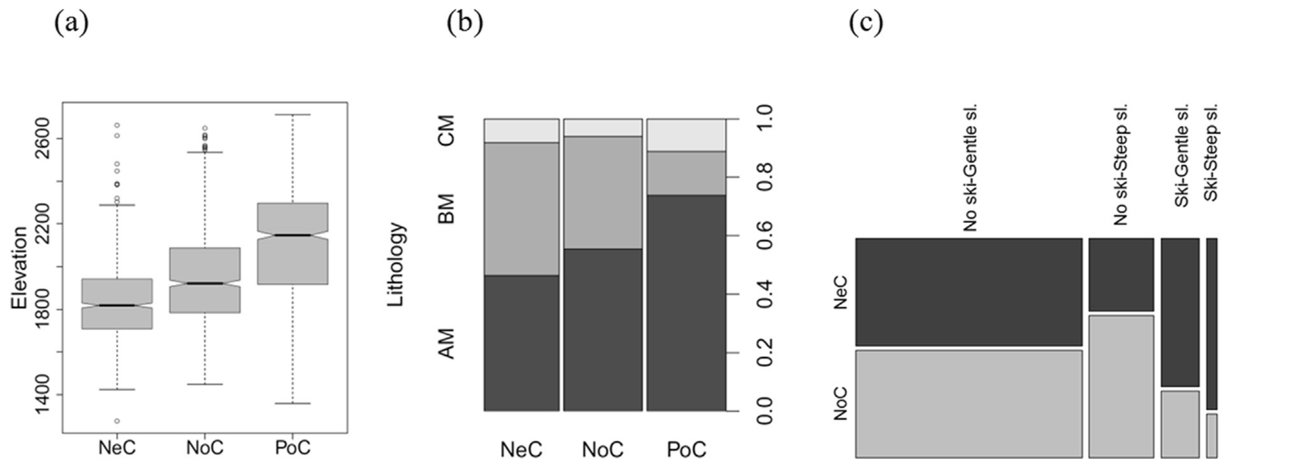

Fig. 7. Factors correlated with the positive changes (PoC), negative changes (NeC) and no changes (NoC) in the indices measuring physiognomic and physiologic properties of the dense grasslands in the Central Pyrenees, Spain, between the late-1980s and the late-2000s. (a) Elevation (data from late summer imagery). (b) Lithology (data from early summer imagery; acidic materials -AM-, basic materials -BM-, and quaternary materials -CM-). (c) Interaction between slope (sl) (steep-gentle) and presence of ski resort areas (NeC data from late summer imagery).

low elevations (Fig. 7(a)), in areas that had a basic lithology (Fig. 7(b)), on steep slopes in ski resort areas, and on gentle slopes elsewhere within the study area (Fig. 7(c)). As well, decreases in biomass and greenness was related with precipitation, with more decreases in biomass and greenness at early summer and less decreases at late summer, in areas that received more rain.

Regarding the anthropogenic factors in relation to increases in biomass and greenness, we only found significant correlation with large livestock unit (Table 2). When the stocking rate was low, the positive changes in the physiognomic and physiologic properties of the grasslands were significant and when the stocking rate was high, significant negative changes were evident. Those correlations are only detected in the late summer. For the same period, pastures on public lands and especially those located in Alto Gállego County, were significantly correlated with negative changes. Short distance to the nearest building and passable road, or ski resort were positively correlated with the decrease in biomass and greenness of the grasslands in early and late summer.

4. Discussion

The physiognomic and physiologic changes in the dense grasslands of the Central Pyrenees, Spain, were widespread and related to current socio-economic situation and climatic trend. The decrease in biomass and greenness detected as negative changes in both indices were most strongly correlated with anthropogenic factors and the increase in biomass and greenness detected as positive changes in both indices were most strongly correlated with environmental factors. The negative changes have patchy distribution and this pattern has been observed in other grazed mountain areas such as the Himalayan Mountains (Paudel & Andersen, 2010). In contrast, the distribution of the positive changes in both indices was more extensive and continuous (Smit et al., 2008; Vicente-Serrano et al., 2005). The differences in the factors correlated with the increase and decrease in biomass and greenness, and the differences in their spatial pattern suggest that the causes of the changes have different origins.

4.1. Decreases in biomass and greenness in the grasslands

The current livestock management has concentrated their activities in specific areas leading to overgrazing in some places with the consequently decrease in biomass and greenness of those grasslands (Li, Wu, & Huang, 2012; MacDonald et al., 2000; Wehn et al., 2011). The changes in the type of grazing animals can contribute to that effect because livestock species differ in the characteristic of the selected grazing areas (Sitko & Troll, 2008; Wehn et al., 2011). Sheep and goat can graze extensively in dense and sparse grasslands, at high elevations, and on steep slopes, but cattle, which is currently more predominant in the summer pastures at the Central Pyrenees, Spain, primarily graze on most productive dense grasslands at gentle slopes, in areas near water and salt points and areas where the stockbreeder has access by vehicle (Aldezabal et al., 2012; Fernandez-Gimenez & Allen-Diaz, 1999; Sitko & Troll, 2008). In the Central Pyrenees, it is common for livestock to roam freely without the supervision of shepherds, which might lead to high stocking rates in some areas (MacDonald et al., 2000). Those areas are the ones that present significantly more grasslands degradation, and the increases of cattle pressure have contributed significantly to that degradation. Furthermore, areas grazed by cattle appear to be particularly attractive to wild boar for its digging activities (Bueno et al., 2010) which causes extensive disturbances that reduce the amount of grassland (Bueno et al., 2009).

In addition, the kind of land ownership can be relevant as it may reflect differences in grasslands management. On private land, with less negative changes than in public ones, typically, livestock pressure is low because it favors high productivity. In this case overgrazing is not a problem, however, it can have a negative effect because low stocking rates are related with increases woody plant encroachment (Archer, Hoffman, & Danckwerts, 1989; Gartzia et al., 2014). In contrast, on public land that have high stocking rates, woody encroachment is reduced (Gartzia et al., 2014) but overgrazing can be a problem.

The presence of infrastructures; e.g., ski resorts, built in mountainous areas were significantly correlated with negative changes in the grasslands, especially, on steep slopes, where the ski runs areas are located. The long-term effects of those infrastructures will be a substantial degradation of the grasslands because of a reduction in native species richness and plant cover, as well as changes in the physical and chemical properties of soils (Barni et al., 2007; Rixen, Stoeckli, & Ammann, 2003) increasing the risk of soil erosion (Barni et al., 2007; Gros et al., 2004).

We found environmental factors less associated with the decrease in biomass and greenness in mountain grasslands, although one notable exception is annual precipitation. Precipitation seems to enhance soil degradation with a decrease in biomass and greenness at early summer. Areas holding a negative change in biomass and greenness related with direct soil disturbance (i.e. constructions, livestock grazing management, rooting activity of wild boars), more precipitation can trigger erosion processes with its subsequent loss of soil, directly impacting vegetation dynamics of these areas (Zhou, Luukkanen, Tokola, & Nieminen, 2008). On the other hand, in late summer, the areas with low precipitations are correlated with areas that decrease the biomass and greenness in the grasslands (Liu et al., 2013), probably because the reduction on water availability limited recover of degraded grasslands.

4.2. Increases in biomass and greenness in the grasslands

Climate warming can affect the phenology of grasslands (Corlett & Lafrankie, 1998; Neuwirth & Hofer, 2013; Xu et al., 2009), especially, the changes in the timing of snowmelt, which dictates the start and duration of the summer growing season (Choler, 2015; Wipf & Rixen, 2010). Thus, climate warming may create favorable conditions for vegetation growth (Vicente-Serrano et al., 2005), although can be constrained by water deficiency, topography or lithology (Zeng & Yang, 2008; Zhao et al., 2015), which were highly variable in our study area. At high elevations and on northern- or western-facing steep slopes, biomass and greenness increased between the late-1980s and the late-2000s, which has been also observed in the Himalayan Mountains (Paudel & Andersen, 2010) and at high elevations in the Rocky Mountains (Bradley & O'sullivan, 2011). Areas that had low continentality and high annual precipitation, with lower risk of water limitations (Del Valle, 1997), particularly at the late summer, might encourage plant growth, thus, increasing biomass in those grasslands (Li et al., 2013; Liu et al., 2013; Smit et al., 2008).

Nevertheless, it cannot be concluded that climate warming was the only cause of the increase in the biomass and greenness of the dense grasslands. Other causes such as the declining in stocking rate can be related with these changes, as suggested by the negative correlation between stocking rate and the increases in biomass and greenness. If stocking rates are low, and grasslands are lightly grazed, biomass can increase (Karnieli et al., 2013; Li et al., 2012; Rose et al., 2013). In any case, the estimates of the stocking rates in each summer pasture unit should be interpreted with caution because an average value for an entire unit can indicate very different situations. In addition, sharp increases in grassland biomass can result in certain loss of quality of the pasture, thus becoming less palatable for livestock (Fernández-Giménez & Fillat, 2012). Therefore, positive change in both indices cannot directly translate into positive consequences for the optimal pastoral use and preservation of these grasslands. The land abandonment exacerbated by climate change, could be a factor that may contribute to a quality and diversity loss of these grasslands, similar to what is happening at lower elevations with the woody encroachment process (Gartzia et al., 2014).

4.3. Management implications: what is missing and where to pay more attention?

Spatial variations in stocking rates are key to understanding grassland biomass and greenness changes. The grazing areas, highly valuable and productive, are now overgrazed by a larger contribution of heavier and less mobile grazers, what accelerates its degradation. Also the lack of supervision by shepherds, where livestock is no longer guided to a better and efficient use of the pastures, exacerbated the situation. The problem is particularly relevant for managers, as they seem to be only concerned by woody encroachment while other degradation processes are happening simultaneously in the grasslands. In addition, the ecological consequences of the tourist-related development in the mountains should be taken into account because it can have deep negative consequences for the grasslands.

5. Conclusions

While increases in biomass and greenness of the dense grasslands detected as positive changes in the indices have occurred throughout the study area, decreases in biomass and greenness detected as negative changes were localized. Environmental factors were more strongly correlated with the increases than were anthropogenic factors, probably, because of the effects of global climatic warming and exacerbated by reduction in the stocking rate. The anthropogenic factors were significantly correlated with negative changes, which might have been caused by overgrazing by cattle and wild boar disturbances, particularly, on public lands at low elevations and where the pastures are easily accessed by vehicle. Ski-resort areas on steep slopes, as well revealed a large negative impact in the grasslands.

Some areas have been overused, while others have been abandoned, especially regarding to the livestock grazing. Perhaps recovering the guidance of shepherds would promote a more balance use and better preservation of these mountain grasslands. In Addition, landowners, land managers, and policymakers should address the negative changes happening in the mountain grasslands with special attention. The main reason for this is that the degraded grasslands were located on the highest quality grasslands for livestock grazing. If this trend continues, we will be risking some of the most valuable and traditional managed grasslands used for centuries.

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Appendices. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.apgeog.2015.11.007.

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