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Reduced snow cover affects productivity of upland temperate grasslands

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ABSTRACT

The 2013/2014 winter season showed exceptionally sparse snow cover conditions north of the Alps, which allowed an in situ investigation of the response of vegetation to changed environmental conditions. Examination of carbon dioxide fluxes at three grassland sites along an elevation gradient from 595 to 864 m a.m.s.l. revealed that elevation, snow cover extent, soil temperature (T_{soil}) and management were determinative factors for productivity. In the absence of snow cover at the highest elevation site (864 m), substantial growth started only when the mean daily T_{soil} exceeded 5 °C. The lack of snow cover at the lowest elevation site (595 m) allowed the vegetation to remain photosynthetically active throughout the winter, with a canopy that developed after the last harvest of the previous season. The reduced snow cover at the lower elevation sites (595 and 769 m) resulted in an earlier spring, a significant increase in gross ecosystem production and ecosystem respiration, as well as enhanced seasonal carbon dioxide uptake. The reduced snow cover in the 2013/2014 winter season is attributed to low precipitation and high energy influx, which in turn were best explained by exceptionally frequent foehn, i.e., southern advection of dry, warm air across the Alps.

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1. Introduction

The impact of climatic change near mountains is likely characterized by shifts in regional weather patterns that change the environmental boundary conditions for natural and managed ecosystems in the mountain range as well as the surrounding foreland. An increase in mean temperature is expected to be the dominant climate change signal in the 21st century for Europe, with regional variability in the magnitude of the temperature change, as well as changes in precipitation (IPCC, 2013; Kjellström et al., 2013; Wagner et al., 2013). Changes in the climate system can first emerge in climate statistics as extremes, particularly in mountain regions (Mountain Research Initiative EDW Working Group, 2015; Fan et al., 2015). Temperature is a driver for regional climate change, but it is suggested that regional trends can be explained best when shifts in large-scale climate patterns are considered (Scherrer et al., 2004). Such shifts translate to changes in intensity, timing and duration of weather systems, as well as the path of weather fronts. Ensuing changes in the thermal and moisture regimes can have substantial implications for ecosystem functioning, particularly in areas near major orographic features such as the Alps.

In general, a change in synoptic scale flow in the Alps promotes changes in distribution and timing of precipitation. A dry, warm and often very turbulent wind develops in the lee of mountain ranges as a result of orographically forced precipitation on the windward side, a phenomena known in the Alps as foehn (Whiteman, 2000). The air warms adiabatically down-slope and is a source of sensible heat advection. Foehn is mainly a result of regional flow over a mountain range, but local foehn-like phenomena can also be found (Hornsteiner, 2005). Typically, the warm and dry air flow coincides with high radiative inputs (clear sky or cloudy) that help heat the surface, particularly if enhanced snow melt exposes the low albedo surface. In addition, the relatively strong, usually gusty wind can amplify evaporation through mechanical turbulence. In winter and spring, foehn is known to greatly enhance snow cover thawing, even at some distance to the Alps (Hoinka et al., 2009). Thus, changes in snow cover extend as well as the warming potential of foehn can influence key ecosystem processes and phenology, such as respiration and the onset of spring.

Changes in temperature and snow cover timing have been shown to influence plant growth of mountain species in alpine and

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sub-alpine zones (Grabherr et al., 1994; Keller and Körner, 2003; Menzel et al., 2006; Jonas et al., 2008). The main environmental controls for initiating plant growth are thought to be temperature, photo period and a winter chilling requirement (a sufficient amount of cold during dormancy), as precursor to the end of a plant's dormant period (Körner and Basler, 2010). Recent studies suggest that the phenology and productivity of agricultural ecosystems in the Alps sub-region, usually found at a sub-alpine elevation, are tightly coupled to differences in timing of spring and season length (Schmitt et al., 2010; Zeeman et al., 2010; Siebert and Ewert, 2012; Galvagno et al., 2013; Wohlfahrt et al., 2013; Peichl et al., 2013; Desai et al., 2016).

We report on the changes in productivity of three managed grasslands north of the Alps in response to a winter season characterized by low snow cover. We used observations of the atmospheric exchange of carbon dioxide to evaluate if the anomalous winter conditions resulted in an advance of phenologic spring and an enhanced carbon sink of managed grasslands in the German Alpine foreland.

2. Materials and methods

2.1. Study sites

The three observation sites used in this study are located along an elevation gradient with increasing terrain complexity towards the south (Fig. 1). The sites Fendt (DE–Fen), Rottenbuch (DE–RbW) are located in the Bavarian Alpine Foreland, which is an area in the south of Germany and north of the Alps with landscape features that were formed by glacial activity and erosion in the Alps (Fig. 1). The area is a transitional zone with increasing mountainous characteristics towards the Alps in the south and is therefore referred to as pre-Alpine. The site Graswang (DE–Gwg) is located in an adjacent sub-alpine valley (Fig. 1). All three sites are grassland used primarily for fodder and hay production, but only limited grazing. Harvest dry weight was approximate 250 g m^{-2} with a leaf area of 5 m^2 m^{-2}. The sites are part of the TERrestrial Environmental Observatory (TERENO) pre-Alpine, which is a recently established long-term research infrastructure in the Ammer river catchment south of lake Ammersee in the Upper Bavaria region, Germany (Zacharias et al., 2011).

The most northerly site is Fendt (47.8329° N 11.0607° E, 595 m above mean sea level), situated at the center of a drained alluvial area. It is located just north of the town of Peissenberg and borders on the west and east to forested hills (Fig. 2a). The Rottenbuch site (47.7299° N 10.9690° E, 769 m a.m.s.l.) is situated south of the town of Rottenbuch and borders on the east to the forested Ammer river ravine (Fig. 2b).

The Graswang site (47.5708° N 11.0326° E, 864 m a.m.s.l.) is situated on the relatively flat alluvial plain of the Linder river in a sub-alpine valley of the upper Ammer catchment near Graswang (Fig. 2c). Local winds are modulated by the East–West orientation of the valley and the steep slopes are mostly forested (Fig. 1).

2.2. Instrumentation

Environmental variables and fluxes of energy and carbon dioxide were recorded using similarly configured stations at all three sites. The eddy-covariance system included a three-dimensional sonic anemometer (model CSAT3, Campbell Scientific, Logan, UT, USA) and an infra-red gas analyzer for observation of water vapour and carbon dioxide concentrations mounted at 3.5 m height (open-path model LI-7500 in Graswang and Fendt and closed-path model LI-7200 in Rottenbuch, Li-Cor, Lincoln, NE, USA). Other environmental observations are listed in Table 1.

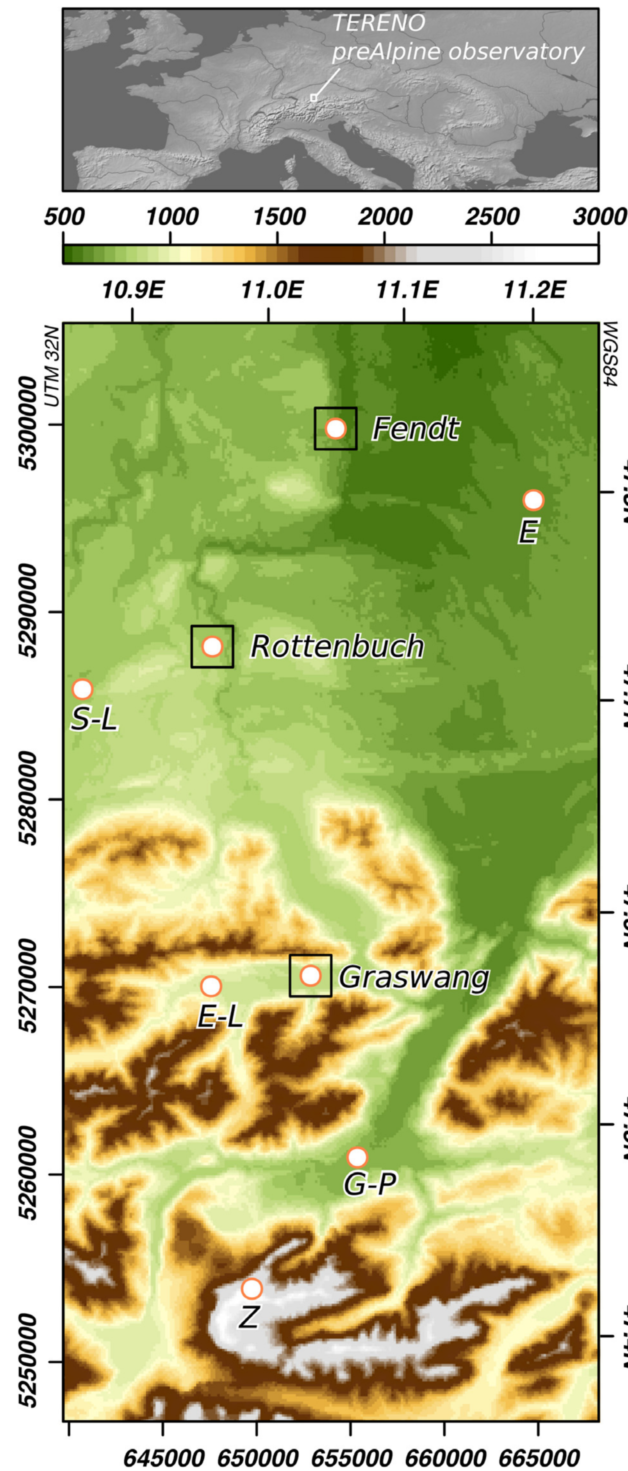

Fig. 1. Elevation of the study area with TERENO pre-Alpine observatory sites Fendt, Rottenbuch and Graswang, as well as the weather stations Garmisch–Partenkirchen (G–P), Zugspitze (Z), Ettal–Linderhof (E–L), Steingaden–Lauterbach (S–L) and Eberfing (E) operated by DWD. The marked areas correspond to Fig. 2a–c. Produced using Copernicus data and information funded by the European Union – EU-DEM layers.

Data were logged (model CR3000, Campbell Scientific) at 20 Hz and 1 min intervals for observations needed in eddy covariance flux calculations and other environmental variables, respectively. Logged data were transferred automatically to a computer (model MSEP800/L, Kontron, Eching, Germany) for the computation of flux statistics and daily transfer to an in-house database for near-realtime evaluation. The Fendt and Graswang sites were fully

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