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Abstract: Research on the potential impact of weather, including its year-to-year variability, and on climate change effects on agricultural systems requires a clear appreciation of their exposure to the related hazards. Usually exposure is assessed through analysis of temporal patterns of physical variables (e.g. temperature, precipitation). The method presented in this paper provides a means of fitting these data into an intelligible frame specific to the grassland-based livestock systems motivating this work. The basic idea consists in quantifying the seasonal balance between herbage growth and livestock feeding requirements, considering a roughly-defined type of grassland systems differentiated on soil type, vegetation type and management practices. Based on a daily growth computer model, the proposed computational method yields several indicators pertaining to the temporal boundaries of three periods called seasons (spring, summer+fall, and winter) and, for each of them, to the balance between herbage production and animal feed requirements. The boundaries of the seasons vary from one year to another and are defined with respect to the daily average available herbage in a grassland system that is assumed balanced (i.e. in which the herbage production meets the animal demand over a sufficiently long period). The indicators defining seasons and surplus-shortage balance are easy to grasp and are highly instructive for scientists, farmers and policy makers. This method, applied to future weather time series, makes it possible to detect potential impacts (positive or negative) of climate change on herbage production and its seasonality in livestock systems.

***Keywords**:* grassland; vulnerability; exposure; climate; simulation

1 INTRODUCTION

Awareness of the effect of current climatic trends and variability, as well as future climate change projections, is essential for farmers who may have to redesign their production systems and for public policy agencies. In particular several impacts can be expected on livestock production. One of the already-observed indirect effects at the farm scale concerns the animal feed supply through change in the grassland production seasonality [Ma et al. 2010]. The vulnerability of a system refers to the extent to which it is likely to be affected and unable to cope with the effects of climate change, either in trends (temperature and CO_2 increase) or variability (increased frequency of extreme events) [IPCC, 2007]. Vulnerability is a function of the exposure, sensitivity and adaptive capacity of the system of interest to changing climate conditions [Nelson et al., 2010]. As such, vulnerability integrates exposure to climate as an external dimension referring to the nature, magnitude and rate of climate variations that the system might experience.

This paper addresses the question of characterisation of climate change exposure of a grassland-based livestock farm. Usually exposure is assessed through analysis of temporal patterns of physical variables (e.g. temperature, precipitation, evapotranspiration) [McCrum et al., 2009; Fraser et al., 2011]. Besides requiring the manipulation of a large amount of meteorological data, the integrative interpretation of the time series to synthesise a meaningful and concise appreciation of the grassland system exposure might be difficult even for knowledgeable and experienced analysts. As part of a project aiming at supporting the collaborative redesign of grassland-based livestock system by farmers and researchers we have developed a computational method that provides an intelligible assessment of climatic exposure of such systems. The method relies on an original framing of the notion of exposure in which:

- the variable position of the season boundaries over time is paid particular attention and;
- the weather data of interest at farm scale are mapped into typical grassland production which provides a seasonal view of surplus or shortage of herbage production with respect to animal intake.

The temporal pattern of herbage surplus-shortage of a reference livestock system is used in our method as a proxy for exposure to climate change and climate variability of a wide range of grassland-based livestock systems. Exposure is directly expressed in terms of likely adverse or favourable consequences on livestock systems at a given location on a seasonal scale which is more appropriate than the year, as argued by McKeon et al. [2009]. Having an appreciation of exposure on a seasonal timescale is crucial in grassland-based livestock systems where farm management decisions depend on the intensity and length of forage production periods and length of shortage periods [Gray et al., 2008].

The developed method exploits scientific knowledge of herbage growth embedded in a dynamic simulation model that responds to various weather variables on a daily time scale. The intelligibility of the output of the method comes from both the use of concepts classically manipulated by livestock farmers (season boundaries, surplus-shortage balance), and by the graphical nature of the communicated results that can concern either past climatic data or generated scenarios of the possible future climate. We first describe this new approach of climatic exposure assessment which relies on indicators that concern the beginning and duration of seasons and the seasonal surplus-shortage balance. Then we illustrate the relevance of the method by assessing the exposure estimated for past and future climates in two locations.

2 INDICATOR-BASED CHARACTERISATION OF CLIMATIC EXPOSURE

In livestock systems, farmers have to match feed supply with energy requirements for maintenance and production performance targets. Feed demand is satisfied by a variable fraction of stored forage such as hay, silage and/or concentrates and a variable fraction of pasture which is produced on the farm fields. The stored forage is either produced on the farm or purchased. The exposure to climate of grassland-based livestock systems is essentially characterised by, first, the duration of periods in which the pasture production is insufficient to meet the herd demand and, second, the ratio of forage consumed to forage produced. The exposure assessment method presented in this paper follows this viewpoint. It considers a virtual balanced system for which herbage production is equal to herd intake over a sufficiently long period (e.g. three decades). Actually, this premise means that the average available herbage is equal to the average feed needed by the herd over this long period. In addition, the method divides a climatic year into seasons defined with respect to seasonal herbage availability. Indeed in temperate regions, spring is characterized by a peak of herbage production that enables full grazing and cutting for hay or silage. In summer, herbage production decreases more or less depending on the year and the location in such a way that the diet is composed of a variable proportion of stored forage (from 0 to 100% of the diet) and grazed grass. The same pattern can be observed in the fall and in some years extra growth may be harvested.

The exposure assessment method refers to a location-specific reference value that is introduced next before defining the exposure indicators.

2.1 Average available herbage as a reference value

The exposure assessment method exploits the notion of average available herbage (AAH) that is defined by Formula (1) as the average of the daily herbage growth (HG) over n years. AAH, computed over the whole period, represents the daily mean of herbage availability and thus, for a balanced system, the daily feed required by the herd. The yearly profile of HG is obtained using any simulation model taking into account the grassland characteristics and the defoliation practises due to grazing and cutting operations. This profile is smoothed over 3-week-long windows (see Figure 1) in order to moderate effects of daily weather variation and to focus on seasonal effects of climatic variation on herbage growth.

$$AAH = \sum_{year=1}^{n} \sum_{jday=1}^{lenght(year)} HG(jday) \Big/ \sum_{year=1}^{n} length(year) \qquad (1)$$

with n the number of years of the whole period and jday the Julian day.

2.2 Exposure indicators: characterisation of seasons and herbage availability

The change of season is defined according to the position of current herbage growth HG and a threshold relative to average available herbage AAH (Figure 1). The beginning of spring (B_{Spring}) is set as the day when HG becomes greater than AAH/2, which indicates a sustained herbage growth significantly greater than the zero herbage growth rate of winter. The beginning of summer ($B_{Summer+Fall}$) is taken as the first day with no herbage growth after the spring peak, which is set as the maximum herbage growth before mid-July. Year-to-year variability of herbage growth in fall precludes the identification of a starting day of fall. Thus, summer and fall are aggregated in the compound summer+fall season. The beginning of winter (B_{Winter}) is the last day of the year for which HG falls below AAH/2, which characterises the beginning of a period without any grazing. Winter ends when the next spring begins.

Having defined the seasons, one can compute for each of them the balance $\int_{season}$ between herbage availability and feed requirements of the herd. Such a quantity might be positive or negative and characterises a situation of surplus or shortage respectively. Formally, $\int_{season}$ is defined (Formula 2) as the sum over the entire season of the difference between the daily herbage growth HG and AAH.

$$\int_{season} = \sum_{d=beginning}^{end} \left(HG(d) - AAH\right) \qquad (2)$$

Over a long period of n years, the sum $\int^{year}$ of all seasonal herbage amounts in shortage or surplus is assumed to be 0. However, this sum could be either positive or negative for a specific year (Formula 3), for which it quantifies the amount to be either purchased or stored for later use.

$$\int^{year} = \int_{Spring}^{year} + \int_{Summer+Fall}^{year} + \int_{Winter}^{year} \qquad (3)$$

In addition, we have defined another indicator operating on annual timescale: annual contrast C^{year}. As shown by Formula 4 C^{year} is defined as the sum of the absolute values of surpluses and shortages over any given year. The higher the production surplus and the amount of hay needed, the higher the contrast effect.

$$C^{year} = \left|\int_{Spring}^{year}\right| + \left|\int_{Summer+Fall}^{year}\right| + \left|\int_{Winter}^{year}\right| \qquad (4)$$

In Figure 1, the use of Formula 2 yields a positive value (surplus) for the Spring, and a negative value (shortage) for the other two seasons. Although not obvious on the graph the herbage production of this particular year did not meet the AAH target; $\int^{\mathbf{year}}$ is negative.

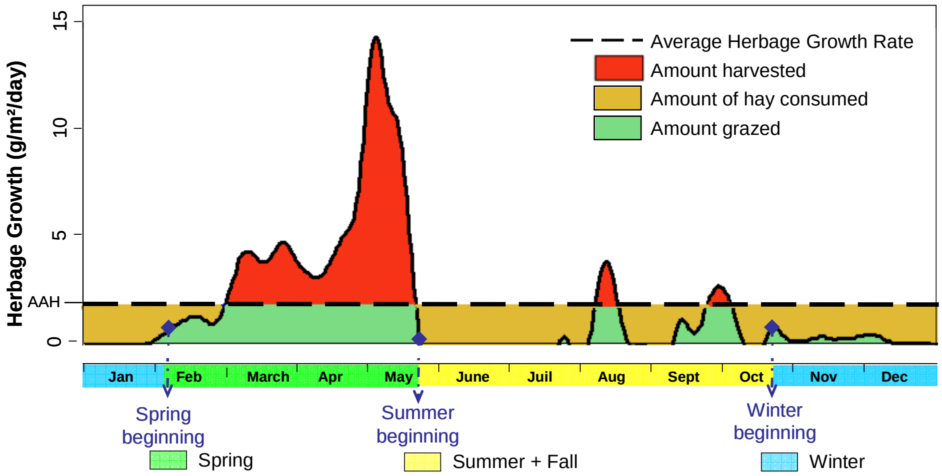

Figure 1. Herbage growth profile and seasonal surplus or shortage

Having annual values of the first day and length of each season and seasonal surplus or shortage enables us to examine statistically if there are trends within a long period and to estimate their year-to-year variability. The variation in annual balance and contrast over several years can be analysed in the same way. These climatic exposure indicators make it possible to compare periods (e.g. past/future) or locations as illustrated in the next section.

3 ILLUSTRATIVE CASE STUDY

For illustrative purpose the method is applied to past and future climatic conditions in France at two locations with contrasting potentialities in forage production: Toulouse (latitude: 43° 36N; longitude: 1° 26E) and Gourdon (latitude: 44° 49N; longitude: 1° 23E). We use measured climatic data for the past period (1980-2006) and simulated climatic patterns for the future (2035-2065). The latter patterns come from climate projections of the ARPEGE-climate model [Déqué et al., 1994] which have been statistically downscaled using the Boé method [Pagé et al. 2008] to generate local (8 x 8 km) precipitation and temperature series from the IPCC A1B SRES scenario [IPCC 2007].

Daily herbage growth (HG) is computed using the herbage growth model developed by Duru et al. [2009]. This dynamic model needs daily values of rainfall (P), potential evapotranspiration (PET), solar radiation (R) and average temperature (T). It also depends on parameters representing soil properties and management strategy. For the future period, the calculation of radiation use efficiency in the model takes into account the effect of CO_2 concentration increase on stomatal closure. In order to calculate variations in herbage growth purely due to weather conditions, herbage growth is simulated for a particular set of parameters characterising: soil (e.g. soil water capacity=80mm), species (cocksfoot - *Dactylis glomerata*) and management practices (early first cut before flowering followed by 2 or 3 grazing; fertilisation enabling 80% of the potential growth). The model returns daily herbage growth. In this way, we can draw a herbage growth profile for each year in order to determine season boundaries, and herbage balance at this seasonal scale.

Regression analysis is used to examine if there is a trend for the past and future climate. Regression results with a p-value lower than 10% are considered significant. Comparison between past and future is done by analysis of variance considering annual indicators of each weather pattern as replications. Past and future are considered to be different when the p-value of the analysis of variance is higher than 1%. Statistical analysis is performed using R software.

4 RESULTS

4.1 Weather data

For the past, the weather data shows considerable year-to-year variability of P-PET at Toulouse and Gourdon (standard deviations of 45% and 185% respective around the mean) and low variability of annual average temperature (standard deviation of 5 and 6% around the mean respectively). Trends in annual average temperature and P-PET are significant for both Gourdon and Toulouse. At Toulouse, annual average temperature increased by 0.45°C/decade (0.58 at Gourdon), P-PET decreased by 0.3 mm/decade (0.24 at Gourdon). Regarding future climate simulation, there are significant trends of increasing annual average temperature (+0.42°C/decade at Toulouse and +0.45 at Gourdon) and decreasing P-PET at Toulouse (-0.16mm/decade). Differences between past and future data are significant for each variable (T, P-PET, PET and annual precipitation) with an increase of temperature (+2.03°C/decade at Toulouse and +2.25 at Gourdon), a decrease of P-PET (-0.31 and 0.41 mm/decade respectively), a decrease of PET (resp. -0.16 and -0.08mm/decade) and annual precipitation (resp. -171 and -180mm/decade).

4.2 Starting dates and lengths of seasons

At Toulouse for the past, Figure 2 shows high variability in seasonal estimated starting dates with a standard deviation of 8 days in spring around Feb. 25th, 28 days in summer around May 29th, and 10 days in winter around Oct. 31st.

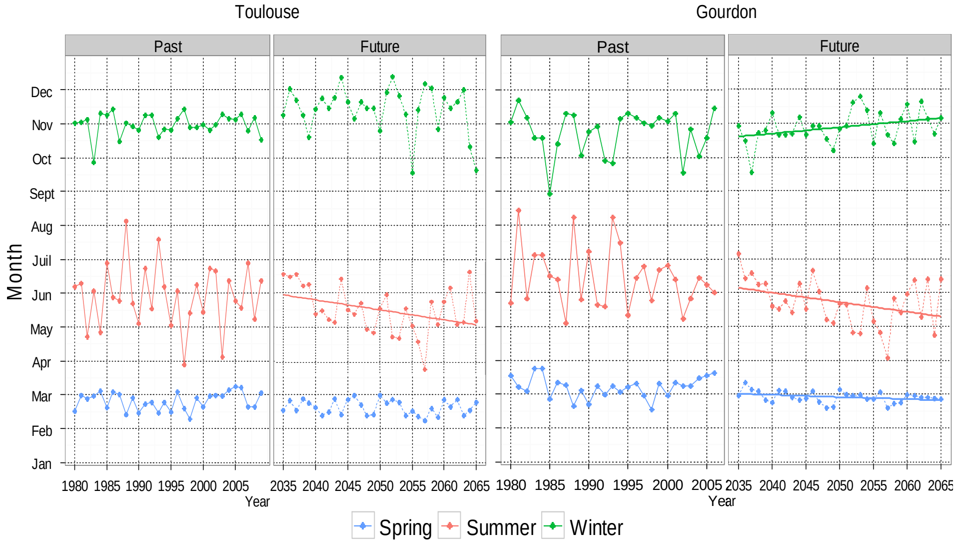

Figure 2. Starting date and length of seasons for past and future. The length of a season is the time from its starting date to the starting date of the next one.

For season length the variability is greater with 30 days of standard deviation for spring length, 33 days for summer and 13 days for winter. Significant trends cannot be identified, partly due to this variability. However, for illustration, the slope of the linear regression is +0.7 days/decade for B_{Winter}, +1.5 days/decade for B_{Spring} and -1.5 days/decade for $B_{Summer+Fallr}$. As to length of season, spring has become shorter (-3 days/decade) and summer+fall and winter have been extended (+2.2 and +0.8 days/decade respectively). This representation also allows extreme situations to be easily detected, as, for example, the early winter in 1983 (34 days before the mean), the late summer in 1988 and the early summer in 2003 (68 days after and 54 days before the mean respectively), and the early spring in 1998 (16 days before the mean). The mean values for B_{Spring} and $B_{Summer+Fallr}$ differ significantly between past and future with a decrease of 5.7 and 7 days, respectively. Summer and winter lengths also differ between past and future, with a longer summer (+ 17%, significant) and a shorter winter (-18%, significant). There is no significant difference between past and future values for B_{Winter} or spring length. For the future, we can detect significant trends for $B_{Summer+Fallr}$ (-8.7 days/decade) but no significant trend for B_{Winter} and B_{Spring}.

At Gourdon, the seasonal starting dates are also highly variable (standard deviation of 10 days in spring, 28 days in summer and 20 days in winter). Thus, no trends in seasonal starting dates were identified. Moreover, B_{Spring} and $B_{Summer+Fall}$ differ significantly between the past and the future (-9 days and +23 days respectively). Finally, there are significant trends in starting date and length of season for the future period: earlier and longer springs, earlier and longer summer+falls and later and shorter winters.

4.3 Herbage balance

In Toulouse and during the past, spring and summer+fall surpluses or shortages are highly variable with a standard deviation of 40% around the mean in spring and 76% around the mean in summer+fall, whereas winter shortages are more stable with a standard deviation of 12% (Figure 3). Considering trends, there is a decrease in annual herbage production (-47 g/m²/day/decade, not significant) that translates into a significant accentuation of the summer+fall shortage (-43 g/m²/day/decade) in association with a stable spring surplus and winter shortage (-1.5 and +2.4 g/m²/day/decade, not significant). The low herbage production in 1997 (74% of average production) results in a low spring surplus (32% of average spring surplus) whereas the high spring surplus in 1985 (146% of average spring surplus) does not induce a high annual herbage production (107% of average production) because of a high summer+fall shortage (180% of average summer+fall shortage). In 2003, the combination of a small spring surplus (30% of the average spring surplus) with a high summer shortage (146% of average summer shortage) explains why the annual herbage production reaches the lowest value. There is no significant difference between past and future values of annual production and the winter shortage and spring surplus, whereas summer+fall shortage is higher in the future (73%, significant). Within the future period, the significant decrease in annual herbage production (-69 g/m²/day/decade) translates into a decrease in the spring surplus (-41 g/m²/day/decade significant) and accentuation of summer+fall shortage (-16 g/m²/day/decade, not significant).

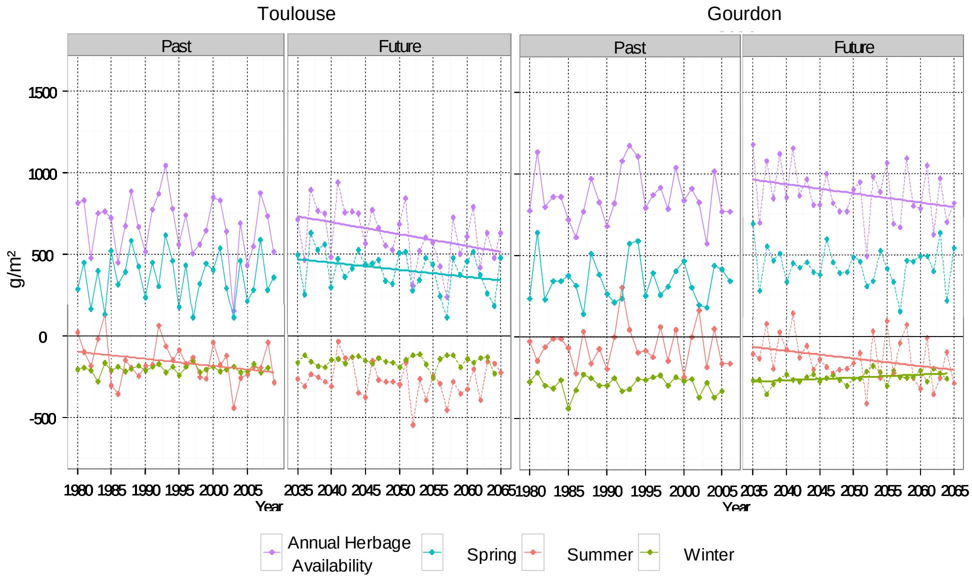

Figure 3. Seasonal herbage surpluses (positive values) or shortages (negative values) and the annual herbage production in Toulouse and Gourdon

In Gourdon, the past spring surplus and summer+fall surplus or shortage are highly variable (with a standard deviation of 27% around the mean in spring and 101% in summer+fall) whereas winter shortages are less variable (standard deviation of 14% around mean). For the past period, no significant trends in seasonal surplus or shortage could be identified. The analysis of variance between past and future values of seasonal surplus or shortage shows significant differences in spring (+26% of herbage surplus in the future), summer+fall (-141% of shortage) and winter (+13% of shortage) whereas no significant change is shown for annual herbage production. Trends in the future are significant for both summer+fall and winter shortages (-47g/m²/decade and +17g/m²/decade respectively) whereas there is no trend for spring surpluses.

In both Toulouse and Gourdon, the annual contrast (the sum of surpluses and shortages over the year) is higher in the future (resp. +71% and + 68% of past mean, significant). This trend is due to a higher summer shortage in the future in Toulouse (and no difference for spring surpluses and winter shortages) whereas it could be explained in Gourdon by higher spring surpluses and summer+fall shortages.

5 DISCUSSION AND CONCLUSION

According to Rivington et al. [2007] stakeholders are willing and able to deal with exposure indicators that integrate several weather variables in terms of potential change. Our method simplifies the interpretation of climate data by integrating links between several meteorological variables through the use of an herbage growth simulator to compute a set of intelligible indicators of exposure. Indeed, the starting dates and length of seasons and herbage shortage or surplus refer directly to indicators used by farmer and advisers such as the date of turnout to pasture, the indoor dates, the amount of forage (hay, silage) harvested and used to feed animals. In addition, general trends in climate variables can be difficult to interpret, because climate effects on grass growth are often non-linear and interactive. For example, we expected a lower herbage production in the future due to higher average temperature and lower P-PET whereas our results for Toulouse show no difference in annual herbage production between past and future, probably due to the effect of the increase of CO_2 on stomatal closure. In this way, the method reduces the leap perceived by Hammer et al. [2001] 'from a seasonal forecast to a decision' and should help farmers to manage or redesign their systems to cope with climate change.

The trend analysis of annual and seasonal indicators of the presented indicators gives highly meaningful information to farmers considering redesign of their farming system and to policy makers involved in adaptation programmes. Trends in annual production indicators inform whether changes in the land area available per animal unit are needed. In contrast, trends in seasonal indicators carry useful farm management advice: starting dates and length of season suggest changes in the farm schedule, the seasonal surplus or shortage inform about the workload to expect for a specific season. The annual contrast tells whether changes in annual herbage production are favourable or not: if the increase of annual herbage production is lower than the increase of annual contrast then the situation is getting worse (the increase of surplus does not balance the increase of shortage). Moreover, the presented method enables one to characterise exposure more precisely than an annual indicator such as annual herbage production or harvest. It breaks down annual potentialities to the seasonal scale. Such information makes it possible to target: (1) which season is problematic or favourable, and (2) if a favourable season will offset an unfavourable one. Thus, exposure to climate variability and change assessment is more informative and more pertinent than annual herbage production for studying climate change impacts. For example, using the method for future climate makes it possible to reveal significant increases of spring surpluses and shortages for the other seasons although no change in annual herbage production is noticed. In addition, on an annual scale, differences between two years or two periods are better highlighted by the annual contrast than by the annual herbage production alone. Indeed, the annual contrast refers indirectly to feed requirements through the summing of surpluses and shortages.

Thus, two situations with the same annual herbage production can be distinguished by considering their respective annual contrasts.

The method proposed for assessing the exposure of grassland-based livestock systems is the first step of a methodological research project on vulnerability design approaches for vulnerability reduction. The subsequent steps concern the characterisation of the sensitivity to climate change of any specific system, and the design process by which adaptation options are elaborated, tuned and combined to yield a more evolutional and less vulnerable system. Whereas the exposure assessment considers a roughly-defined class of grassland systems the investigation of sensitivity and adaptation issues deals with specific systems and, most importantly, production management aspects.

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