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EFFECT OF PRECIPITATION ON THE YIELD OF HAY MEADOWS WITH CONTRASTING NUTRIENT SUPPLY

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Abstract

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Available nutrients and water are known as major factors influencing the production of grasslands. In the present paper effects of precipitation on hay production was studied on nutrient-rich (NR) and nutrient-poor (NP) soils, in a long-term field experiment from 2002 to 2012. The most effective period of precipitation was also investigated. Using a mixture of 8 grass species, we established a grassland (near to Sárbogárd, Hungary) where 16 permanent quadrates each 6 m by 6 m in area were marked out, of which 8 were abundantly and other 8 were poorly supplied with N, P and K nutrients. Quadrates were harvested in early June, and air dried hay production were measured. Precipitation was recorded by a Hellmann rain meter established in the experimental area. Air dried hay production was 92 g m^{-2} for the NP and 572 g m^{-2} for the NR treatments as the average of eleven years. Winter season precipitation showed no effect on biomass production. Increasing rainfall of the spring season significantly raised the air-dried hay biomass on NR treatments. Focusing the monthly precipitations of spring, rainfall in March increased considerably the biomass only on NR plots. Precipitation in April had significant effect on both NR and NP quadrates. Rainfall of May had no significant positive effect on the hay production. The most effective period on the increment of hay production was the total precipitation of March and April which had significantly positive effect on the production of both NP and NR quadrates; moreover the coefficients were statistically different from each other with a steeper slope for the NR quadrates. It seems that there is a critical amount of nutrient supply above which precipitation becomes increasingly effective on elevating hay production of mixed grass meadows.

Key words: fertilization; field experiment; long term studies; mixed grassland; nitrogen supply

Abbreviations: NP: nutrient-poor, NR: nutrient-rich

Introduction

Grasslands are one of the most widespread biomes and have also multifunctional use in human society. Grasslands have great influence on biodiversity and also play indispensable role regarding hay and livestock production (Fitzhardinge, 2012; Pajor et al., 2012). Vigorous grass stands are also required for parks and recreation areas (Casler, 2006).

Available nutrients and water are known as major factors influencing the production of grasslands (Koerselman and Meuleman, 1996; Fay et al., 2003; Knapp et al., 2006). On heavily and moderately grazed pastures Rogler and Lorenz (1957) examined the effect of nitrogen fertilization for 6 years in North Dakota, and found that 33 kg ha^{-1} annual N dose doubled, while the 100 kg ha^{-1} treatment tripled the yield on average, independently from the grazing intensity. In a Slovakian experiment, hay production on unfertilized plots of a natural alluvial meadow was 414 g m^{-2} on average, whereas moderately fertilized and intensively fertilized plots produced 460–550 and 650–680 g m^{-2} hay, respectively (Vargová et al., 2012). Fertilized rangelands in Argentina also showed increased yields compared to control but only in the most humid year of the study (Guevara et al., 2000).

Precipitation definitely increased the phytomass of African semi-arid grasslands, although its effect was more pronounced under good range condition, and the precipitation-

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use efficiency had a maximum around 650 mm year^{1} level for poor, medium and good range conditions, uniformly (O'Connor et al., 2001). Effect of supplementary irrigation, in order to satisfy evapotranspirational demands increased aboveground net primary production by an average of 26% compared to control in a mesic temperate grassland, in Kansas (Knapp et al., 2001). Herbage production was higher in years with increased precipitation when four consecutive years were compared in a grazed steppe of Inner Mongolia (Schoenbach et al., 2012).

Distribution of precipitation within a growing season can also be influential (Swemmer et al., 2007), and some studies underlined the importance of previous year's precipitation as well (Oesterheld et al., 2001). Worldwide meta-analysis of climate change experiments also supported these findings (Wu et al., 2011).

Positive interaction between effects of water and nutrient was also reported (e.g. Seagle and McNaughton, 1993; Copeland et al., 2012), however, the magnitude of this interaction is not the same for the whole range of these variables. A 90-year old Park Grass Experiment at Rothamsted Experimental Station in Hertfordshire, England showed that rainfall significantly increased biomass. The positive relationship occurred more often on plots not treated with nitrogen (Silvertown et al., 1994). In the Czech Republic, the effect of applied nitrogen on the productivity of two expanding grasses (*Calamagrostis epigejos* and *Arrhenatherum elatius*) was substantially reduced during dry years compared to wet ones, but was still significant (Fiala et al., 2011). For better understanding of limitation or co-limitation of water and nitrogen, Hooper and Jonhson (1999) carried out detailed analyses. Their work underlines the need of further investigations, especially long-term data sets and manipulation experiments.

In the present paper, the following questions were studied, based on multi-year data sets. How does precipitation affect hay production of mowed grasslands on nutrient-rich and nutrient-poor chernozem soil of a loess region in Hungary? In which period of the year has precipitation the most significant effect on multi-species grassland's above-ground biomass production?

Materials and Methods

The experimental site is located near to Sárbogárd, Hungary (GPS N 46° 51' 56.84"; E 18° 31' 10.17"; alt. 140 m a.s.l.). The calcareous chernozem soil of the site contained about 3% humus, 3–5% $CaCO_3$, 20–22% clay in the 0-20 cm soil layer and was originally moderately well supplied with available Mg, Mn, Cu and poor in Zn. The area was drought sensitive with the groundwater table at a depth of 13–15 m and had an average yearly precipitation of 544 mm (1961-2010).

In the study area (1.1 ha) previously applied treatments resulted in zones either abundantly or poorly supplied with P and K nutrients. The concentrations of ammonium-lactate soluble P_2O_5 and K_2O (Egner et al., 1960) in the soil on the well supplied zone were 574 and 372 mg kg^{-1}, whereas in the soil of the poorly supplied zone were 151 and 209 mg kg^{-1}, respectively.

For the present experiment 8-8 quadrates (replicates) were selected, sized 6 m by 6 m each, from the abundantly and poorly supplied zones described above. Then quadrates of the abundantly supplied zone received additional 300 kg ha^{-1} year^{1} N dose in the form of Ca-ammonium-nitrate.

In the area containing the 16 quadrates (hereafter called nutrient-rich and nutrient-poor quadrates) a long term grassland production experiment was initiated, by sowing a mixture of 8 grass species (Table 1), in autumn 2000.

In each quadrate aboveground vegetation was harvested yearly in late May or early June from 2001 to 2012. Data from 2001 were neglected because of the initial phase of grassland community development. Clipping height was 4 cm. Harvested hay was air-dried in a drying room at 30°C tempera-

Table 1
Seed mixture of the eight grass species sown in autumn 2000

Components	Sown seed, kg ha^{-1}	Seed weight rate, %	Grass species rate, %
Meadow fescue (*Festuca pratensis* Huds.)	15.0	25	18
Tall fescue (*Festuca arundinacea* Schreb.)	12.6	21	12
Perennial ryegrass (*Lolium perenne* L.)	12.6	21	13
Crested wheatgrass (*Agropyron pectiniforme* Roem. & Schult.)	5.4	9	6
Red fescue (*Festuca rubra* L.)	3.6	6	8
Timothy (*Phleum pratense* L.)	3.6	6	19
Reed canarygrass (*Phalaris arundinacea* L.)	3.6	6	15
Cocksfoot (*Dactylis glomerata* L.)	3.6	6	9
Total	60	100	100

ture then measured with 1 g accuracy. Hay was harvested once in dry years and two times in wet years, therefore yield data from the first harvest were considered only to ensure the comparability of the dataset.

Precipitation was measured by Hellmann rain meter, consisting of two main parts: a tin collecting unit and a glass measuring cylinder. The equipment was installed at 1 m height above the ground and emptied daily at 7 a.m. according to the general meteorological practice. The accuracy of the measurement was 0.1 mm. The solid snow, sleet, freezing rain and hail were measured after melting. Characteristic values for the seasons of each year are shown in Table 2.

Relationship between precipitation and hay production was analysed by linear regression. Deviation of slopes from zero as well as differences between corresponding slopes obtained for nutrient-rich and nutrient-poor treatments were considered significant at $P< 0.05$. Computations were made by InStat programme package (InStat 2003).

Results

Air dried hay production was 92 g m^{-2} for the nutrient-poor and 572 g m^{-2} for the nutrient-rich treatments as the average of eleven years. The lowest hay production detected was 46.8 g m^{-2} (on nutrient-poor quadrats, in 2007) whereas the highest value was 824.2 (on nutrient-rich quadrats, in 2008; Table 2).

During the winter season from December to February biomass production of nutrient-rich and nutrient-poor quadrats showed no response to precipitation amount, the linear regression coefficients were not significantly different from zero (Table 3).

Summarized precipitation of the spring season (from March to May) had no effect on nutrient-poor plots, however

Table 2
Average above ground air-dried hay biomass of nutrient-poor and nutrient-rich quadrates (with S.d. values in parentheses), and sum of precipitation in the examined years

Year	Above ground biomass, g m^{-2}		Precipitation, mm		Temperature, °C	
	Nutrient-poor	Nutrient-rich	Winter Dec.–Feb.	Spring Mar.–May	Winter avg. (min.; max.)*	Spring avg.(min.; max.)*
2002	125.8 (30.0)	653.4 (92.0)	53.7	110.2	1.3 (-5.4; 86)	14.0 (9.6; 19.8)
2003	75.7 (24.5)	361.3 (48.2)	90.8	57.5	-2.9 (-4.9; -1.2)	13.9 (8.0; 21.1)
2004	118.6 (10.2)	513.8 (33.8)	94.1	177.8	1.1 (-1.6; 3.6)	12.3 (7.2; 17.0)
2005	104.3 (26.7)	676.0 (96.7)	92.9	97.3	-0.5 (-2.5; 1.3)	11.8 (5.3; 17.4)
2006	149.2 (25.7)	815.5 (64.1)	121.6	91.2	0.2 (-1.5; 1.2)	12.8 (6.0; 17.4)
2007	46.8 (7.6)	414.9 (17.7)	61.5	120.8	5.3 (3.4; 6.9)	14.2 (8.9; 18.7)
2008	97.5 (30.7)	824.2 (214.3)	74.1	98	2.4 (-0.2; 5.9)	13.0 (7.2; 18.6)
2009	51.7 (17.6)	336.9 (73.8)	139.4	28.6	1.0 (-1.0; 2.1)	14.0 (7.3; 18.8)
2010	56.2 (67.2)	761.3 (66.6)	42.7	197.8	-0.4 (-2.1; 0.5)	12.3 (7.8; 16.8)
2011	95.6 (45.9)	534.9 (77.6)	50.5	54.4	-0.2 (-0.8; 0.3)	12.8 (6.8; 17.8)
2012	85.1 (28.2)	403.4 (56.0)	77.8	94.3	0.9 (-3.0; 3.6)	14.1 (9.2; 19.0)

* Minimum and maximum of the montly average temperatures of the season

Table 3
Parameters of the linear regression model (Y'= aX + b) describing dependence of grassland's hay production on the seasonal or monthly precipitation in nutrient-poor (NP) and nutrient-rich (NR) quadrates, near Sárbogárd, Hungary

Time period	Regression coefficient (Standard error)		Y-intercept		Determination coefficient, R^2	
	NP	NR	NP	NR	NP	NR
Winter (Dec.-Feb.)	0.1674ns (0.1626)	–1.3182ns (0.7148)	77.81	680.06	0.0122	0.0380
Spring (Mar.-May)	^{A}0.0351ns (0.0979)	^{B}1.4694** (0.4068)	87.90	421.66	0.0015	0.1317
March	0.3973ns (0.2572)	2.6369* (1.1260)	81.86	508.36	0.0270	0.0599
April	0.5716** (0.1797)	2.4107** (0.8054)	73.05	494.50	0.1053	0.0943
May	–0.3247* (0.1295)	0.8527ns (0.5907)	106.43	533.09	0.0681	0.0237
March-April	^{A}0.3883** (0.1271)	^{B}1.8911** (0.5603)	69.54	465.40	0.0979	0.1170

Difference of slope from zero: ns= not significant, *= significant at $p< 0.05$, **= significant at $p< 0.01$. Capital letters in superscript indicate significant differences between slopes of NP and NR increasing precipitation significantly raised the air-dried hay biomass on nutrient-rich treatments (Figure 1). The linear regression coefficients of nutrient-poor and nutrient-rich cases differed significantly (Table 3).

Effects of the monthly precipitations within the spring season varied greatly. Rainfall in March had no effect on nutrient-poor quadrates, but increased considerably the biomass of nutrient-rich plots based on data of the eleven examined years (Table 3).

Precipitation in April had significant effects on both nutrient-rich and nutrient-poor subsets of quadrates. Biomass on nutrient-rich quadrates responded more enhanced to the higher rainfall, but the difference between the two regression coefficients was not significant (Table 3).

Rainfall of May had no significant effect on the hay production of nutrient-rich quadrates, though regression coefficient of 0.8528 was still remarkable. In case of nutrient-poor treatments elevating precipitation did not increase the production, but instead a negative effect appeared (Table 3). It is difficult to interpret, but one of the reasons could be the residual effect of heavy rainfall events in the preceding days of the studied month.

In the search of most effective period on the increment of hay production, merged precipitation data of March and April were also considered, since these months expressed remarkable effects in the previous analyses (Table 3). Precipitation of this period had significantly positive effect on the production of both nutrient-poor and nutrient-rich quadrates (regression coefficients: 0.3883 and 1.891, respectively). Moreover, the coefficients were statistically different from each other with a steeper slope for the nutrient-rich quadrates (Figure 2). Further combinations of two months periods proved to be less effective.

Discussion

In an extensive study across the temperate zone of China, grassland production ranged between 20 and 2020 g m^{-2} (Ni 2004). Across the Central Grassland region of the United States, production varied from 100 to 700 g m^{-2} depending on environmental constraints (Sala et al., 1988). Concerning Europe, the highest production was about 1000 g m^{-2} in the Atlantic regions whereas the lowest occurred in the Mediterranean with 150 g m^{-2} in average (Smit et al., 2008).

Within Hungary, various types of native grasslands yielded 200-450 g m^{-2} above ground biomass (Molnár, 1975). On two nature conservation areas, natural grassland production was 180-290 g m^{-2} (Cserkeszőlő) and 130-160 g m^{-2} (Bakonszeg) when moderately grazed by sheep (Kádár et al., 2007). Two years after clear cutting, herb layer production was 520 g m^{-2} in a forested area of Central Hungary (Csontos, 2010).

Nutrient-rich treatments of the present study yielded 572 g m^{-2} what fits well to European average and is in accordance with the climatic conditions of Hungary. However, yield of the nutrient-poor treatments (92 g m^{-2}) was lower than that reported even for the Mediterranean region, and achieved only 50% of the values reported for natural grasslands on poor quality habitats of Hungary (Molnár, 1975). One of the possible reasons for this could be that the species composition of the sown grass was not perfectly adequate to the maximum utilization of the habitat. In addition, many of the sown grass species failed to establish on nutrient-poor quadrates resulting in a high rate of colonization by weeds, most of them with prostrate growth form or basal rosette with negligible erect stems at the time of harvesting (*Medicago lupulina* L., *Cerastium* spp., *Crepis rhoeadifolia* Bieb., *Hieracium pilosella* L.,

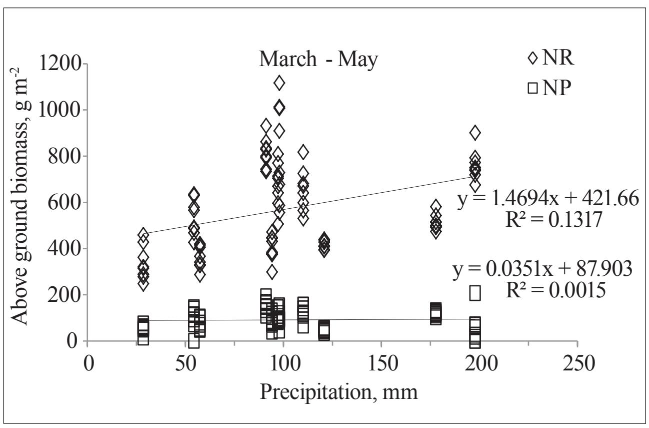

Fig. 1. Above ground air-dried hay biomass of nutrient-poor (NP) and nutrient-rich (NR) grassland quadrates depending on the spring precipitation (from March to May) of the eleven experimental years

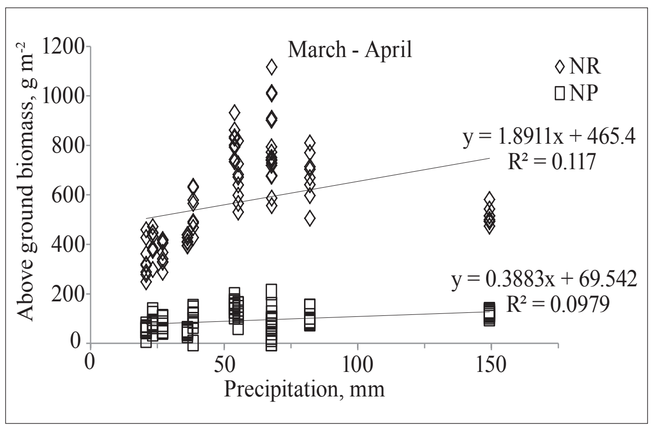

Fig. 2. Above ground air-dried hay biomass of nutrient-poor (NP) and nutrient-rich (NR) grassland quadrates depending on the summarized precipitation of March and April of the eleven experimental years

Taraxacum officinale F.H. Wigg), thus having a rather limited contribution to the hay production, clipped at 4 cm height above soil surface.

In our case, fertilization results six-fold increase in the yield of the grassland. On heavy-clay soil, Elberse et al. (1983) reported a nearly 2-fold increase of the dry matter yield when unfertilized and NPK fertilized treatments were compared. Moderate NP fertilization increased the yield by 37% in annual east Mediterranean grassland (Alhamad et al., 2012). In a *Brachypodium pinnatum* chalk grassland, moderate N supply (about 70 kg ha^{-1}) resulted 20-30% increase of the yield, in The Netherlands (Bobbink et al., 1988). Further studies applying N-fertilization up to 200 kg ha^{-1} achieved up to three-fold increment (Rogler and Lorenz, 1957; Smika et al., 1963; Wight and Black, 1979; Jacobsen et al., 1996). In the case of the present study effects of nutrient supply were remarkable and resulted two groups of quadrates with contrasting above ground hay production.

Amount of annual precipitation generally has a positive effect on grassland production (Sala et al., 1988; O'Connor et al., 2001; Hu et al., 2012). But the distribution of precipitation has diverse effect depending on the phenophase of the grasses. In the present experiment winter season precipitation of the study years did not correlate with the corresponding hay production data. Although, winter precipitation had a positive effect on wheat yield in Russia (Mladenov and Przulj, 1999), Kristensen et al. (2011) found no effect on winter wheat's grain yield, in Denmark. In our multi-species plots, winter precipitation effect, if any, was either cancelled out by opposite responses of different grass species, or simply overridden by the effect of precipitation during later months.

Seasonal precipitation often has a stronger correlation with yield than annual precipitation (Shiflet and Dietz, 1974; Lauenroth and Sala, 1992). In the present study spring precipitation was found an effective predictor for production as it was also reported in many other cases (Smart et al., 2007). Of course, spring precipitation and its effect have a geographical variability. May – June precipitation had the highest effect on forage production in Western Kansas and North Dakota while April – May precipitation in Montana and April – June for Wyoming (Hulett and Tomanek, 1969; Wiles et al., 2011). Though, controlled spring precipitation, when 80% of the yearly amount was applied between April and July, was less effective compared to elevated precipitation of other periods of the year (Bates et al., 2006).

Considering individual months, in our experiment March and April precipitation effectively increased hay yield. But in May the response was ambiguous, presumably because grasses reached their grain production phenophase and suspended investing further resources for vegetative growth. The total of March and April precipitation was the best predictor variable for hay production of the studied grassland. Use of this longer period presumably ensured a more balanced dataset compared to the 1 month term, and this revealed two important interrelations: i) there is a critical period of the year when hay yield significantly determined by the amount of precipitation, ii) quadrates treated with different levels of nutrients showed significantly different increase in hay production as a response of increased amount of precipitation.

Interactions between precipitation and fertilization have long been studied. Seagle and McNaughton (1993) found that production was primarily limited by water followed by the effect of nitrogen, in the Serengeti National Park. Hooper and Johnson (1999) found fertilization effect more important than that of precipitation. Hooper and Johnson proposed two alternative hypotheses for the relationship between nitrogen supply and precipitation: (a) Water especially limits production at the drier section whereas nitrogen mostly limits at the humid section of the precipitation gradient; (b) water and nitrogen together limit the production at any level of precipitation occurring at natural grassland areas (Hooper and Johnson, 1999). Hypothesis (b) implies that relative increase should be the same independently from the dose of added nitrogen, along the precipitation gradient. It was supported by Fiala et al. (2011) who reported higher yield increment in wetter years than in drier ones, but the rate of the increase was just the same. However, in our case the steeper slope obtained for the nutrient-rich quadrates denies this hypothesis. According to hypothesis (a), there is a certain level of precipitation above which nitrogen supply has an increasing relative effect on plant growth. Wight and Black's finding is in accordance with Hypothesis (a) because when nitrogen and phosphorus deficiencies were eliminated by fertilization on a mixed prairie range site in eastern Montana, herbage yields increased 32% in a dry year but increment was 218% in a wet year (Wight and Black, 1979).

Conclusion

Our results were similar to the mixed prairie case, since hay production of nutrient-rich quadrates responded more intensively to the increased precipitation than nutrient-poor quadrates. It seems that in addition to the suggestion of Hooper and Johnson (1999) about a critical level of precipitation above which fertilization becomes increasingly effective, there is also a threshold amount of nutrient supply above which increasing amount of precipitation is able to realize its positive effect in hay production. Practical considerations of our study are: a) irrigation results in more effective increase of hay production only when available nutrients are not limiting plant growth; b) the most effective period of irrigation for increasing hay production is a time window that begins 90 days and ends 30 days prior to the first cut.

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