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Water stress due to increased intra-annual precipitation variability reduced forage yield but raised forage quality of a temperate grassland

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ABSTRACT

Due to climate change an increase in the intra-annual precipitation variability including extreme drought and heavy rainfall events is predicted to impact major ecosystem processes. Evidence suggests that crop and forage production will be affected by altered climate variability. Due to the growing human population and rising demand for high quality animal feed it is necessary to determine the consequence of increased precipitation variability on forage yield and quality in order to adapt or implement compensation strategies against possible negative effects.

Here, we present data from a field experiment in which a temperate European grassland was subjected to altered intra-annual precipitation variability (low, medium, high) in interaction with management strategies namely fertilization and alteration of harvest date (delay by 10 days). We measured forage yield and root length, quantified parameters of forage quality (crude protein, crude fiber, crude ash, crude fat, sugar, neutral detergent fiber (NDF), acid detergent fiber (ADF), in vitro gas production) and estimated relative feed value, net energy for lactation and metabolizable energy. Additionally, we tested the influence of seasonality of extreme weather events on the responsiveness of forage yield and quality to management strategies.

Increased intra-annual precipitation variability decreased forage yield of the grassland. Furthermore, the proportion of functional groups was altered toward less grass and more forb biomass with amplified precipitation variability. Increased crude protein content and reduced fiber content (crude fiber, NDF, ADF) with increasing precipitation variability improved the relative feed values. Crude protein content was enhanced by fertilization during drought but reduced by delayed harvest after the drought period. Fertilization reduced losses in grassland annual yield caused by extreme precipitation. Management strategies proved less effective if precipitation variability occurred later in the season than earlier in the season.

A nitrogen dilution effect (decreased plant nitrogen concentration with increasing shoot biomass) likely influenced the grassland crude protein contents under altered precipitation regimes and might have masked possible effects of precipitation variability on plant nitrogen and therefore on quality of grassland species. Nevertheless, alterations in the plant community composition and plant senescence seem to be the main drivers of forage quality change. Fertilization during drought periods and harvest delay after drought periods were only partially successful as management strategies to sustain forage production in more extreme precipitation regimes of the future. Further strategies need to be developed that acknowledge the shift in plant species compositions as the main driver of changes in forage quality in the face of changing precipitation patterns.

1. Introduction

Intra-annual precipitation variability is predicted to increase due to global warming, leading to longer dry periods and more intense rainfall events with strong impacts on agriculture and food security (Fay et al., 2011; IPCC, 2012; Jentsch and Beierkuhnlein, 2008). Greater precipitation variability increases

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soil moisture variability, which leads to increased plant water stress and therefore alters grassland productivity (Fay, 2009; Heisler-White et al., 2008; Nippert et al., 2006). Forage and crop production will be altered directly through climatic changes and indirectly through changes in nutrient availability, resulting in higher yield variability and altered forage quality (Buxton, 1996; Olesen et al., 2011). Livestock production, which depends on grazing or the use of fresh forage, will in turn also be affected by alterations of climate variability (Olesen et al., 2011). With steadily rising demand for food and high quality animal feed it is important to determine the consequences of increased precipitation variability on forage production so that animal requirements are met and the vulnerability of markets to price swings can be reduced (Battisti and Naylor, 2009; Bruinenberg et al., 2002; Buxton, 1996; Huyghe et al., 2008).

In the absence of weather extremes the most important factor influencing the forage quality of a given species is the plant maturity stage, i.e. its phenology (Buxton, 1996). With advancing maturity and increasing age within a given growing season, forage quality declines (Ball et al., 2001; Bruinenberg et al., 2002). This is reflected by a decrease in digestibility of plant components and declining nitrogen content, due to altered leaf/stem ratio and increasing fiber content (Bruinenberg et al., 2002; Collins and Casler, 1990; Hopkins and Wilkins, 2006). Furthermore, forage of different plant functional groups differ in their phenological development of feeding value and digestibility (Duru et al., 2008). Legumes are of higher forage quality and their digestibility decreases over time at a slower rate than the digestibility of grasses (Ball et al., 2001; Buxton, 1996). Plant development and therefore forage quality depends on abiotic factors such as temperature, water availability, solar radiation, and soil nutrient status (Andueza et al., 2010; Buxton, 1996). Rising temperature leads to increased rates of plant development, alterations of plant chemical composition, and to reductions of the leaf/stem ratio and digestibility (Ansquer et al., 2009; Buxton, 1996). Rising spring temperatures in particular strongly interact with advancing plant maturity and lead to higher variation and faster decline in nutritive value than high temperatures later in the summer (Buxton, 1996; Cop et al., 2009a).

Moderate water deficit slows plant maturation, and if it does not cause severe leaf loss, forage quality and digestibility can be maintained or even slightly improved (Buxton, 1996; Reddy et al., 2003). However, long and extreme drought events inhibit tillering and branching, accelerate the death of tillers and senescence of leaves, and relocate protein, nitrogen, and soluble carbohydrates from leaves to roots, reducing the nutritive value of the plant (Buxton, 1996; Durand et al., 2010). Drought also affects the nitrogen nutrition of aboveground plant parts due to reduced uptake and use of soil mineral nitrogen (Durand et al., 2010). Nonetheless, protein content was found to increase under drought in plants in symbiosis with arbuscular mycorrhizal fungi (Subramanian and Charest, 1995). In some species, sugar and proline are accumulated with water stress, the latter improving the recovery of plants from drought (Saglam et al., 2008).

With global climate change, forage quality of grasslands will not only be altered directly via changes in abiotic factors governing plant growth and development, but also via alterations in the community composition (Kreyling et al., 2011b; Stampfli and Zeiter, 2004). The nutritive value of grassland is strongly influenced by community composition mainly due to strong variation in species identities, chemical composition, phenological stages, functional groups, and photosynthetical pathways (Huyghe et al., 2008; Cop et al., 2009a; Andueza et al., 2010). Although increased species richness can ensure the stability of biomass yield, differences in nutritive value are more related to species composition and functional group proportions than to species number (Baumont et al., 2008; Sanderson, 2010). For instance, crude protein content of mixed-species grasslands is controlled by the legume component due to its ability to fix atmospheric nitrogen, and the fiber content by the grass proportion (Sanderson, 2010).

In the light of potential direct and indirect effects of climate change on forage production there is an urgent need to develop adaptation or compensation strategies to ensure high forage yield and quality under increasing precipitation variability. Generally, strategies to cope with increasing variability will differ from strategies to adapt to trends of mean climatic conditions (Battisti and Naylor, 2009; Olesen et al., 2011). Since variability and mean climatic conditions will likely change together these strategies must be comprehensive. Possible management strategies include specific species mixtures, schemes of fertilizer application, irrigation techniques, and cutting regime. It might be helpful to identify or breed key species varieties with improved drought resistance (Beierkuhnlein et al., 2011) or that maintain forage quality at advanced stages of maturity (Buxton, 1996).

Fertilizer, especially nitrogen, is known to affect yield, functional community composition and forage quality (Cop et al., 2009b). In addition, fertilization can change the proportion of leaves (Duru et al., 2008). Besides raising crude protein content, decreasing fiber content and improving digestibility, the timing of N fertilization and the amount of fertilization could be used to improve drought resistance. N uptake is reduced during drought (Durand et al., 2010), though the uptake rates of plant nutrients such as ammonium and nitrate can rise rapidly within a few days after N starvation (Lee and Rudge, 1986). Thus, higher nutrient availability due to fertilization may ensure an even quicker recovery of plant tissue, and thereby forage quality after the drought period. In the absence of drought, a 1-week delay in harvesting decreases digestibility and crude protein content and increases fiber concentration of forage (Bruinenberg et al., 2002; Buxton, 1996). A delay of harvest after a rewetting period following drought might therefore provide enough time to improve the nutrient availability for plants. Furthermore, harvest delay, especially in combination with fertilization during drought may allow plants to recover tissue and forage quality by promoting new leaf development and relocating nutrients from roots to leaves.

Here, we experimentally studied the consequences of increased precipitation variability on the forage yield and quality of a temperate grassland in Central Europe. We further tested two management strategies, namely fertilization during drought periods and delayed harvest after the drought periods. Together, these strategies aim to recover forage quality and yield after drought periods.

Thus, our hypotheses are as follows:

(I) Increased intra-annual precipitation variability decreases the yield and quality of forage in temperate, semi-natural grasslands.
(II) A 10-day delay of harvest after drought periods increases forage yield and quality, in particular if accompanied by fertilization during the drought period, compared to a grassland which is harvested immediately after drought periods.

2. Methods

2.1. Study site

The study is part of the EVENT II experiment which tests the effects of altered precipitation regimes in interaction with land use methods on the ecosystem functions of semi-natural grassland. It is located in the Ecological–Botanical Garden of the University of Bayreuth, Germany (49°55′19″N, 11°34′55″E, 365 m asl). The regional climate is characterized as temperate and moderately continental with a mean annual air temperature of 8.2 °C and