Hessisches Landesamt
für Naturschutz, Umwelt und Geologie

Fachzentrum Klimawandel und Anpassung Hessen

HESSEN

FACE experiments: Free Air CO_2 Enrichment in grassland, vineyards and horticulture

Climate change impact research in Hesse – focus topic

FACHZENTRUM KLIMAWANDEL UND ANPASSUNG

Impressum

Climate change in Hesse – focus topic

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Prof. Dr. Thomas Schmid
President of the
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Environment and
Geology

Many events in recent years have made it clear that man-made climate change is already here. Extreme events such as droughts or heavy rainfall and various changes in nature are omnipresent. The question of the best possible adaptation to climate change is therefore extremely urgent in order to safeguard our livelihoods in the future. In addition to rising temperatures and changes in the distribution of precipitation over time and space, rising carbon dioxide concentrations in the air also play a role. Under their influence, ecosystems will change. This can have serious consequences for the agricultural sector and thus for our food security.

In Hesse, there are unique prerequisites for the investigation of these pressing issues. For more than 20 years, they have been jointly investigated by Justus Liebig University and the Hessian State Agency for Nature Conservation, Environment and Geology. This is done in large field experiments, so-called FACE facilities, in which grassland is exposed to elevated CO_2 concentrations. In the meantime, the data series collected has become one of the longest in the world and is of outstanding scientific importance.

Through the Hessian Excellence Initiative LOEWE, the Hochschule Geisenheim University was able to set up further FACE facilities for the investigation of vines and vegetables. Together with the Philipps University Marburg and the Max Planck Institute for terrestrial Microbiology Marburg, the participating institutes founded the research network $FACE_2FACE$ that is unique in the world. $FACE_2FACE$ carried out extensive research in a LOEWE project 2014–2017, which produced a large number of important results. This brochure attempts to present the most important of these to the general public in a generally understandable form.

LOEWE Research cluster FACE$_2$FACE – Impacts of climate change, adaptation to climate change and reduction of greenhouse gas emissions by 2050

LOEWE's FACE$_2$FACE research cluster explores the impacts of climate change on major agroecosystems. The aim of FACE$_2$FACE is to investigate the influence of increased atmospheric CO_2 concentrations, warming and altered water availability on the interactions between plants and their environment. In particular, the reactions of plants and the effects on carbon and nitrogen cycles and product quality under a changing climate are in the focus of the FACE$_2$FACE network.

With the FACE$_2$FACE network, a unique long-term research network has been created, which is a nucleus for international cooperation and ongoing collaborative projects.

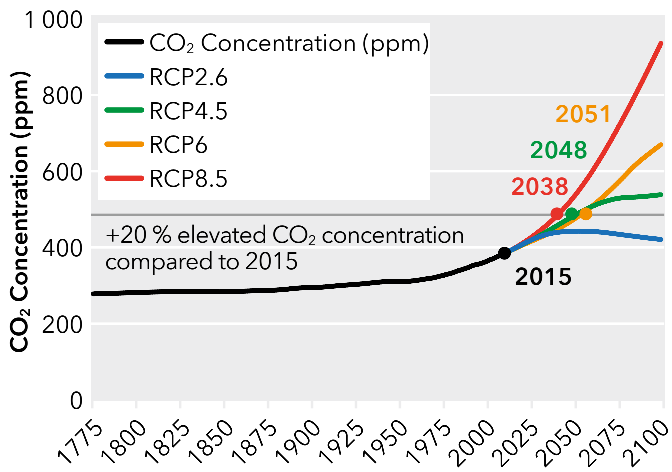
Cooperation partners of the project:

- Justus Liebig University Giessen (JLU)
- Hochschule Geisenheim University (HGU)
- Philipps University Marburg (PU)
- Max Planck Institute for terrestrial Microbiology Marburg (MPItM)
- Hessian State Agency for Nature Conservation, Environment and Geology (HLNUG)

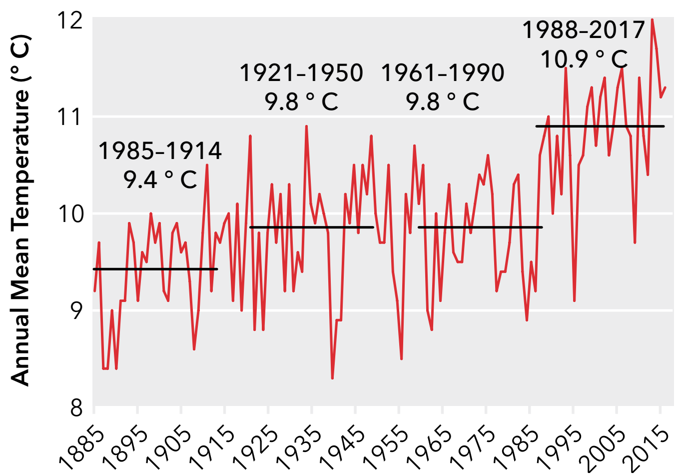
Heating and CO_2 enrichment experiment Giessen T-FACE (free air Temperature and Free Air CO_2 Enrichment) © Gerald Moser

The mean atmospheric concentration of the greenhouse gas carbon dioxide (CO_2) rose from 280 ppm in 1750 to 406 ppm (+45 %) in 2017. The direct effects of a further increasing atmospheric CO_2 concentration on ecosystems in the future can only be investigated with free air CO_2 enrichment systems, so-called FACE (Free Air CO_2 Enrichment) experiments. In the $FACE_2FACE$ focus, the current CO_2 concentration in three Hessian facilities was increased by 20 %, so that during 2014–2017 a concentration level was reached, which, depending on the climate scenarios of the Intergovernmental Panel on Climate Change (IPCC), is expected to be reached between 2038 and 2051.

The increased atmospheric concentrations of CO_2 and other greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O) led to a warming of the air. In Geisenheim, for example, this led to an increase of 1.5 °C in the 30-year mean temperature between the periods 1885–1914 and 1988–2017. However, the temperature increase was not linear. The increase in temperature was slowed down *(global dimming)* by heavy air pollution between 1960 and 1990. As a result of the effective reduction of pollutant emissions, e.g. sulfur dioxide *(global brightening)*, rapid warming occurred, which was previously hidden by the pollutant gases.



Historical global mean of atmospheric CO_2 concentrations and IPCC projections (RCP2.6-8.5) Data: http:// www.esrl.noaa.gov/ gmd/ccgg/trend and https://tntcat.iiasa.ac.at:8743/RcpDb



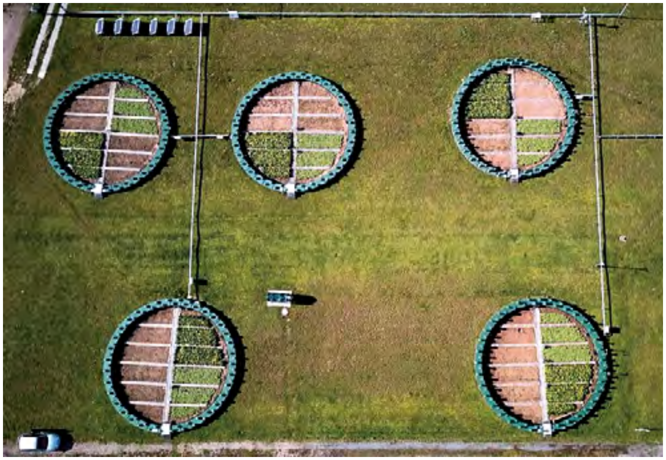
Annual mean temperature and 30-year mean temperatures in Geisenheim, data DWD: https://www.dwd.de/DE/leistungen/cdcftp/ cdcftp.html

CO_2-Enrichment facilities in grassland ...

At the Environmental Monitoring and Climate Change Impact Research Station Linden, south-east of Giessen, a field CO_2 enrichment system (= FACE – Free Air CO_2 Enrichment) was put into operation in 1998 to assess the effects of the rising CO_2 concentration on grassland. Grassland is of great importance as a source of fodder for live-stock farming.

The station in Linden is operated jointly by the Justus Liebig University of Giessen and the Hessian State Agency for Nature Conservation, Environment and Geology. The free air CO_2 enrichment system consists of three CO_2 enrichment rings and three control rings with no change in air composition, each 8 m in diameter[1]. It is compared whether the growth within the rings with increased CO_2 concentrations develops differently than in the control rings. The CO_2 enrichment is controlled depending on wind speed and direction. The required amount of CO_2-enriched air is thus blown downwards from the high bent pipes and blown through the rings by the wind. The enrichment takes place all year round during the daylight hours and achieves a CO_2 concentration that is 20 % higher than the CO_2 concentration in the control rings.

Giessen grassland FACE ring (8 m inner diameter)
© Eva Diehl



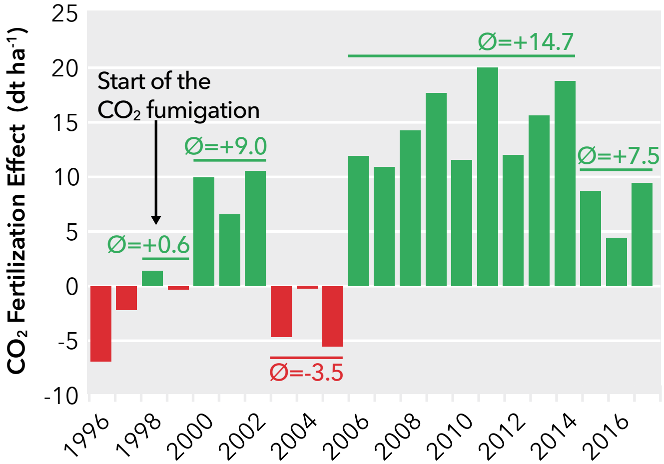
Geisenheim vegetable FACE rings (12 m diameter)
© Hochschule Geisenheim University

... and in vegetable production and viticulture

The vineyard FACE and vegetable FACE were established at the Hochschule Geisenheim University during the term of the LOEWE research cluster FACE$_2$FACE. The vegetable FACE is based on a similar technique as the Giessen Face, but the diameter is 12 m each. The design of the vineyard FACE differs considerably, as the CO_2 enrichment has to be distributed over the entire height of the grapevine hedgerows. But here, too, the enriched air is blown downwards from a height of 2 m and blown over the 12 m diameter rings. Since drier summers and wetter winters are likely to become the rule in Hesse in the future, the water availability factor is also being investigated in vegetables. Also new is the combination of +20 % CO_2 and +2 °C air temperature in the new Giessen T-FACE.

Geisenheim vineyard FACE ring (12 m diameter) © Winfried Schönbach

Effects of increased air CO_2 concentrations on grassland productivity …



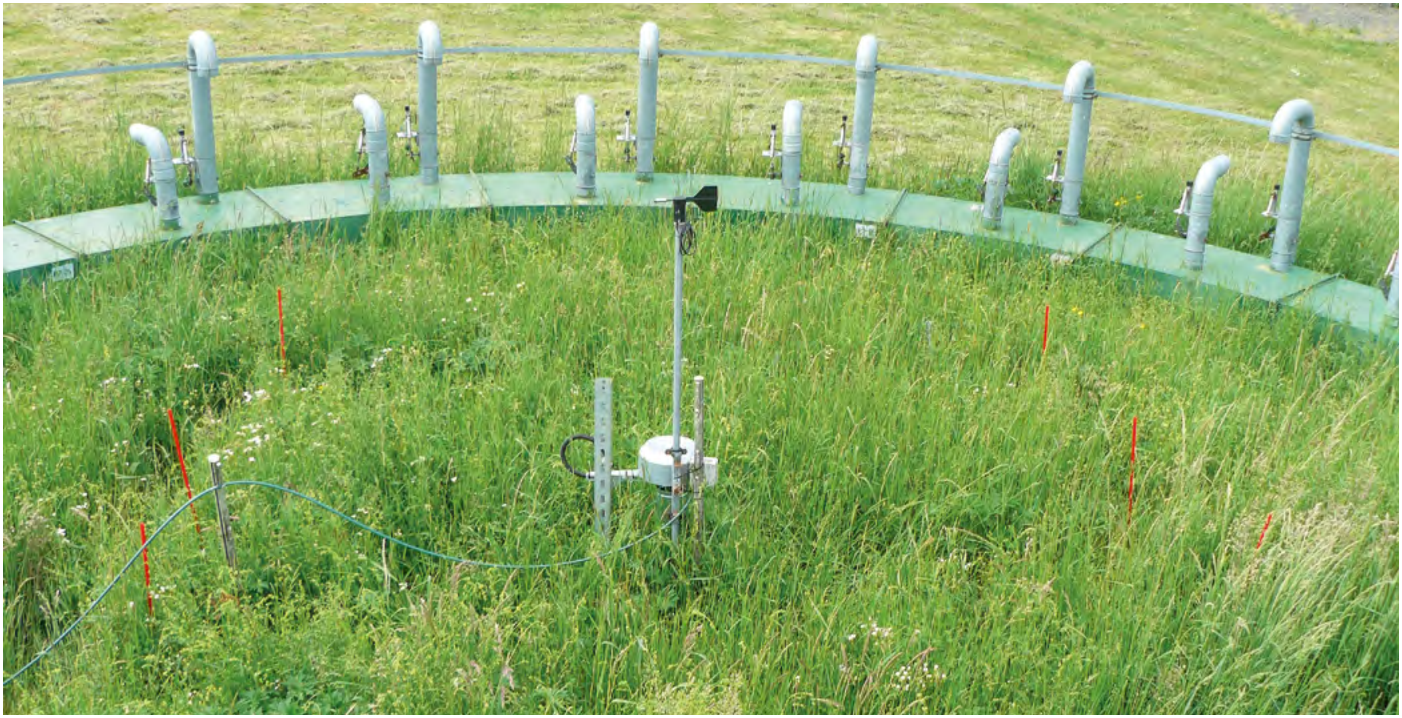
Influence of the CO_2 fertilization effect in the Giessen FACE on yield performance in decitonnes per hectare (dt ha^{-1})

Spring in the Giessen grassland FACE © Gerald Moser

Results from over 20 years of research

In principle, plants can grow better under increased CO_2 concentrations, since they can assimilate more carbon through photosynthesis. This is the so-called CO_2 fertilization effect, which leads to increased yields. In the Giessen grassland FACE, the annual increase in yield due to the CO_2 fertilization effect over the 20-year duration of the experiment was 8.4 decitonnes per hectare (dt ha^{-1}) on average compared with the control, for the period 2006–2014 even 14.7 dt ha^{-1} on average. What is new, however, is the insight that the CO_2 fertilization effect on plant growth depends very much on the weather and occurs most strongly under average temperatures and precipitation sums during the growing period[2]. If the temperature and soil moisture were significantly above or below the long-term average (e.g. 2015), the CO_2 fertilization effect was reduced. It even turned negative in and after the dry and hot summer of 2003. By modelling it could be shown that the biomass production of the grassland investigated will be lower in the future (mid-21st century) despite increased CO_2 concentrations due to changed climatic conditions[3].

The chemical analysis of the grassland biomass showed a decrease in the energy content, i.e. the nutritional value of the plants that grew under an increased CO_2 concentration. Due to the decrease in the energy content of fodder due to rising CO_2 concentrations in the atmosphere, cows will have to eat more green fodder in future in order to be able to draw sufficient energy from it. Increased feeding and the associated digestion and ruminant chewing would in turn probably lead to increased methane production and emissions in cows. That means that under increased CO_2 the feed value decreases with simultaneous increase of greenhouse gas emissions.



Spring growth in Giessen grassland FACE © Gerald Moser

Effects of climate change on the reproduction of grassland plant species …

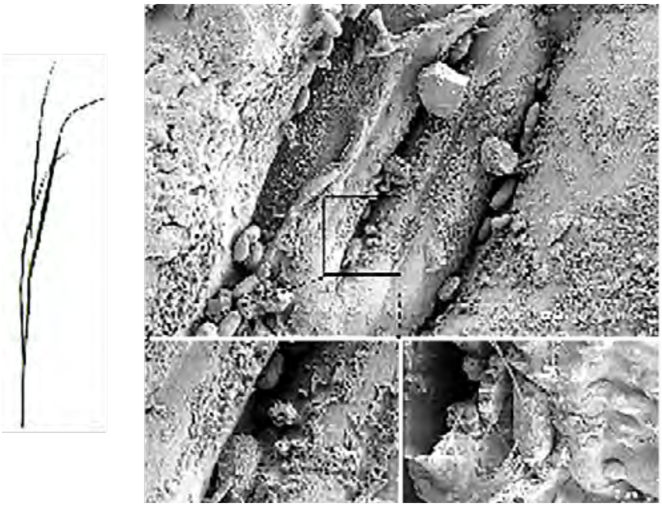
The composition of the plant species community in Giessen Face has remained very constant over the last 20 years. There was no species change, only the proportions of the individual species vary slightly between the years. In grassland, plant species are divided into three functional groups: grasses, herbs and legumes. Irrespective of the CO_2 concentration, the mass proportion of these groups in the mown grass shifted slightly over the 20 years in favour of the herbs[4]. Investigations of the plant seeds in the soil showed that increased CO_2 leads to a change in the number of seeds of the different species. Species which reproduce predominantly by long-lived seeds have a competitive advantage under increased CO_2 over species which form short-lived seeds and reproduce predominantly asexually, e.g. by runners.

Winter in the Giessen grassland FACE © Christoph Müller

… and the microbial community on leaves and in soil

The new research findings showed that the two factors, increased CO_2 and increased temperature, also lead to significant changes in the composition of the bacterial species growing on the leaf surfaces. Frequent and for the plant advantageous bacterial genera were displaced by potentially pathogenic bacterial genera[5]. It could be observed that the changed composition of the metabolic products of the leaves correlated clearly with the changed metabolism of these bacteria.

The investigations showed that in root-free soil parts under increased CO_2 the diversity of the fungal species community as a whole and that of the N_2O-emitting fungal species was significantly increased and can thus contribute to an increase in emissions of the greenhouse gas N_2O, while it remained unchanged in rooted soil parts. The combined effect of increased CO_2 and the dry heat period of 2015 led to a significant reduction in the abundance of fungi in soil, while the bacterial abundance in roots and soil increased. This influences various processes in the soil, which leads to an impairment of the nutrient supply of the plants.



Electron microscope image of the bacterial community on the leaf surfaces of smooth oats (left) and white bedstraw (right) © Ebru Aydogan

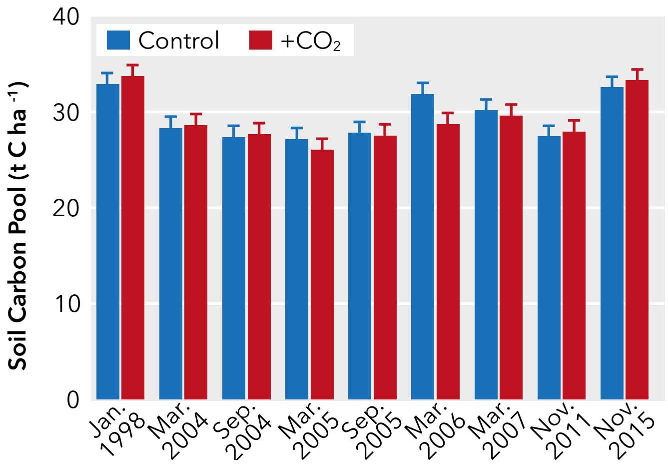
Is the climate tipping due to increased greenhouse gas emissions from grassland?

Recently there has been talk of so-called "tipping points" of the climate. This refers to warming mechanisms that are self-reinforcing above certain threshold values of greenhouse gas concentrations *(positive feedback)* and can no longer be stopped or reversed. However, many such feedback mechanisms are still insufficiently known, such as the effects of the rising atmospheric CO_2 concentrations on biological soil processes that release greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O). Over 100 years, these two gases have a global warming potential of 34 and 298 times greater than that of CO_2, respectively.

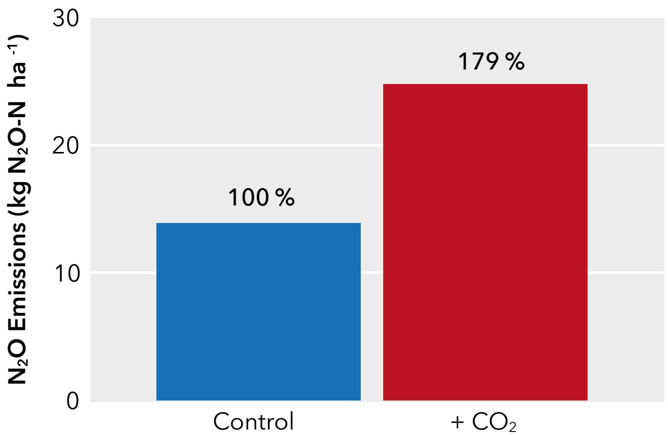
Extensively farmed grassland is more or less climate-neutral or can even be a sink for greenhouse gases, in which the carbon in the soil is enriched and stored. However, the soil carbon stock in the Giessen Face has not changed significantly over time[6], so that no additional CO_2 has been stored as carbon in the soil.

The results of the greenhouse gas balance of the Giessen Face grassland for the whole period 1998–2017 show that under increased CO_2 through increased ecosystem respiration[7], increased nitrous oxide emissions[8,9], etc. grassland might develop into a greenhouse gas source in the future. From the point of view of climate protection, this should be viewed very critically and could further accelerate global warming.

Soil profile in grassland © Gerald Moser



Soil carbon stock (in tons of carbon per hectare within soil depth 0-7.5 cm) over 17 years of CO_2 enrichment in the Giessen Face



Cumulative nitrous oxide emissions in kg N_2O-N per hectare over 20 years (1998–2017) of the control plots (blue) and CO_2 enrichment plots (red) in the Giessen Face experiment

Effects of elevated temperatures on grassland

Climate change also has an impact on ecosystems through temperature increases. In order to investigate the effects of higher soil temperatures on carbon storage and greenhouse gas fluxes in grassland, from 2007–2014 infrared lamps, which were installed at three different heights above the ground were used, simulating a 1–3 °C increase in soil surface temperature. The results show a decrease in soil carbon content due to increased soil respiration and a reduction in N_2O emissions when heated[10,11].

However, these results should be considered with caution, as climate change does not increase infrared radiation (which predominantly leads to surface warming), but increases air temperature. However, increased air temperature causes different physiological responses in plants and soil microorganisms than increased leaf and soil surface temperatures. Therefore the T-FACE technology, which is explained on the next page was developed.

Giessen warming experiment © Jochen Senkbeil

Combination experiment Giessen T-FACE

After an intensive test phase, the combination experiment in grassland was put into operation in 2018 on an extension area investigated since 2012. Since then the air temperature was simultaneously heated by 2 °C and the atmospheric CO_2 concentration enriched by 20 % (Giessen T-FACE = free air Temperature warming and Free Air CO_2 Enrichment). Depending on the wind direction and speed, the ring constructions of the newly developed facility can heat the passing air with heating mats and enrich it with CO_2 via nozzles.

The phenology of the plants (= growth and development stages recurring periodically in the course of the year) will presumably change with the combination of air heating with CO_2 enrichment and the plants will react with altered photosynthesis rates and water balance. An important research question is how large the CO_2 fertilization effect will be on plant growth at 2 °C higher air temperature. In addition it is to be clarified whether the CO_2 or the temperature effect on the N_2O-emissions prevails and how these and other ecosystem reactions will look under different weather conditions including extreme weather events such as heat and drought.

Giessen T-FACE – air Temperature warming and Free Air CO_2 Enrichment, with +2 °C air temperature and +20 % CO_2, inside diameter: 4.3 m, start 2018; arrows = air flow in wind, blue = ambient temperature, red = +2 °C © Gerald Moser

Effects of climate change in a vinyard ecosystem …

The first three years of the 20 % CO_2 enrichment the Geisenheim Vineyard FACE showed that increased CO_2 concentrations had hardly any influence on the phenological development in the course of the year.

Irrespective of the grapevine cultivar (Riesling, Cabernet Sauvignon), a significant CO_2 fertilization effect was observed from the second year of investigation onwards. Photosynthetic rates and water use efficiency at leaf level increased significantly, resulting in increased leaf and shoot biomass and up to 18 % higher grape yield. The unchanged must weight plus higher overall grape yield resulted in a significantly higher sugar yield[12].

Compared to the control rings without increased CO_2, transpiration via the leaves was increased and may be related to site adaptation and the water balance of the grapevines. Under increased CO_2 an improved water use efficiency could be observed.

Vineyard FACE Panorama © Hochschule Geisenheim University

Gas exchange measurement on vine leaves of the Riesling variety in a FACE ring. Shown is M. Sc. Yvette Wohlfahrt during measurement. © Moustafa Selim

Extreme weather events also have a significant influence on viticulture. In the extremely dry year of 2015, the total N concentration, the sum of all nitrogen-containing chemical compounds in musts, which is important for the quality of the wine, generally decreased compared to 2014. Contrary to expectations, Cabernet Sauvignon must from grapes that grew under elevated CO_2 levels showed an increase in relation to the total N content in favour of nitrogen, which was chemically present as so-called Amino-N. This Amino-N content significantly influences the alcoholic fermentation by the yeasts and is particularly important for the wine quality.

Sensory investigations regarding the differentiability of the wines or their aroma intensity have so far shown no qualitative differences between the wines of the first three vintages, which were produced under increased CO_2 concentrations. It remains to be investigated whether sensory differences will show up in future vintages or during the ageing of the vintages. The slight changes that occurred in the composition of berries and must under increased CO_2 did not lead to any qualitative changes in the wine. Whether the increased CO_2 changes the shelf life of the FACE wines is a further research topic.

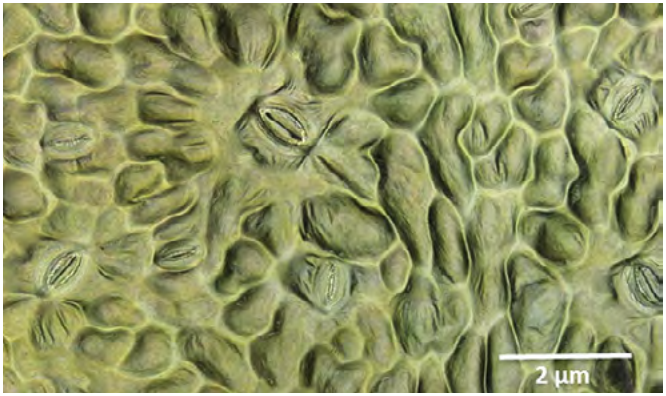
Vineyard FACE Panorama © Hochschule Geisenheim University

Ripe grapes of Riesling (top) and Cabernet Sauvignon (bottom) in vineyard FACE before harvest © Yvette Wohlfahrt

Effects of climate change on vine pathogens …

Riesling vines growing under elevated CO_2 show anatomical adaptation, e.g. by forming a larger number of stomata. This could lead to increased infection frequency by downy mildew in the future, but this has not yet been observed.

In the interaction of grapevines with pathogens such as downy mildew infestation and also after feeding by larvae of the European grapevine moth, the vines showed a physiologically clear influence by the increased CO_2 concentration: the synthesis of more secondary metabolites of plants and thus defense reactions were activated[13]. The populations of the grapevine moth, a pest insect, also adapted physiologically to higher CO_2 concentrations and, after several generations, showed changes in developmental biology, including a shortened development period of the larvae or a higher pupal weight.



Microscopic image of the underside of a grapevine leaf with stomata © Moustafa Selim

Artificial infection of outdoor grapes with larvae of the European grapevine moth © Moustafa Selim

… as well as the soil microbial community and greenhouse gas fluxes

It was possible to gain the new insight that increased CO_2 concentrations in the vineyard soil lead to a different species diversity of fungi in the rooted and unrooted parts of the soil.

The results from the first years showed that an increased CO_2 concentration does not change the greenhouse gas balance of the vineyard soils. However, the detailed data analysis showed that, irrespective of the CO_2 concentration, the greening of the vine rows between the vines led to a worsened greenhouse gas balance compared to plant-free vine rows. This reduced the absorption of methane in the soil by 33 % and increased the release of nitrous oxide by 46 %. The soil in plant-free, open rows of vines is presumably better aerated by regular breaking of the soil, which reduces the formation of nitrous oxide.

Geisenheim vineyard FACE © Hochschule Geisenheim University

Effects of climate change …

As it is likely that due to climate change the frequency of water shortage during heat and drought waves will increase, this factor is investigated within the vegetable FACE experiment. Spinach, radish and pickling cucumber as representatives of leaf, root and fruit vegetables were cultivated several times a year. Even a small reduction in the amount of available water led to significant changes in the ingredients of the harvest products. These changes led to significant changes in the quality of all three vegetables, which could affect further processing, the content of essential nutrients and taste. The lower water content of the harvested vegetables with reduced water availability increases the concentration of the ingredients. Results to the effect of increased CO_2 concentration on the yield and the quality of the vegetables are not yet available.

Geisenheim vegetable FACE, behind it the vineyard FACE © Hochschule Geisenheim University

Measurements and work in the vegetable FACE rings, Benjamin Spehle in the foreground, Viktor Rempel left, Uwe Loos back © Hannah-Rebecca Klostermann

A comprehensive literature analysis has shown that a very strong reaction to the increased CO_2 concentration can be observed in protected cultivation. It becomes smaller in the order leaf vegetables ➞ tubers & blossom vegetables ➞ fruit vegetables. These findings suggest that the level of absorption capacity of vegetable plants for additional CO_2 sugar from increased photosynthesis determines the response of plants.

Laboratory experiments have shown that pickling cucumbers in the vegetative stage show almost no CO_2 effect on the leaf sizes with a good water supply. However, with reduced water availability, the length-to-width ratio of the leaves changes. This and further negative effects of poorer water supply on the plant can be reduced by increased CO_2. An increased CO_2 concentration in the air promotes the growth of the total leaf area.

Radish in vegetable FACE © Hannah-Rebecca Klostermann

Conclusion

The Hessian FACE studies show that the effects of the increased CO_2 concentrations in the range that can be expected mid-century will have significant effects on the various agricultural ecosystems and thus on human food security. On one hand, rising yields can be positive. On the other hand, declining feed quality of grassland, poorer nutrient supply and increased susceptibility of plants to infection or faster development of pests pose challenges for which adaptation strategies must be found. In addition, results show a significant increase in the emissions of climate-damaging greenhouse gases, which must be viewed very critically.

Aerial view of the Giessen free air CO_2 enrichment experiments GiFACE (Giessen Free Air CO_2 Enrichment) in the foreground and parts of the T-FACE (free air Temperature and Free Air CO_2 Enrichment) in the background © Sebastian Egli 2018

Internet links, references and sources

Links

Project homepage of the LOEWE research cluster $FACE_2FACE$
http://www.$FACE_2FACE$.center

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T-FACE globe © Gerald Moser

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