Research Article

Piotr Goliński*, Marek Czerwiński, Marit Jørgensen, Jørgen A.B. Mølmann, Barbara Golińska, Gregory Taff

Relationship between climate trends and grassland yield across contrasting European locations

https://doi.org/10.1515/biol-2018-0070
Received December 8, 2018; accepted January 14, 2019

Abstract: We investigated climatic trends in two contrasting locations in Europe at a regional level and at two specific sites, and we analysed how these trends are associated with the dry matter yield (DMY) of agriculturally improved grasslands. Trends of different meteorological variables were evaluated for Wielkopolska province, central Poland (1985-2014) and Troms county, northern Norway (1989-2015), as well as for two research stations located in these regions. Significant trends of increased mean air temperatures annually, and in April, June, July, August and November were identified both at the regional and site levels in Wielkopolska. In addition, growing degree days were increasing in Wielkopolska. In Troms, the common trends for the region and site studied were increase in mean air temperature in May and decrease in January. Grassland DMY was subsequently regressed against those meteorological variables for which significant trends were detected. In the Wielkopolska region, yields were negatively associated with the increase in air temperature in June, August, and the annual air temperature. The last relationship was also detected at the site level. We did not find any significant effects of climate trends on grassland DMY in the Norwegian study site or region.

***Corresponding author: Piotr Goliński,** Department of Grassland and Natural Landscape Sciences, Poznań University of Life Sciences, 60632 Poznań, Poland, E-mail: pgolinsk@up.poznan.pl
Marek Czerwiński, Barbara Golińska, Department of Grassland and Natural Landscape Sciences, Poznań University of Life Sciences, 60632 Poznań, Poland
Marit Jørgensen, Jørgen A.B. Mølmann, Division of Food Production and Society, Norwegian Institute of Bioeconomy Research – NIBIO, Office Location Holt, 6269 Tromsø, Norway
Gregory Taff, Division of Survey and Statistics, Norwegian Institute of Bioeconomy Research – NIBIO, Office Location Ås, 1430 Ås, Norway

Keywords: climatic variable trends, agriculturally improved grassland, yield

1 Introduction

Observed climate change trends and weather anomalies have intensified in recent decades in almost all regions of Europe. The annual average temperature has increased, and there are more frequent high-temperature extremes. The warming has increased more in winter than in summer in Scandinavia [1], while summer temperatures have increased more in central and eastern Europe [2]. Precipitation has generally increased in northern Europe and decreased in southern parts of Europe, but heavy precipitation events have increased in many parts irrespective of total precipitation [1, 3].

Climate change is affecting grassland productivity across Europe [4]. Rising temperatures and altered amounts and pattern of precipitation affect water balance, grassland composition, biomass accumulation, and grassland quality, which has large consequences for feed production for livestock [1, 5-9]. Some studies have considered effects of projected climate changes on grassland productivity on a regional or broader geographical basis, e.g. for northern Europe [10], or for Mediterranean regions [11]. However, few studies address observed climate trends and their effect on local grassland productivity. Such studies could support the elaboration of models of grassland growth and be useful for management and efficient utilization of these changing ecosystems.

Climate change trends may differentially influence the growth and development of individual species and cultivars of forage grasses. In northern latitudes, the impact of changing winter climate on important grassland species and cultivars has been the focus of several studies [12 - 14], while in central Poland more attention is paid to drought stress [15].

This study addresses climate trends effects on grassland productivity in central Poland and northern Norway. In Poland, grassland yield has been reduced by increases in air temperature, water shortage and less favourable precipitation distributions during the growing season [16, 17]. In northern Norway, annual average temperature has increased with a prolonged growing season, warmer winter season and more episodes of extreme winter warming events in recent years [18, 19], influencing the de-hardening of the most important grass species and in consequence negatively affecting productivity of grassland [12, 13].

The objectives of this study were: 1) to evaluate the trends of climatic variables in two contrasting geographical locations in Europe (central Poland and northern Norway), and 2) to assess the influence of the detected trends on dry matter yield of agriculturally improved grasslands.

2 Materials and Methods

2.1 Study areas

The impact of changing climate on grassland yield was investigated at regional and site levels. Within Poland, the Wielkopolska province (regional) located in the west-central part of the country and the Brody experimental station (site-level) of Poznań University of Life Sciences (PULS) (52°26' N, 16°18' E; 92 m a.s.l.) were selected as study areas. For Norway, Troms county (regional) and the Holt research station (site-level) of the Norwegian Institute of Bioeconomy Research (NIBIO) (69°65' N, 18°54' E; 20 m a.s.l.) were chosen as study areas. Both regions, Wielkopolska province and Troms county cover about 30,000 km^2. Troms is situated above the Arctic Circle more than 1900 km north of Wielkopolska, at a similar longitude. According to the Köppen-Geiger system, the climate in Wielkopolska is warm, humid continental (Dfb) and the climate in Troms is subarctic (Dfc) [20]. To show differences in climate variables in those contrasting locations, the monthly and annual averages of daily air temperature and precipitation sums for Brody and Holt in the multiyear period are presented in Figure 1.

2.2 Weather data

Daily weather data for both regions were obtained from the national meteorological institutes based on statistical data in Poland [21] and Norway [22]. Data for Wielkopolska province (29827 km^2) were homogenized from five meteorological stations distributed within this region of The Polish Institute of Meteorology and Water Management – National Research Institute and data for Troms county (25877 km^2) were received from seven stations of The Norwegian Meteorological Institute located in this region of northern Norway. Weather data for Brody were collected by PULS's weather station and for Holt from NIBIO's weather station (Agrometeorology Norway, lmt.nibio.no). In Norway, these data covered the years from 1989 to 2015 and in Poland from 1985 to 2014. To determine specific climatic changes, trends in the following variables were analysed: i) annual and monthly

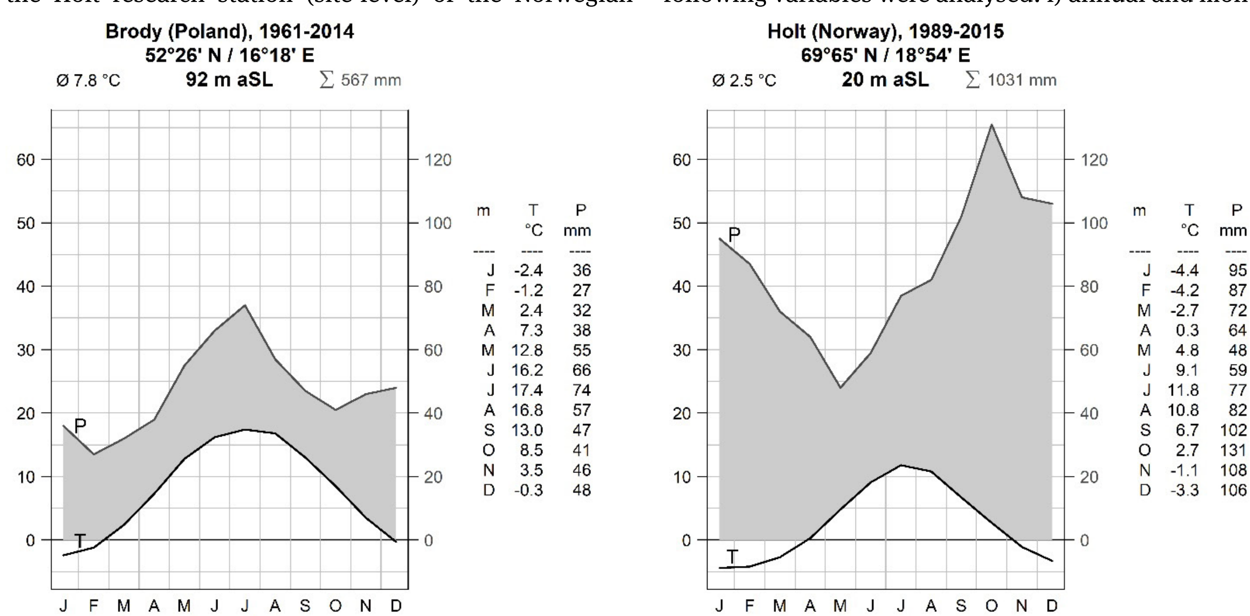

Figure 1. Climatic diagram according to Walter and Lieth for Brody and Holt

average daily air temperature, ii) annual and monthly total precipitation, iii) start and length of growing season, and iv) growing degree days during each growing season at base temperature 5°C. For this study, the beginning of the growing season was defined as the first spell of at least six days with average daily temperature above 5°C (as defined by Alexander et al. [23]) and the end of growing season was defined to be the approximate date of the last harvest cut, i.e. 31 August in Troms and 30 September in Wielkopolska.

2.3 Grassland yield data

The yield data in our study are based on forage yields from agriculturally improved grassland [24]. Data on annual dry matter yield (DMY) of grasslands in Wielkopolska province for the period of the considered time series were sourced from electronic data, yearbooks and bulletins published by the Central Statistical Office (CSO) of Poland [21]. According to the methodology of CSO, data of grassland DMY were gathered in each of 226 communes (gminas) belonging to this region as a total yield from three cuts per year. In the reference farms, a biometrical method using 0.5 m x 0.5 m quadrats and shares was used for yield determination of representative areas of grassland. For Troms, grassland yield data were obtained from the electronic records of Statistics Norway [25]. The records of total grass production per area are obtained from questionnaires to a subset of farmers. Before 1997 the methodology of estimating grassland DMY in Norwegian sites was calculated as hay yield (85% DM) on the basis of the energy content of the different types of forage (silage, bales, hay etc.). In 1997 the methods changed, and the estimated hay yield per ha is now based on average DM content of different types of forage. This caused a considerable difference in the estimated yield between the time series 1989-1996 and 1997-2015. Therefore, only the second (longer) time series was used for the analysis of the relationship between the detected climatic trends and grassland yield in Troms.

At the site level, data on DMY of agriculturally improved grasslands were obtained from the local research stations. In Brody, DMYs were collected for the analysed period from trials evaluating grass mixtures typical for site-specific conditions and also from trials testing individual grasses (perennial ryegrass, timothy, meadow fescue and cocksfoot – the most important and dominant grass species in the sward of agriculturally improved grassland in Wielkopolska). These data were collected from variety testing experiments set-up on 10 m^2 plots, in random block design, in three-four replicates, and were averaged by year. The plots were harvested with an experimental front mower, weighed fresh and then herbage subsamples of 0.5 kg were dried in a forced-draught oven for DMY determination after ca. 48 hours at 60°C. In Holt, DMY data were used from the national program for variety testing of timothy and meadow fescue, conducted on plots (1.5 m x 7.0 m) with three replicates and the same experimental design as above. The plots were cut with a Haldrup experimental harvester at ca. 5-7 cm stubble height, and DMY was determined in the same manner as in Brody. In the data analysis we used the annual DMY (a single value per year), which was the sum of DMY of two cuts in Norway and three cuts in Poland. The methodology of grassland DMY determination in both sites was based on commonly accepted protocol of assessment of variety value for cultivation and use.

2.4 Data analysis

For detection of climatic trends, a non-parametric Mann-Kendall test was used, since it does not require the data to be normally distributed, and has low sensitivity to abrupt breaks due to inhomogeneous time series [26 - 28]. Trends at the 5% significance level were flagged as statistically significant. Sen's slope estimator was used to assess the magnitude of trends, as the non-parametric proxy of a simple linear regression coefficient with time on the x-axis [29]. The sign of Sen's slope reflects the direction of a trend, while its value expresses the slope of the trend.

Before performing the Mann-Kendall test, all atmospheric data series were visually inspected for autocorrelation using the autocorrelation function "acf" in R [30]. Autocorrelation describes the so-called persistence of continuous variables, i.e. statistical dependence with their own past or future values. When present, autocorrelation has important implications for statistical inferences drawn from atmospheric data [28] and thus should be taken into account in further calculations. The generated plots indicated that there was no significant autocorrelation present in any of the series, so we applied the Mann-Kendall test "as is", without correcting the test for serial correlation.

The effect of the detected climatic trends on grassland yield was determined using simple linear regressions. The response variable was annual DMY of grasslands in the analysed regions or sites. The explanatory variables were climatic variables for which significant trends over the last three decades had been observed. The date of start of growing season was analysed as the Julian Date.

All statistical calculations were done in the R software environment, version 3.2.3 [30]. For the Mann-Kendall test, the 'Kendall' library was used [31]. Walter and Lieth climatic diagrams were plotted using the package 'berryFunctions' [32].

3 Results

3.1 Climatic trends

The analysis of precipitation sums and mean air temperature trends over the study period, carried out for individual months (Figures 2 and 3), showed that trends observed at the site level (for Brody and Holt) are consistent with trends observed at the regional level (for Wielkopolska and Troms, respectively). This accordance concerns particularly the changes in air temperature. In the case of precipitation, there are some discrepancies between regional and site levels, as this climatic variable varies more locally within these regions.

As far as monthly air temperature is concerned, a general warming trend was observed for Wielkopolska. The significant changes were detected for as many as five months (April, June, July, August and November), and the greatest temperature rise, almost 0.10°C per year was observed for June, July, and November (Figure 2). These monthly trends also contributed to the significant increase in average annual temperature in Wielkopolska and Brody (Table 1). For Troms, considerable warming was detected for May, September, October and November, but only the rise of temperature in May was significant (*p*-values for May, September, October and November in Troms were 0.0110, 0.0763, 0.2602, and 0.2783, respectively). For Troms, a significant decrease in air temperature in January was also observed (*p*-value = 0.0156). Similar trends were detected for Holt, however decrease in air temperature in January was not significant.

The majority of the trends in the monthly precipitation series were not significant (Figure 3). The only significant changes were observed for January in Troms (decrease) and March and April in Holt (increase) as well as for May and December in Wielkopolska (increase and decrease, respectively) and for January and December in Brody (increase and decrease, respectively). These monthly trends did not translate into significant trends in annual precipitation sums in Norway, nor in Poland (Table 1).

No significant trends were detected in the start of growing season for the studied areas and sites (Table 1), but at Holt Station, there was a near-significant trend of earlier start (*p*-value 0.0758). However, it was observed that growing degree days have been increasing over the

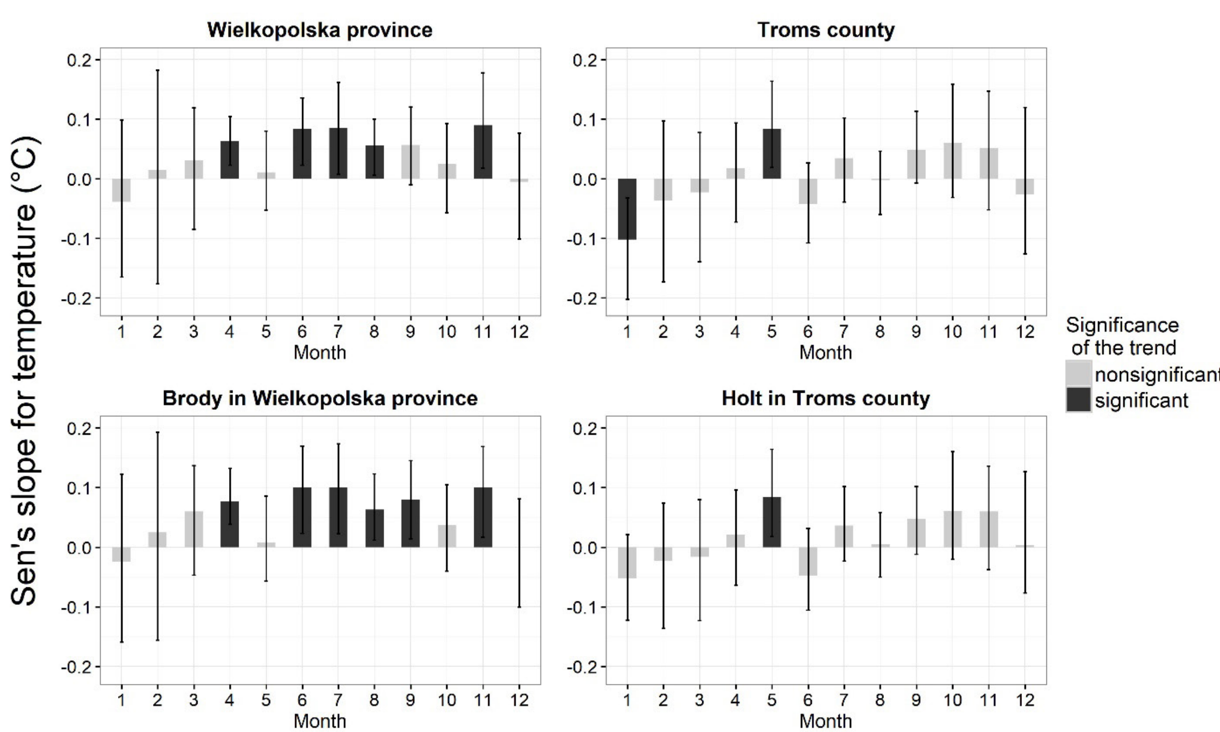

Figure 2. Direction and magnitude of trends of monthly mean air temperature in analysed regions and sites in central Poland (1985-2014) and northern Norway (1989-2015); the height of the columns designates the value of Sen's slope, which is the magnitude of change, and the error bars represent confidence intervals; the results marked as significant are those for which the *p*-value was lower than 0.05

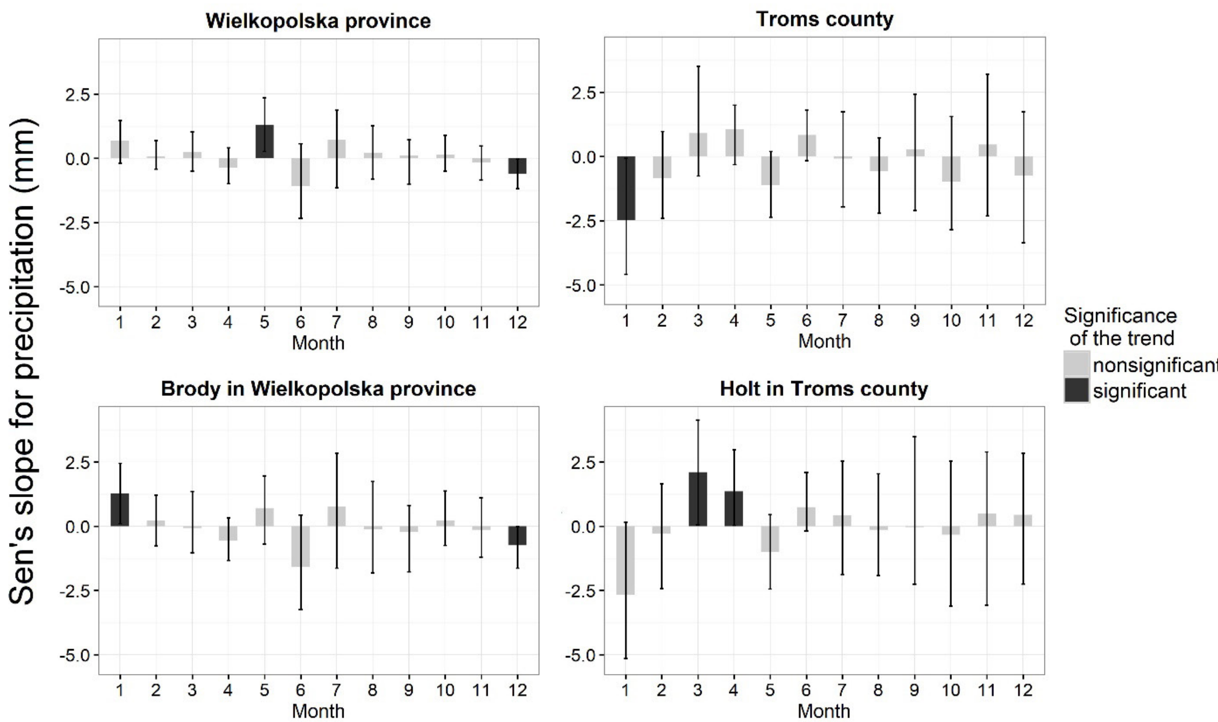

Figure 3. Direction and magnitude of trends of monthly precipitation sums in analysed regions and sites in central Poland (1985-2014) and northern Norway (1989-2015); the height of the columns designates the value of Sen's slope, which is the magnitude of change, and the error bars represent confidence intervals; the significant results are those for which the *p*-value was lower than 0.05

Table 1. Climatic trends for yearly parameters in analysed regions and sites in central Poland (1985-2014) and northern Norway (1989-2015)

Climatic variable	Estimator	Wielkopolska province	Brody in Wielkopolska province	Troms county	Holt in Troms county
Yearly mean air temperature	Mean (°C)	8.8	8.8	3.4	3.9
	Sen's slope (°C)	0.04	0.06	0.02	0.02
	Two-sided *p*-value	0.0153*	0.0083**	0.3170	0.2266
Yearly precipitation sum	Mean (mm)	538	653	939	964
	Sen's slope (mm)	1.2	0.5	-2.0	3.3
	Two-sided *p*-value	0.5680	0.8865	0.2034	0.4044
Growing season start	Mean (day of a year)	82	80	133	133
	Sen's slope (day of a year)	-0.47	-0.39	-0.29	-0.56
	Two-sided *p*-value	0.1006	0.2449	0.3923	0.0758
Growing degree days (5°C base)	Mean (°C)	2789	2773	1154	1116
	Sen's slope (°C)	13.6	15.5	4.9	5.9
	Two-sided *p*-value	0.0004***	0.0004***	0.0799	0.0411*

*; **; *** - denotes significance at the 0.05; 0.01; 0.001 levels, respectively

last three decades in Wielkopolska and Brody (p-value 0.0004), as well as in Troms and Holt (p-values 0.0799 and 0.0411, respectively).

3.2 Impact of climatic variables on the yield of grasslands

In Wielkopolska, among the detected climatological trends, DMY of agriculturally improved grassland was found to be negatively associated with the increase of temperature in June and August, the increase of growing degree days, and by the rise in annual temperature. The increase of annual temperature by 1°C was associated with an average reduction of grassland yield by 33 kg ha^{-1} of DM (regression coefficient -0.33, Table 2). The effect of the increase of each growing degree day on the DMY is marginal (regression coefficient -0.001 kg ha^{-1} of DM). At Brody, DMY of grasslands was shown to be negatively associated with the increase in mean annual air temperature (regression coefficient -0.60, meaning an increase of 1°C results in an average decrease of 0.6 kg ha^{-1} of DM, Table 2). No significant relationships between grassland yield and the changing climatic variables were found for northern Norway at regional or site level, except for sa lightly positive effect of the increasing growing degree days on the DMY at the site level.

4 Discussion

4.1 Detected climatic trends

The obtained results confirm the general climatic trends for the whole of Europe. During the 20th century, Europe experienced an increase in average annual surface temperature of 0.8°C, with an increased rate of warming over time [33]. Our study shows that annual temperature and several monthly temperatures have increased significantly over the study period in central Poland (April, June, July, August and November), and for May in Troms county, Norway. In Wielkopolska, temperatures were increasing in most months, even if these increases were not statistically significant. For Troms, Norway, monthly temperature changes were more varied (Figure 2). Yearly air temperature data for central Poland and northern Norway were increasing but the trend was statistically significant only in Poland, at both the regional and site levels. The results are in line with the conclusions of other authors, e.g. [16, 18, 34], concerning significant climate trends in central Poland and northern Norway. These changes in temperatures were statistically significantly associated with grassland productivity in Poland, but not in Norway.

Precipitation trends are more varied by regions across Europe. Trends in the 20th century showed an increase in precipitation in northern Europe by 10-40% and decrease in some regions in Southern Europe by up to 20% in average annual precipitation [33]. Significantly more precipitation occurred in May in the Wielkopolska region, and in January at the Brody site, and in the March-April period at the Holt site (Figure 3). Significantly less precipitation was confirmed in the Wielkopolska region and at the Brody site in December, and visibly less (although not significant) in June in central Poland and in May in northern Norway. Changes in timing of precipitation affect soil water capacity and can have major effects on grass growth [4, 15], particularly in Poland, where a strong relationship between hot weather and lack of precipitation since 1950 was recorded by Wibig [35].

4.2 The impact of climate trends on grassland yield

Trnka et al. [36] reported that in central Europe, the projected climate change would bring more rainfall in winter, less in summer and an increased drought risk. As confirmed by Smith et al. [9] and Dai [37], drier summers can lead to significant drops in grassland productivity, as a consequence of reduction of the intensity of photosynthesis and transpiration [15]. In the case of Wielkopolska region, the increased temperatures during the summer months accompanied by less precipitation (although not significant) in June has led to drought which likely limited grassland yield. However, the effect of climate variables on grassland productivity greatly depends on site soil conditions. In another study [38], climate change at Brody during a 50-year period with increasing mean annual air temperature ($p<0.001$) and increasing precipitation sum ($p<0.05$) had significant impact on yield of grasslands located on mineral soils. The relationship between standardized precipitation evapotranspiration index (SPEI) estimated for the 6-month period from April to September and annual DM yield was positive, while no significant effect was found for any quantified change in climate on grassland yield located on organic soils [38]. For the Norwegian study areas we found a significant effect of the increasing growing degree days on grassland yield in Holt, but this effect was very small (regression coefficient 0.01) and it was not found at the regional level. Although significantly increasing

Table 2. Association of climatic variables with significant trends on the DMY of agriculturally improved grassland in central Poland (1985-2014) and northern Norway (1989-2015)

Climatic variable	Regression coefficient	Standard error	*t* value	*p*-value[1]	R^2 adj.
Wielkopolska province					
Mean air temperature yearly	-0.33	0.112	-2.93	0.0069**	0.43
Growing degree days (5°C base)	-0.001	0.001	-3.48	0.0017**	0.48
Mean air temperature in April	-0.06	0.083	-0.78	0.4450	0.26
Mean air temperature in June	-0.25	0.073	-3.45	0.0019**	0.48
Mean air temperature in July	-0.13	0.056	-2.38	0.0244	0.38
Mean air temperature in August	-0.19	0.084	-2.28	0.0308*	0.37
Mean air temperature in November	-0.10	0.055	-1.81	0.0817	0.33
Sum of precipitation in May	0.01	0.004	1.38	0.1789	0.30
Sum of precipitation in December	0.00	0.006	0.37	0.7177	0.25
Brody in Wielkopolska province					
Mean air temperature yearly	-0.60	0.260	-2.29	0.0304*	0.64
Growing degree days (5°C base)	0.00	0.001	-1.48	0.1500	0.60
Mean air temperature in April	-0.21	0.176	-1.21	0.2376	0.59
Mean air temperature in June	-0.22	0.152	-1.45	0.1588	0.60
Mean air temperature in July	-0.10	0.124	-0.83	0.4133	0.58
Mean air temperature in August	-0.26	0.182	-1.41	0.1694	0.60
Mean air temperature in September	-0.22	0.150	-1.45	0.1588	0.60
Mean air temperature in November	-0.10	0.132	-0.73	0.4695	0.47
Sum of precipitation in January	0.00	0.009	-0.38	0.7040	0.57
Sum of precipitation in December	0.00	0.009	0.54	0.5959	0.46
Troms county					
Growing degree days (5°C base)	0.00	0.001	0.63	0.5361	-0.03
Mean air temperature in January	-0.02	0.044	-0.35	0.7298	-0.05
Mean air temperature in May	-0.03	0.065	-0.48	0.6309	-0.04
Sum of precipitation in January	0.00	0.002	0.12	0.9037	-0.05
Holt in Troms county					
Growing degree days (5°C base)	0.01	0.003	3.42	0.0027**	0.34
Mean air temperature in May	0.56	0.361	1.55	0.1380	0.06
Sum of precipitation in March	0.01	0.010	0.77	0.4493	-0.02
Sum of precipitation in April	0.00	0.015	0.30	0.7653	-0.05

[1]significant trends (*p*-value < 0.05) were marked with asterisks.

*; ** - denotes significance at the 0.05 and 0.01 levels, respectively.

temperatures in May and an increase in growing degree days were found, which is expected to increase DMY, these changes may have been modified by substantial (though not significant) decreases in temperatures in June. In addition, winter months have been colder in northern Norway (January – statistically significant, February, and March, see Figure 2). Higher temperatures in autumn (though not significant at the regional and site levels) will shift cold acclimation of the plants to a time when less light is available and impairs freezing tolerance of many grass species [12, 39]. In addition, unstable winter temperatures and early springs can cause plants to de-acclimate, when there is still a risk of freezing [13]. Repeated freeze-thaw cycles during winter also increase the risk of impermeable layers of ice forming in the grass fields, which can cause substantial winter losses due to the anoxic conditions that arise under the ice [12].

4.3 Implications for grassland management

The recognition of regionally-specific changing climate trends is an important part of sustainable grassland management. In both analysed cases in Poland and Norway, climate trends may affect grassland productivity positively as well as negatively, depending upon the magnitude of the trend and on the water holding capacity of the soil on which the specific meadow or pasture is located [38]. Thus, the projected IPCC climate scenarios could lead to various outcomes on grassland yield, depending on the specific timing of temperature and precipitation changes. It is therefore necessary to build and maintain monitoring systems of productivity of grasslands with implications of difference between regions, and refine analysis methods to understand trends and anomalies that are likely to continue into the future. It has been shown that synthetic indices are most relevant for Polish study sites, such as standardized precipitation evapotranspiration index [38, 40], HTC Selyaninov hydrothermal coefficient [41], and Vinczeffy climate index [42], but for northern Norway, in addition to the climate indices measured in this study, winter climate, soil frost and ground-ice accumulation should be studied and incorporated to model effects of climate changes on productivity and winter kill of grasses [12, 14]. The growing supply of remote sensing data and products provide opportunities for more rapid detection and monitoring of grassland conditions and associated changes in productivity at the national, regional and the individual grassland scale [16].

It should be underlined that these case studies focus on agriculturally improved grasslands. The impact of climate change trends on grasslands renovated, fertilized and utilized for forage may be much stronger than that of natural and semi-natural grassland communities (not managed by means other than grazing or mowing). The sward of agriculturally improved grassland is composed of highly productive varieties of grass and legume species obtained as a result of plant breeding. Their productivity potential can be achieved only by optimal management in appropriate weather conditions. Our results show that more significant associations of climatic variable with grassland DMY occurred in Wielkopolska and Brody, compared to northern Norway, although the grassland swards in central Poland are typically multi-species, in contrast to northern Norway where grasslands are mostly dominated by timothy. Ergon et al. [43] argue that in the face of unstable and uncertain climatic conditions, a high diversity of cultivated forage species, high intraspecific genetic diversity, and the use of species and variety mixtures can enhance productivity and resilience of grasslands. Higher species richness can affect yield stability positively in intensively managed grasslands, and can increase drought resistance as long as the management does not lead to plant-species loss [44], but only if there is sufficient amount of water available.

Management practices well adapted to more variable and stressful environments are needed for maintaining the agricultural productivity of grasslands and their other ecosystem functions in both analysed regions in the future. Breeding and research efforts should be directed both towards improving plant strategies to cope with abiotic stresses, and towards adaptation to new seasonal patterns and management, while minimizing possible trade-offs with productivity [43]. There are challenges to obtain grass varieties resistant to drought in central Poland [15, 45] and to winterkilling in northern Norway [46, 47], while maintaining high productivity. Other adaptation approaches to climate changes are new strategies of grassland fertilization [17], soil moisture optimization by irrigation and/or drainage, use of variable cutting dates, and flexible grazing plans [8, 10].

Acknowledgements: This work was supported by the Polish-Norwegian Research Programme Project ‘Finegrass’ (grant 203426/82/2013), and by the Fram Centre (grant 362208, 2014, 2015, 2016).

Conflict of interest: Authors state no conflict of interest.

References

[1] Kovats RS, Valentini R, Bouwer LM, Georgopoulou E, Jacob D, Martin E, et al. . Europe. In: Barros VR, Field CB, Dokken DJ, Mastrandrea MD, Mach KJ, Bilir TE, et al. editors. Climate Change 2014: Impacts, Adaptation and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press; 2014. p. 1267-326.

[2] Anders, I., Stagl, J., Auer, I., & Pavlik, D. Climate Change in Central and Eastern Europe. In: Rannow S, Neubert M, editors. Managing Protected Areas in Central and Eastern Europe Under Climate Change. Advances in Global Change Research. Dordrecht: Springer; 2014. p. 17-30.

[3] Seneviratne SI, Nicholls N, Easterling D, Goodess CM, Kanae S, Kossin J, et al. Changes in climate extremes and their impacts on the natural physical environment. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge and New York: Cambridge University Press; 2012. p. 109-230.

[4] Kipling RP, Virkajärvi P, Breitsameter L, Curnel Y, De Swaef T, Gustavsson A-M, et al. Key challenges and priorities for modelling European grasslands under climate change. Sci Total Environ 2016;566-567:851-64.

[5] Cantarel AM, Bloor JMG, Soussana J. Four years of simulated climate change reduces above-ground productivity and alters functional diversity in a grassland ecosystem. J Veg Sci 2013;24:113-26.

[6] Hoffstätter-Müncheberg M, Merten M, Isselstein J, Kayser M, Wrage-Mönnig N. Drought effects on herbage production of permanent grasslands in northern Germany. Grassland Sci Eur 2014;19:106-8.

[7] Huyghe C, De Vliegher A, Goliński P. European grasslands overview: temperate region. Grassland Sci Eur 2014;19:29-40.

[8] Joyce CB, Simpson M, Casanova M. Future wet grasslands: ecological implications of climate change. Ecosyst Health Sustain 2016;2(9):e01240.

[9] Smit HJ, Metzger MJ, Ewert F. Spatial distribution of grassland productivity and land use in Europe. Agr Syst 2008;98:208-19.

[10] Höglind M, Thorsen SM, Semenov MA. Assessing uncertainties in impact of climate change on grass production in Northern Europe using ensembles of global climate models. Agr Forest Meteorol 2013;170:103-13.

[11] van Oijen M, Balkovič J, Beer C, Cameron DR, Ciais P, Cramer W, et al. Impact of droughts on the carbon cycle in European vegetation: a probabilistic risk analysis using six vegetation models. Biogeosciences 2014;11:6357-75.

[12] Höglind M, Bakken AK, Jørgensen M, Østrem L. Tolerance to frost and ice encasement in cultivars of timothy and perennial ryegrass during winter. Grass Forage Sci 2010;65:431-45.

[13] Jørgensen M, Østrem L, Höglind M. De-hardening in contrasting cultivars of timothy and perennial ryegrass during winter and spring. Grass Forage Sci 2010;65:38-48.

[14] Bjerke JW, Tømmervik H, Zielke M, Jørgensen M. Impacts of snow season on ground-ice accumulation, soil frost and primary productivity in a grassland of sub-Arctic Norway. Environ Res Lett 2015;10:095007.

[15] Staniak M, Kocoń A. Forage grasses under drought stress in conditions of Poland. Acta Physiol Plant 2015;37:116.

[16] Dąbrowska-Zielińska K, Goliński P, Jørgensen M, Mølmann J, Taff G, Tomaszewska M, et al. New methodologies for grasslands monitoring. In: Vijay D, Srivastava MK, Gupta CK, Malaviya DR, Roy MM, Mahanta SK, et al. editors. Sustainable use of grassland resources for forage production, biodiversity and environmental protection. Proceedings of the 23rd International Grassland Congress, New Delhi: Rangeland Management Society of India; 2015. p. 30-40.

[17] Golińska B, Czerwiński M, Goliński P, Blecharczyk A, Sawińska Z. Effect of climate changes on productivity of fresh meadows on the background of their different fertilization. Fragmenta Agronomica 2016;33(4):18-28.

[18] Hanssen-Bauer I, Førland EJ. Daily maximum and minimum temperatures. In: Førland EJ, editor. Background information for “Klima i Norge 2100” on freezing/thawing, minimum/ maximum temperature, short-term rainfall, wind and permafrost. NCCS report no. 1/2016. Norwegian Centre for Climate Services; 2016. p. 15-20.

[19] Vikhamar-Schüler D, Isaksen K, Haugen JE, Tømmervik H, Luks B, Vikhamar-Schüler T, et al. Changes in winter warming events in the Nordic Arctic Region. J Climate 2016;29:6223-44.

[20] Pidwirny M. Climate Classification and Climatic Regions of the World. Fundamentals of Physical Geography, 2nd Edition. Date Viewed. 2006. Available from: http://www.physicalgeography.net/ fundamentals/7v.html.

[21] Statistical Yearbook of the Regions – Poland (years 1985-2014). Warsaw: Central Statistical Office; 2015.

[22] MET info (years 1989-2015). Oslo: The Norwegian Meteorological Institute; 2016.

[23] Alexander L, Yang H, Perkins S. ClimPACT - Indices and software. A document prepared on behalf of the commission for climatology (CCl) expert team on climate risk and sector-Specific Climate Indices (ET CRSCI). 2013. Available from: http://www.wmo.int/.../ETCRSCI_software_documentation_v2a.doc.

[24] Velthof GL, Lesschen JP, Schils RLM, Smit A, Elbersen BS, Hazeu GW, et al. Grassland areas, production and use. Lot 2. Methodological studies in the field of Agro-Environmental Indicators. Wageningen: Alterra Wageningen UR; 2014.

[25] Statistics Norway (years 1989-2015). Oslo: Statistics Norway; 2016.

[26] Mann HB. Nonparametric tests against trend. Econometrica 1945;13:245-59.

[27] Kendall MG. Rank Correlation Methods, 4 Edition. London, UK: Charles Griffin; 1975.

[28] Wilks D. Statistical Methods in the Atmospheric Sciences, 3rd Edition. Academic Press; 2011.

[29] Sen PK. Estimates of the regression coefficient based on Kendall’s tau. J Amer Stat Ass 1968;63(324):1379-89.

[30] R Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. 2015. Available from: https://www.R-project.org/

[31] McLeod AI. Kendall: Kendall rank correlation and Mann-Kendall trend test. R package version 2.2. 2011. Available from: https://CRAN.R-project.org/package=Kendall

[32] Boessenkool B. berryFunctions: Function Collection Related to Plotting and Hydrology. R package version

1.17.0. 2018. Available from: https://CRAN.R-project.org/package=berryFunctions
[33] Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE. IPCC Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK; 2007.
[34] Karlsen SR, Høgda KA, Wielgolaski FE, Tolvanen A, Tømmervik H, Poikolainen J, et al. Growing-season trends in Fennoscandia 1982-2006, determined from satellite and phenology data. Climate Res 2009;39:275-86.
[35] Wibig J. Has the frequency or intensity of hot weather events changed in Poland since 1950? Adv Sci Res 2012;8:87-91.
[36] Trnka M, Olesen JE, Kersebaum KC, Skjelva AO, Eitzinger J, Seguin B, et al. Agro-climatic conditions in Europe under climate change. Global Change Biol 2011;17:2298-318.
[37] Dai A. Drought under global warming: a review. Wiley Interdisciplinary Reviews: Climate Change 2011;2:45-65.
[38] Goliński P, Czerwiński M, Golińska B. Effect of climate change in 50-years period on grassland productivity in central Poland. In: Roy AK, Kumar RV, Agrawal RK, Mahanta SK, Singh JB, Das MM, et al. editors. Sustainable use of grassland resources for forage production, biodiversity and environmental protection, Extended Abstracts 23rd International Grassland Congress, New Delhi: Rangeland Management Society of India; 2015. p. 286-9.
[39] Dalmannsdottir S, Jørgensen M, Rapacz M, Østrem L, Larsen A, Rognli OA. Cold acclimation in warmer extended autumns impairs freezing tolerance of perennial ryegrass (Lolium perenne L.) and timothy (Phleum pratense L.). Physiol Plant 2017;160:266-81.
[40] Vicente-Serrano SM, Beguería S, López-Moreno JI. A multiscalar drought index sensitive to global warming: the standardized precipitation evaporation index. J Climate 2010;23:1696-718.
[41] Selyaninov GT. Methods of climate description to agricultural purposes. In: World Climate and Agriculture Handbook. Leningrad-Moscow; 1937.
[42] Vinczeffy I. The effect of some ecological factors on grass yields. In: The impact of climate on grass production and quality. Proceedings of the 10th General Meeting of the EGF, 1984 Jun 26-30; Ås, Norway. European Grassland Federation; 1984. p. 76-9.
[43] Ergon Å, Seddaiu G, Korhonen P, Virkajärvi P, Bellocchi G, Jørgensen M, et al. How can forage production in Nordic and Mediterranean Europe adapt to the challenges and opportunities arising from climate change? Eur J Agron 2018;92:97-106.
[44] Klaus VH, Hölzel N, Prati D, Schmitt B, Schöning I, Schrumpf M, et al. Plant diversity moderates drought stress in grasslands: implications from a large real-world study on ^{13}C natural abundances. Sci Total Environ 2016;566-567:215-22.
[45] Kopecký D, Loureiro J, Zwierzykowski Z, Ghesquière M, Doležel J. Genome constitution and evolution in Lolium × Festuca hybrid cultivars (Festulolium). Theor Appl Genet 2006;113:731-42.
[46] Østrem L, Rapacz M, Jørgensen M, Höglind M. Impact of frost and plant age on compensatory growth in timothy and perennial ryegrass during winter. Grass Forage Sci 2010;65:15-22.
[47] Thorsen SM, Höglind M. Assessing winter survival of forage grasses in Norway under future climate scenarios by simulating potential frost tolerance in combination with simple agroclimatic indices. Agr Forest Meteorol 2010;150:1272-82.