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Primary productivity and physiological responses of *Vitis vinifera* L. cvs. under Free Air Carbon dioxide Enrichment (FACE)

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ABSTRACT

Two *Vitis vinifera* L. cultivars, Riesling and Cabernet Sauvignon, were grown in the Geisenheim VineyardFACE (Free Air Carbon dioxide Enrichment) system under rain-fed conditions to investigate the effects of elevated CO_2 on the productivity of grapevines for three consecutive years (2014–2016) following planting in 2012. The FACE system consisted of six 12 m diameter rings, with three at ambient CO_2 (aCO_2, 400 ppm), and three rings at elevated CO_2 (eCO_2, + 20% of aCO_2 level). Vegetative growth, single leaf gas exchange and yield parameters were monitored for the three growing seasons. Vegetative growth parameters responded differently to CO_2 treatments depending on biomass components. Trunk cross section area, as an indicator of perennial growth, showed a significant increase for Riesling under eCO_2 but not for Cabernet Sauvignon. Fresh biomass as lateral leaf area and fresh weight of summer pruning were stimulated by elevated CO_2 for both cultivars. Leaf gas exchange measurements for both cultivars showed a significant increase in net assimilation rate and an improved intrinsic water use efficiency for all three years under eCO_2 conditions. However, contrary to expected stomatal behaviour of grapevines, transpiration rate and stomatal conductance were higher under elevated CO_2 for Riesling and Cabernet Sauvignon in all three seasons. Higher values of pre-dawn leaf water potential recorded under eCO_2 point towards an interaction with soil water availability and root system development. Elevated CO_2 resulted in higher yield in terms of higher bunch weight, but did not affect average number of bunches per vine or sugar content of must at harvest date. Accordingly, bunch architecture was altered under elevated CO_2 levels. The increase in primary productivity of grapevines under eCO_2 indicates yield gains that can be expected under even modest near-future CO_2 scenarios. However, higher water use, particularly if maintained as grapevines transition to maturity, may have critical implications for the future adaptation of non-irrigated viticulture to increasing temperature and periods of rainfall deficit.

1. Introduction

A key factor driving the climate change since pre-industrial times is the continuously rising atmospheric carbon dioxide (CO_2) concentration. The associated increase in global mean surface temperature, together with elevated CO_2 concentrations, has the potential to alter physiological responses and yield performance of plants. Vegetative and reproductive plant growth is highly dependent on interrelated effects of CO_2, temperature, nutrition and water availability. These lead to changes in plant phenology, photosynthesis, respiration and transport of assimilated carbon and potentially crop quality. The most frequent response of plants to rising atmospheric CO_2 is an enhanced growth and yield, but the level of CO_2 enrichment could also play a key role within plant response mechanisms.

The Intergovernmental Panel on Climate Change (IPCC) has predicted an annual atmospheric CO_2-increase of 1.5–3 ppm based on four main emission-scenarios, representing an increase of 20% by mid-century (Ciais et al., 2013). By targeting the predicted 2050 CO_2 concentration, and thereby simulating a near future climate scenario, suggestions for implications on plant management and therefore adaption to climate change can be provided.

Many studies have been conducted regarding the impact of elevated CO_2 on agricultural crops e.g. barley, cotton, peanut, rice, ryegrass, soybean, sugar beet, sweet potato and wheat (Allen et al., 1987; Bhattacharya et al., 1990; Chambell et al., 1990; Chen and Sung, 1990; Baker and Allen, 1993; Drake et al., 1997; Kimball et al., 2002; Long et al., 2004; Ainsworth and Long, 2005; Manderscheid et al., 2009, 2010; Vanuytrecht et al., 2012c; Weigel and Manderscheid, 2012;

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O'Leary et al., 2015). The common benefits of eCO_2 for most of the annual crops were higher net photosynthesis rates (A), biomass and yield production, as well as improved water use efficiency (WUE). Associated with the gain in WUE were predominantly decreases in transpiration (E) and stomatal conductance (g_s) under eCO_2 and therefore an enhanced whole-plant water status. However, a recent synthesis of g_s responses in FACE experiments revealed that 11.8% of g_s responses under experimentally elevated CO_2 were positive (Purcell et al., 2018). Studies of perennial fruit tree responses to eCO_2 are less numerous, but similar productivity and gas exchange responses have been reported for citrus (Koch et al., 1986; Downton et al., 1987; Idso et al., 1991; Idso and Kimball, 1992, 1997; Vu et al., 2002; Vu, 2005) and pear (Ito et al., 1999; Han et al., 2012). Sour orange trees, as an example of the additional aspect of perennial biomass response, showed an increased trunk plus branch volume, as well as higher numbers of oranges per tree, greater fruit size and volume classes over an 8-year study under eCO_2 (700 ppm) treatment (Idso and Kimball, 1997). Pears reacted to long-term CO_2 enrichment with improved vegetative growth, fruit size, weight and volume, but no changes in acidity or hardness of fruit have been observed (Ito et al., 1999; Han et al., 2012).

Viticulture is renowned for being sensitive to changing climate, and many studies have investigated grapevine physiology, yield efficiency and grape composition responses to environmental conditions over the last decades (e.g. Coombe, 1987; Bindi et al., 1996b; Jones and Davis, 2000; Schultz, 2000; Tate, 2001; Duchêne and Schneider, 2005; Jones et al., 2005; Mira de Orduna, 2010; Hannah et al., 2013; Martinez-Lüscher, 2016). However, fewer studies are available on the influence of elevated CO_2 concentration on grapevines, particularly in a free air enrichment system (Bindi et al., 1996a, 2001a, 2001b, 2005; Tognetti et al., 2005; Moutinho-Pereira et al., 2009, 2010; Gonçalves et al., 2009; Edwards et al., 2016, 2017). Studies that have been conducted used open top chambers (OTC) or Mini-FACE conditions, and established red grape cultivars (cv. Sangiovese, cv. Touriga Franca and cv. Shiraz) under warm or hot climate conditions and eCO_2 treatments ranging from 500 to 700 ppm. Results showed increased A, WUE, light- and nutrient efficiency, vegetative and fruit biomass while E and g_s decreased under elevated CO_2 concentrations (Bindi et al., 2001b; Moutinho-Pereira et al., 2009; Edwards et al., 2017). The most recent of these studies also examined the interactive effects of elevated air temperature (eTemp) and eCO_2, where a combination of eTemp + eCO_2 produced higher A than eCO_2 alone. So far, on white wine cultivars (cv. Chardonnay, cv. white Tempranillo) only greenhouse experiments were conducted. These resulted on the one hand in decreased stomatal density for cv. Chardonnay grown under ambient (336 ppm) as compared to subambient (94 ppm) CO_2 regimes (Rogiers et al., 2011). On the other hand, elevated CO_2 concentration attenuated negative effects of drought on vegetative growth and grape yield of white Tempranillo (Kizildeniz et al., 2015) when elevated temperature and water deficit were also investigated. For grapevines growing in cool climate, rising temperatures *per se* may be less of a concern than for current hot climate regions around the world. However, understanding how rising CO_2 will influence productivity, leaf gas exchange responses and interactions with grapevine pests and diseases against a background of changing temperature and rainfall will be critical for planning the adaptation of existing regions to what may be inevitable changes in growing conditions.

The aim of this study was to compare two CO_2 regimes (aCO_2 and eCO_2) for two commercial grapevine cultivars (Riesling and Cabernet Sauvignon) by using the recently developed VineyardFACE-system at Hochschule Geisenheim University. Vegetative growth, physiological response and yield were determined for the different treatments over three consecutive years (2014–2016). Furthermore, we investigated the impact on bunch parameters in detail, e.g. number of bunches, bunch weight, bunch length or bunch compactness at ambient and elevated CO_2 levels.

Fig. 1. VineyardFACE experimental site at Hochschule Geisenheim University with associated CO_2 tank. Three FACE-rings were assigned to the two CO_2-levels aCO_2 (A1, A2 and A3) and eCO_2 (E1, E2 and E3).

2. Material & methods

2.1. Field site

The VineyardFACE field experiment is located at the Hochschule Geisenheim University (49° 59′ N, 7° 57′ E) in the Rheingau wine region, Germany. The vineyard used for the study was planted in 2012 using one year old pot-grown vines, and arranged across a total area of 0.5 ha in a six ring FACE system (Fig. 1). The vines were planted at a spacing of 0.9 m within rows and 1.8 m between rows, with rows orientated north-south, and trained using a vertical shoot positioning system (VSP) with one year old canes pruned to 5 nodes per m^2 or approximately 8 nodes per vine. The two cultivars used in the field experiment were *Vitis vinifera* L. cv. Riesling (clone 198-30 Gm) grafted on rootstock SO4 (clone 47 Gm), and L. cv. Cabernet Sauvignon (clone 170) grafted on rootstock 161-49 Couderc.

The soil at the field site is characterized as a sandy loam, and results of soil analyses from samples collected around bud break in 2014 are shown in Table S1. Management of vines was in accordance with the code of good practice (Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz - BMELV, 2010). Summer pruning was conducted as described subsequently, but no other canopy manipulations were undertaken. Cover crop consisted of Freudenberger WB 130 mulch mixture III, permanent vineyard greening I (Feldsaaten Freudenberger, Krefeld, Germany) in every second row. Every other row was cultivated. The cover crop mixture consisted of 5% perennial ryegrass, 30% creeping red fescue, 20% Kentucky bluegrass, 5% perennial ryegrass, 20% Chewing's fescue and 20% Kentucky bluegrass. The cover crop was mowed several times during the vegetation period.

The climate conditions are characterized by a temperate oceanic climate with mild winters and warm summers represented by an average annual temperature of 10.5 °C (long-term average from 1981 to 2010) and mean annual rainfall of 543 mm. Weather data were collected from a weather station within the FACE experimental site. Precipitation and air temperature for the seasons 2014, 2015 and 2016