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Impact of Extreme Weather Events on Aboveground Net Primary Productivity and Sheep Production in the Magellan Region, Southernmost Chilean Patagonia

Pamela Soto-Rogel [1,*], Juan-Carlos Aravena [2], Wolfgang Jens-Henrik Meier [1], Pamela Gross [3], Claudio Pérez [4], Álvaro González-Reyes [5] and Jussi Griessinger [1]

1 Institute of Geography, Friedrich–Alexander-University of Erlangen–Nürnberg, 91054 Erlangen, Germany; wolfgang.jh.meier@fau.de (W.J.-H.M.); jussi.griessinger@fau.de (J.G.)
2 Centro de Investigación Gaia Antártica, Universidad de Magallanes, Punta Arenas 6200000, Chile; juan.aravenadonaire@gmail.com
3 Servicio Agrícola y Ganadero (SAG), Punta Arenas 6200000, Chile; pamela.gross@sag.gob.cl
4 Private Consultant, Punta Arenas 6200000, Chile; cj.perezcas@gmail.com
5 Hémera Centro de Observación de la Tierra, Escuela de Ingeniería Forestal, Facultad de Ciencias, Universidad Mayor, Camino La Pirámide 5750, Huechuraba, Santiago 8580745, Chile; alvaro.gonzalez@umayor.cl
* Correspondence: pamela.soto.rogel@fau.de

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Abstract: Spatio-temporal patterns of climatic variability have effects on the environmental conditions of a given land territory and consequently determine the evolution of its productive activities. One of the most direct ways to evaluate this relationship is to measure the condition of the vegetation cover and land-use information. In southernmost South America there is a limited number of long-term studies on these matters, an incomplete network of weather stations and almost no database on ecosystems productivity. In the present work, we characterized the climate variability of the Magellan Region, southernmost Chilean Patagonia, for the last 34 years, studying key variables associated with one of its main economic sectors, sheep production, and evaluating the effect of extreme weather events on ecosystem productivity and sheep production. Our results show a marked multi-decadal character of the climatic variables, with a trend to more arid conditions for the last 8 years, together with an increase in the frequency of extreme weather events. Significant percentages of aboveground net primary productivity (ANPP) variance is explained by high precipitation, mesic temperatures, and low evapotranspiration. These conditions are, however, spatially distributed in the transition zone between deciduous forests and steppe and do not represent a general pattern for the entire region. Strong precipitation and wind velocity negatively affect lamb survival, while temperature and ANPP are positively correlated. The impact of extreme weather events on ANP and sheep production (SP) was in most of the cases significantly negative, with the exception of maximum temperature that correlated with an increase of ANPP, and droughts that showed a non-significant negative trend in ANPP. The examination of these relationships is urgent under the current scenario of climate change with the acceleration of the environmental trends here detected.

Keywords: extreme weather events; climate variability; aboveground net primary productivity; sheep production; Magellan region; Patagonia

1. Introduction

In the Magellan Region (MR, Figure 1), sheep farming has been an important extensive land-use activity for more than 120 years, consuming large parts of the natural grassland area [1]. The MR region contributes 56% to the overall Chilean sheep production (SP) and with 80% to the national sheep meat production [2]. Consequently, the regional income from this economic sector in 2018 accounted to 63.8 billion USD, representing 0.5% of the country's GDP [3]. The geographical area of the MR is, however, environmentally heterogeneous featuring a high climatic variability that defines different bioclimatic zones (Figure 1). Sheep ranching areas are associated with the zone of deciduous woodlands and the stepparic grasslands, along the west-northeast gradient from mesic to more xeric conditions [4].

Climatologically, the MR is prone to a marked west-to-east rainfall gradient, with more than 5000 mm per year at the western Pacific coast decreasing to less than 200 mm towards the eastern Atlantic coast (Figure 1). The forest-to-steppe transition zone reveals a strong decadal to multidecadal variability of the annual and seasonal precipitation, indicating a decrease in annual and summer precipitation whereas winter precipitation tends to increase [5]. Air temperature shows a warming trend of about 0.15 °C per decade over the period 1960–2010 [6]. Regional climate in the MR is characterized by extreme events (EE), defined as events that are rare at a particular place and time of year, with high intensity and with acute environmental effects [7]. EE can cause catastrophic conditions at the ecosystem level [8], including flooding, droughts, as well as being known to have vast impacts on the regional socio-economic level [9]. Examples of EE in MR are severe droughts (1920–1926, 1928, 1966), heavy rainfall events with floods (1983, 1990, 2012, 2015), and devastating snowfall storms [10–12]. The most noticeable EE by sheep farmers is named as the "great snowfall" in 1995, having a high economic impact caused by the loss of 24% in regional SP [11]. Another significant EE occurred during the summer of 1988 with extremely low rainfall and high wind speed, causing an important decrease in SP and problems with the Punta Arenas water supply [10].

Under current climate change scenarios, an increase in the frequency and intensity of such types of EE is expected for the Magallanes Region [13]. Climate projections based on the global climate model CMIP5 (2022–2044) predict for the MR three crucial trends for the regional climate prediction: (i) an increase in precipitation of up to 3–4% during the austral winter (JJA), (ii) an increase in mean annual temperature between 0.5 °C and 0.7 °C, and (iii) increasing wind speeds between 0.07 and 1.1 ms^{-1} [14]. Negative effects associated with these trends are expected by sheep farmers in the MR. According to perception surveys, they feel threatened by a decrease in rainfall (droughts) leading to a reduced water availability and, consequently, a lower productivity of grasslands for fodder, generating a strong socio-economic impact [13].

In general, sheep production in Patagonia is being affected by climate change mainly through the effects of the aforementioned trends on the aboveground net primary productivity (ANPP) of the Patagonian ecosystems [15]. Seasonality is another factor connected with the maximum values of grasslands productivity for the spring–summer months from September to April [16,17]. Land-use mitigation and adaptation strategies of this important economic sector, based on regional-scale approaches, may help to use the forage resources in a more sustainable way [18]. During the last few decades, research on natural grasslands and its relationship to climatic variability in the Argentinean part of Patagonia revealed that the most important factors for ANPP is precipitation and temperature. The significant effects can be related to climate conditions during the previous year and growing season, suggesting that ANPP will respond in a retarded way to e.g., changes in soil water availability driven by climate variations [19–22]. Unfortunately, for the MR a lack of long-term studies on topics focusing on hydroclimate is apparent. Most of the existing studies are either limited in their spatio-temporal validity, or the underlying data has not been updated [13]. Some of the previous studies highlight the importance of precipitation on the productivity of natural pasturelands, but the used datasets are neither widely representative [1,23], nor do long-term series exist to estimate trends and produce future projections on the relationships. This lack of information for the MR exposes us to a low capacity for adaptation and mitigation to climate change due to the degraded condition of soils and grasslands, under traditional techniques, with extensive and intensive land-use for livestock [13]. As a consequence of the high international demand for wool and sheep meat from the MR, SP and its extensive and intensive grazing has had a strong impact on the carrying capacity of the stepparic grasslands [24,25]. Only during the recent decades, precautions arose to improve the carrying capacity of the grasslands and forage supplies by establishing new species of forage plants or improving the soil by fertilizers as a way to advance towards agropastoral systems [26]. Such strategies, however, do not yet consider the risk of climate variability, consequences due to climate change, or extreme weather events (EE).

The assessment of the impact of climate change on the regional SP will require a better understanding of the sensitivity of grassland productivity to climate variability, with a regional spatial and temporal wide coverage. This would have an impact on this important economic activity through improving the efficiency and sustainability of the regional vegetational resources [20]. In the present work we propose the following group of hypotheses associated with climate control (climatic variability and extreme events) over vegetation growth and sheep production at MR:

Hypotheses 1 (H1). *Aboveground Net Primary Productivity*

Water availability determined by precipitation, air temperature and potential evapotranspiration is a key factor for the onset of the ANPP growing season in MR. We expect ANPP variance at MR to be explained by these referred climatic variables.

Hypotheses 2 (H2). *Sheep Production*

SP is determined by the winter–spring critical period of mating and lambing. We expect that winter-spring precipitation and wind velocity negatively affect lamb survival, while temperature and ANPP of the same period have a positive effect.

Hypotheses 3 (H3). *Extreme Weather Events Impact on ANPP and SP*

Extreme weather events determine severe harsh environmental conditions. We expect that extreme weather events will increase the environmental stress conditions, affecting ANPP and SP negatively.

We propose to test our hypotheses using an approach that considers spatial climatic gradients and climatic fluctuations time series. With this purpose, we aim to assess the following specific objectives: (1) to describe the regional variability of precipitation, temperature, wind speed and aridity index, (2) to quantify spatio-temporal relationships between local climate and ANPP, (3) to investigate monthly trends in regional SP and link them to derived variations in global/regional climate change, and (4) to evaluate the impact of extreme weather events on monthly ANPP and annual sheep production.

2. Study Area

The Magellan Region includes the southernmost part of the Chilean Patagonia and Tierra del Fuego (48.50° to 56.50° latitude S, 66.5° to 75.5° longitude W; Figure 1). The Andes Cordillera is longitudinal aligned acting as a orographic barrier between the high-precipitation western area with 5000 mm per year (mma^{-1}), and the eastern part with approximately 200 mma^{-1} [5,27,28]. Analyses on air temperature data reveal a distinct spatial pattern with variations associated with seasonality and local conditions such as the vicinity of glaciers or lakes, distance to the dominant mountain chain, among others [29]. Four biotic communities can also be classified [4]: Magellanic moorland, Evergreen forest, Deciduous Beech forest and Patagonian Steppe (Figure 1). Sheep farming activities are located within the two areas of the Patagonian steppe and the woodland transition zone between deciduous forests and steppe. The steppe area is characterized by the dominance of grass-like species ("coiron" grasslands) including the genera *Stipa*, *Festuca* and *Poa*, together with cushion-like small thorny shrubs such as *Azorella prolifera*, *Anarthrophyllum* spp., and *Mulguraea tridens.* The ecotone between the deciduous forest and woodland area is dominated by the presence of different shrub species such as *Chiliotrichum diffusum*, *Berberis microphylla*, *Gaultheria marticorenae*, associated with shrub-like tree species *Embothrium coccineum* and *Nothofagus antarctica*.

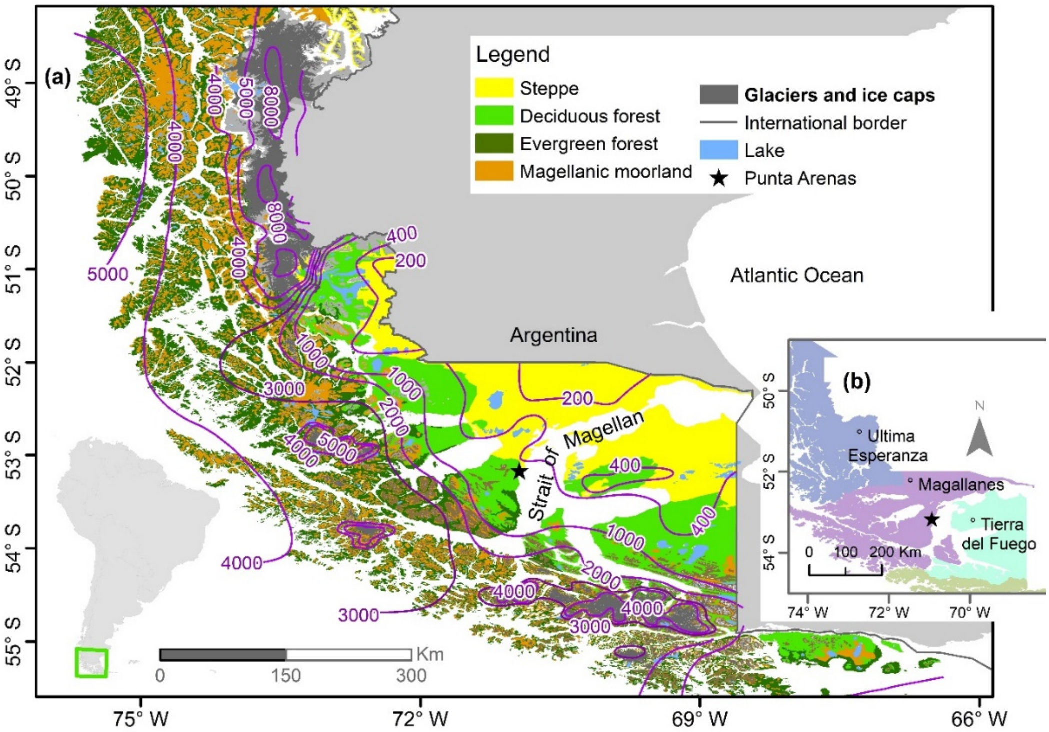

Figure 1. (**a**) Map of the study area including main vegetation types, isolines of precipitation, glacier extents, and lakes. Inlay: (**b**) names of Chilean provinces covered in this study. Vegetation distribution [4,30], while the information of isohyets, glaciers, lakes and political limits are from Infraestructura de Datos Geoespaciales de Chile [31].

The local SP system in the MR is based on grazing mainly on grass steppe resulting in large extensive and intensive sheep ranching areas. The total area for agriculture and livestock use (excluding native forests) accounts to 4.2 million hectares in the MR. Out of this, 98% of the total area corresponds to dry grasslands (Figure 1) [2].

3. Methods

3.1. Regional Climate Variability

Climate data and EE analysis for the last 34-years were analysed using a regional data set of precipitation (pre), minimum temperature (tmn) and wind speed at 10 m height (ws), derived from the gridded datasets of the Climatic Research Unit Time-Series (CRU TS v.4.03; [32]) and Era-Interim [33]. To quantify regional drought/wet conditions we calculated the SPEI index [34] for a 12-months interval using the free software R project [35]. We considered two parameters for its calculation: precipitation (pre) and potential evapotranspiration (pet) based on monthly data from CRU TS v.4.03 [32].

3.2. Relationship between Climate Variability and Vegetation Cover

To investigate the relationship between regional-scale climate variability and vegetation cover we used a 34-years NDVI database for the MR from 1985/86 to 2018/19 [36]. The NDVI represents a valuable proxy for the above ground net primary production (ANPP: [20,37,38]). Climate variables were analyzed using periods from September to December, January to April, and May to August from ERA-Interim [33]. Using this approach, we performed a geographically weighted regression analysis (GWR, [39] within the ArcGis software program [40]). We conducted the GWR analysis on average NDVI values for the periods September to December and January to April (dependent variables) and average values for precipitation (pre), minimum temperatures (tmn) and potential evapotranspiration (pet) of the corresponding same periods (independent variables). The respective maps with the projection and reference datum Universal Transverse Mercator (UTM-zone, 19 S, World Geodetic System 84, WGS 84) are finally generated by ArcGIS. For GWR the kernel was constructed at a fixed distance, Akaike information criterion (AICc) was the bandwidth method selected, and cell size was 0.25 determined for grilled data [39].

3.3. Relationship between Climate Variability and Sheep Production

For the quantification of the relationship between sheep production and climate variability, we performed Pearson's correlation analysis comparing sheep production with climate data and aboveground net primary productivity, considering a confidence level of 95% and 99% with two degrees of freedom. We used a monthly time series of the number of sheep being processed in the slaughterhouses of the MR for the period 1987–2019 as provided by the Servicio Agrícola y Ganadero (SAG, Chilean Agriculture and Livestock Service). We used this database as a surrogate or proxy for the complete data due the lack of sheep farming censuses after the year 2007. We chose three climatic variables (pre, tmn, and ws), and NDVI data [36]. The monthly regional precipitation data were obtained from the CRU TS v.4.03 data set [32], while minimum temperature and wind speed data were obtained from two weather stations in Punta Arenas (WMO codes: DGA, DMC), respectively. These climatic variables were used for the correlation analysis here described assuming a direct impact on the sheep survival. Critical survival periods are before and after lambing months (September to December) and harsh weather conditions may provoke an increase in mortality [11,41].

3.4. Impact of Extreme Event on Aboveground Net Primary Productivity and Sheep Production

To gain a more precise estimation of the effect of the EE on aboveground net primary productivity (ANPP; [21]) and SP we performed a superposed epoch analysis (SEA) [42,43]. This analysis allowed us to test the effect on the ANPP and SP of a time series of extreme weather events, evaluated at the same time of the event occurrence (lag = 0) and after four-time lags. SEA is widely used to estimate the effects of catastrophic events such as volcanic eruptions and droughts on the tree-growth series. To apply this analysis in this study we defined as extreme weather events those climatic records (pre, tmn, tmx and ws, already described in Section 3.1) with values below the 1st percentile or above the 99th percentile. Then we calculated how significant was the deviation from the mean value for ANPP and SP during the occurrence of EE and after four-time lags. ANPP data was provided by the NOAA [36], while SP data was provided by SAG (see Section 3.3).

4. Results

4.1. Recent Changes in Regional Climate Variability

Figure 2 illustrates the MR monthly time series plots of precipitation, minimum temperature, wind speed and SPEI from January 1985 to December 2018, showing a marked multi-decadal character. For each of these series, the extreme events are indicated as values below (above) the 1st (99th) percentile. Air temperature time series (Figure 2a) presents extreme events of minimum temperature only for the 9-year period from July 1992 to July 2001. After 2001, the values vary close to the entire period average (1985–2018) with only a slight positive trend. For the period February 2010 to December 2018 minimum temperature values stay above the overall mean. The wind speed time series (Figure 2b) only reveals EE values since December 1998, and in every case those values above the 99th percentile occurred during periods when wind speeds were above average. The longest lasting of these periods are the five years between 2006 and 2013, including two of the four EE observed for the entire analysed period. The precipitation series (Figure 2c) shows a marked multi-decadal variability, with phases below the average (1988–1990, 1999–2003 and the longest 2010–2018), and two phases of higher rainfall (1990–1993, and 2003–2010). Interestingly, during the longest dry phase or meteorological drought (2010–2018), there are also a couple of extreme precipitation events.

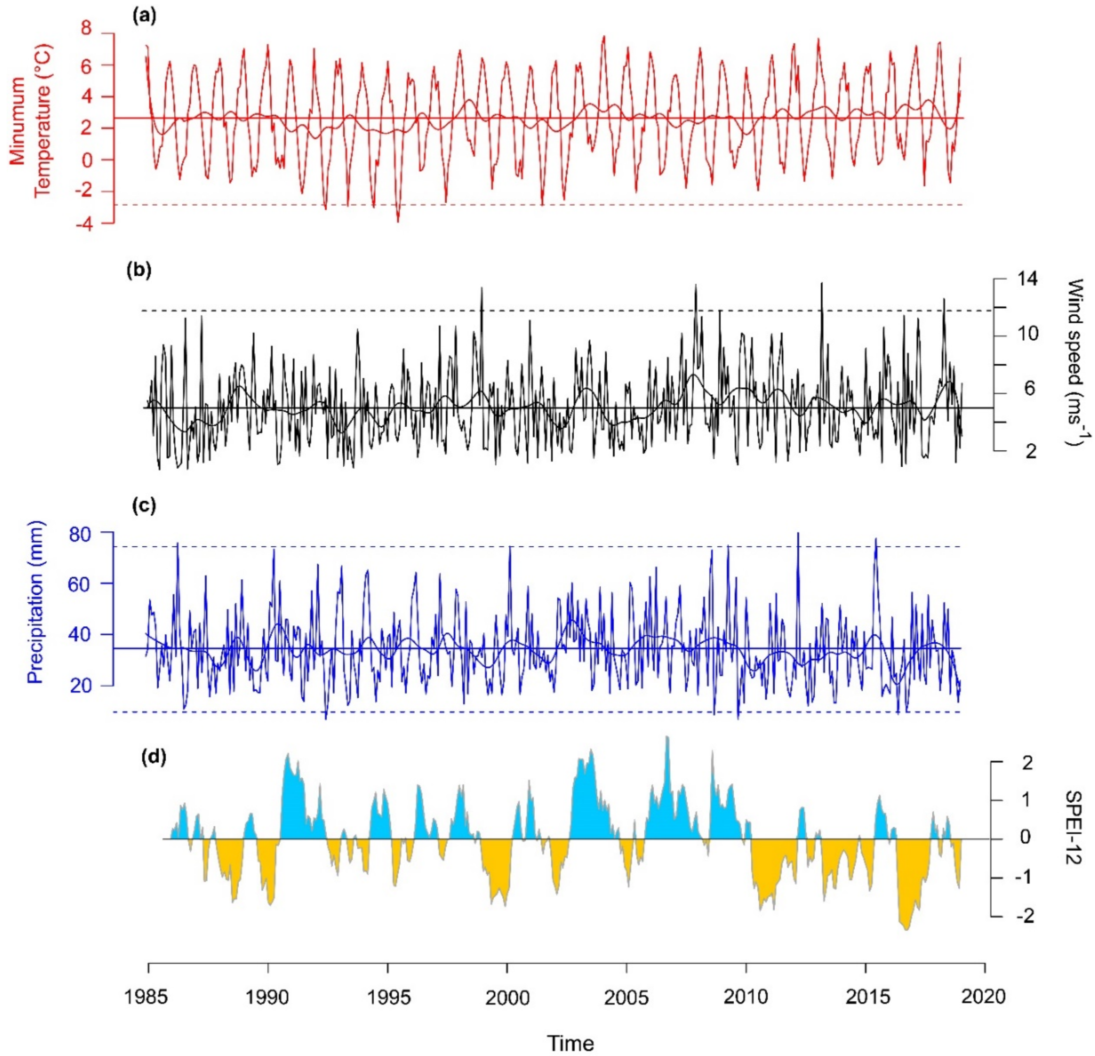

Figure 2. Magellan Region (MR) monthly climate time series (Climatic Research Unit Time-Series (CRU TS) 4.03) from January 1985 to December 2018 for: (**a**) minimum temperature (in °C); (**b**) wind speed (in ms−1), (**c**) precipitation (in mm), (**d**) standardized precipitation-evapotranspiration index (SPEI). Extreme events (EE) below the 1st percentile and above the 99th percentile are indicated (values surpassing dotted lines). SPEI scale ranges from −2 (very dry) to +2 (very wet). Pink (light blue) shaded stripes indicate dry (wet) periods.

The aridity index SPEI-12 (Figure 2d) is, as described, strongly influenced by the dry or wet precipitation periods. Thus, conditions with low precipitation values, higher minimum temperature and strong winds determine low values of SPEI-12 (drought) and vice-versa for wet periods. We found that most of the maximum precipitation events, in May 1986, March 2000, April 2009, March 2012, and winter 2015, occurred within phases of relatively dry conditions. In these cases, the erosion associated with the extreme events, with soil losses produced by an abrupt increase of running water, was higher than if these had occurred in more mesic conditions. These consequences included 2012 flooding in Punta Arenas [12], with more than 360 people affected [44].

4.2. Relationship between Climate Variability and Seasonal Vegetation Cover

Furthermore, we investigated the relationship between climatic variability, represented by the best-correlated variables precipitation (pre), minimum temperature (tmn), and potential evapotranspiration (pet) and the variations of regional vegetation cover (NDVI) as proxy for the aboveground net primary productivity (ANPP: [20,37,38]) on a spatio-temporal scale. We investigate the vegetation explained variance (LR2) by each of these climatic variables in the MR using a GWR analysis. We used a gridded climate dataset from 1985 to 2018, and NDVI from 1985/86 to 2018/19. Table 1 and Figures 3–5 show the results for the climatic variable with higher explained variance (LR2) for the regional NDVI data.

Table 1. Geographically weighted regression (GWR) analysis for NDVI data as a measure of aboveground net primary productivity (ANPP) using different climatic variables. Most significant results are shown in Figures 3–5, while those with less significance are not shown.

Dependent Variables	Independent Variables	Reference	R2	R2 Adjusted	LR2 Steppe & Transition Area
NDVI (sond)	pre (mjja)	Figure 3	0.76	0.72	60
NDVI (jfma)	pre (sond)		0.70	0.62	42
NDVI (jfma)	tmn (jfma)	Figure 4	0.67	0.62	47
NDVI (sond)	tmn (mjja)		0.83	0.77	50.5
NDVI (jfma)	pet (jfma)	Figure 5	0.67	0.62	39
NDVI (sond)	pet (sond)		0.77	0.74	57.5
NDVI (ann)	pre (ann)	Not shown	0.73	0.63	30
NDVI (ann)	tmn (ann)	Not shown	0.66	0.59	25
NDVI (ann)	pet (ann)	Not shown	0.62	0.57	30

Values of May to August and September to December average precipitation for this study were 6.6 mm and 7.3 mm, respectively (Figure 3). The spatial patterns for the distribution of precipitation illustrate the pronounced west-to-east regional gradient, reaching maximum values at high elevated glaciers and ice caps. NDVI presents values between 0.2 and 0.3 with more abundant vegetation cover occurring during the southern hemispheric spring months (SOND).

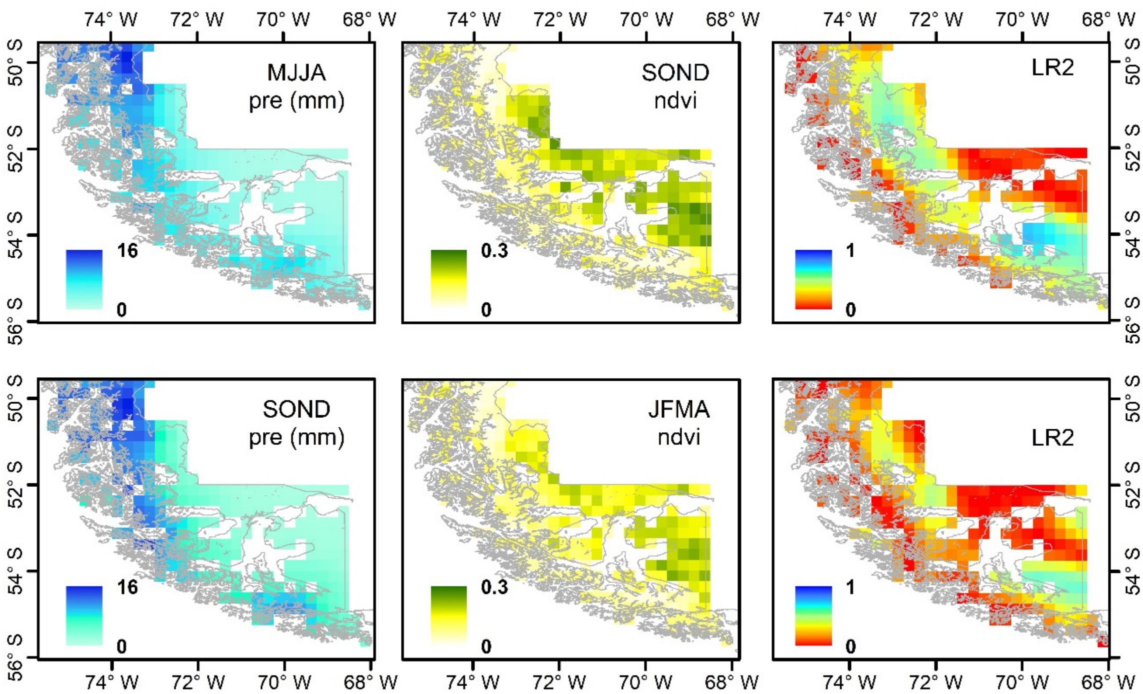

Figure 3. Spatial patterns of precipitation (left-hand plots), NDVI (center plots) and explained variance of the regression between precipitation and NDVI values from 1985–2018 (right-hand plots). JFMA = January to April, MJJA = May to August, SOND = September to December, LR2 = local squared regression coefficient.

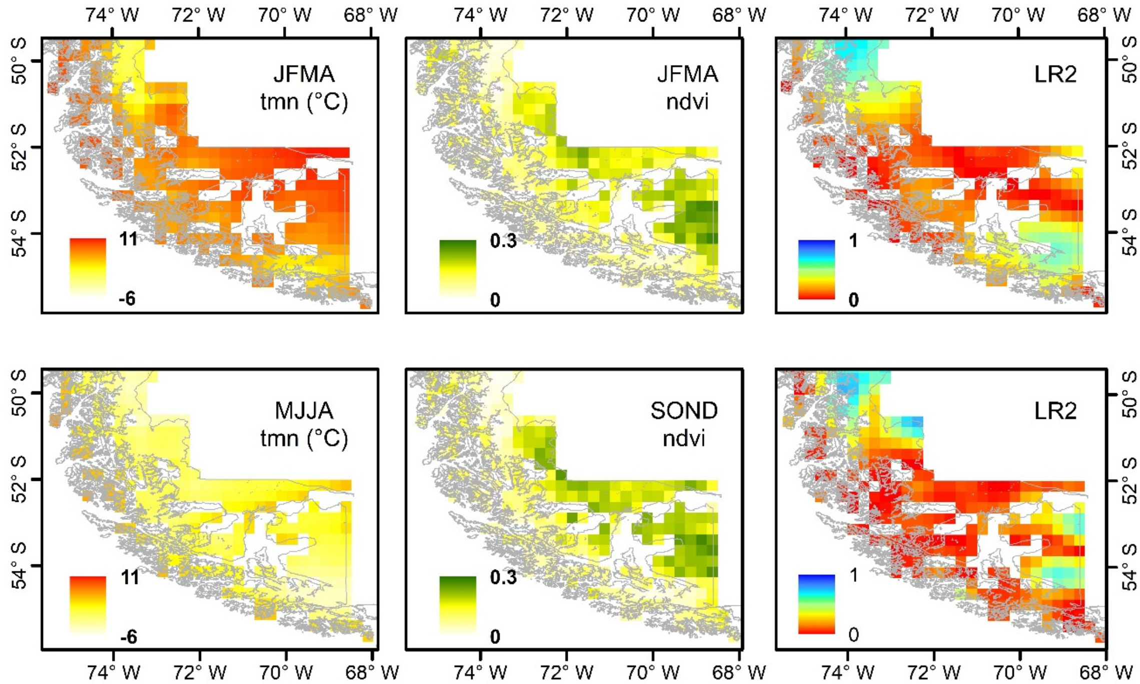

Figure 4. Spatial patterns of mean minimum temperature (left-hand plots), NDVI (center plots) and explained variance of the regression between mean minimum temperature and NDVI values from 1985–2018 (right-hand plots). JFMA = January to April, MJJA = May to August, SOND = September to December, LR2 = local squared regression coefficient.

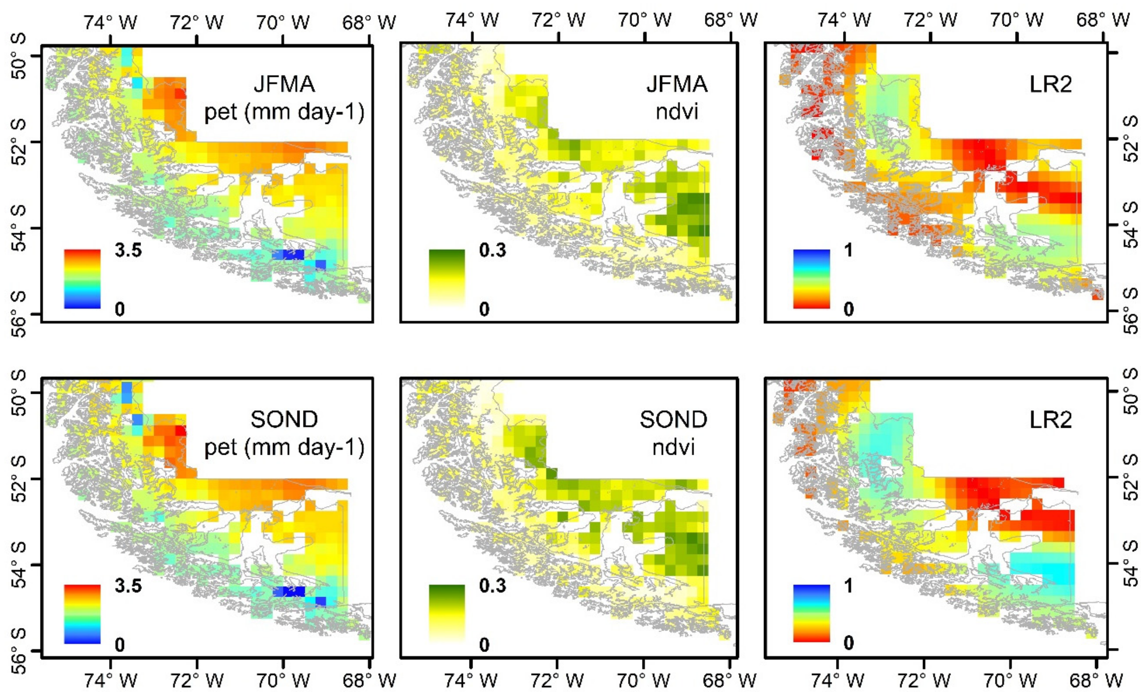

Figure 5. Spatial patterns of potential evapotranspiration (left-hand plots), NDVI (center plots) and explained variance of the regression between potential evapotranspiration and NDVI values from 1985–2018 (right-hand plots). JFMA = January to April, SOND = September to December, LR2 = local squared regression coefficient.

In general, we found the best levels of explained variance of vegetation cover, both with May to August and September to December precipitation, along the transition zone between forest-woodland

and steppe from north of Ultima Esperanza province and south of the Tierra del Fuego province (Figures 1 and 3). Not surprisingly, this is the zone where the most productive livestock farms in the MR are located. The amount of variance explained by the winter precipitation varied from 45 to 75% for Ultima Esperanza and south of Tierra del Fuego, respectively. Variance explained by spring precipitation varied between 45% and 60% in a northwest to southeast direction from Ultima Esperanza to south of Tierra de Fuego, while for the north-east steppe areas of Tierra del Fuego the explained variance varied from 24 to 45%. The resulting maps clearly indicate areas of strong positive correlation values between precipitation and vegetation cover. Significant values of explained variance (yellow to blue pixels) are found also in areas where high values of precipitation coincide with high values of NDVI.

Figure 4 indicates that January to April and May to August mean minimum temperatures were 6.6 and 0.76 °C, respectively. The spatial patterns for the minimum temperature during winter clearly indicate high values in the eastern area contrasted by low values in the surroundings of glaciated areas in the western parts. The pictured and temporal patterns of the NDVI are the same as already described in Figure 3. The amount of variance of vegetation cover explained by the minimum temperature varied from 48% to 60% from northern Ultima Esperanza to south of Tierra del Fuego. In contrast, the northernmost region of Tierra del Fuego presents an explained variance of 34%. May to August minimum temperature determines three areas of significant explained variance for the vegetation cover, namely northern Ultima Esperanza (25–76%), the north eastern parts of Tierra del Fuego (32–60%) and the southern parts of Tierra del Fuego (24–60%).

Figure 5 illustrates that the potential evapotranspiration per day for January to April and September to December were 2.1 mm in both cases. The highest values of pet are visible for the northern Ultima Esperanza province, east of Magallanes and Tierra del Fuego province with values of around 3 mm, indicating high values of loss of water by evaporation and transpiration. These values can be associated with solar radiation, temperature and wind [45,46]. The areas of the MR having the most significant values of explained variance by January to April of 40% and 50% are situated between Ultima Esperanza and south of Tierra del Fuego, and the northern parts of Tierra del Fuego with 34%. In addition, the eastern zone of Magallanes obtained explained variance values of around 28%. During the September to December period, the pet shows its highest values of explained variance at northern Ultima Esperanza (60%) and in the south of Tierra del Fuego (55–60%).

The spatial distribution of the vegetation cover explained variance (LR2) shows a similar geographical pattern for the different environmental factors considered here (Figures 1 and 3–5). In all cases, values with highest significance are the north-eastern zone of Ultima Esperanza province, the central part of Magallanes province and the southern zone of Tierra del Fuego province. These areas correspond to the transition zone between the deciduous forest-woodlands and the steppe. In contrast, the lowest values as displayed for the extreme west area of the MR, and the northern area of Tierra del Fuego can be associated with zones of less significance in terms of livestock usability (mountains, icefields, etc).

4.3. Relationship between Sheep Production and Climate Variability

Pearson Correlation analyses were performed for climatic variables (precipitation, wind speed and minimum temperature), NDVI and annual SP in the MR (Table 2 and Figure 6). Our target was to detect if any climate variable and NDVI indicate a direct and significant impact for SP. Since 1960 the SP has had a negative trend associated with the degraded grasslands [10]. We also found the same negative trend during the studied period and two short periods, 1995–1997 and 2015–2019, with extremely low SP.

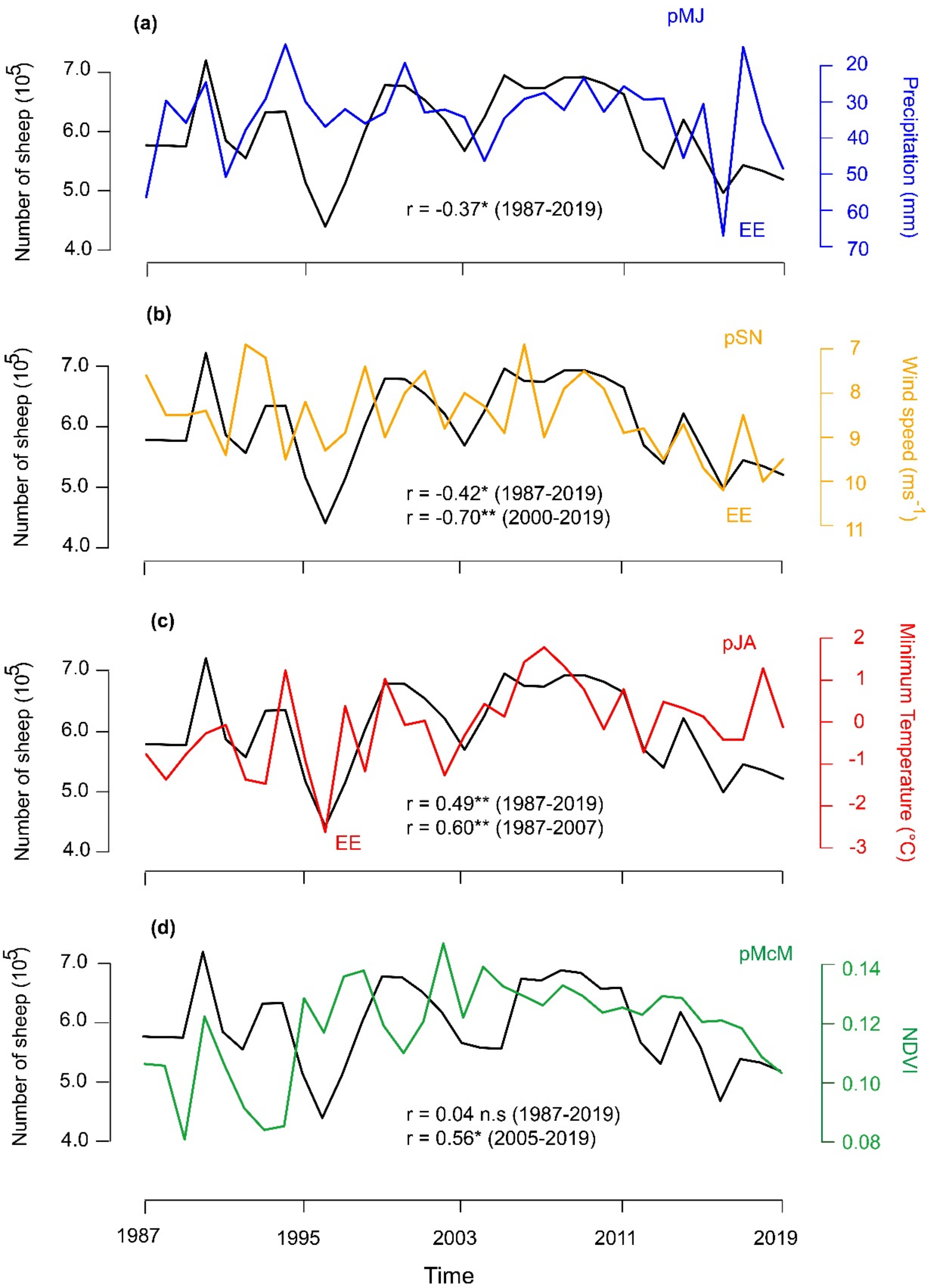

Figure 6. Pearson correlation analysis of sheep production (SP) with regional climatic variability and NDVI data as a measure of ANPP. Number of sheep (black line) against (**a**) previous May and June precipitation (pMJ: blue line), (**b**) previous September and November wind speed (pSN: orange line), (**c**) minimum temperature of previous July and August (pJA: red line) and (**d**) NDVI from NOAA of previous May and current May (pMcM: green line). The correlations coefficient are indicated at $p < 0.05$ (*), $p < 0.01$ (**) and no significant (n.s). Note that precipitation and wind speed values are displayed inverted for better understanding.

Table 2. Correlation analysis for sheep production and climatic variables. Significance is indicated by. * 95%, ** 99%, or n.s = not significant.

Dependent Variables	Independent Variables	Reference	Correlation
SP	pre (MJ)	Figure 6a	−0.37 * (1987–2019)
SP	ws (SN)	Figure 6b	−0.42 * (1987–2019) −0.70 ** (2000–2019)
SP	tmn (JA)	Figure 6c	0.49 ** (1987–2019) 0.60 ** (1987–2007)
SP	NDVI (pMcM)	Figure 6d	0.04 n.s (1987–2019) 0.56 * (2005–2019)
SP	pre (ann)	Not shown	0.24 n.s (1987–2019)
SP	ws (ann)	Not shown	−0.11 n.s (1987–2019)
SP	tmn (ann)	Not shown	0.33 n.s (1987–2019)
SP	NDVI (ann)	Not shown	−0.14 n.s (1987–2019)

In our study area, decreasing sheep production is strongly determined by the previous-year May–June precipitation, September–November wind speed, July–August minimum temperature and May to May ANPP. The SP time series clearly shows previously reported events that directly and indirectly affected production: (i) increased mortality by water deficit conditions in 1988, mid-1989 and early 1990, with negative effect in SP over the 1991–1992 period [10] (Figures 2c and 6a), (ii) low SP in 1996 can be clearly attributed to the harsh winter condition during the event called the "great snowfall" in 1995 [11] (Figure 6c). Previous May and June precipitation reveals a significant negative correlation with r = −0.37 ($p < 0.05$) (Figure 6a). June 2015 precipitation was approximately 70 mm, representing an EE and showing a strong negative impact on the annual sheep production (Figure 6a). In addition, a strong coincidence between the wind speed of around 10 ms−1 in September and November 2015 and the respective decline in sheep production is apparent (Figure 6b). This is further underlined by correlation analyses between both time series revealing a significant negative relationship (r = −0.42, $p < 0.05$) when considering previous September and November. By contrast, the correlation between sheep production and minimum temperature is positive with previous July and August (r = 0.49, Figure 6c), showing a direct influence of this climatic variable on the sheep production. Low SP for 2016 may be related to the extreme precipitation event of May–July of 2015, with values exceeding the 70 mm, and strong wind speed in September and November of the same year.

Despite correlation between SP and ANPP was not significant for the entire period, showed a positive correlation for the 2005–2019 period (r = 0.56, $p < 0.05$) (Figure 6d). The same is true when we consider shorter periods for the correlation between SP and temperature for the period 1987–2007 (r = 0.60, $p < 0.01$) and for the correlation between SP and wind speed during the 2000–2019 (r = −0.70, $p < 0.01$) (Figure 6b,c, respectively).

In addition, two low SP periods are influenced by the "great snowfall" and extreme weather events such as heavy rainfall and strong wind speed. Interestingly, all significant correlations are obtained with months and seasons of the previous year and not with the current vegetation period. The two extreme decays in sheep mass observed during these last 34 years coincide with extreme events of the climate variables selected for the previous years, indicating a clear delayed effect.

4.4. Impact of Extreme Events on Above Net Primary Productivity and Sheep Production

SEA results show that EE impacts critical stages of the SP as well as vegetation life cycles severely affecting their growing and survival rates (Figure 7). Vegetation cover is negatively affected by EE of both precipitation and frost events (Figure 7a). Heavy rainfall would affect growth for several months, while drought conditions do not show significance but showed a negative trend. Maximum summer temperatures have a positive effect on vegetation growth for the next month and negative effect on the next third and fourth months. Our SEA indicated that there is a negative effect for the same and the following month, most likely associated with the winter snow covering resulting in low grassland productivity; whereas, there would be a positive effect for the fourth month due to water storage availability (Figure 7a).

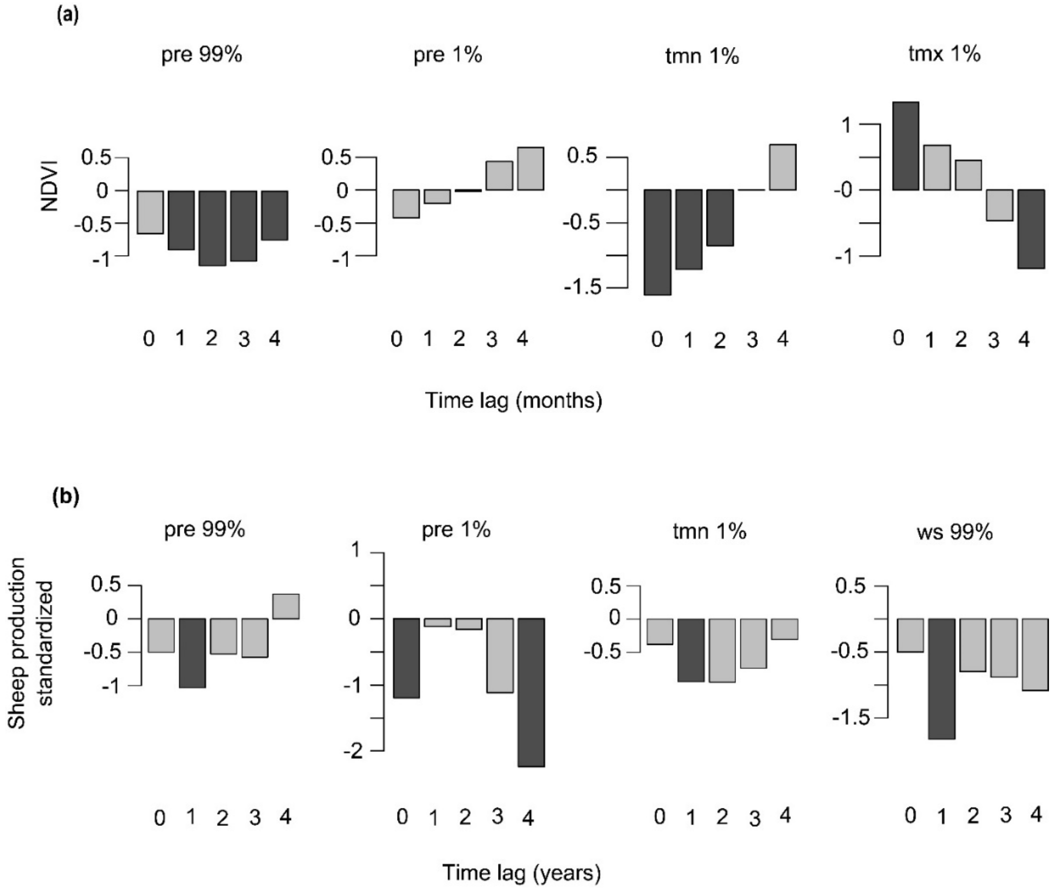

Figure 7. Superposed epoch analysis (SEA) comparing the effect of extreme weather events on (**a**) NDVI time series from 1985 to 2018, and (**b**) SP time series from 1987 to 2019. The black bars indicate values significant at the $p < 0.05$ level. Plot labels pre 99% and pre 1% represent EE defined by precipitation values above the 99th percentile and below the 1st percentile, respectively; tmn 1% represents EE defined by minimum temperature values below the 1st percentile; ws 99% represents EE defined by wind speed values above the 99th percentile; and tmx 99% represents EE defined by maximum temperature values above the 99th percentile.

SEA results for SP show only negative effects of EE either considering precipitation or temperature. The clearer effect is related to the year after decrease of SP due to strong rainfall/wind speed and frost. Droughts, for its side, show a direct negative effect on SP during the same year of the EE occurrence (Figure 7b).

5. Discussion

5.1. Extreme Weather Events, Net Primary Productivity and Sheep Production

MR time series of temperature, precipitation, wind velocity and aridity index show marked multi-decadal fluctuations as a general pattern. Climatic conditions fluctuate between wet-cold to dry-warm several times during the last decades. Climatic trends indicated by our work are coincident with the climatic projections for the next 50 years under the climate change in the Magallanes Region [14]. In addition, the large-scale climatic forcings such as the Antarctic Oscillation (AAO) with an increasing trend towards positive index values during the summer and autumn seasons may have a sustained effect on evaporation [47,48] Positive AAO values are also associated with dry conditions, which can also translate into a reduced cloud cover and more input of solar energy to the surface, increasing the evaporation process. During positive phases of the AAO, the advection of cooler sub (polar) air masses diminish, favouring the pronounced westerly airflow that would result in slightly higher temperatures during the winter season and a milder summer season.

An examination of the last three decades of climatic data show slight trends of increasing minimum temperatures. In contrast, precipitation is decreasing, leading to increasing aridity conditions. Under this general pattern, our study area showed recurrent extreme events (EE) such as the water deficit condition in 1988 [10], "great snowfall" of August 1995 [11], or extremely high precipitation over winter 2015 at Punta Arenas [12]. Wind speed is another important factor of environmental stress, which can directly impact vegetation cover and SP. The impact of increasing wind velocity has been demonstrated in wind exclusion essays for different crops that have a negative effect for its erosional and desiccant actions [46,49].

SEA results showed significant effects on ANPP and SP derived from stressed conditions associated with EE. ANPP for example is negatively affected by extreme rainfall-provoked flooding and frosting under extreme low minimum temperature as is shown also by recent work [17]. They studied the relationship between snow cover and NDVI for Tierra del Fuego, found out that strong snowfall may have a year-long effect on vegetation, prolonging the dormancy period. This would determine an opposite relationship between NDVI and snowfall and a legacy effect [21]. The correlation analyses between climate variables such as minimum temperature, reasonably associated with snowfall conditions in the MR and SP supports a one-year legacy effect (Figures 6 and 7).

Gestation and lambing periods during the 2015 winter–spring transition were affected by the extreme precipitation event of May–July of 2015 that provoked flooding. During this strong rainfall season sheep were giving birth or were already pregnant [41]. Therefore, the occurrence of an extreme event may affect fertility and/or the viability of newborn lambs, causing the low SP one year later (Figure 7b). During or soon after labor, ewes and lambs are outdoors, solely depending on the weather conditions, being ewes supply of colostrum of vital importance to avoid hypothermia. Spatial patterns of climate variability and ANPP and its associated SP reveal a more heterogeneous picture. Temporal trends in climate variability and its effect on vegetation cover do not reflect a uniform spatial expression across the MR. Spatial patterns of a strong relationship between precipitation and NDVI were already described for this region [4]. In our study we found similar results to those already reported for the Argentinian Patagonian steppe where precipitation and mean temperature are valuable predictors for vegetation growth [19–22]. We also found that the steppe and woodland vegetation is affected by summer minimum temperatures and spring–summer potential evapotranspiration. The north-eastern steppe areas of the MR with low amounts of precipitation, high temperatures and high potential evapotranspiration, are more prone to environmental stress. Potential evapotranspiration values are a good indicator of the areas with highest water loss, representing a parameter to be considered by sheep farmers looking to diminish irrigation costs [13,45]. These ecosystems must cope with higher water losses and consequently react with a corresponding high impact on plant iWUE strategies [50,51]. Differences in environmental stress along the southwest-to-northeast gradient determine differences on the response of the vegetation to climatic variability. Studies in Argentinian Patagonia pointed out that the ANPP in a network of ecosystems from arid to sub-humid is better correlated with climatic variables when the spatial distribution of these ecosystems are considered (based on multi-annual averages for different localities), more than using a temporal approach (based on inter-annual changes in single localities) [21]. More detailed studies including ecophysiological monitoring of the different ecosystems would allow us to look for a biological explanation for these differences, and more precise estimation of the effect on growing seasons of the plant communities [20].

5.2. Sheep Production, Climate and Aboveground Net Primary Productivity (ANPP)

Due to SP and ANPP being affected by biotic and abiotic factors, in livestock farming activities the management of biotic factors such as the appropriate choice of the animal variety, the forage availability along the year, animal loading and grazing period, and supplementary food use, will determine the overall success or failure of livestock production. In this work, we found that the percentage of explained variance for precipitation, temperature, wind, aboveground net primary productivity and its impact on the livestock population is highly significant. In this way, it is possible to analyse how extreme events can have additional effects on SP, if they are combined within multi-annual climatic variability. The low SP in 1991–1992 as consequence of water deficit in 1988, mid-1989 and early 1990 [10] and 1996 is attributed to harsh winter conditions during the "great snowfall" event in 1995 [11]. In our study, we detected that decreasing SP in 2016 relates to heavy precipitation and strong wind conditions of the previous months (Figures 6 and 7). In addition, the conditions of the previous years' spring-summer season are of similar relevance. We also identify better correlations when we compared SP with wind speed, minimum temperature and ANPP considering alternated shorter periods of analysis, reinforcing the idea that the climatic and ANPP influence on SP changes over time.

In general terms, current climate change in Fuego-Patagonia with its accelerated warming and dryness trend, together with increased wind velocities, have produced a vulnerable scenario without short- or long-term mitigation measures. The increase in minimum temperatures, winter precipitation, and the number of maximum wind speed events during spring, have led to several impacts on the grassland growth cycle and in consequence strongly affect the sheep production in the MR. Although some works speculate on possible beneficial effects of warming trends in areas traditionally affected by cold stress [17] our results indicate that the projections must consider the local characteristics in every case. Depending on the position of the management area in the MR environmental gradient, these effects must be positive or negative.

In summary, the SP sector must be aware of the climatic variability of this region and its potential impacts and of the months when these effects are more frequent. For this purpose, we suggest that public services and farming associations check monthly DMC reports [52] with seasonal and sub-seasonal meteorological forecasts (temperature, precipitation) three months in advance.

6. Conclusions

Our first hypothesis (H1) is partially accepted given that a significant percentage of ANPP variance is explained by high precipitation (400 to 1000 mm), more mesic temperatures, and lower evapotranspiration. These conditions are, however, spatially distributed in the transition zone between deciduous forests and steppe and is not a general pattern for the entire region. The second hypothesis (H2) is also accepted, with strong precipitation and wind velocity negatively affecting lamb survival, while temperature and ANPP present a positive correlation. The third hypothesis (H3) that tests the impact of EE on ANPP and SP, is also partially accepted. Most of the climatic variables negatively affect ANPP and SP; nevertheless, extreme events of maximum temperature resulted in an increase of ANPP, and droughts only showed a negative but non-significant trend in ANPP.

Our results found marked multi-decadal climatic fluctuations for the last 34 years with increasing importance of EE. These trends are affecting vegetation productivity and consequently SP in MR. Although sheep farming of Magallanes represents most of the total country's production, this important factor has not been studied from the perspective of the recent trends in climate change. Our results indicated that climate variables impact vegetation cover and sheep production, in a combined way. By not considering the result of our study and using only traditional practices, pasturelands deterioration might increase and farming productivity may be reduced accompanied by decreasing stocking rate.

Farmers in the MR should consider that the frequency of extreme events (EE) might increase in future due to climate change. Under this probable enhancement of extreme events the 3-month forecasting document developed by DMC, using temperature and precipitation, is an interesting tool of early alert for winter EE. Given our results, we support the conclusions in terms that the MR is a vulnerable zone prone to further pressure by EE under climate change scenario(s) [(Meza, 2014)].

This type of study fulfills the permanent analysis that should be submitted on the variations of the referred factors and its impacts on the local economy. The comparison of these variables should provide possibilities and recommendations for mitigation and/or adaptation measures, and to open communication channels among academia, public services, and local farmers, these last being the users of the resulting information.

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