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Author(s):
Buchmann, Nina; Fuchs, Kathrin; Feigenwinter, Iris; Gilgen, Anna K.

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Multifunctionality of permanent grasslands: ecosystem services and resilience to climate change

Buchmann N., Fuchs K., Feigenwinter I. and Gilgen A.K.
Institute of Agricultural Sciences, ETH Zurich, Universitätstrasse 2, 8092 Zürich, Switzerland

Abstract

Permanent grasslands are highly relevant for the provision of many ecosystem services in Switzerland. This includes not only forage production for livestock, but also climate regulation, erosion control and cultural services (among others). How these services are affected by climate change, but also to what extent Swiss grasslands contribute to climate change or can actually mitigate it, are important research questions. Within the Swiss FluxNet, a network of ecosystem flux measurement sites in Switzerland, greenhouse gas (GHG) fluxes and C sequestration have been measured at three grassland sites of different management intensities for more than a decade. At the intensively managed site on the Swiss Plateau, legumes are currently tested as a N_2O mitigation option. Overall, environmental conditions as well as management events have clear impacts on net ecosystem fluxes. Particularly during a restoration year (which included ploughing, harrowing, resowing, fertilisation), the grassland turned into a large GHG source, driven by extraordinarily high N_2O and CO_2 losses. On the other hand, increasing the legume fraction in the sward, thereby substituting organic nitrogen fertiliser, reduced N_2O emissions while still maintaining yield and forage quality levels. Thus, management strongly affected the climate regulation service provided by the grassland. Climate impact studies, but also agroeconomic assessments complemented these long-term GHG measurements. All three grasslands were surprisingly resilient to severe droughts, both simulated and naturally occurring. Feed production, but also sward composition did not show any legacy effects of preceding droughts. Thus, multifunctionality, i.e. the provision of multiple services, seemed resilient as well, and offers promising options with respect to anthropogenic climate change.

Keywords: forage production and quality, climate regulation, legume fraction, restoration, drought impact, economic assessment

Introduction

Grasslands in Europe occur under highly variable environmental and socio-economic conditions. Thus, a wide variety of management intensities and vegetation compositions exist. This also applies to Switzerland where about 70% of the Swiss agricultural area consists of grasslands, i.e. about 737,000 ha (FOAG, 2017). These grasslands range from the Swiss Plateau up to the alpine areas, with temporary grasslands in crop rotations but also permanent grasslands (with regular restoration) at lower elevations.

Permanent grasslands, used as meadows and pastures, are highly relevant for the provision of many ecosystem services in Switzerland. According to MA (2005), four types of ecosystem services are differentiated: supporting, provisioning, regulating and cultural ecosystem services. Among others, forage production for livestock (provisioning service), but also climate regulation and erosion control (both regulating services) as well as cultural services (e.g. for tourism) are in the focus of current attention. For example, climate regulation is assessed from different perspectives, since on the one hand, grasslands contribute to the greenhouse gas (GHG) emissions of Swiss agriculture (which contributes 12.6% to overall Swiss emissions; FOAG, 2017), while grasslands, on the other hand, are also strongly impacted by more frequent droughts and heatwaves (e.g. Reichstein *et al.*, 2013). About 55% of agricultural GHG emissions in Switzerland originate from livestock, 19% from manure management, while 25% can be traced to soils and <1% to limestone and urine applications (FOAG, 2017). How these services are affected by climate change, but also to what extent Swiss grasslands contribute to climate change or can actually mitigate it, are thus important research questions.

Materials and methods

Within the Swiss FluxNet (http://www.gl.ethz.ch/research/bage/fluxnet-ch.html), a network of ecosystem flux measurement sites in Switzerland, GHG fluxes and C sequestration have been measured at three permanent grassland sites of different management intensities for more than a decade (Figure 1; Table 1).

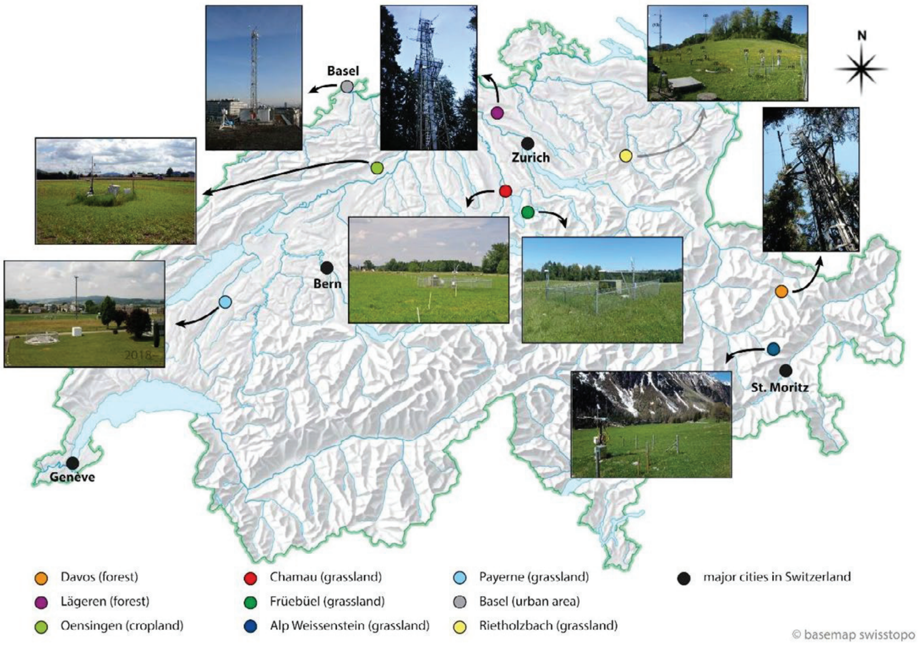

Figure 1. The Swiss FluxNet, a network of flux sites for measuring biospheric-atmospheric gas exchange. It currently encompasses seven long-term ecosystem sites, six run by the Grassland Sciences (ETH Zurich), covering the major land-use types in Switzerland: forest (coniferous: Davos; mixed deciduous: Lägeren), cropland (Oensingen), grassland (Chamau, Früebüel, Alp Weissenstein, Payerne – run by MeteoSwiss). Flux measurements in an urban setting (Basel) as well as within a watershed (Rietholzbach) complement the Swiss FluxNet. Map: Courtesy of W. Eugster.

Table 1. Site characteristics of the three grassland sites within the Swiss FluxNet.

Site characteristics	Chamau (CHA)	Früebüel (FRU)	Alp Weissenstein (AWS)
Latitude, longitude	47° 12′ 37″ N, 8° 24′ 38″ E	47° 6′ 57″ N, 8° 32′ 16″ E	46° 34′ 60″ N, 9° 47′ 26″ E
Elevation in m ASL	393	982	1,978
Annual precipitation in mm	1,150 to 1,200	about 1,600	about 900
Average annual temperature in °C	9 to 10	8	2
Soil type	Cambisol	Gleysol	Humous sandy loam
Management	intensive (4-6 cuts/yr, manure/slurry applicat-ions, regularly restored	intermediate (1-2 cuts/yr, some fall grazing, manure/slurry applications)	extensive (grazing)
Sward composition	about 25 species, incl. *T. repens*, *L. perenne*	about 35 species, incl. *D. glomerata*, *A. pratense*	about 20 species, incl. *F. rubra*, *T. repens*
Continuous flux measurements since	July 2005	August 2005	Summer campaigns from 2006 to 2014, continuously since winter 2014/2015
Drought experiment	2005 to 2007, 2009 to 2011	2005 to 2007, 2009 to 2011	2006 to 2007, 2009 to 2011
Legume experiment	Since 2015	-	-

Fluxes are measured with the eddy covariance (EC) method, which is based on high frequency measurements (10-20 Hz) of the vertical wind velocity and the mixing ratio of a trace gas, e.g. CO_2, CH_4, N_2O or water vapour. The turbulent flux is calculated from the covariance between these two measurements using time averaging of typically 30 minutes (for details, see Eugster and Merbold, 2015). Thus, these measurements run continuously, 24 hours a day, for 365 days per year, preferentially for many years. Flux measurements at Chamau (CHA), Früebüel (FRU) and Alp Weissenstein (AWS) started between 2005 and 2006 (Table 1), have been complemented by dedicated measurements campaigns or long-term experiments, such as drought simulations using portable rain shelters or manipulations of the vegetation composition of the sward (legume experiment at CHA). All data are available as open access.

At CHA, the intensively managed, permanent grassland site on the Swiss Plateau, legumes are currently tested as a N_2O mitigation option (Table 1, Legume experiment). The footprint of the flux tower, i.e. the area where the fluxes come from, has been divided into two parcels in 2015. The legume fraction of one of these parcels has been increased to 20 to 40% and no fertiliser has been applied, while the legume fraction of the other parcel stayed at 10 to 20% and fertiliser application continued. N_2O fluxes are measured continuously with the EC method described above (for further details, see Fuchs *et al.*, 2018).

In addition, research on drought impacts has been carried out at all three permanent grassland sites (Table 1, Drought experiment) to test the response of Swiss grasslands, located along an elevation gradient, to extreme drought as projected for the future (NCCS, 2018). Portable rain shelters were used to simulate consecutive, severe summer droughts during two three-year periods (2005-2007, 2009-2011), complemented by two years without drought simulations but with a similar measurement portfolio (2008, 2012). Rain shelters were typically set up for six to twelve weeks, reducing precipitation input by up to 50% (for details, see Gilgen and Buchmann, 2009; Prechsl *et al.*, 2015). In addition, agroeconomic assessments were carried out to determine the economic consequences of summer drought for Swiss farmers, based on yield responses scaled up to the farm level (for details, see Finger *et al.*, 2013).

Results and discussion

Net ecosystem CO_2 exchange, measured with the EC method, clearly shows CO_2 losses and gains at a very high temporal resolution (Figure 2), here for an intensively managed grassland on the Swiss Plateau (CHA).

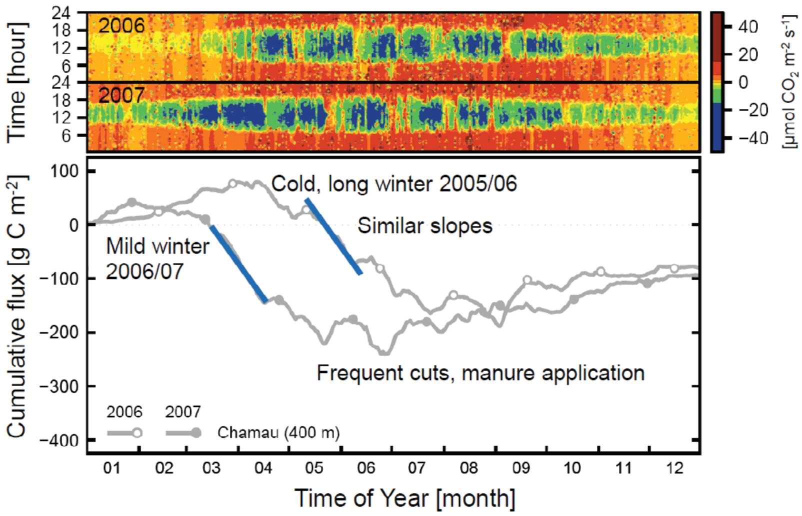

Figure 2. Net ecosystem CO_2 fluxes from a permanent grassland on the Swiss Plateau (CHA) for two years (2006, 2007). Top panels: Temporal variability of CO_2 fluxes is shown on diel as well as on annual scales. Colour codes depict CO_2 losses from the grassland (red/dark colours, positive sign) and CO_2 gains by the grassland (green-blue/light colours, negative sign). Bottom panel: Cumulative net ecosystem CO_2 fluxes are shown for two consecutive years. The same sign convention applies (losses: positive; gains: negative). Data based on Zeeman *et al.* (2010).

During the night and during cold winter months (as in 2006; Figure 2 top panels), the grassland was a strong CO_2 source because respiration from plants and soils dominated the ecosystem fluxes and sward photosynthesis was not large enough to (over-)compensate these CO_2 losses (Zeeman *et al.*, 2010). However, during the day and particularly during the summer months, the grassland was a strong carbon sink due to high photosynthesis rates. Mild winters, such as in 2007, can lead to carbon sink behaviour as early as in January, indicating that CO_2 uptake via photosynthesis overcompensated CO_2 losses via ecosystem respiration. Frequent cuts with subsequent applications of organic fertilisers during the growing season in both years led to immediate responses of the net ecosystem CO_2 fluxes, such that the grassland was a carbon source until photosynthesis of the regrowing sward again became larger than respiration. Adding up all fluxes cumulatively nicely illustrated the delayed start of sink activities in 2006 compared to 2007 (Figure 2 bottom panel), while uptake rates during both summers were very similar, only interrupted by management events (i.e. zigzag patterns). At the end of both years, regrowth decreased, and respiration again dominated the overall CO_2 fluxes. The total CO_2 flux budget summed up to a sink of about 90 g C m^{-2} $year^{-1}$. Accounting for all harvests (C exports) as well as organic fertiliser applications (C imports), the grassland was a small carbon sink of about 70 g C m^{-2} $year^{-1}$ during these two years (not shown) and thus contributed to the ecosystem service of climate regulation.

Since both environmental conditions as well as management events have clear impacts on the net ecosystem CO_2 fluxes and thus on the sink/source behaviour of this grassland, long-term measurements gain particular importance, namely to understand the underlying mechanisms but also to differentiate among drivers. During 2012, the grassland at CHA was restored, i.e. the grassland was ploughed under and re-sown to restore sward composition and thus yield and forage quality. However, during this year, the grassland turned into a large GHG source, driven by extraordinarily high N_2O and CO_2 losses (Table 2; Merbold *et al.*, 2014). The N_2O fluxes in 2012 were a magnitude higher than those in two benchmark years (2013 and 2014), representing about 50% of the total GHG flux budget compared to on average 5%. Although the vegetation re-established during the growing season 2012, the CO_2 budget was dominated by respiratory losses. This means, at a 10-year return time of such a restoration, about 50% of the long-term grassland carbon sink can be lost by one management event during these 10 years.

Strategies to reduce GHG losses from managed grasslands are therefore urgently needed. Options to reduce N_2O losses include reduction of nitrogen (N) fertiliser or increasing the legume fraction in the sward, thereby substituting (at our site, organic) nitrogen fertiliser application with N_2 fixation by legumes and their symbionts. Since 2015, a legume experiment at CHA helps to test this option on two neighbouring parcels (Fuchs *et al.*, 2018). While N_2O losses were similar for both parcels during the two years prior to the experiment (2013, 2014), increasing the legume fraction and simultaneously decreasing N fertilisation during 2015 and 2016 resulted in strongly reduced N_2O emissions (Figure

Table 2. Greenhouse gas (GHG) flux budget of the site Chamau in the restoration year 2012 compared to a benchmark year (average 2013 and 2014). Data from Merbold *et al.* (2014).

GHG fluxes	CO_2-C	CH_4-C	N_2O-N	Total GHG flux budget
Restoration year				
g m^{-2}	339	2.65	2.91	
g CO_2-eq. m^{-2}	1,245	88	1,363	2,696
%	46.2	3.3	50.6	100
Benchmark year				
g m^{-2}	-655	1.44	0.28	
g CO_2-eq. m^{-2}	-2,398	65	131	-2,202
%	92.3	2.6	5.1	100

3A). This reduction was between 40 and 50% (Figure 3B), accompanied by lower soil mineral N concentrations (not shown). Yields were about 10% lower on the unfertilised parcel but forage quality in terms of raw protein content tended to be higher due to the higher legume fraction (not shown). Thus again, management strongly affected the climate regulation service provided by the grassland. Moreover, increasing the legume fraction is a valid option to reduce N_2O emissions to mitigate climate change.

As shown above, Swiss grasslands can drive climate change and can help to mitigate it, but they are also driven by climate change. During an eight-year climate impact study (see Table 1, Drought experiment), the response of Swiss grasslands to severe summer drought was investigated along an elevational gradient (Gilgen and Buchmann, 2009; Prechsl *et al.*, 2015). Community above-ground biomass production of the three permanent grasslands responded quite differently to the simulated summer drought (Figure 4). While the grasslands at 400 m (CHA) and 2,000 m (AWS) showed significantly reduced biomass production in response to drought during most of the experimental treatment periods, the grassland at 1000 m (FRU) showed no reduction at all (or rather an increase for some periods). These site-specific responses scaled with annual precipitation: more pronounced reductions in biomass production occurred at lower annual precipitation (not shown). Thus, direction and magnitude of any effect of severe summer drought on feed production, a supporting ecosystem service in grassland, was highly variable and management adaptation strategies cannot be easily transferred across space.

On the other hand, all three grasslands were surprisingly resilient to severe droughts, one of the most prominent extreme weather events in global climate scenarios (Figure 4). Typically, already during the first, but certainly by the second regrowth after the removal of the rain shelters, biomass production did not show any drought effect any longer but recovered rather quickly. This was supported by fast recovery of leaf gas exchange and chlorophyll fluorescence (not shown; Signarbieux and Feller, 2011). Moreover, during 2008 and 2012, two years when no drought was simulated, no legacy effects were detectable, although grasslands had experienced three (2008) and six (2012) years of preceding severe summer droughts (Figure 4). Thus, performance of grassland plants as well as feed production, i.e. one of the most important ecosystem services in grassland, were surprisingly resilient, and offer promising options with respect to anthropogenic climate change.

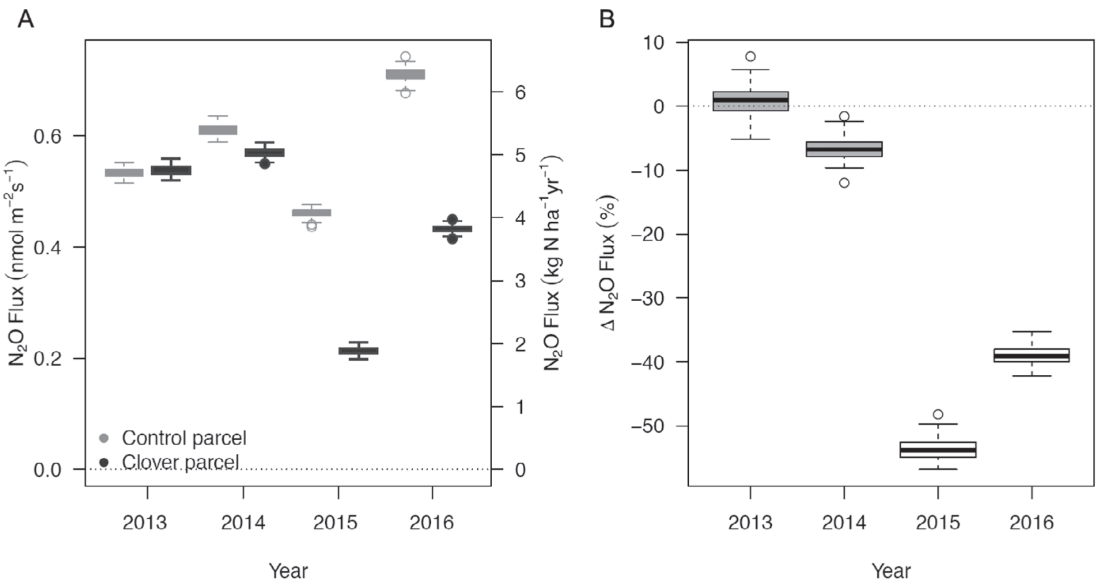

Figure 3. N_2O fluxes from a permanent grassland site in Switzerland (CHA). (A) Annual N_2O fluxes from the control (light grey) and the clover parcels (dark grey) for 2013 and 2014 (before the experiment) as well as 2015 and 2016 (during the experiment). (B) Relative differences between N_2O fluxes from the control and the clover parcels for all four years. Interquartile ranges are plotted, bold black lines represent respective medians (Figure from Fuchs *et al.*, 2018).

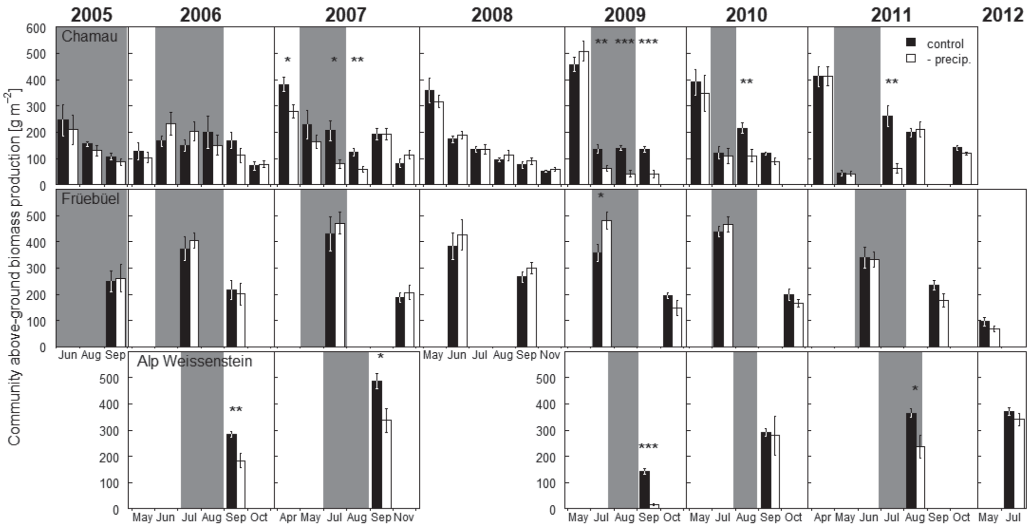

Figure 4. Effect of summer drought on community above-ground biomass production (feed production) at the three Swiss grassland sites Chamau, Früebüel and Alp Weissenstein. Periods of drought treatment are shaded in grey. No drought was simulated in 2008 and 2012. * 0.05≥*P*>0.01, ** 0.01≥*P*>0.001, *** *P*≤0.001. Data from Gilgen and Buchmann (2009), Prechsl (2013) and Prechsl *et al.* (2015).

In order to understand this fast recovery of plants in permanent grassland under drought conditions, the water uptake and uptake depths were studied in more detail using stable oxygen and hydrogen isotopes of soil and plant xylem waters (Prechsl *et al.*, 2015). Analysing the stable isotopic signatures with a Bayesian calibrated mixing model revealed that during pre-treatment periods in spring, plants took up water mainly (i.e. 70-90%) from the topsoil (except 2011; Figure 5). However, during the summer treatment period, drought-subjected plants relied more strongly (i.e. 40-70%) on water in the topsoil (top 10 cm) than control plants (only <40%). Instead, control plants shifted to deeper soil depths (20-35 cm) for water uptake (30-50%) in summer, while drought-subjected plants did not. After rain shelter removal and first rain events, in particular the drought-subjected plants took up their water in the topsoil (>90%,

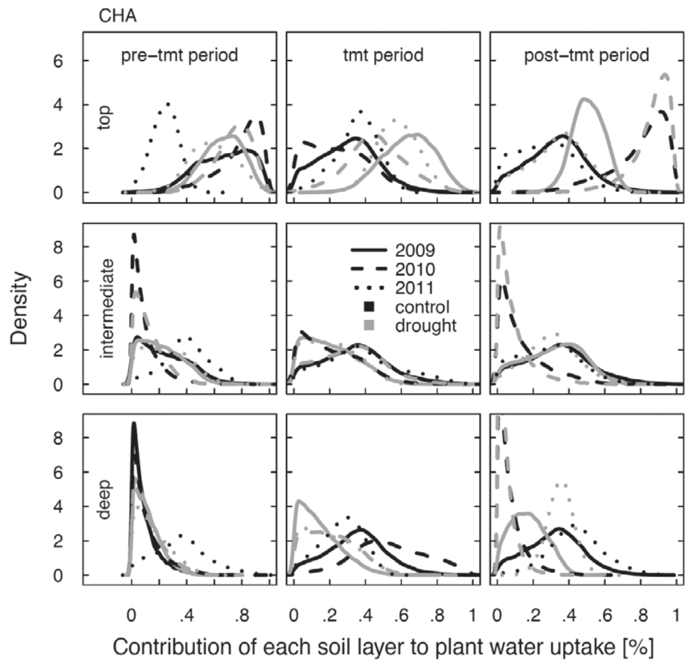

Figure 5. Effect of drought on water uptake depths of plants in a permanent grassland site (CHA). Probability density distributions for the contribution of three different soil layers (top, 0-10 cm deep; intermediate 10-20 cm; deep, 20-35 cm) to total plant water uptake are plotted for 2011. The density distribution was calculated with a Bayesian calibrated mixing model (SIAR) based on the measured water isotope data of soil and plant xylem waters (Figure from Prechsl, 2013).

except 2011), while control plants used the entire soil profile. This unexpected behaviour of drought-subjected plants was supported by root growth which mainly occurred in the top soil during the drought experiment (not shown; Prechsl *et al.*, 2015). Thus, location of meristems (close to the root collar) as well as abiotic conditions (most likely high oxygen as well as nutrient concentrations) triggered root growth and thus water uptake by root tips in the topsoil under drought. This in turn allowed very fast recovery of all performance and growth variables as soon as the first rain event occurred and water availability increased after shelter removal.

Complementing these grassland performance and ecosystem services assessments, an agroeconomic assessment was carried out as well (Finger *et al.*, 2013). Using the yield data from the three grassland sites and their responses to drought, loss of farmers' income due to drought was calculated. It turned out that the farmers on the Swiss Plateau lost the most income (about 30%), while the farmers in the alpine area lost the least (about 10%), despite yield losses being rather similar (about 30%: 2.4 t ha^{-1} vs 0.9 t ha^{-1}, respectively). These counter-intuitive results had their origin in the Swiss ecological direct payment scheme: while farmers in the lowlands relied heavily on hay prices and thus on hay production for their incomes, the income at alpine elevations strongly depended on direct payments which were independent of production levels. Thus, considering the increasing risk of such extreme weather events in the future, new economic instruments might be needed for farmers to deal successfully with drought risks.

Conclusion

Grasslands are both drivers of, as well as driven by, climate change. We provide ample evidence that grassland management is highly influential in achieving either positive or negative impacts of grasslands on climate change. This in turn allows the development of climate-smart agricultural practices to reduce or avoid GHG emissions. Moreover, our studies suggested a high resilience of grasslands against severe summer droughts, despite immediate, potentially also strong negative responses to these extreme events. Thus, multifunctionality, i.e. the provisioning of multiple ecosystem services, is high in permanent grasslands, even under drought.

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