Crop and Pasture Science, 2013, 64(7)

Use of productivity-defined indicators to assess exposure of grassland-based livestock systems to climate change and variability

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Summary

Livestock systems that rely on pasture resources are threatened by increasing climatic variability and, in the long run, by climate change.

This study presents two methods to characterise variability and change by clustering climatic-year patterns and rating the frequency of anomalies.

Such assessments can be used to foster discussion among researchers, advisers and farmers to design grassland systems adapted to new climatic conditions.

Abstract

Climate change research that aims to accelerate the adaptation process of agricultural production systems first requires understanding their climatic vulnerability, which is in part characterised by their exposure. This paper's approach moves beyond traditional metrics of climate variables and proposes specific indicators for grassland-based livestock systems. They focus on the variation in seasonal boundaries and seasonal and yearly herbage productivity in response to weather conditions. The paper shows how statistical interpretations of these indicators over several sites and climatic years (past and future) enable the characterisation of classes of climatic years and seasons as well as their frequencies of occurrence and their variation from the past to the expected future. The frequency of occurrence and succession of seasonal extremes is also examined by analysing the difference between observed or predicted seasonal productivity and past mean productivity. The data analysis and corresponding statistical graphics used in our approach can help farmers, advisers and scientists envision site-specific impacts of climate change on herbage production patterns. An illustrative analysis is performed on three sites in south-western France using a series of climatic years covering two 30-year periods in the past and the future. We found that the herbage production of several clusters of climatic years can be identified as "normal" (i.e. frequent) and that the most frequent clusters in the past become less common in the future, though some clusters remain common. In addition, the year-to-year variability and the contrast between spring and summer-fall herbage production are expected to increase.

Additional key words: herbage balance, rainfall, temperature, abnormal weather pattern

Introduction

Climate is a primary determinant of agricultural productivity. In particular, livestock systems that rely on pasture resources are increasingly exposed to threats from increased climatic variability and, in the long run, to climate change (Graux *et al.* 2013). Abnormal changes in air temperature and rainfall and resulting increases in frequency and intensity of drought events have long-term implications for the viability of these production systems. Designing new systems adapted to new climatic contexts is therefore necessary. Addressing this issue first requires a better understanding of such systems' exposure to climate change at particular locations and periods in the future. Exposure to climate is an external dimension of a system's vulnerability and usually refers to the duration, extent and frequency of weather perturbations that impact it (Adger 2006). Classically, exposure is assessed by analysing temporal patterns of raw physical variables (e.g. temperature, precipitation, evapotranspiration) (McCrum *et al.* 2009; Fraser *et al.* 2011). To contribute to farmer-centred redesign of production systems, the notion of exposure must be re-engineered in a way that corresponds to farmers' mental models and facilitates connecting scientific knowledge with action (Meinke *et al.* 2009). In contrast to climatologists who emphasise the physical and natural science dimension, farmers make sense of climate change primarily through their perception of potential risks encountered in their production systems (Hulme *et al.* 2009). Through their experiences and memories, they can build implicit categories of "normal" or "abnormal" climatic patterns and events. However, retaining and recalling past weather is often biased towards extremes or exceptional episodes, such as the 2003 drought in Europe (Ciais *et al.* 2005).

Livestock farms, especially those which are essentially grassland-based, are highly vulnerable to climatic trends and variability because feedstuffs are mainly provided by grasslands through cutting and grazing (Hopkins and Del Prado 2007). These systems, due to soil and climate induced constraints, are unable to grow annual crops (especially irrigated), dual-purpose crops (e.g. maize for grain or silage) or intercrops to cope with climate variability. They also cannot rapidly change plant genotypes when their grassland system is based on permanent pastures. In temperate regions, the impact of climatic trends and variability on livestock farms can be assessed through two main features relating weather to feeding management: (i) the dates and periods when grazing is sufficient to feed the herd and surplus herbage yield transformed into hay or silage (ii) and when there is a herbage shortage for grazing and feedstuffs should be supplied as hay or silage (Girard *et al.* 2001). Accordingly, exposure indicators should be determined according to herbage production at a seasonal scale, although most approaches in applied research use annual production as the primary indicator. When season-scale approaches are considered, unrealistic assumptions are often made, such as fixed calendar-based definitions of seasons (e.g. Graux *et al.* 2013); these approaches also refer to and use ad-hoc expertise that is difficult to generalise (Chapman *et al.* 2008). Furthermore, exposure assessments should consider inter-annual variability (Chapman *et al.* 2008) and alternation of favourable and unfavourable weather episodes because feeding system exposure depends less on the occurrence of a single unfavourable event than on a succession of two or more (Charpenteau and Duru 1983; Gibbons and Ramsden 2008).

The essence of farm management deals with change and uncertainty, in both the short and long term. Technical activities (day-to-day actions) are driven by management strategies that coherently organise activities over time as a function of farm resources and production objectives. These strategies incorporate flexibility to deal with weather variability, enabling them to cope with perturbations that are within the bounds of typical variability (Sebillotte and Soler 1990; Vanclay 2004). With larger deviations (e.g. the 2003 drought) the usual flexibility is no longer sufficient, which can prompt farmers to consider a far-reaching farming system redesign.

Regarding future climate, most farmers in France consider high annual weather variability a greater problem than long-term climate change (Duru *et al.* 2012). Similar observations have occurred in other countries (e.g. Australia; Pannell 2010), where extreme events are more intense and frequent than in temperate regions such as the one considered in this paper. Farmers have almost no benchmarks for future climate conditions; at most they have heard about global-change scenarios with little regional contextualisation (Zhang *et al.* 2007). Thus, they need site-specific projections of the weather and its impacts on production. Model-based agronomic knowledge can help to assess the potential consequences of new climatic conditions, which is a first step toward designing adapted systems. For this purpose, we previously proposed (Sautier *et al.,* 2013) six model-based exposure indicators that outline key distinguishing features of the behaviour of a grassland-based livestock system under a given climatic scenario. Briefly, these indicators characterise a climatic year, also called a "forage year", as three productivity-defined seasons. For each season, the herbage shortage or surplus at grazing is assessed with respect to the herd's feeding demand. Identifying the boundaries of these weather-dependent seasons and calculating seasonal surplus or shortage contribute directly to characterising climatic exposure as a function of the duration and extent of the impact (Sautier *et al.,* 2013). The frequency dimension involved in defining exposure requires consideration of a set of climatic years and the performance of statistical analyses of the values of each indicator each year. This paper presents two frequency-focused analyses of the exposure of grassland-based livestock systems using the seasonal-scale indicators mentioned above. The first analysis identifies clusters of climatic years in past and future datasets according to forage productivity and the timing of production and compares the resulting cluster frequencies between past and future. The second analysis examines the frequency of extreme values of seasonal balances. It highlights a change in the frequency of anomalies, whose amplitudes are reported as multiples of standard deviations (σ) from the mean of past years' seasonal balances.

Material and methods

Exposure indicators

We followed the method described in a previous article (Sautier *et al.*, 2013) to calculate six exposure indicators specific to grassland-based livestock systems: the dates of the beginning of spring, summer-fall and winter (resp. B_{sp}, B_{sf} and B_w) and the balance between herbage availability and herd feed requirements for each season (resp. Bal_{sp}, Bal_{sf} and Bal_w).

Each exposure indicator is calculated from the "average available herbage" (AAH), defined as the mean daily herbage growth (HG) over n years as follows

$$AAH = \left(\sum_{year=1}^{n} \sum_{jdoy=1}^{length(year)} HG_{jdoy}^{year} \right) / \sum_{year=1}^{n} length(year)$$

with n the number of years of the whole period, length (year) the number of days in the year considered, and jdoy the day-of-year number. Calculated for a given period and location, AAH represents daily mean herbage availability. In a balanced system, AAH is the daily feed required by the herd per area unit (g/m²/day). Daily HG can be predicted by any simulation model that considers grassland characteristics and defoliation practises due to grazing and cutting operations. As explained in Sautier *et al.* (2013), we used the herbage growth model developed by Duru *et al.* (2009) to calculate daily HG. Herbage growth was simulated with a constant set of parameters characterising soil (e.g. soil water-holding capacity = 80 mm), species (cocksfoot - *Dactylis glomerata L.*) and fertilisation rate enabling 80% of potential growth to calculate variations in herbage growth that are due purely to weather conditions. We chose intermediate harvest frequency (early cut before flowering followed by 2 or 3 grazing periods) and grazing intensity (residual sward height of 4 cm) to limit the effect of defoliation management upon herbage growth rate.

A year is divided into three productivity-defined seasons – spring, summer-fall and winter (Fig. 1) – defined from AAH. The beginning of spring (B_{sp}) is the theoretical beginning of grazing. Summer and fall are aggregated into the compound summer-fall season because year-to-year variability of herbage growth in fall prevented identification of a fall starting date. The beginning of summer-fall (B_{sf}) is the first day after the spring peak when full-time grazing is impossible. Winter begins (B_w) when grazing stops and ends when the next spring begins. Practically, during a phase of accelerating herbage growth (e.g. between winter and spring), spring grazing can begin once sufficient herbage has accumulated. In this case, grazing begins before herbage growth equals AAH, which means that the spring threshold of herbage growth could be set to any value less than AAH. In the same way, during a phase of decelerating herbage growth (e.g. between spring and summer or fall and winter), grazing can be extended beyond the date at which daily herbage growth equals AAH to graze the herbage accumulated during the latest surplus period, which means that the summer-fall and winter thresholds of herbage growth could be set to any value less than AAH. As explained in Sautier *et al.* (2013), we smoothed daily herbage-growth values over 10-day windows and applied the method with a spring threshold of 0.75×AAH, a summer-fall threshold of 0.75×AAH and a winter threshold of 0.5×AAH.

The balance between herbage availability and herd feed requirements (Bal_{sea}, in g/m^2) is defined as the sum of the difference between HG and AAH over the entire season. Bal_{sea} can be positive (i.e. surplus that can be cut for hay or silage) or negative (i.e. shortage that requires feeding the herd with hay or silage) and can be converted into feeding days. One feeding day represents the amount of herbage needed per area unit to feed the herd for one day, which equals AAH in a balanced system.

Clustering years and characterising abnormality and frequency of seasons

Climatic-year clustering according to the exposure indicators

Variability in seasonal conditions for herbage growth is often analysed empirically by grouping seasons with roughly similar profiles (e.g. early vs. late start of growth, short vs. long summer period, high vs. low annual production) (Chapman *et al.* 2008). We retained the idea of dividing climatic years into classes (clusters) with similar natures, which is useful for understanding and summarising large datasets. Clusters were defined by agglomerative hierarchical clustering (AHC) of the exposure indicators using Ward's criterion.

We built eight clusters of climatic years by performing AHC of their seasonal characteristics (season beginning and herbage balance) for the 60-year dataset presented below (30 years each in the past and future, see "Case Study" section). To facilitate visual comparison, clusters were ranked by letter according to decreasing annual herbage production (i.e. cluster "A" the highest and cluster "H" the lowest). ANOVAs and multiple-range tests were performed to determine which indicators were most discriminating between the clusters. Then, for each site, the relative frequency of each cluster (the number of years in the cluster divided by the sample size) was calculated for the past and future periods. Cumulative distributions of the relative frequency of clusters, put in order of decreasing relative frequency, were used to visualise differences between past and future and identify the smallest set of clusters that covered at least 80% of the years. These years were considered "normal" years. All statistical analyses were performed using Statgraphics (StatPoint Technologies, Warrenton, VA, USA).

Standard-deviation classification

A second kind of statistical analysis was performed to highlight the years with extreme values of seasonal herbage balance and to study the change in their frequencies from past to future. Several studies consider the standard deviation of a dataset as the typical magnitude of variations and its multiples (up to 3) as anomalies (Anwar *et al.* 2012; Hansen *et al.* 2012;). In this manner, Niu *et al.* (2009) classified climate data using long-term means and standard deviations.

The mean and standard deviation of each indicator over the 30 years of the past scenario were used to classify the indicator's annual value in both past and future scenarios. The deviation of the indicator's annual value from its past mean was divided by its past standard deviation to determine its class. Seven classes were defined from σ-based intervals: $]-\infty, -3\sigma]$, $]-3\sigma, -2\sigma]$, $]-2\sigma, -\sigma]$, $]-\sigma, \sigma[$, $[\sigma, 2\sigma[$, $[2\sigma, 3\sigma[$, and $[3\sigma, +\infty[$. The further the interval from 0, the more abnormal the season compared to its usual variability in the past.

Case study

The approach was applied in a research project aimed at assessing the climatic vulnerability of grasslands and livestock-farming systems in mainland France. Typically, when dealing with short-term adaptations, farmers and advisors tend to discuss small changes in farm structure and management. The 2050 time horizon was chosen because considering long-term adaptations encourages stakeholders to propose more substantial changes. We used 1980-2010 weather data (precipitation, potential evapotranspiration, solar radiation and mean temperature) for the past and scenarios of climate patterns generated for 2035-2065. For these future scenarios we used climate simulations of the IPCC A1B SRES scenario (Nakicenovic *et al.* 2000). Climate simulations were provided by Météo France via the ARPEGE-Climat model (Déqué *et al.* 1994) and were statistically downscaled by the CERFACS using the Boé08 method (Pagé *et al.* 2008) to generate the weather series at local scale (8 x 8 km).

The southern Midi-Pyrenees (France) was chosen as a case-study region to develop and discuss climate-change adaptation options in livestock-farming systems. Three locations were selected (Table 1):

- Aulus, located in the Pyrenees Mountains. Farms are beef-cattle production systems based on semi-natural grasslands practising long-distance transhumance for summer pasturing.
- Saint Girons, located in the Pyrenean foothills. Farms are beef- and dairy-cattle production systems based on grasslands (e.g. grass-legume mixtures) for beef-cattle farms and forage crops (e.g. silage maize) for dairy farms.
- Toulouse, located in the Garonne River valley, was used as a reference to compare its current climate to the future climate of Saint Girons and Aulus. Currently, the agriculture of this zone is essentially oriented toward cash crops, with a small amount of livestock production.

The past climate of the three locations can roughly be compared with the de Martonne aridity index (Table 1), defined as P/(T+10), where P is annual precipitation (mm) and T mean annual temperature (°C). Due to hot and dry summer, Toulouse has the lowest index. Aulus has the highest index thanks to its mountainous location.Toulouse is the most arid.

Results

Inter-annual variability of seasonal indicators for past and future periods

A visual examination of the indicators for past and future periods for each site reveals that some features are common to the three locations (Fig. 2a, b, c):

- beginning dates and herbage balances in winter were significantly correlated, meaning that either variable can be used for further analysis;
- the variability in beginning date was lower for spring than for summer-fall and winter, and the variability in herbage balance was higher for spring than for other seasons;
- compared to the past scenario, the future scenario had an earlier summer and later winter, and to a lesser extent, earlier spring and lower herbage surplus (or greater shortage) in summer.

Comparing sites (Fig. 2d), we noticed (i) a small shortage of herbage in summer in Aulus but a large one in Toulouse, (ii) the difference in herbage balance between spring and summer was the lowest in Aulus and the highest in Toulouse, and (iii) the difference in herbage balance between spring and winter was the lowest in Toulouse and the highest in Aulus.

Clustering of forage climatic years according to seasonal indicators

As the above analysis showed that the beginning of spring had low variability and the winter start date and herbage balance were correlated, the indicators “beginning of spring” and “beginning of winter” were excluded from the clustering. Thus, the AHC was performed on the basis of four indicators: the seasonal herbage balance for each season ($Bal_{s,}$ Bal_{sf} and Bal_{w}) and the beginning of summer-fall (B_{sf}).

The clustering resulted in distinct classes of forage years. The ANOVA of clusters per site based on the four exposure indicators shows that three clusters (out of eight) for each site significantly ($P<0.05$) differed from each other (Table 2) for at least three of the indicators. When considering only three of the four indicators, the number of distinct clusters grew from three to four (data not shown). The multiple-range test for the four indicators indicates that, depending on the site and the indicator considered, two to five clusters (out of eight) significantly ($P<0.05$) differed from each other (Table 2).

Annual herbage production was discriminated most by spring surplus, then by the summer beginning and the herbage balance of summer-fall (as shown in Fig. 3). For each row (site) and each column (indicator) of the figure, the 8 clusters (from A to H on the x-axis of each case) of climatic years (30 years each in the past and future) are ranked according to decreasing annual herbage production; the y-axis (labelled on top of each column) is expressed as day-of-year for the date and feeding days for the herbage balance. For each indicator, the range is kept constant over locations and criteria. When the boxplot panel exhibits a negative slope for a given indicator, the order of clusters according to this indicator is consistent with the order induced by the annual production. In all three sites, the higher the herbage surplus in spring, the higher annual production (panels b, f and j). In Saint Girons and Toulouse (panels e and i), the beginning of the summer-fall season was correlated with annual herbage production (a late summer-fall corresponding to high annual production). In Saint Girons the summer-fall herbage balance had a significant influence on annual production (panel g), meaning that a high-production year resulted most often from the conjunction of a favourable spring and favourable summer.

In Toulouse and only there, the median and mean values of the summer-fall herbage balance were negative for every cluster (Fig. 3, panels c, g and k). For Saint Girons and Aulus, both negative and positive values were observed. Putting the clusters together (i.e. considering the full sample of 60 years), large variability was observed in the spring balance at the three sites (panels b, f and j). Variability in the summer-fall balance was larger for Toulouse and Saint Girons and smaller for Aulus (panels c, g and k). Variability in the winter balance was relatively large in Toulouse due to the high variability in the beginning of winter (panels d, h and l).

Similar annual production can be achieved with different distributions of herbage production during the year (Fig. 3). Indeed, different combinations of seasonal balances were observed for forage-year clusters with similar annual herbage production (i.e. two clusters of adjacent rank). For example, in Aulus, a high spring balance and a negative summer balance were observed for cluster D, whereas a low spring balance and positive summer balance were observed for cluster E. Similar phenomena were observed in Toulouse and Saint Girons with the pairs of clusters (B, C) and (D, E), respectively.

Depending on the site and the time series considered, covering 80% of the sample required grouping three to five forage-year clusters. Therefore, no single cluster could be identified as a prototype of “normal” forage years. For all sites and both periods, at least three clusters occurred more than 12.5% of the time. This threshold (Table 3) represents an equal distribution of years among clusters (100% divided by 8 clusters = 12.5%). A cluster was subsequently considered “frequent” if its relative frequency exceeds 12.5%. For each site, there was a highly frequent cluster (relative frequency ≥ 16%) in both the past and the future (cluster F in Aulus, C in Saint-Girons and B in Toulouse) (Table 3).

The relative frequencies of clusters differed significantly between past and future scenarios, with the most frequent clusters in the past becoming less common in the future and vice versa (new clusters appearing in the future, some disappearing). Some common clusters in the past were not observed or were infrequent in the future (e.g. clusters B and H in Aulus, F and H in Saint Girons, C in Toulouse) (Table 3). The opposite was true for clusters C in Aulus, E in Saint Girons and F in Toulouse (Table 3). Broadly speaking, from the past to the future, the frequency of years with high annual herbage production (clusters A and B) decreased in Aulus and Toulouse, but increased in Saint Girons. At the same time, the frequency of years with low herbage production (clusters G and H) decreased in Aulus and Saint Girons but increased in Toulouse. After reordering clusters of years according to decreasing frequency (from 1 to 8 in Fig. 4), a clear change was identified in the characteristics of dominant forage years from past to future climates. The three most common clusters in the past covered more than 71% of cases, whereas these three clusters covered at most 53% of cases in the future (Fig. 4). The greatest change was observed in Aulus (greatest distance between past and future curves in Fig. 4). Moreover, the three most frequent clusters in the past included 71-77% of past years, whereas the three most frequent clusters in the future included 65-80% of future years.

Standard-deviation classification based on past mean seasonal herbage balance

The standard-deviation classification reveals and quantifies the amplitude and frequency of divergence of seasonal balances compared to their means in the past. The percentage of seasons in classes]-∞, -2σ] and [2σ, +∞[changed from 7% in the past to 18% in the future in Aulus, 12% in the past to 17% in the future in Saint Girons, and 3% in the past to 11% in the future in Toulouse (Table 4). Consequentially, the frequency of seasons corresponding in the]-σ, σ[interval decreased by at least 11% in the future (Table 4). Seasons in the extreme classes (above 3σ or below -3σ) were exceptional in the past (only one case observed in Saint Girons), whereas the future time series shows two, three and four seasons in the extreme classes in Aulus, Saint Girons and Toulouse, respectively (Fig. 5). The largest deviations were generally positive in winter and negative in summer-fall in the future climate (Fig. 5).

Sequences of seasons are also worth studying because the consequences of climate change are more severe for farmers when two consecutive seasons fall into extreme classes. Examination of sequences of seasons during the most critical years in the past (2003) and the future (2057, Fig. 5) showed that in Toulouse, herbage balance lay below the mean for three consecutive seasons (especially summer-fall, which lay 2-3σ below) (Table 5). A similar pattern was observed in Saint Girons, but nothing significant was noticed in Aulus. In the future, the number of successive seasons below the mean was greater in Toulouse than in the other two sites, and there was a trend toward a worsening situation (the balance decreases further below the mean for two seasons but less so for the last season).

Discussion

Lessons about climate change and variability

The indicators break down annual potentials into seasonal potentials, making it possible to: (i) predict whether productivity-defined seasons become hindrances or opportunities, (ii) determine, over several years, whether a favourable productivity-defined season can counterbalance an unfavourable one and (iii) compare sites.

Regardless of the method used for characterising years (year clustering or σ-based classes), we found it nearly impossible to define a single average or normal productivity-oriented climatic year for past or future climate series. For a given site, we identified several clusters of forage years with a significantly high probability of occurrence. Such climatic years, however, differ in the characteristics of their seasons, which can have favourable or unfavourable forage production. Sometimes above-average grass production occurs in the spring, followed by a dry summer, while in other years the inverse occurs. These differences between years are particularly important from a management perspective. Unusual patterns of favourable or unfavourable seasons induce constraints that strongly impact on management (Charpenteau and Duru 1983), especially in the case of a dry spring, even when followed by a wet summer (Aulus in 1998).

In contrast with research that focuses only on summer biomass production (e.g. Lamarque 2012), our results show that the amount of herbage surplus in spring (depending on temperature and water availability) and surplus or shortage in summer (depending on water availability) need to be considered jointly for the adaptation of grassland-based livestock systems. The year 2003 in Toulouse, which was considered exceptional at the European level (Ciais *et al.* 2005), brought about the greatest deviation from mean herbage balance ($-\sigma$ for spring and -2σ for summer); i.e. it simultaneously exhibited the lowest herbage surplus in spring, the greatest herbage shortage in summer-fall and the earliest beginning of summer-fall (cluster H, Fig. 3). The two other sites, located at higher altitudes, did not experience such dramatic consequences, which is consistent with de Martonne aridity indices (Table 1).

For the future climate, results of several crop simulation models predict that the expected impact of climate change on grassland production depends greatly on the geographic area and time horizon considered. After a slight increase in forage production in the first half of the 21st century, a reduction is expected in France (e.g. Graux *et al.* 2013) and the rest of Europe (Höglind *et al.* 2012). More specifically, Ruget *et al.* (2010) showed that for France in the near future (2020-2050), a production increase is expected in almost all regions, while towards the end of the century the trends differ by region, with a production decrease expected, especially in south-western France. Comparing the periods 1980-2010 and 2035-2065, we found an average decrease in biomass production for Toulouse (-6%) and Saint Girons (-12%) and a slight increase for Aulus (+2%) (Sautier *et al.,* 2013). These results are within the range of changes obtained in the above mentioned studies that concerned lower scales (national or regional rather than local) and different (although overlapping) periods. They corroborate the intuitive prediction that the switch from increasing to decreasing annual production will occur later in mountainous zones. In addition to these results, we found that climatic shifts are expected in four ways:

- infrequent forage-year clusters in the past become frequent in the future;
- some clusters with high annual herbage production in the past are expected to disappear (cluster B in Aulus and clusters A or C in Toulouse);
- clusters with low annual herbage production that did not occur in the past are likely to occur in the future (cluster G in Aulus and Saint Girons);
- variability in seasonal herbage production increases.

Based on comparison of forage-year clusters (Figs. 3 and 4), as well as quantification of variations from the mean (Fig. 5), we substantiated the claim that a shift in seasonal biomass production is expected. Clusters of climatic years infrequent in the past will become more common, and new clusters will emerge. The magnitude and direction of change in weather induced by climate change indicate that a substantial readjustment in management practices will be required. Therefore, incremental adaptations will probably be insufficient to cope with climate change. Instead, transformational (e.g. land-use) changes (Rickards and Howden 2012) and adaptive risk-management approaches will be required.

Consistent with Seneviratne *et al.* (2012), our simulation results indicate a probable increase in year-to-year climate variability and an accentuation of the contrast between spring and summer-fall herbage balance (productivity increases for spring and decreases for summer-fall). These changes, highlighted by the methods presented here, have important management implications for farmers. Shifting the grazing period due to an earlier spring and summer requires organisational adaptations. It could lead to changing the temporal distribution of work, with more harvesting in spring due to higher herbage growth and more time spent distributing conserved feed in summer due to a shorter grazing period. More generally, higher seasonal variability requires specific risk-management strategies (e.g. larger forage stocks or other feeding resources), and this need increases if between-year variability also increases.

Contribution to the participative design process

The data analysis and corresponding statistical graphics used in our approach can help farmers, advisers and scientists envision site-specific impacts of climate change on herbage production patterns. Such information can provide useful material for participatory design workshops focusing on adaptation of grassland systems to new climatic conditions (Duru *et al*. 2012).

The originality of our two methods of weather-pattern characterisation stems from the concept of a "forage year", defined as seasonal dynamics of forage production and intake. The seasonal assessment of herbage surplus or deficit makes it possible either to categorise a series of years into a small number of clusters or to classify seasons according to their deviations from past means. When represented graphically, these synthetic and quantitative descriptions can become generic tools due to the model-based assessment involved, its suitability for any soil or climatic context and the ease of obtaining the required data. Climatic years and seasons are quantified as the number of days of feed available (Fig. 3), which fits well with farmers' management-oriented mental models, as previously experienced in grazing management projects (Duru *et al.* 2000; Cros *et al.* 2004). Such representations are therefore cognitive tools (Duru and Martin-Clouaire 2011) that can be used to raise agricultural stakeholders' awareness of climate change and its likely consequences on grassland systems.

The approach for characterising climate exposure presented in this paper applies to roughly defined grassland systems. It does not deal, for instance, with specific field characteristics (e.g. topography, soil bearing capacity). Other indicators sensitive to these aspects are required when more elaborate characterisation of livestock systems' climatic exposure is needed.

These two methods were developed as part of a project to design grassland-based livestock systems that are less vulnerable to climate change and variability. The vehicle for implementing the methodology is a series of participative-design workshops. Each workshop begins with the facilitator introducing the game-based design methodology (Martin *et al.* 2011) and playing material. The system to design must initially comply with the system features desired by the participants and then consider the weather conditions encountered, which takes the form of a weather time-series and contextual data about past weather and projected future weather. This part of the method is specifically described in the present paper. The design problem consists of dimensioning the system, configuring and planning land-use, and devising conditional adjustments to cope with adverse situations or to take advantage of opportunities. Participative design is truly an iterative, on-going interactive process. Participants are provided a methodology to continually assess the system under construction and adapt to newly introduced constraints or changes. The interaction between farmers in the workshops promotes understanding and learning about the potential threat brought by climate change and ways to reduce the system vulnerability (Fleming and Vanclay 2010). In the design process, the visual and tangible representations of climate change and variability provide a science-based account of the uncertainty about possible future weather. The tools presented in this paper contribute insightful design information by enabling comparison of forage-year clusters in time and space. For instance, for clusters that were rare in the past and are likely to become common in the future, farmers can design systems similar to those that survived such difficult weather conditions in the past. Also, by comparing sites at different altitudes or biogeographic regions, farmers can exploit a design-by-analogy approach that considers the future weather of a site is likely to be similar to that experienced at a different site in the past.

Conclusion

The exposure of grassland-based livestock systems to climate change and variability drives the identification and evaluation of management adaptations. However, exposure is difficult to assess from only climate data given the joint effects of weather variables on grass growth throughout the year. Therefore, we proposed two methods for defining and ranking clusters of "forage years" to characterise climate change and variability. The methods were tailored to produce outputs that can serve as cognitive tools for farmers and agricultural advisors. Forage years were defined from exposure indicators specific to grazing systems: starting dates of seasons and seasonal grass production surplus or deficit. The first method clustered years with similar herbage growth profiles, while the second classified the deviation of seasonal herbage balances from their respective means. Both methods can be used as an initial step for designing farming system adaptations for feeding herds. They provide a synthetic and quantitative view of problematic weather patterns likely to occur in the future. Since exposure indicators were based on generic grass-growth models, the method is easily applicable to other sites and periods than those considered here. The main lessons from the case studies are the following.

- Several "normal" forage years can be identified, albeit with different seasonal patterns.
- While no trend of change was observed in exposure indicators over the last 30 years, a shift is expected for the medium future (2050 ± 15 years); the most frequent clusters of climatic years in the past become less common, although some clusters remain common.
- An increase in year-to-year variability in seasonal herbage balance and an accentuation of the contrast between spring and summer-fall herbage balance are expected, which call for substantial adaptations to livestock systems.

Acknowledgements

This work was funded by the French National Research Agency through the project O2LA (Organismes et Organisations Localement Adaptés) (contract ANR-09-STRA-09), the INRA Meta-programme ACCAF through the project FARMATCH and the PSDR project Climfourel INRA-Midi-Pyrenees region. We thank Mathilde Piquet for her early contribution to the analysis of exposure indicators.

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Figure captions

Fig. 1. Determination of season boundaries and surplus or shortage of grazing resources according to the herbage-growth profile.

The dark blue region under the dashed line indicates when the livestock is fed (partially in summer-fall and totally in winter) with silage or hay.

Fig. 2. Scatter plot of exposure indicators at the seasonal level (spring, summer-fall, winter) for the past (1980-2010, unfilled symbols) and future (2035-2065, filled symbols).
2a, b, c: Herbage balance (y-axis in feeding days) and beginning date of season (x-axis in day-of-year) in Aulus, Saint Girons and Toulouse. Each symbol corresponds to one season in a given year (□ = spring, ○ = summer-fall, Δ = winter).
2d: summary of 2a, 2b and 2c. Means and standard deviations of beginning date of season (x-axis) and seasonal herbage balance (y-axis) for past (1980-2010, unfilled symbols) and future (2035-2065, filled symbols) climates for Aulus (□), Saint Girons (Δ) and Toulouse (○). Seasonal herbage balance equals herbage production minus the amount of herbage needed to feed animals.

Fig. 3. Medians (lines), inter-quartile ranges (boxes), and outliers (dots) of the beginning of summer (left) and seasonal herbage balances for spring, summer-fall and winter (right). .

Fig. 4. Cumulative relative frequency of forage-year clusters ranked (from 1 to 8) according to decreasing relative frequency in the past weather series for three sites (Aulus (□), Saint Girons (Δ) and Toulouse (○)). The three upper curves represent the past (open shapes), while the other three concern the future (filled shapes).

Fig. 5. Deviations of herbage balances in spring (●), summer-fall (■) and winter (Δ) in past and future climate series from their means in the past climate series. Classes based on the number of standard deviations are denoted by a number from -3 to 3, where -3 represents]-∞, -3σ]; -2 represents]-3σ, -2σ]; -1 represents]-2σ, -σ]; 0 represents]-σ, σ[; 1 represents [σ, 2σ[; 2 represents [2σ, 3σ[; and 3 represents [3σ, +∞[.

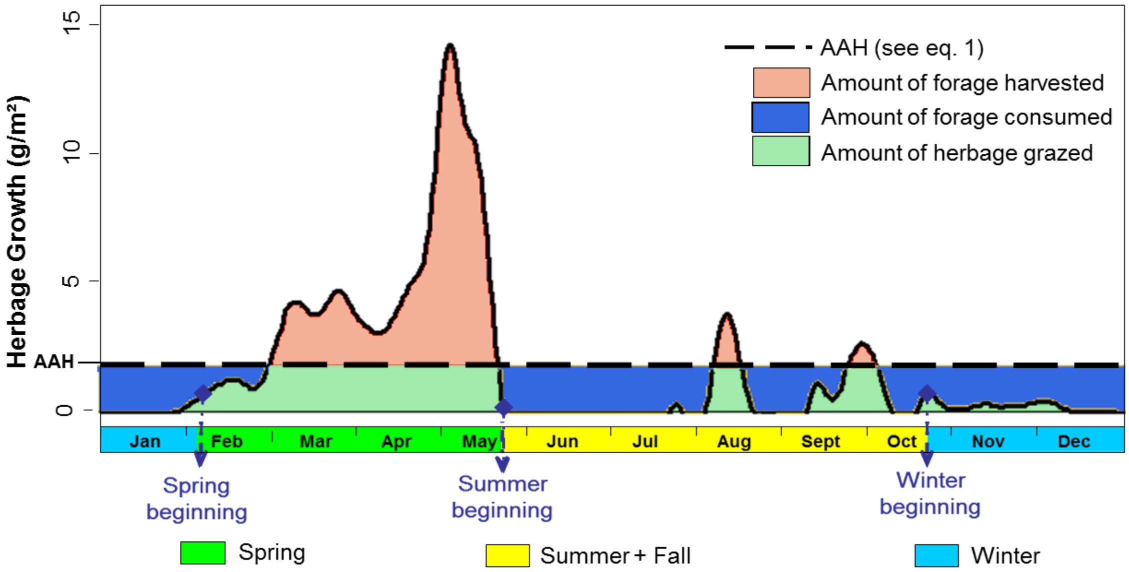
Herbage Growth (g/m²)
15
10
5
AAH
0
AAH (see eq. 1)
Amount of forage harvested
Amount of forage consumed
Amount of herbage grazed
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sept
Oct
Nov
Dec
Spring beginning
Summer beginning
Winter beginning
Spring
Summer + Fall
Winter

Fig. 1

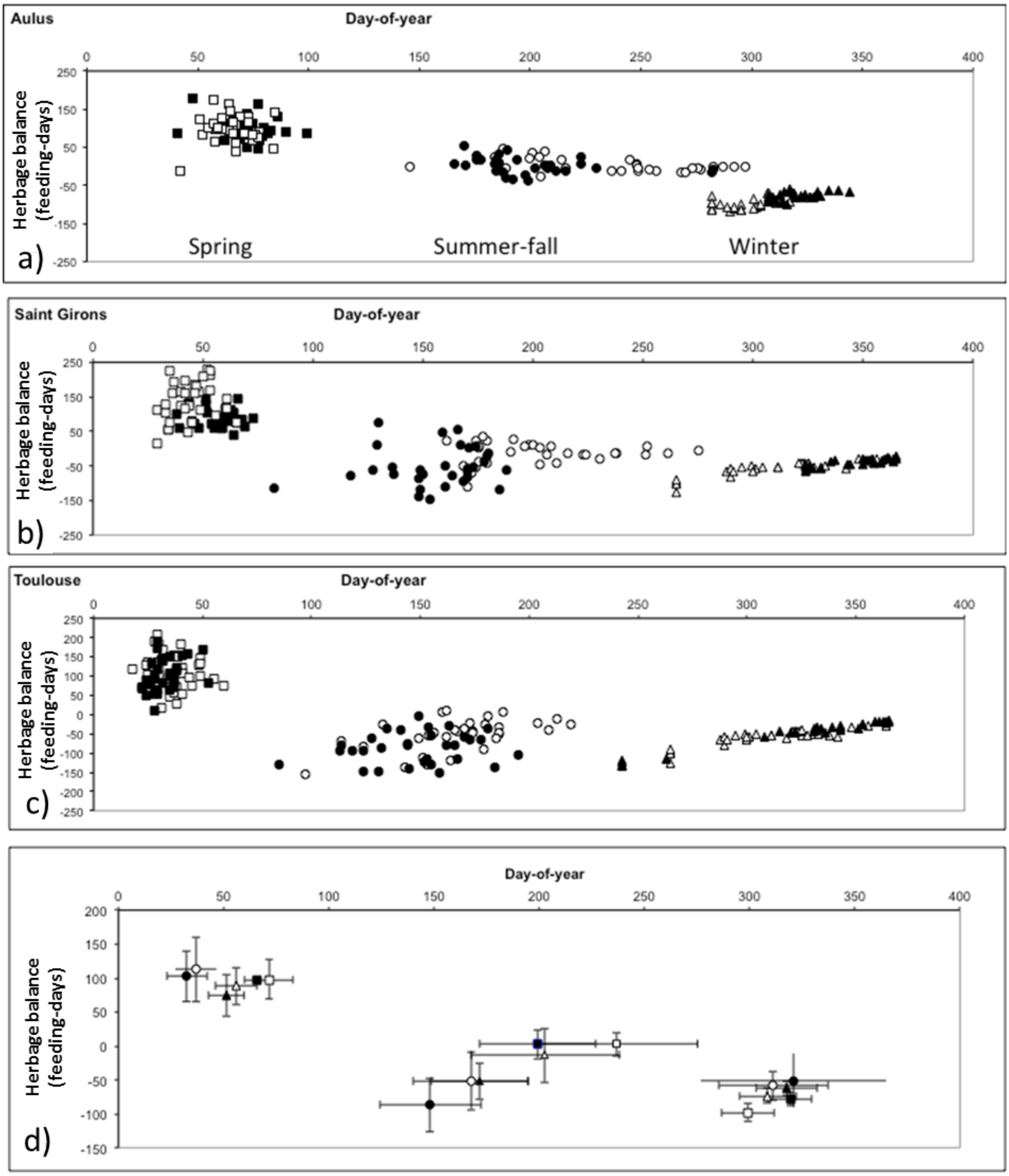
Aulus
Day-of-year
0
50
100
150
200
250
300
350
400
250
150
50
-50
-150
-250
Herbage balance (feeding-days)
a)
Spring
Summer-fall
Winter
Saint Girons
Day-of-year
b)
Toulouse
Day-of-year
200
100
0
-100
-200
c)
Day-of-year
d)

Fig. 2

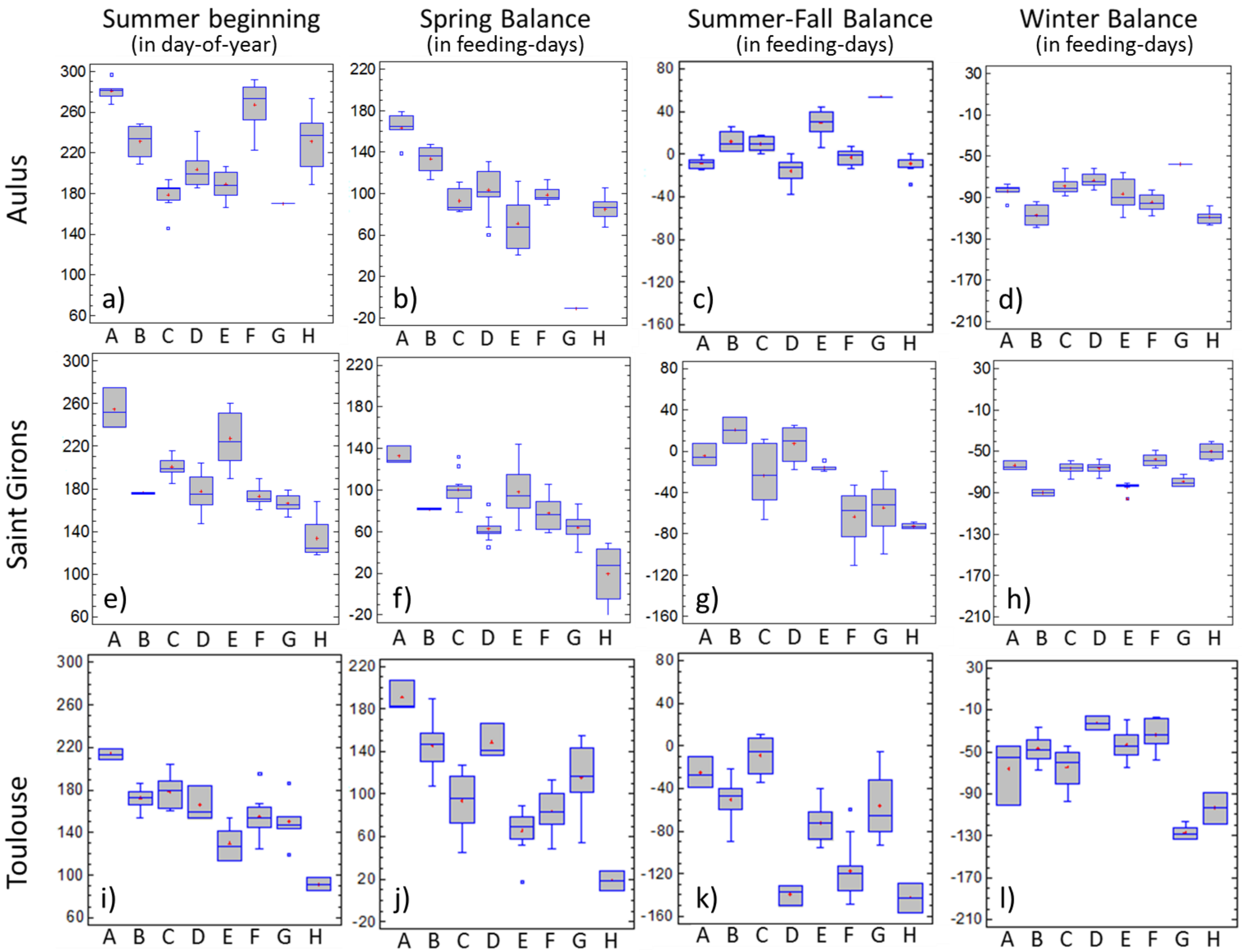
Summer beginning
(in day-of-year)
Spring Balance
(in feeding-days)
Summer-Fall Balance
(in feeding-days)
Winter Balance
(in feeding-days)
Aulus
Saint Girons
Toulouse
300
260
220
180
140
100
60
220
180
140
100
60
20
-20
80
40
0
-40
-80
-120
-160
30
-10
-50
-90
-130
-170
-210
a)
b)
c)
d)
e)
f)
g)
h)
i)
j)
k)
l)
A
B
C
D
E
F
G
H

Fig. 3.

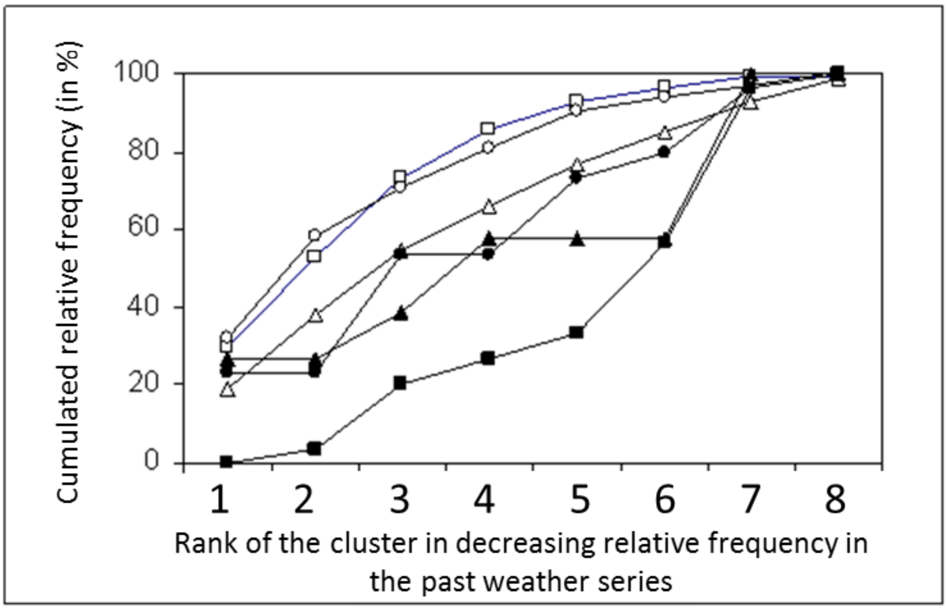
Cumulated relative frequency (in %)
100
80
60
40
20
0
1
2
3
4
5
6
7
8
Rank of the cluster in decreasing relative frequency in the past weather series

Fig. 4.

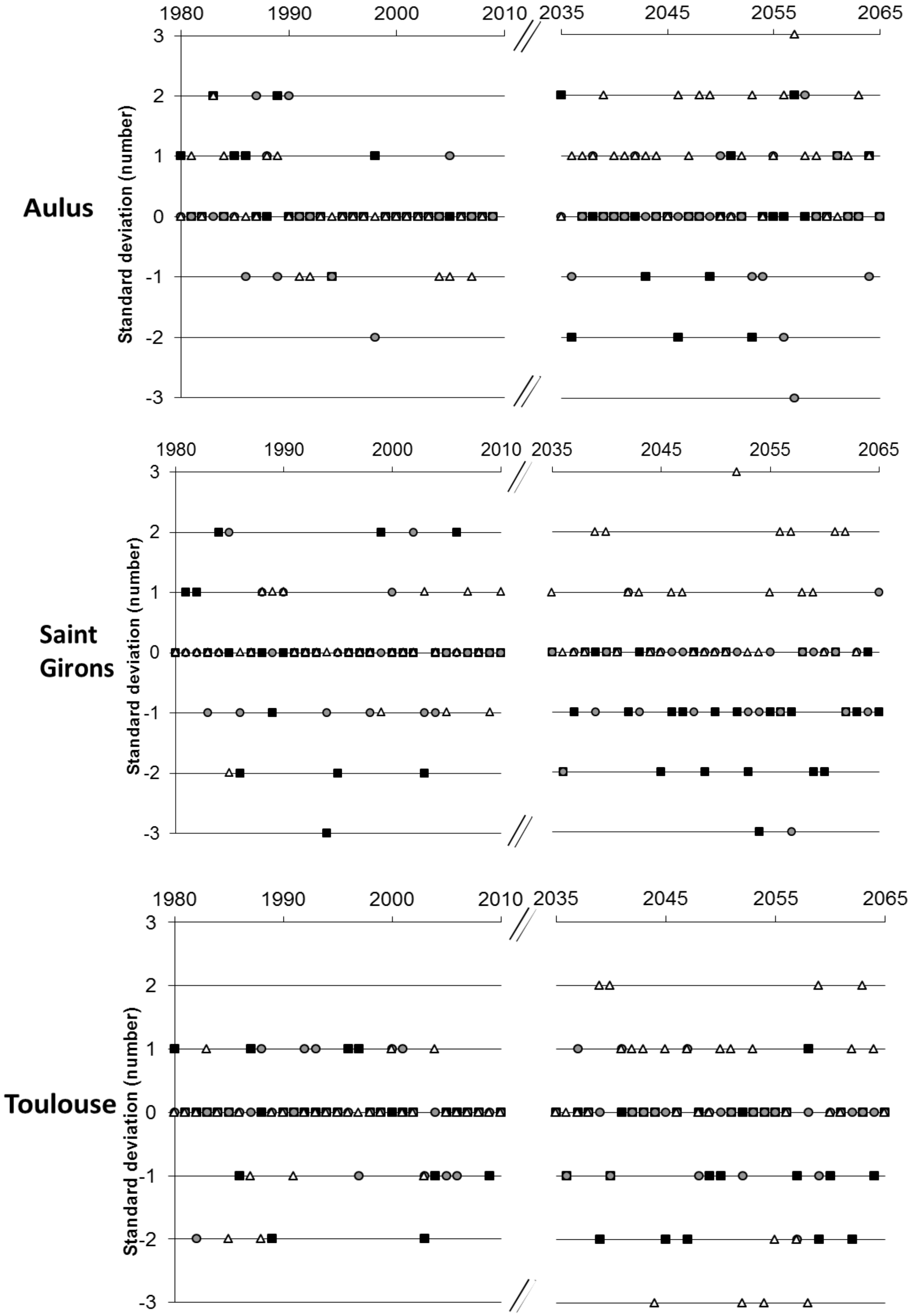
Aulus
Saint Girons
Toulouse
Standard deviation (number)
1980
1990
2000
2010
2035
2045
2055
2065
3
2
1
0
-1
-2
-3

Fig. 5

Table 1. Locations and De Martonne aridity indices (P/(T+10) (P= annual precipitation, T= mean annual temperature)) of the three study sites for the period 1980-2010 and the year 2003.

Site	altitude	latitude	longitude	Envrionmental zones†	Aridity index for past (mm/°C); (2003)
Aulus	733m	42° 47N	1° 20^{E}	Mediterranean mountains	82 (80)
St Girons	414m	44° 49N	1° 23^{E}	Mediterranean North	43 (37)
Toulouse	150m	43° 36N	1° 26^{E}	Lusitanian (oceanic)/ Mediterranean North	27 (21)

† after Metzger *et al.* 2005

Table 2. Number of significantly (P<0.05) different clusters (out of 8) per indicator and identity of those significantly different for at least 3 of the indicators

	Beginning of summer	Spring balance	Summer-fall balance	Winter balance	Identity
Aulus	3	4	4	2	D,E,F,G
Saint Girons	5	3	3	3	A,B,H
Toulouse	4	3	2	3	A,B,E

Table 3. Cluster sizes (as a percentage of the sample size) in past and future scenarios

	Aulus		Saint Girons		Toulouse	
Year cluster	Past	Future	Past	Future	Past	Future
A	8	7	0	10	10	0
B	**23**	3	0	6	**32**	**23**
C	3	**23**	**23**	**23**	**26**	0
D	**13**	7	10	**19**	3	7
E	3	**40**	0	**23**	10	**20**
F	**20**	**17**	**37**	10	**13**	**30**
G	0	3	**17**	10	3	**17**
H	**30**	0	**13**	0	3	3

In bold: %≥12.5

Table 4. Relative frequency (%) of deviation classes defined by σ, calculated considering the seasonal indicators for each year

Range	Past			Future		
	Aulus	St Girons	Toulouse	Aulus	St Girons	Toulouse
]-∞, -2σ]	1	6	3	6	9	7
]-2σ, -σ]	10	9	8	8	21	9
]-σ,σ[	72	69	80	50	52	69
[σ, 2σ[	11	10	9	24	10	11
[2σ, +∞[	6	6	0	12	8	4

Table 5. Deviation (expressed as the number of standard deviation) of seasonal herbage balance indicators from their means in the past climate series for the two most critical periods during past and future climate series.

	2002		2003		2004	2056		2057		2058
	winter	spring	summer-fall	winter	spring	winter	spring	summer-fall	winter	spring
Aulus	0	0	0	0	-1	2	-3	2	3	2
Saint Girons	0	-1	-2	1	-1	1	-3	-1	2	0
Toulouse	0	-1	-2	-1	0	0	-2	-1	-2	0

Supplementary Material

Table A1: Table of correspondence between rank (by number) of forage-year clusters by decreasing relative frequency in the past and rank (by letter) of forage-year clusters by decreasing average annual herbage balance in the past, at the three study sites.

Cluster rank by decreasing relative frequency in the past	Cluster rank by decreasing average annual herbage balance in the past and relative frequency of the cluster in the past (%)					
	Aulus		Saint Girons		Toulouse	
Rank	Rank	%	Rank	%	Rank	%
1	H	30	F	37	B	32
2	B	23	C	23	C	26
3	F	20	G	17	F	13
4	D	13	H	13	A	10
5	A	8	D	10	E	10
6	C	3	A	0	D	3
7	E	3	B	0	G	3
8	G	0	E	0	H	3