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Assessing the Effects of Grassland Management on Forage Production and Environmental Quality to Identify Paths to Ecological Intensification in Mountain Grasslands

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Abstract Ecological intensification in grasslands can be regarded as a process for increasing forage production while maintaining high levels of ecosystem functions and biodiversity. In the mountain Vercors massif, where dairy cattle farming is the main component of agriculture, how to achieve forage autonomy at farm level while sustaining environmental quality for tourism and local dairy products has recently stimulated local debate. As specific management is one of the main drivers of ecosystem functioning, we assessed the response of forage production and environmental quality at grassland scale across a wide range of management practices. We aimed to determine which components of management can be harnessed to better match forage production and environmental quality. We sampled the vegetation of 51 grasslands stratified across 13 grassland types. We assessed each grassland for agronomic and environmental properties, measuring forage production, forage quality, and indices based on the abundance of particular plant species such as timing flexibility, apiarian potential, and aromatic plants. Our results revealed an expected trade-off between forage production and environmental quality, notably by stressing the contrasts between sown and permanent grasslands. However, strong within-type variability in both production and environmental quality as well as in flexibility of timing of use suggests possible ways to improve this trade-off at grassland and farm scales. As achieving forage autonomy relies on increasing both forage production and grassland resilience, our results highlight the critical role of the ratio between sown and permanent grasslands as a major path for ecological intensification in mountain grasslands.

Keywords Ecological intensification · Agricultural practices · Mountain grassland management · Livestock farming system · Environmental properties

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Introduction

One of the main recent challenges for agriculture has been to reconcile an increasing demand for food production and environmental sustainability (Sutherland et al. 2006; Henle et al. 2008; Le Roux et al. 2008). If this central issue has been primarily addressed for intensive agriculture (cropping, intensive farming), it is now also considered for more extensive livestock farming systems due to the major contribution of permanent grasslands to land use and to a large panel of ecosystem services (Lemaire et al. 2005). This thinking includes more extensive systems and practices such as organic farming that address the growing demand for environmental-friendly food production. However, in Europe most of this research has focused on the conservation value of grassland area with high environmental value through subsidies and agri-environment schemes (e.g., Kleijn and Sutherland 2003; Bengtsson et al. 2005) reflecting a dichotomous approach opposing, within farm systems, intensively managed areas with a high level of production and more extensive areas with higher environmental value but less productive. However, this approach is not necessarily always relevant for achieving synergies between agricultural policy, agriculture production, and environmental quality (Mattison and Norris 2005; Macfadyen et al. 2012).

The more recent concept of ecological intensification (EI) has focused on the possibilities of managing service-providing organisms or using biological regulation in agro-ecosystems to maintain a high level of food production while improving positive secondary effects on other ecosystem services (Doré et al. 2011; Bommarco et al. 2013). So far, EI has mostly concerned intensive agriculture (Malézieux 2012; Wezel et al. 2014). However, EI can also apply to more extensive production systems like livestock farming relying on semi-natural grasslands (Rey et al., in press). Indeed, in livestock farming systems similar challenges have arisen on how to improve the use and sustainability of ecological functions to meet the growing demand on animal products (Dumont et al. 2013), specifically in mountain areas (Botreau et al. 2014). Even if the concept of EI is not yet widely applied in livestock farming research, a few studies, while not explicitly referring to EI, can fall under its scope (see for example Farruggia et al. 2014; Fraser et al. 2014).

In the 'Val d'Autrans' mountain territory (Vercors massif, France), dairy cattle farming is the major agricultural production. Forage and livestock production is mainly structured around a registered designation local cheese and is challenged by the environmental issues inherent to its location within a Natural Regional Park and the territory attractiveness for tourism. The most salient issue raised by farmers is how to achieve forage sufficiency at farm level while sustaining environmental quality, in order to meet expectations on tourism and the "green" image of local dairy products (Dobremez et al. 2012). In addition, in this territory, forage sufficiency relies on two main goals (Dobremez et al. 2013): (i) increasing current forage production in order to reduce or even avoid hay purchases and (ii) improving resistance and resilience to disturbances and climatic stresses, forage production in the Alps being increasingly affected by recurrent summer droughts, late frosts in spring (Sérès 2010), and vole outbreaks (Delattre et al. 1999). Addressing this issue, of increasing forage production while improving its resilience and environmental quality, is a relevant EI process.

Local field management has been proved to be one major determinant of diversity, species composition, and many ecosystem functions in grasslands (Klimek et al. 2007; Lavorel et al. 2011). Indeed, grassland management can influence agronomic and environmental properties not only directly through external inputs (labor, sowing, and fertilization) but also indirectly through responses of plant species composition and trait values to specific management type such as date of use, management type or intensity, and their subsequent effects on ecosystem properties. Specific and functional diversities are key components determining grassland properties as well as their resilience and resistance to disturbances and climate constraints (Quijas et al. 2010). Grass functional types' abundance and diversity have been identified as relevant proxies for many agronomic properties and thus can be used to maximize forage quality (Duru et al. 2013). Moreover, plant diversity and composition support valuable environmental properties such as habitat conservation value, pollination, pest control, and esthetic value (Wittig et al. 2006; de Bello et al. 2010). They also can be of importance for improving the quality of animal products such as honey production (Ricou et al. 2014) or aromatic quality of animal products such as milk or cheese (Martin et al. 2005). Thus, using grassland plant composition to assess both agronomic and environmental properties according to grassland management is relevant from an EI perspective, especially in an agricultural territory like the Val d'Autrans where farm systems incorporate a diversity of grassland types (Dobremez et al. 2013). In order to identify pathways to EI for mountain grasslands, we hypothesized that understanding the effects of grassland management on both sets of properties, agronomic and environmental, is critical to understand options for increasing forage quantity and/or quality while supporting high environmental quality of grasslands and their resilience.

In this study, we sampled 51 grasslands within the Val d'Autrans territory, covering most of the grassland types available for livestock farming. We quantified a set of agronomic and environmental properties at the date of first use, mowing or grazing. The 51 grasslands were assigned to one of three types of uses: hay meadows, pastures, and summer upland pastures (>1300 m asl). We split these into 13 grassland types from intensive sown hay meadows to extensive upland pastures. We suggest that the assessment of two kinds of field-scale information is relevant for EI: (i) differences and trade-offs in grassland properties between grassland types to understand how grassland-type diversity can be harnessed to operate EI at farm scale, and (ii) within-grassland-type variability in ecosystem properties to highlight potential EI at the parcel scale within a given type (a parcel is considered here as a continuous area of grassland on which a same management use is conducted by a single farmer). This second aspect is of particular importance as structural constraints within farm systems may prevent changing the main use of a grassland, for example, converting pastures into hay meadows or conversely. It also makes sense in this territory where soil/environmental conditions have minor effects compared to management on the properties of grasslands of the plateau (Gos 2013). We believe that both are crucial to identify possible pathways to EI through the adjustment of grassland management in this mountain area.

Methods

Study Area

This work was conducted within the Vercors Natural Regional Park (VNRP), in a mountain massif located at the border between the northern and the southern French Alps. Our study focused on the northern part of the Park including the "Val d'Autrans" territory and the "Plateau de la Molière" upland pastures (45°07′N, 5°31′E, Fig. 1). Both areas are located within the municipalities of Autrans and Méaudre in Isère department. The "Val d'Autrans" is situated at a mean altitudinal range of ~1000 m asl and covers an area of 7800 ha including some ski slopes grazed in summer. Upland pastures of "La Molière," at ~1600 m asl, cover an area of 300 ha of utilized agricultural land. For the last 30 years, the upland pastures have been grazed from early June to mid-October by roughly 300 heifers mainly originated from local breeders. Annual mean temperature in the Val d'Autrans is 7.2 °C and annual total precipitation is 1093 mm. The all study area includes 32 different farms with a mean utilized farm area of 55 ha.

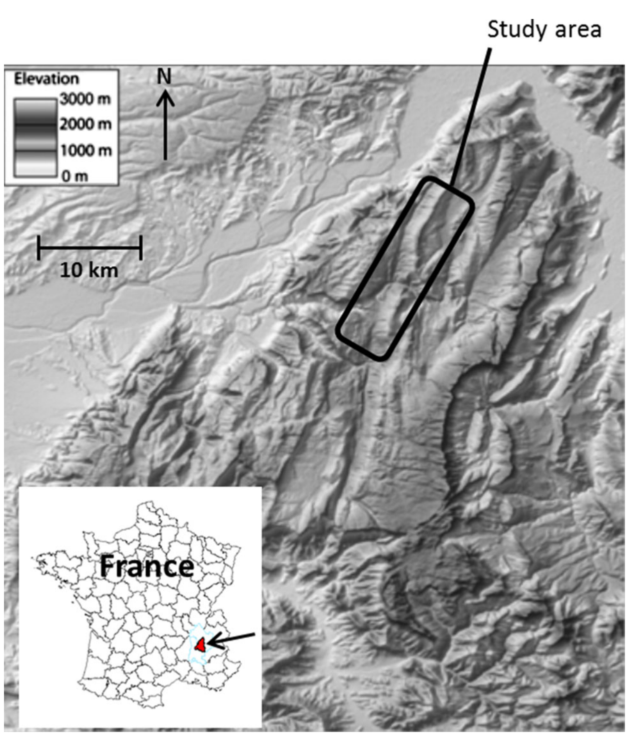


Fig. 1 Location of the study site in the Vercors Massif, France

Selection of Grasslands and Typology

Fifty-one grassland parcels were chosen across 10 different farms and the upland pastures to best represent most of the gradient of grassland types used by farmers. Grasslands were then classified into 13 grassland types according to a simplified typology (GIS Alpes Du Nord 2002) based on the main use either mowing, grazing, or upland summer grazing, the time since the last sowing, vegetation composition depending on the grass/forb ratio, as well as topography or soil type for upland pastures (Table 1). We stratified the sampling of grasslands according to the relative importance of each type on the Val d'Autrans, resulting in an unbalanced sampling between grassland types due to the pre-dominance of certain types (e.g., intensive pastures, grass-dominated permanent grasslands) and the weak representation of others, such as grass-dominated extensive pastures or legume-dominated sown grasslands. The area covered by the 13 grassland types represents more than 90 % of the UFA of the study site (Dobremez et al. 2013).

Grassland Properties

A central plot (20 m × 20 m), representative of the grassland vegetation cover, was located within each of the 51 grassland parcels. All measurements and sampling were done within the plots at most a few days before the first harvest for hay meadows or the first grazing period for pastures, ski slopes, and upland pastures, to best match with actual properties of the grasslands when used by farmers.

Plant Species Abundance

For each parcel, vegetation composition was assessed in 2011 or 2012 independently of grassland type. Plant species abundances were calculated using the "point-quadrat" sampling method (Levy and Madden 1933). For each plot, the local abundance of each species was determined as the number of hits among 160 sampling points evenly distributed within four 50 cm × 50 cm (20 sampling points each) and two 2 m × 2 m (40 sampling point each) quadrats. Additional species with no hit were thoroughly searched in each quadrat to accurately estimate species richness.

Agronomic Properties

Eight agronomic properties were estimated which all refer to four essential components of agronomic value of grasslands: productivity, forage quality, forage production timing, and flexibility of use (Duru et al. 2010b).

Table 1 Classification of the 51 grasslands plots with their main management characteristics

Type of use	Grassland type	Abbreviation	Main location	Main use	Past and current use	Altitudinal range (m asl)	Number of plots
Hay meadows (M)	Legume-dominated sown grasslands	SGL	Val d'autrans	Mowing	Previous sowing <6 years, mown 2–3 times a year	1015–1023	2
	Grass-dominated sown grasslands	SGG	Val d'autrans	Mowing	Previous sowing <6 years, mown 2–3 times a year	984–1043	6
	Grass-dominated permanent grasslands	PGG	Val d'autrans	Mowing	Previous sowing >10 years, mown 2–3 times a year	995–1078	5
	Forb-dominated permanent grasslands	PGF	Val d'autrans	Mowing	Previous sowing >10 years, mown 2–3 times a year	999–1064	4
	Grass-dominated extensive permanent grasslands	PGGE	Val d'autrans	Mowing	Previous sowing >25 years, mown once-twice a year	987–1076	5
	Forb-dominated extensive permanent grasslands	PGFE	Val d'autrans	Mowing	Previous sowing >25 years, mown once-twice a year	1057–1157	4
Pastures (G) (<1200 m asl)	Grass-dominated intensive pastures	IPG	Val d'autrans	Dairy cows and/or heifer grazing	Intensive grazing starting April–May	995–1138	8
	Forb-dominated intensive pastures	IPF	Val d'autrans	Dairy cows and/or heifer grazing	Intensive grazing starting May	988–1195	3
	Grass-dominated extensive pastures	EPG	Val d'autrans	Dairy cows and/or heifer grazing	Extensive grazing starting June	988–1024	2
Upland summer pastures (UPP) (>1300 m asl)	Pastures on ski slopes	GSS	Ski slopes	Heifer grazing	Extensive grazing starting June	1275–1334	3
	Upland pastures: plateau	UPP	La Molière	Heifer grazing	Grazed by cattle for more than 30 years	1592–1632	3
	Upland pastures: slopes	UPS	La Molière	Heifer grazing	Grazed by cattle for more than 30 years	1600–1625	3
	Upland pastures: acidic soil	UPA	La Molière	Heifer grazing	Grazed by cattle for more than 30 years	1561–1577	3

Studied grasslands are classified according to (i) their main use and location (Type of use) and (ii) to their past and current use (Grassland type). Abbreviations for each grassland type and the associated number of plots are given

Aboveground biomass (1) was estimated in 2012 using calibrated height measurements (Lavorel et al. 2011). For 20 parcels distributed among the different grassland types (i.e., to cover the all range of biomass production levels), vegetation height of the dominant biomass was measured through visual estimation using a graduated steel tape in four randomly 50 × 50 cm^2 quadrats. Biomass within the quadrats was clipped, dried and weighted. Using these 80 height measurements and biomass samplings, a calibration curve was plotted to determine the equation of the relationship between vegetation height and available biomass ($R^2 = 0.788$; $P < 0.001$). Vegetation height was then assessed on 80 measurements in each plot. The mean height per plot was used to determine the available aboveground forage biomass (in tons of dry matter per hectare) before harvest or grazing using the calibration. Forage digestibility (2) and total nitrogen content (3) were measured on four 50 cm × 50 cm vegetation samples per plot. Samples were mixed, dried for 72 h at 60 °C, ground with a 0.5 mm grid, and then analyzed using Near Infra-Red Spectrometry (Gardarin et al. 2014). The other five agronomic properties were derived from the relative abundance of grass species. They are based on a classification of the grass species encountered in French mountain grasslands in five grass functional types, according to their major growth strategies measured through key functional traits such as leaf dry matter content, specific leaf area, leaf lifespan, or flowering date (Cruz et al. 2010; Duru et al. 2013). Duru et al. (2010b, c) then proposed several indices to estimate agronomic potentialities of grasslands: (4) early growth index, referring to the potentiality of a grassland to grow high-quality forage early in the season, (5) late growth index as the potentiality of a grassland to maintain high-quality forage late in the season, (6) forage production index, the vegetation ability for forage production throughout the whole growing season, (7) a flexibility index, calculated from the evenness and richness of the grass functional types (Duru et al. 2013) representing the stability of forage production and quality throughout the season and thus the flexibility for harvest/grazing date, and (8) a short leaf lifespan index as a proxy to global forage quality. Those five indices are not relevant for legume-dominated sown grasslands so were not calculated for the two plots of this grassland type.

Environmental Properties

Six environmental properties were assessed for each of the 51 grassland plots. (1) Species richness was calculated as the total number of species found across all quadrats per plot including species with no hit. (2) Shannon diversity index was computed from the relative abundance of species calculated by pooling together the 6 quadrats of each 20×20 m^2 plot. As pollination value may be considered as a central service for grasslands (Ricou et al. 2014), we calculated the potential of grasslands for honey production and pollination (3) using the abundance (percentage cover) of honey plants in each plots. Likewise, we assessed the abundance (cover percentage) of aromatic plants (4) considering that is an important component for the quality of milk products in mountain grasslands (Martin et al. 2005). As grassland management can strongly modify esthetic value through changes in color diversity (Binkenstein et al. 2013), we computed a flower color diversity index (5): each non-graminoid species was assigned to one of 7 colors according to the main color of its inflorescence (blue, brown, green, red, purple, white, yellow) and we calculated a Shannon diversity index using the relative abundance of each color. Finally, we used a flowering grassland index (6) calculated from the abundance (percentage cover) of indicator species selected from the "Flowering grassland" agri-environment measure list (Plantureux et al. 2010). According to the protocol, the abundance was calculated only when at least 4 species of the list were present in vegetation survey, otherwise the index value was zero. The inclusion of species in the list was previously based on a multi-criteria choice relevant for the agro-ecological balance of the grassland. Such an approach with indicator species has been proved of interest for the assessment of ecosystem services (Wittig et al. 2006; de Bello et al. 2010).

Analysis

Overall Response of Agronomic and Environmental Properties

To describe the overall response of all studied properties across the 13 grassland types and to evaluate the relationships among grassland properties, we used a Principal Component Analysis (PCA, Manly 2004). The two legume-dominated sown grasslands were added as passive samples as we did not calculate the five agronomical properties based on abundance of grass-species types for the concerned plots. Data were centered and standardized. We used the score of the two first PCA axes as a proxy for the general assemblage of properties for each grassland plot. PCA was performed with Canoco software 4.5 (ter Braak and Šmilauer 2002).

Statistical Analysis

The effects of the main use and of grassland types were analyzed using nested ANOVA with the "type of use" as fixed factor to check for differences between general location and management. The three levels of "type of use" considered in the analysis are (i) hay meadows, (ii) pastures on the plateau at ~1000 m asl, and (iii) summer upland pastures (>1300 m asl). "Grassland type" was a random factor nested within "type of use." For all environmental properties, the following agronomic properties: biomass, forage nitrogen content and digestibility, and grasslands scores on the first two axes, all types were included in the analysis ($n = 51$). For agronomic properties derived from grass-species abundance, the legume-dominated sown grasslands were not included ($n = 49$). Multiple comparisons were done using Fisher's LSD post hoc comparison within each "type of use." All tests were run with Statistica (Statsoft 2011).

Results

The inertia of the first 4 axes of the PCA was, respectively, 0.33, 0.16, 0.13, and 0.10. For simplicity of interpretation, we extracted only the first two principal components explaining 49 % of the variation of agronomic and environmental properties among grasslands (Fig. 2). Grassland properties that accounted for the highest amount of variation on the first axis were related to plant diversity (Shannon plant diversity, species

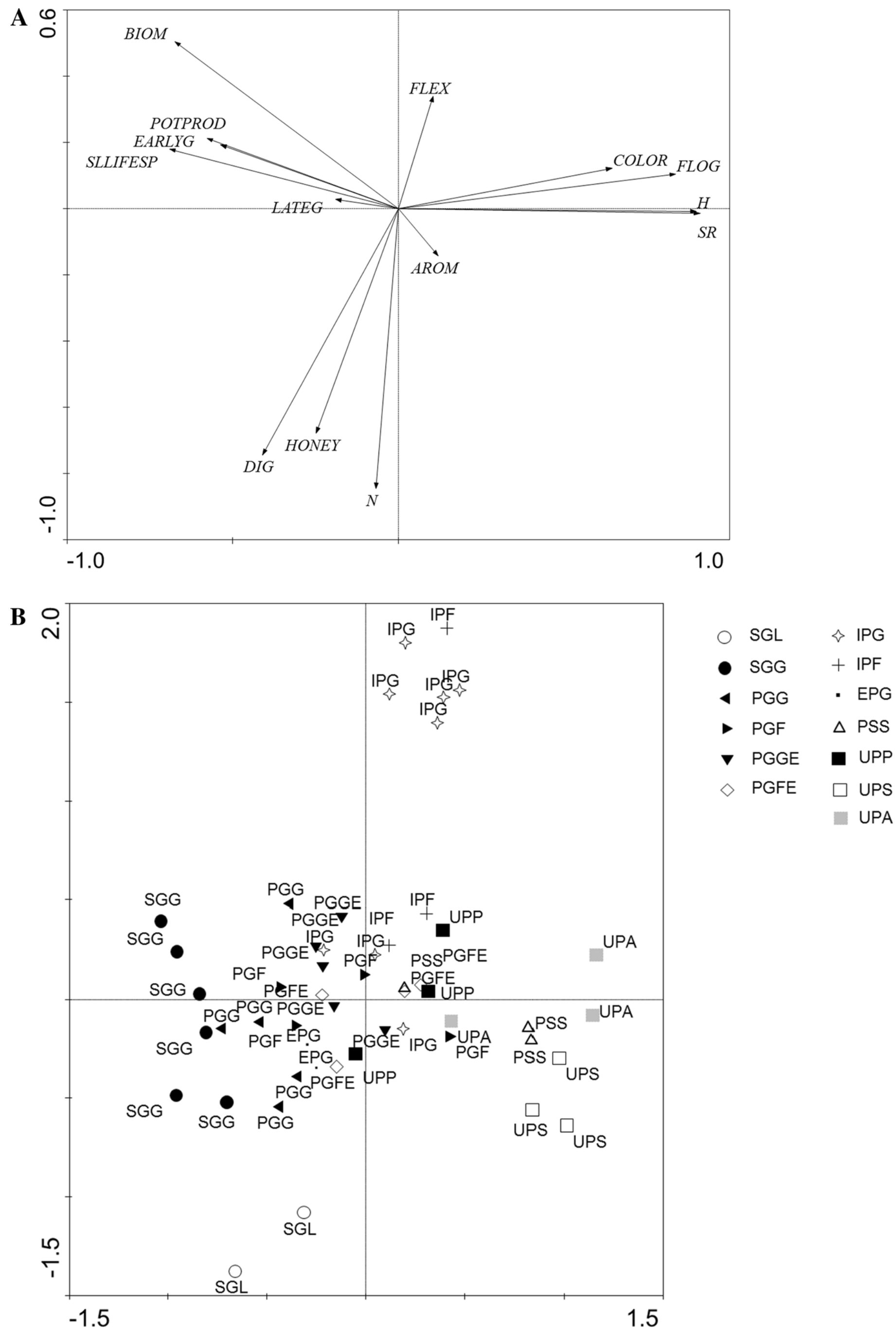


Fig. 2 Results of the Principal Component Analysis including the 8 agronomic and the 6 environmental properties. **a** Diagram of the correlation circle including the 14 grassland properties in the factorial plan composed of the two first axis (*BIOM* biomass at first harvest/grazing, *DIG* forage digestibility, *N* forage nitrogen content, *EARLYG* early growth index, *LATEG* late growth index, *POTPROD* potential production index, *FLEX* flexibility index, *SLLIFESP* short leaf lifespan index, *SR* species richness, *H* Shannon diversity index, *HONEY* abundance of plant for honey production, *AROM* abundance of aromatic plants, *COLOR* color index, *FLOG* flowering grassland index). **b** Scatter diagram for factor scores of the 51 grassland plots in the factorial plan composed of the two first axis (explaining 49 % of the total variability). Abbreviations of grassland types are as in Table 1

richness, flowering grassland index) on the positive side of the axis. At the opposite, agronomical properties such as short leaf lifespan index, early growth, and potential production index were negatively correlated to the first axis (Fig. 2a). Variation along axis 2 was mainly related to properties relating to forage quality (digestibility and nitrogen content) and the honey production index, opposite the flexibility index (Fig. 2a). Plotting individual grasslands according to their type discriminated clearly summer pastures (mainly UPA, UPS, and PSS) on the positive side of the axis from grass-dominated hay meadows (SGG and PGG) and forb-dominated hay meadows (PGF). More extensive hay meadows (PGGE, PGFE) were poorly discriminate from each other with an intermediate position along the axis. Axis 2 discriminated mainly legume-dominated sown grasslands from intensive pastures on the plateau (mostly IPG, Fig. 2b). Nested ANOVA on ordination scores of grasslands plots showed significant differences among types of use (hay meadows, pastures, and upland pastures) and among grassland types

Table 2 Results of the nested ANOVA (grassland type nested within type of use, *M* hay meadows, *G* pastures, *UPP* summer upland pastures) for the plot ordination on the two main PCA axes, agronomic and environmental properties

	Type of use (M, G, UPP)		Grassland type	
	d.f.	*F*	d.f.	*F*
Plot ordination on PCA axis 1	2, 38	**7.59*****	10, 38	**75.36*****
Plot ordination on PCA axis 2	2, 38	**10.85*****	10, 38	**2.73***
Agronomic properties				
Biomass at first use (tDM/ha)	2, 38	**36.43*****	10, 38	**4.31*****
Forage digestibility (%)	2, 38	**4.75***	10, 38	1.67
Forage nitrogen content (g/kg)	2, 38	0.85	10, 38	0.92
Early growth index	2, 37	1.71	9, 37	1.62
Late growth index	2, 37	0.73	9, 37	1.3
Forage production index	2, 37	**12.31*****	9, 37	1.79
Flexibility index	2, 37	**3.31***	9, 37	**4.53*****
Short leaf lifespan index	2, 37	**8.82*****	9, 37	**2.51***
Environmental properties				
Species richness	2, 38	**41.31*****	10, 38	**2.31***
Shannon diversity index	2, 38	**21.95*****	10, 38	**4.18*****
Abundance of plants for honey production (%)	2, 38	**8.53*****	10, 38	**4.54*****
Abundance of aromatic plants (%)	2, 38	1.38	10, 38	1.49
Color diversity index	2, 38	**14.37*****	10, 38	**1.16*****
Flowering grassland index (%)	2, 38	**28.31*****	10, 38	**8.62*****

Degrees of freedom (d.f.) and *F* values are showed

Significant differences between types are indicated in bold: * ($P < 0.05$), *** ($P < 0.001$)

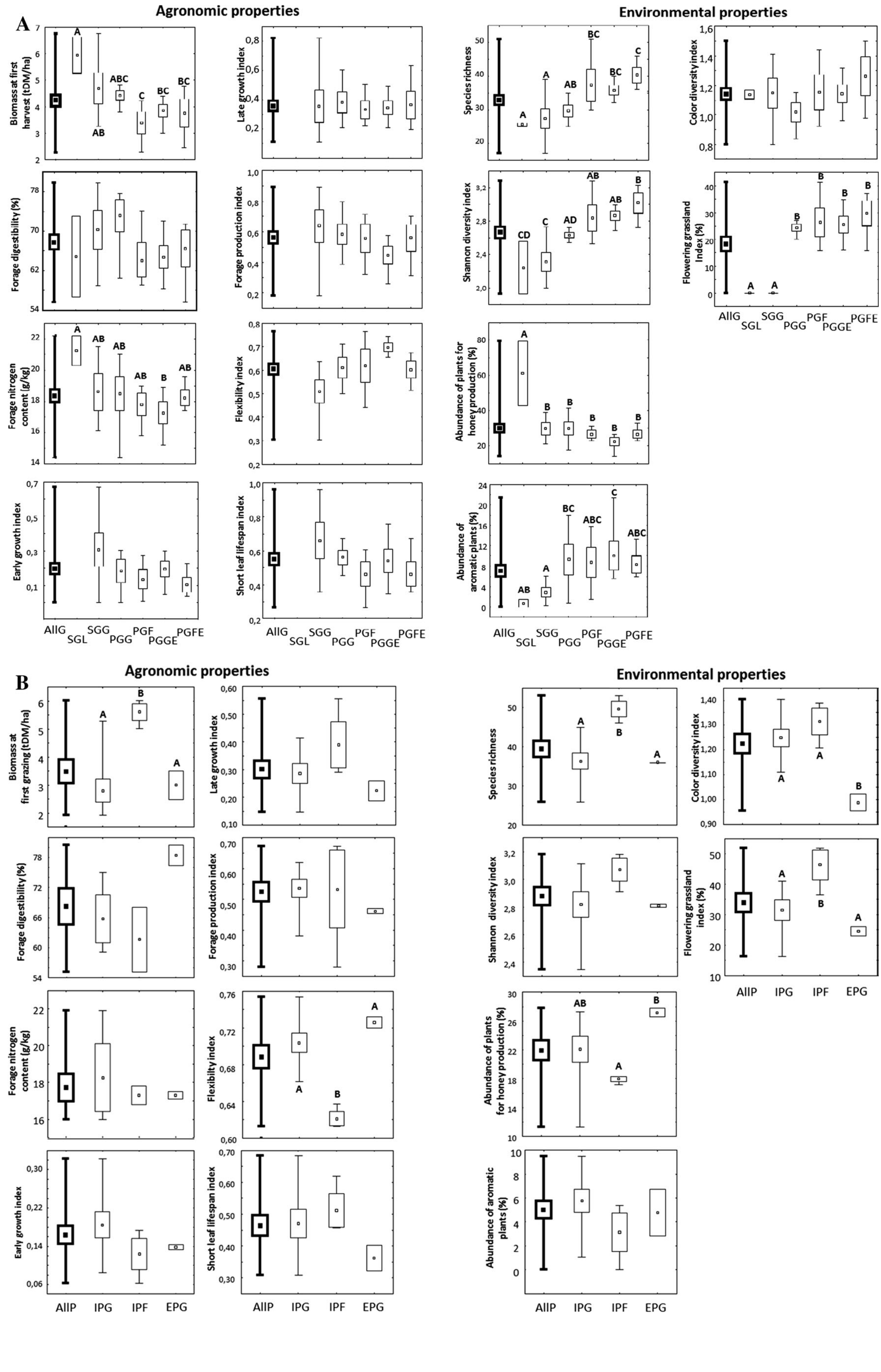
for both axes (Table 2), suggesting differences in the set of grassland properties according to type of use and specific management.

Several grassland properties showed significant differences between both types of use and/or grassland types (Table 2). Forage biomass at first harvest/grazing, flexibility index, and short leaf lifespan index were significantly influenced by both type of use and grassland type, while forage digestibility and the forage production index significantly differed across types of use. Except for the abundance of aromatic plants, all environmental properties responded significantly to the type of use of grasslands and to grassland types (Table 2).

Multiple comparison tests for specific grassland types within "hay meadows" showed significant differences for two agronomic properties: biomass at first harvest and forage nitrogen content. There was a non-significant trend of decreasing biomass at first harvest from the most intensive grassland types (SGL, SGG) to the most extensive ones. Higher mean value for forage nitrogen content was found in legume-dominated sown grasslands (SGL; Fig. 3a). The most intensive mown grassland types (SGG, PGG, and PGF) showed large ranges of values for many agronomic properties, sometimes close to the total range observed for all "hay meadows," demonstrating strong within-type variability. Environmental properties were more sensitive to grassland types, with all of them but color diversity index showing significant differences between grassland types (Fig. 3a). There was a clear trend of greater species richness and Shannon diversity index in the most extensive mown grassland types (PGF, PGGE, PGFE), while other agronomic properties showed significant differences mostly between sown grasslands on one hand and permanent grasslands on the other hand with lower mean values in sown grasslands (flowering grassland index, abundance of aromatic plants), or higher mean value for the abundance of plants for honey production (SGL).

In "pastures," biomass at first grazing period was greater in intensive pastures with more abundant forbs (IPF) and also these had a lower flexibility index. IPF also showed higher species richness or flowering grassland index. Grass-dominated extensive pasture (EPG) showed lower color diversity index. The most represented pasture type in the territory, grass-dominated intensive pastures (IPG), exhibited strong within-type variability for most of the properties, covering sometimes the whole range of variation observed in the pasture type (Fig. 3b).

Upland pastures types differed more from each other on agronomic properties than in environmental properties (Fig. 3c). Upland pastures on acidic soil (UPA) and on slopes (UPS) had lower biomass at first grazing and a lower forage production index than pastures on ski slopes or on the upland plateau. Forage digestibility is lower in UPA which showed a higher late growth index. Upland pastures


A
Agronomic properties
Environmental properties
Biomass at first harvest (tDM/ha)
Late growth index
Species richness
Color diversity index
Forage digestibility (%)
Forage production index
Shannon diversity index
Flowering grassland index (%)
Forage nitrogen content (g/kg)
Flexibility index
Abundance of plants for honey production (%)
Early growth index
Short leaf lifespan index
Abundance of aromatic plants (%)
AllG SGL SGG PGG PGF PGGE PGFE
B
Agronomic properties
Environmental properties
Biomass at first grazing (tDM/ha)
Late growth index
Species richness
Color diversity index
Forage digestibility (%)
Forage production index
Shannon diversity index
Flowering grassland index (%)
Forage nitrogen content (g/kg)
Flexibility index
Abundance of plants for honey production (%)
Early growth index
Short leaf lifespan index
Abundance of aromatic plants (%)
AllP IPG IPF EPG

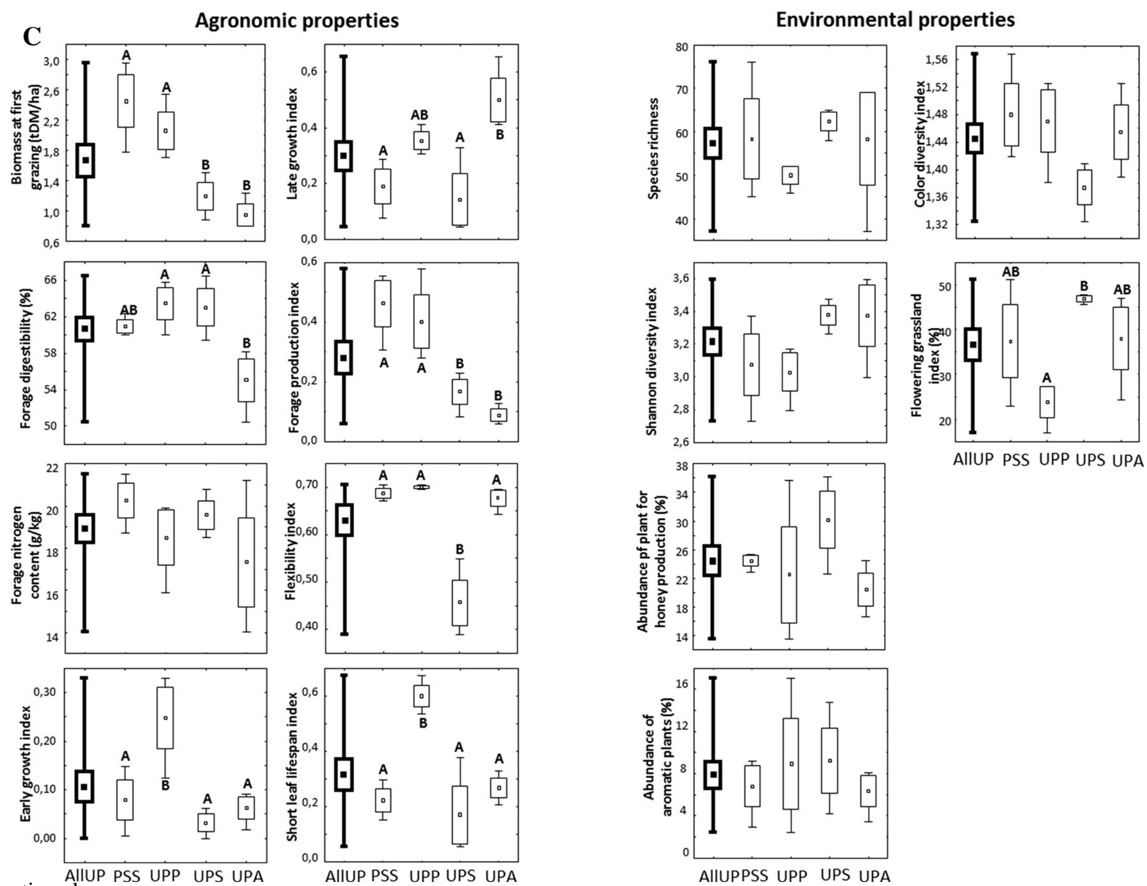
◀**Fig. 3** Mean values ± standard errors (*boxes*) and ±minimal and maximal values (*bars*) of the eight agronomic and the six environmental properties for each grassland type and, in *bold*, for all the grassland types together for each type of use. *Different letters* indicate significant differences between grassland types according to Ficher's LSD paired comparison tests (*no letter* indicates no significant difference). **a** Mown grasslands in the Val d'Autrans (*AllG* all mown grassland types, *SGL* legume-dominated sown grasslands, *SGG* grass-dominated sown grasslands, *PGG* grass-dominated permanent grasslands, *PGF* forb-dominated permanent grasslands, *PGGE* grass-dominated extensive permanent grasslands, *PGGF* for-dominated extensive permanent grasslands). The agronomic indices based on grass-species abundances were not calculated for the SGL grassland type. **b** Pastures in the Val d'Autrans (*AllP* all pastures, *IPG* grass-dominated intensive pastures, *IPF* forb-dominated intensive pastures, *EPG* grass-dominated extensive pastures). **c** Upland pastures on ski slopes and La Molière (*AllUP* all upland pastures, *PSS* pastures on ski slopes, *UPP* upland pastures on the high-plateau, *UPS* upland pastures on slopes, *UPA* upland pastures on acidic soil)

on the upland plateau (UPP) had higher early growth and short leaf lifespan indices. Overall, environmental properties were high in all upland pastures types, the only significant difference concerning the flowering grassland index which was lowest value in UPP and highest in UPS.

Discussion

Agronomic and Environmental Properties According to Management

The sets of agronomic and environmental properties assessed at parcel scale differed between types of use (hay meadows, pastures, and summer upland pastures) as well as between more specific grassland types. Overall our results are consistent with other studies in mountain grasslands which showed higher plant diversity in upland grasslands where soils are usually less fertile and/or on steeper slopes (Klimek et al. 2007) and highlighted the predominant role of management in influencing many grassland properties: plant species and traits composition and diversity (Schläpfer et al. 1998; Tasser and Tappeiner 2002; Quétier et al. 2007; Kampann et al. 2008), forage production (Marriott et al. 2004), or forage quality (Farruggia et al. 2014). However, few studies have addressed the simultaneous responses of a wide range of both agronomic and environmental grassland properties to different management practices (but see Lavorel et al. 2011).



◀**Fig. 3** continued

Across the whole range of grassland types, we found a trade-off between agronomic and environmental properties, especially between plant diversity indices and forage production, which is usually expected in agricultural and farm systems (Wrage et al. 2011). This trade-off is mainly supported by high contrasts between upland pastures and intensive hay meadows regarding forage production indices on the one hand, and diversity or esthetic value indicators on the other hand.

Interestingly, other grassland properties such as forage quality as directly assessed through digestibility and nitrogen content, and flexibility of timing of use, showed independent responses from this production-diversity trade-off. This result suggests that management can partially decouple forage production from forage quality despite the higher potential of the most productive grasslands for forage associated with a short leaf lifespan index. This relative potential for decoupling production and quality may reflect a major influence of grass functional composition rather than a direct effect of management (Duru et al. 2008; Gardarin et al. 2014). Although Lavorel et al. (2011) showed that forage quality decreased with extensification of management in mountain grasslands, we found no significant differences in forage quality between the different grassland types within hay meadows or pastures. This can be related to differences in the timing of grazing or mowing within these two types of use. Date of use can indeed significantly influence forage quality since digestibility usually decreases at late phenological stages (Duru et al. 2008). Farmers are likely to adjust the timing of use to maximize forage quality. For example, late mowing in extensive meadows can still provide good forage quality since the dominant conservative species show limited decrease in digestibility after flowering; contrary to intensive meadows where exploitative grass species are much more digestible at earlier stages but lose that benefit at later stages (Duru et al. 2008). The flexibility index was also found to be independent of the production-diversity trade-off and significantly influenced by grassland types, suggesting differences among grassland types in flexibility of timing of use. Moreover, the flexibility index was greater in pastures, which is consistent with grazing producing more flexible vegetation regarding the optimal time of use for forage quality (Martin et al. 2009).

Overall, our study underpins the major role of grassland-type diversity to ensure provision of multiple ecosystem services at the farm and territory scales through complementarity between grasslands (Andrieu et al. 2007). For example, the highest forage nitrogen content and potential for honey production were found in sown legume-dominated hay meadows, notably through the abundances of the alfalfa *Medicago sativa* and *Trifolium* species which have a high apiarian potential (Pywell et al. 2011). This reveals a potential for both agronomic and specific environmental properties in this grassland type despite low species diversity and flowering grassland index. On the other hand, upland pastures are characterized by higher levels of environmental properties (e.g., species richness, diversity, color diversity index), yet some of them could also have high forage production and flexibility index. This highlights the non-negligible role of upland pastures to improve environmental as well as production performances of mountain farms (Sturaro et al. 2013) and their possible relevance in partially offsetting negative impacts of climatic stresses on farm systems (Rigolot et al. 2014).

While indicator species for environmental properties have already proved to be a useful tool for agri-environment schemes in extensive grasslands (Matzdorf et al. 2008), our study showed that it can be expanded to a wider range of grassland situations. The flowering grassland index (Plantureux et al. 2010) was strongly associated to species richness and diversity. Our results validate the use of a targeted species list as a good proxy for plant diversity-related properties (de Bello et al. 2010). Other properties based on indicator species, such as abundance of aromatic plants or abundance of plants for honey production, provided additional information to species richness or diversity to discriminate the sets of properties between grassland types. Abundance of aromatic plants, a well-recognized component of gustatory quality of mountain dairy products (Martin et al. 2005; Farruggia et al. 2014), showed limited variation across grassland types with a global mean around 8 % of the total vegetation cover, except in recently sown grasslands (mean cover lower than 4 %). This highlights the quality of the forage from permanent mountain grasslands for the production of highly differentiated gustatory milk products.

Within-Grassland-Type Variability in Agronomic and Environmental Properties

A notable aspect of our results is the strong within-grassland-type variability for most of the assessed grassland properties. In many cases, the total variability of a property within a grassland type was close to the total variability of the corresponding type of use (hay meadows, pastures, upland pastures). This aspect has been quite unexplored in the literature, although one can consider it is of central importance to identify pathways to improve multi-services trade-offs at the parcel/grassland scale (Duru et al. 2011).

The most intensive and fertile hay meadows and pastures showed the highest within-variability for properties compared to more extensively managed grasslands. How can such important within-type variability in both agronomic and environmental properties be explained? First of all, there are several options to establish fertile hay meadows with different sowing mixes. The grass-dominated sown hay meadows and permanent hay meadows had sometimes contrasted species composition according to the relative abundances of the dominant productive grass species e.g., *Lolium perenne*, *Dactylis glomerata*, *Festuca pratensis,* or *Poa trivialis* as well as to the co-dominant grass species (data not shown). Hence, parcels within a same grassland type can have marked differences in the assemblages of grass functional types and therefore different levels for some agronomic properties such as flexibility or short leaf lifespan indices. So, at the parcel scale, the farmer may achieve the same 'field function' for the farm using different species assemblages and levels of diversity (Van Ruijven and Berendse 2003; Nyfeler et al. 2011). In addition, a same grassland type can fulfill different functions in the farm according to the goals set by farmers (Fleury et al. 1996), thus can promote such within-grassland-type variability at the territory scale. Lastly, depending on expectations between different farms, parcels of a grassland type could have different histories of use. This can lead to strong within-grassland-type variability in grassland properties notably as a result of the differential responses of individual grass species to management (Duru et al. 2010a). Overall, this variability highlights that, for grasslands with the same expected functions within a farm, improved trade-offs between agronomic and environmental properties are possible and thus could be harnessed in an EI process at parcel scale.

Parcel and Farm Scales: Two Complementary Scales for EI of Mountain Grasslands

One of the current most salient challenges for livestock farming systems is to achieve forage autonomy. In the context of dairy farming in the Vercors mountains, this challenge fits into the paradigm of EI, aiming at increasing forage production and improving its resilience to disturbances and climatic stresses by limiting external inputs and managing service-providing organisms, plant species for example in grasslands. Our results regarding (i) differences in agronomic and environmental properties between grassland types and (ii) strong within-type variability for these properties advocate for possible paths to ecologically intensify forage production at two scales: parcel and farm scales.

At the parcel scale, the coexistence of grasslands of the same type and with similar agronomic functions for farmers (Fleury et al. 1996; Dobremez et al. 2013) but with contrasted levels of agronomic and environmental properties demonstrated that improving the trade-off between both kinds of properties is feasible. The challenge is then how to increase forage production and/or quality in parcels with high environmental properties but lower productivity and, conversely, how to increase environmental quality of highly productive parcels with lower levels of environmental properties. Two major strategies can be inferred from our results and the literature in this perspective. First, manipulating plant species composition of parcels can enhance both forage production and plant diversity (Goslee et al. 2013). In sown and intensive grasslands, species and functional composition and diversity may play a fundamental role in both agronomic and environmental properties. Nyfeler et al. (2011) showed that using more diverse sowing mixtures, while even reducing the share of legumes, can have strong positive effects on both forage production and quality of sown grasslands while improving environmental quality. Moreover, such mixtures may have positive effects on the stability and resilience of agronomic properties (Pakeman 2014), particularly when facing climatic variability and stresses (see Tracy and Sanderson 2004 for meadows; Deak et al. 2009 for pastures), and secondary effects on other ecosystem functions able to support an EI process (Grigulis et al. 2013). The functional diversity of grass species included in some of these mixtures may also help to provide better flexibility in the timing of use through phenological complementarity between species (Michaud et al. 2011).

At the field scale, a second level of action can be to adjust the timing of first use (mowing or grazing) in order to maximize both agronomic and environmental properties. Timing of first use can impact significantly forage quality according to the relative abundances of grass functional types (Ansquer et al. 2009). O'Donovan et al. (2004) as well as Kennedy et al. (2006) showed some positive effects of early and late grazing to improve forage quality for livestock. However, such early or late grazing requires a fine-tuned adjustment of grazing management to not affect grassland environmental properties.

Overall, these two potential pathways to EI at parcel scale rely on limiting grassland specialization for one or few properties through improving flexibility of use, a property too often neglected in farms (Martin et al. 2009). However, such adjustments in order to develop flexibility at the parcel scale may not always be easy to implement because of the constraints inherent to farms due to temporal distribution of mowing periods, field distance to the farm, or accessibility.

The interaction between farm organization and vegetation at parcel scale is central in livestock farming (Méot et al. 2003). Indeed, at farm scale, EI may benefit from a diversity of grassland types (Andrieu et al. 2007) and practices (Fraser et al. 2014), providing a wide range of levels of agronomic properties (Bullock et al. 2007) as well as improving resilience of forage production at farm level to climatic stresses (Sabatier et al. 2012). EI also has a positive impact on environmental quality (Kampann et al.

2008). The key to achieve forage autonomy at farm level is to maintain or increase forage production, especially in temperate mountain areas where pastures are not accessible to livestock at least 5 months a year. Hence, sown grasslands, usually more productive and designed to be mown early, play an essential role for farms. We thus suggest that a crucial component for diversity of grassland types in livestock farming areas is the ratio between sown and permanent grasslands. Although intensive sown grasslands are essential to achieve forage autonomy, minimizing their importance within a farm system may help improving resistance and resilience of forage production to climatic stresses (Mosnier et al. 2013). Recent observations in Vercors and other similar alpine regions have suggested that sown grasslands were more impacted by vole outbreaks than permanent grasslands. However, modifying grassland-type diversity and/or the ratio between sown and permanent grasslands could be more or less difficult according to structural constraints at farm level. For example, some farm systems in this territory have important limitations regarding pasture areas available at spring, and then, those parcels must be mowed and stored early in order to be released as soon as possible for grazing (Dobremez et al. 2013). This can be a strong limitation for flexibility of timing of first use. On the other hand, one recent debate for mountain livestock farming has regarded the maximization of grazing rather than mowing to limit hay purchase and/or storage areas for hay. In mountain areas, this process is difficult to implement due to climatic constraints; however, with decreasing snow cover duration over the past years, this could become an option in the future.

Conclusion

To meet the challenge of ecological intensification, it is critical to determine the potential key features to be harnessed in grassland management. We conclude that possible pathways to ecological intensification for dairy livestock farming in mountain grasslands should rely on four major components: at farm scale, (1) the ratio between sown and permanent grasslands which could be tailored according to farm structural constraints and (2) the maintenance of a wide diversity of grassland types ensuring flexibility in use; at field scale (3) optimization of plant species mixtures used in sown grasslands and (4) fine-tuned adjustment of timing of first grazing/mowing to promote stability of agronomic and environmental properties. Further research should now focus on experiments aiming at understanding how adjustments in grassland management can help improving the trade-off between agronomic and environmental properties and forage production resilience. In addition, taking into account the scale of the territory and its fabric of farms is a next step toward EI. Options for exchanges of parcels between farms should be explored. While current opinion about livestock production in Europe considers relying more on grassland-based livestock farming rather than on intensive systems (Pfimlin and Faverdin 2014), it is crucial to better understand processes that can be harnessed to meet the challenge of EI for livestock farming in different contexts and territories.

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