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The AgraSim (Agricultural Simulator) facility for the comprehensive experimental simulation and analysis of environmental impacts on processes in the soil-plant-atmosphere system

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Abstract

The AgraSim large-scale research infrastructure is an experimental simulator consisting of six mesocosms (each mesocosm consisting of an integrated climate chamber, plant chamber and lysimeter system) for studying the effects of future climate conditions on plant physiological, biogeochemical, hydrological and atmospheric processes in agroecosystems, which was designed and built by the Forschungszentrum Jülich.

AgraSim makes it possible to simulate the environmental conditions in the mesocosms in a fully controlled manner under different weather and climate conditions ranging from tropical to boreal climate. Moreover, it provides a unique way of imposing future climate conditions which presently cannot be implemented under real-world conditions. It allows monitoring and controlling states and fluxes of a broad range of processes in the soil-plant-atmosphere system. This information can then be used to give input to process-models, to improve process descriptions and to serve as a platform for the development of a digital twin of the soil-plant-atmosphere system.

1 Introduction

Climate change in combination with a steadily growing world population and a simultaneous decrease in agricultural land is one of the greatest global challenges facing mankind (Molotoks et al., 2020). Investigating the effects of the changes in air temperatures and precipitation that have already occurred and are still to be expected in the future on the fundamental processes in agroecosystems, which form the basis for the sustainable management of arable land while maintaining other ecosystem services, such as the recharge of clean groundwater, the storage of carbon and nutrients and the preservation of biodiversity, is of central importance here.

In this context, IBG-3 at Forschungszentrum Jülich decided to establish an "agricultural simulator" (AgraSim), which enables research into the above-mentioned effects of climate change on agricultural ecosystems and the optimization of agricultural cultivation and management strategies with the aid of combined experimental and numerical simulation. The funding for AgraSim was obtained from the Helmholtz Association and it is embedded in the Research Program “Changing Earth - Sustaining our Future”. ZEA-1 is the technology and engineering partner with the task of development and construction of Agrasim.

AgraSim enables the analysis of carbon, nutrient and water fluxes and thus the nutrient and water use efficiency in the soil-plant-atmosphere system under controlled conditions. Using stable isotope analysis, the net fluxes of carbon dioxide, water vapor and nitrogen gases can be disentangled into their component fluxes. This provides the basis for taking these processes into account in model calculations for sustainable agriculture. Extensive isotope labeling experiments will make it possible to quantify material fluxes between all compartments.

In its combination of experimental, analytical and simulation capabilities, AgraSim is unique worldwide. By intimately integrating real-time observations and modelling of states and fluxes, a digital twin of the soil-plant-atmosphere system has been created. Understanding the effects of climate change on agricultural yields, the role of the soil for resource use efficiency and the feedback to climate-relevant parameters can be studied and quantified in a way that is unique to date. AgraSim can also be used to test the cultivation of new varieties and their performance under changing climatic conditions. This opens up new opportunities for application-oriented bioeconomic modelling, in particular for the exploration and optimization of new and sustainable cultivation methods.

A comparison of previously implemented ecotrons is described in publication (Roy et al., 2020). In addition, there are other large chamber systems, e.g. by NASA in the USA (Wheeler, 1992), at Kyoto University, Japan (Horie et al., 1995) and at Mendel Agriculture and Forest University in the Czech Republic (Urban et al., 2001), as well as small mobile variants, such as those described in (Leadley & Drake, 1993) (Morrow & Crabb, 2000). With Agrasim, statistical studies are possible due to the six-fold design of the chambers. At the same time, its size allows experiments to be carried out with a variety of agricultural crops.

2 Performance of the system

The technical specifications of the AgraSim research facility are as follows:

Pos.	Description	Performance data
1.	Air temperature	-5 … +40 °C Without condensation inside the plant chamber
2.	Air temperature change rate	Maximum ±5 °C h^{-1} at a humidity of 80 % rH (A larger temperature change rate is possible at lower humidity)
3.	Minimum humidity	The minimum humidity depends on the transpiration rate of the plant. Assuming a maximum transpiration rate of 2.5 mmol m^{-2} s^{-1} at an air temperature of 25 °C and 5 m² leaf area as well as a maximum supply air volume flow of 1,000 l min^{-1} of dry air, this results in a relative humidity (rH) of approx. 60 %. With lower transpiration rates, significantly lower air humidities can be set (e.g. 10 % rH).
4.	Maximum humidity	80 % rH No condensation occurs inside the plant chamber or the atmosphere-carrying components.
5.	Carbon dioxide content	ca. 385 … 2,000 ppm
6.	Air pressure	+ 4 mbar to the environment to prevent external contamination
7.	Light intensity	0 … 1,000 µmol m^{-2} s^{-1} on the plant chamber floor 0 … 2,500 µmol m^{-2} s^{-1} at a distance of 2.6 m from the floor surface
8.	Light spectrum	Spectrum similar to daylight in the wavelength range of approx. 360-740 nm (without infrared component). Variation of the light spectrum via 8 LED channels, including a channel for the UV-A range.
9.	Supply air volume flow	50 … 1.000 l min^{-1}
10.	Supply air, lowest dew point	-40 °C
11.	Irrigation quantity	6 … 48 l h^{-1}
12.	Soil temperature control	-5 … +30 °C
13.	Purity	All relevant surfaces in contact with the atmosphere have inert properties thanks to an appropriate choice of materials (mainly glass or an inert metal coating), (Vaittinen et al., 2013) with Silconert-2000 (Silcotek, Bad Homburg Germany).
14.	Plant chamber dimensions	1,600 x 1,600 x 2,700 mm (L x B x H)
15.	Weight of the plant chamber	ca. 1,500 kg

Table 1: Technical specifications of the AgraSim research facility

3 Structure and function of the system

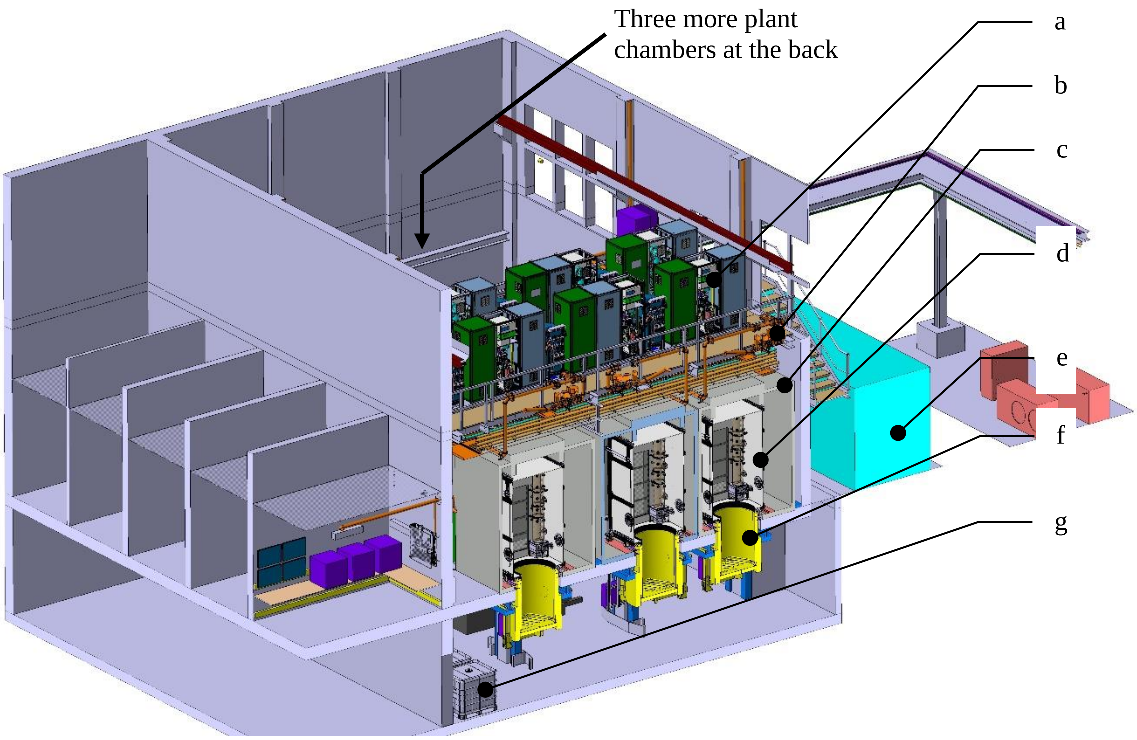

Figure 1: Setup of the experimental research infrastructure AgraSim

The core of the Agrasim research infrastructure (see Figure 1) consists of a total of six plant chambers (Figure 1, d) which can be operated independently of each other. Three chambers can be seen in Figure 1, three more are located on the opposite side of the hall. The system extends over three floors. On the ground floor the plant chambers are located (Figure 1, d), which in turn are each arranged in a climate chamber (Figure 1, c, chamber-in-chamber system). The lysimeter system (lysimeter: soil container) with one lysimeter (Figure 1, f) per plant chamber is located in the basement. The process technology (Figure 1, a), which is used to condition the supply air to the plant chamber, for example, is located on the technical platform on the first floor. The ultra-pure air system (Figure 1, e) for supplying air to the plants is located outside the hall. This produces dry and purified compressed air for the air supply to the plant chambers. The compressed air enters the process technology racks (Figure 1, a) on the technology platform, where it is regulated to a defined volume flow, tempered, humidified and mixed with CO_2. This conditioned air enters the plant chambers (Figure 1, d) and supplies the plants on the lysimeter (Figure 1, f) with air. The air is led out of the plant chamber through the exhaust pipe (Figure 1, b) and the pressure inside the plant chamber is regulated to a low overpressure (400 Pa). A gas sample of the supply air and a gas sample of the exhaust air from each plant chamber are taken via a valve terminal and sequentially connected to gas analyzers for the determination of water vapor, greenhouse gases (CO_2, CH_4, N_2O) and reactive nitrogen gases (NO, NO_2, NH_3, HONO). The irrigation station (Figure 1, g) in the basement is used to irrigate the surface of the soil in the lysimeters (Figure 1, f).

4 Plant chamber

The plant chamber (Figure 2, a) is located inside a climate chamber (Figure 2, b) and is centered and sealed on the lysimeter (Figure 2, c).

The climate chamber (Figure 2, b) supports the temperature control of the plant chamber and prevents condensation inside and outside the plant chamber by ensuring that all external surfaces of the plant chamber, as well as all pipes and hoses, are tempered to the target temperature of the plant chamber by the climate chamber air. The plant lighting is installed in the climate chamber ceiling.

The choice of materials for the construction of the plant chamber and built-in parts is severely restricted, as many materials would change the plant chamber atmosphere through outgassing and/or cause interactions between the plant chamber atmosphere, the soil, the water for irrigation or the plant itself and other materials, which is also undesirable. Some materials, for example, release heavy metals, plasticizers, hydrocarbons or xylene from paints and epoxy adhesives (Knight, 1992) Metallic surfaces made of aluminum, copper, brass, nickel and galvanized zinc can form toxins on contact with nutrient-containing irrigation water (Knight, 1992) (Graves & Adatia, 1983, p. 103-104). Plastics contain fats, acid and vegetable oil derivatives, which are subject to degradation by microorganisms, as well as ester compounds, phthalic acids, maleic acid and phosphoric acids (Knight, 1992) (Mathur, 1974), which are also undesirable in this environment. In addition, some plastics, e.g. polyvinyl chloride (PVC) and polyethylene (PE), contain the plasticizer dibutyl phthalate (DBP), which is toxic to plants at high concentrations (which has already been proven in plant chambers made of plastics) (Knight, 1992). Contact between Plexiglas surfaces and water containing calcium produces gases that are harmful to plants (Mortensen, 1982). Brush motors are another source of hydrocarbons (Knight, 1992).

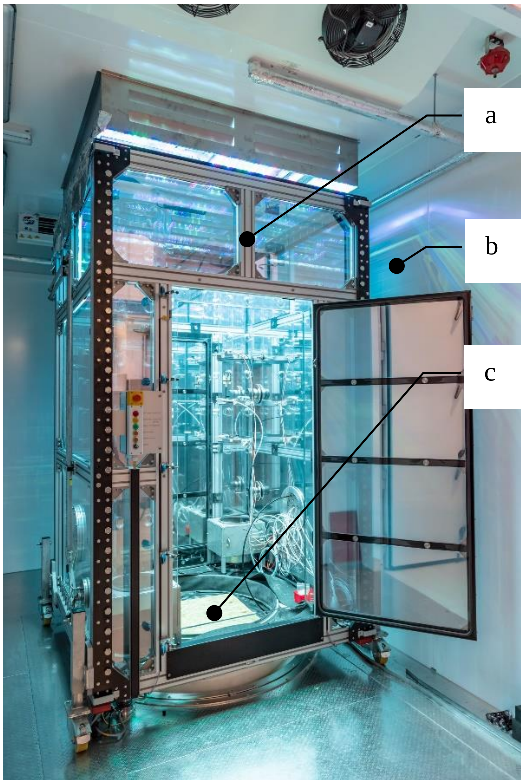

Figure 2: Plant chamber
Source reference: U. Limbach | Forschungszentrum Jülich

Applicable materials

PTFE (polytetrafluoroethylene) and glass are materials that have been shown to have a low impact on the plant's environment (Knight, 1992). O-rings made of Viton or FKM (fluororubber) only release very small amounts of hydrocarbons when exposed to radiation (Knight, 1992). At the same time, O-rings are often concealed and are therefore not irradiated by plant lighting. Furthermore, a surface coating of stainless steel with Silconert-2000 from Silcotek (Bad Homburg, Germany) results in an inert surface (Vaittinen et al., 2013).

Structure

The outer surfaces of the plant chambers were realized using the following types of glass sheets from the manufacturer Schott (Mainz Germany) and the company Kastenholz (Frechen Germany):

- Side walls: Laminated safety glass consisting of white glass ESG-H (t = 6 mm), 1.52 mm PVB Interlayer clear UV, white glass ESG-H (t = 8 mm). Mirror foil was applied to the outside of the side walls to reduce the decrease in light intensity over the height (in the lower area with a height of 1 meter, the reflectance is 80 %, above a reflectance of 97 % was selected).
- Floor: Laminated safety glass consisting of 2 x 8 mm white ESG-H glass with 1.52 mm PVB interlayer clear UV
- Ceiling: ESG-H white glass with Conturan green anti-reflective coating from the manufacturer Schott (Mainz, Germany). This glass has a very low reflectance of 1-2 % in the 450-650 nm range. In addition, the transmission is very high at over 97 % in the 450-650 nm range (Schott, 2015, p. 9, p. 12). At shorter and longer wavelengths, the reflectance is higher and the transmission lower, see (Schott, 2015, p. 9, p. 12), which is why this must be compensated for with a higher light intensity.

The plant chamber is sealed using precured, individually manufactured FKM seals (fluororubber, company Flohreus, Veitsbronn Germany). For sealing, all outer edges of the glass panes are pressed against each other with springs with a contact pressure of 3,000 N m^{-1}. The heat exchangers (stainless steel 1.4571) and the fan blades (stainless steel 1.4301) arranged in the plant chamber have a large exchange surface with the atmosphere. They were therefore provided with the inert coating Silconert-2000 (Silcotek, 2023) (vaporization with silicon). These measures lead to very little influence on the atmosphere from the plant chamber and the built-in parts.

5 Temperature control of the plant chamber atmosphere via two cooling towers

The plant lighting can generate up to 3 kW of heat load within the plant chamber. Figure 3 shows the cooling towers used to control the temperature of the plant chamber atmosphere.

The two cooling towers (Figure 3) inside the plant chamber are used to control the temperature of the plant chamber atmosphere. In addition to controlling the temperature to the desired value, the cooling towers also ensure homogeneous mixing of the atmosphere.

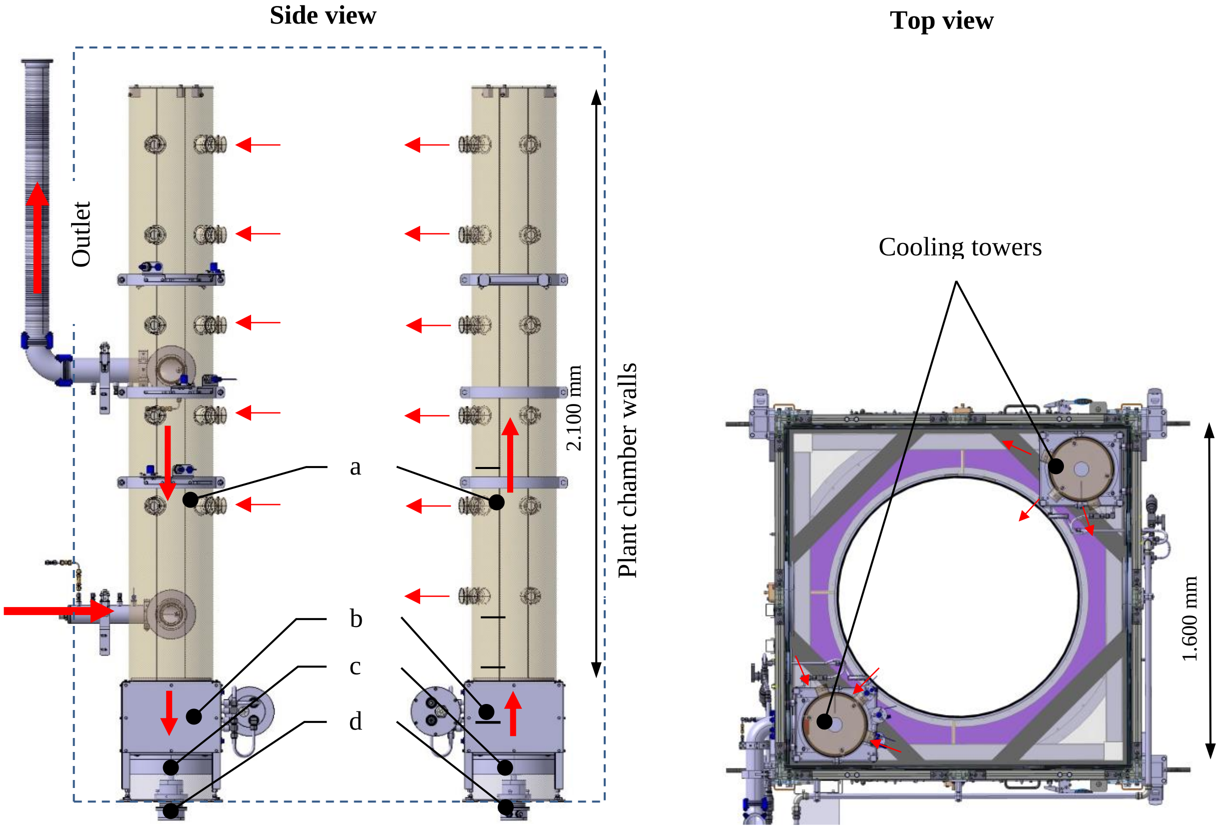

Figure 3: Cooling tower inside the plant chamber

Each of the two cooling towers consists of a fan (Figure 3, c, Pelzer Ventilatoren, Dortmund, Germany, $\dot{V} = 1{,}800$ m^3 h^{-1} at $\Delta p = 140$ Pa, with Silconert-2000 coating), a heat exchanger arranged above it (Figure 3, b, manufacturer: Schwämmle, type: ELW 4-HP stainless steel, with Silconert-2000 coating) and a mounted air distribution tube made of borosilicate glass (Figure 3, a, Aachener Quarzglas Technologie, Aachen, Germany, and Landgraf Laborsysteme HLL GmbH, Langenhagen, Germany, Ø300 mm). The flow directions within the two cooling towers are opposite, so that a diagonal flow is created within the plant chamber via the side nozzles of the air distribution pipes. This ensures good mixing of the atmosphere over the entire height of the plant chamber. All components must have a surface temperature above the dew point of the air, including the heat exchangers for cooling. At high humidity, there is therefore only a small ΔT available for cooling the plant chamber atmosphere (e.g., at 75 % rH, the dew point is only 4.7 °C below the air temperature), to ensure that condensation is avoided. However, this low permissible ΔT makes efficient cooling difficult and costly. Therefore, a high air flow rate (approx. 1,600 $m^3\ h^{-1}$ per cooling tower) and a high cooling water flow rate (approx. 1,000 $l\ h^{-1}$ per cooling tower) are required to achieve a cooling capacity of approx. 3 kW with such a low ΔT.

At the same time, the air speed should be limited so that the plants are not exposed to too strong air flow, which is why many side nozzles (air speed max 12 m/s directly after a side nozzle) were provided in the air distribution pipes (pipe on the left: 15 side nozzles, pipe on the right: 18 side nozzles, Figure 3). Individual side nozzles can be closed to adapt the flow conditions to the plant. The drive of the fan blades (Figure 3, d) was equipped with a brushless motor and arranged outside the plant chamber. The rotary motion is transmitted into the plant chamber by means of an inert feedthrough. The rotary feedthrough also has a desirable, minimal air purge to the outside of the plant chamber to prevent contamination of the atmosphere by the bearings or the drive itself.

Figure 4 shows the target temperature (black) and the actual temperature (red) inside the plant chamber at maximum plant lighting output over a period of approx. 3 hours. The temperature was reduced from 34.5 °C to 19.5 °C. The humidity curve (blue) is also shown (the humidity was also controlled using the profile shown).

- Temperature sensor: Combined sensor for temperature and humidity
- Manufacturer/Type: Rotronic/HC2A-SM
- Control accuracy in this scenario: ± 0,25 °C (see Figure 4)
- Measurement deviation at 23 °C and ±5 °C: ± 0,10 °C

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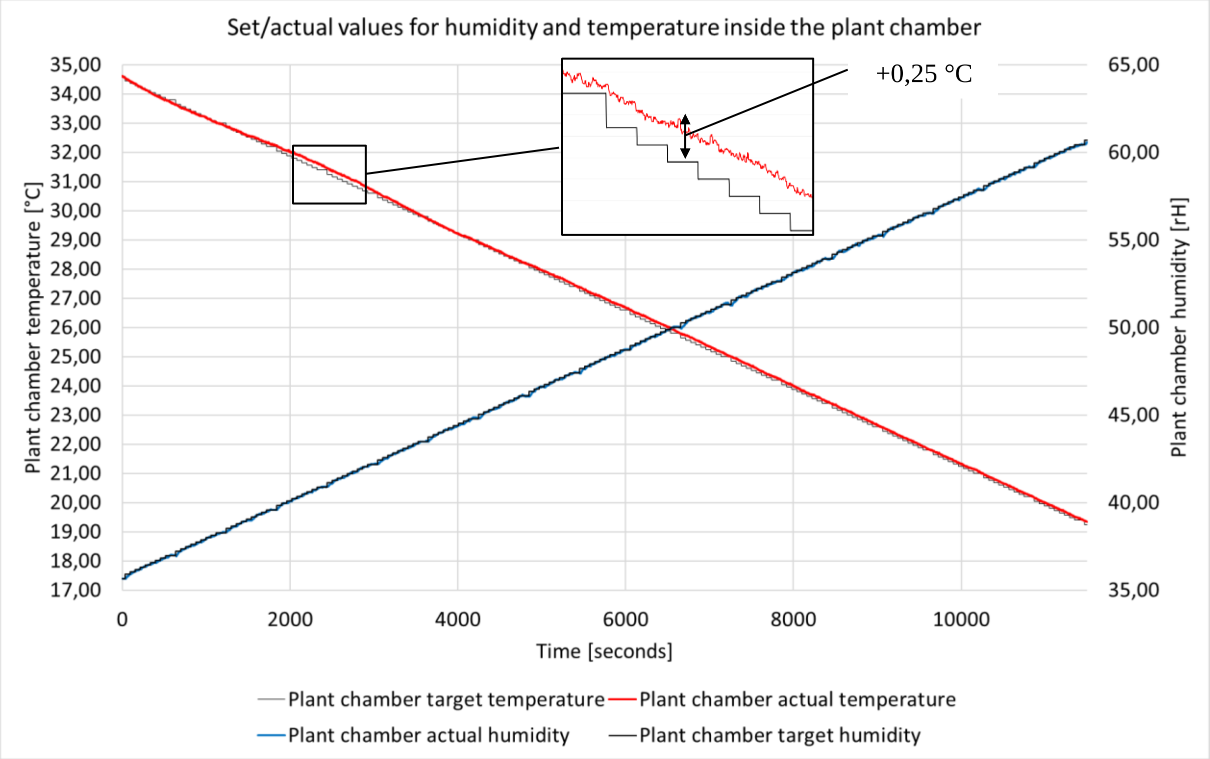

Figure 4: Measured temperature and humidity curve inside the plant chamber

6 Concepts investigated for temperature control of the plant chamber atmosphere

During the development phase, three concepts for controlling the temperature of the plant chamber atmosphere and for dissipating the heat load from the plant lighting (approx. 3 kW) were investigated using CFD (computational fluid dynamics) simulations.

Requirements for the cooling concept

- Removal of the heat load introduced by the plant lighting to a maximum of 3 kW with a ΔT between the plant chamber air and the cooling medium of less than 4.7 °C in order to be able to implement an air humidity of 75 % rH without condensation occurring in this extreme scenario. This corresponds to a required cooling capacity of 640 $W\ K^{-1}\ \Delta T$.
- As space-saving as possible to minimize the impact on the growing space for the plants (diameter: 1,129 mm, height: 2,500 mm).
- Use of inert components, especially for components that have a large contact surface with the atmosphere.

The concepts examined were:

1. Cooling via a temperature-controlled plant chamber ceiling
2. Cooling via heat exchangers in the side walls of the plant chamber
3. Implemented and described above: cooling via two cooling towers equipped with heat exchangers and fans

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6.1 First cooling concept: Cooling via the plant chamber ceiling

In this concept, the ceiling glass panel of the plant chamber was double-walled, with a cooling liquid flowing through the gap. This allowed the ceiling to be tempered to the desired temperature. A silicone oil was chosen as the cooling medium, which only slightly affects the light spectrum of the plant lighting, even in the UV range. In order to achieve good heat transfer on the inner surface of the plant chamber ceiling, a ceiling fan was provided. The fan blades of which are made of glass and therefore only slightly interfere with the plant lighting. The walls of the plant chamber were also cooled from the outside by the climate chamber air. However, the influence of the climate chamber air on the internal wall temperature of the glass panels was significantly lower than the influence of the tempered ceiling glass panel with plant chamber air flowing against it.

Input variables and boundary conditions for the CFD heat balance simulation

- Ceiling fan data: Ø250 mm | Axial air speed: 10 m s^{-1}
- Temperature of ceiling glass panel: 3 °C
- Air temperature of climate chamber: 3 °C
- The application of the heat load of 3 kW is simplified as follows:
    - 52% of the energy is absorbed by the floor slab outside the lysimeter (corresponding to the area share).
    - 36% of the energy is considered as heat flow on the upper sides of the leaves, Reflection of typically 15% of the radiation is neglected.
    - 12% of the energy is transferred to the bottom of the lysimeter.

Result of the CFD heat balance simulation

The evaluation showed that the temperature homogeneity was not sufficient if plants are located in the chamber which will prevent even mixing of the cooled air in the whole chamber. High temperatures of up to 30 °C will occur in the lower area of the plant where the air exchange is strongly decreased by the leaves. Moreover, the leaves might suffer from high temperatures due to radiation and in-sufficient cooling. It should be mentioned here that the plant temperatures at the leave-air interfaces shown in Figure 5 do not consider any heat conduction through the leave or cooling effect due to evaporation and are therefore quite conservative. The main purpose of the modelled plant is to study the influence on the temperature distribution of the air in the chamber. The average air temperature of 15 °C was also clearly too high. For these reasons, this concept was not pursued further.

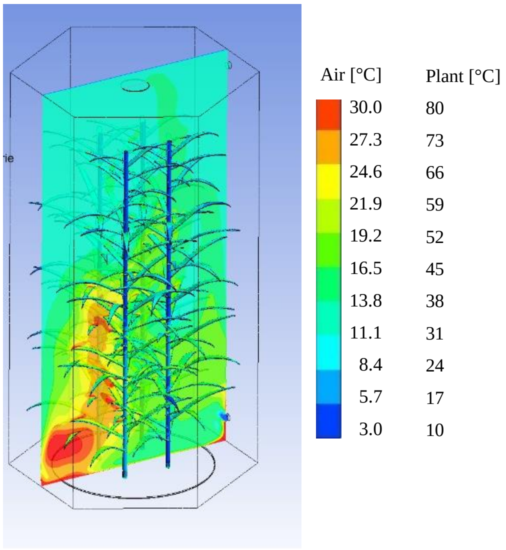

Figure 5: Result of CFD simulation

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6.2 Second cooling concept: Cooling via heat exchangers in the plant chamber walls

In this concept, a heat sink with a fan was arranged in the side wall of the plant chamber. The significantly larger cooling surface of the aluminum plate equipped with ribs was intended to significantly increase the cooling capacity compared to the first concept. In this variant, only the performance of this cooling concept was investigated for an aspired temperature difference of 5 °C between the air in the chamber and the heat sink itself without considering the whole chamber and the influence of plants inside the chamber.

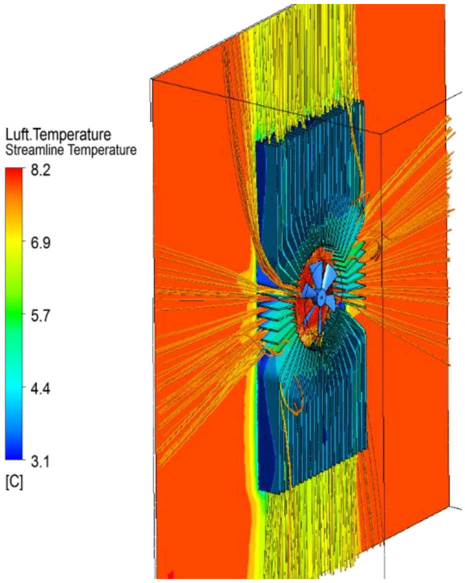

Figure 6: Second concept: heat sink in the side wall of the plant chamber

Input variables and boundary conditions for the CFD heat balance simulation

- Heat sink dimensions:
  W = 600 mm | H = 1.200 mm | T = 120 mm
- Cooling fan: Ø250 mm | ca. 1350 m³ h^{-1}
- Temperature heat sink: 3 °C
- Air temperature: 8 °C

Result of the CFD heat balance simulation

The cooling capacity for this system is approx. 180 W K^{-1} of air temperature, or 360 W K^{-1} if two of these systems are used. The increase in cooling surface area resulted in a significant improvement compared to the first concept, but the cooling capacity was still below the required cooling capacity of 640 W K^{-1}. Moreover, the problem of insufficient mixing of the air within the chamber, especially if plants are located within the chamber, is not solved by this concept. For this reason, this concept was also not pursued further.

In the third concept, the cooling surface was increased once again and the distribution of the air flow in the plant chamber was also improved.

6.3 Third cooling concept: cooling via two cooling towers equipped with heat exchangers and fans

This concept corresponds to the variant described in Chapter 5 and implemented in practice, namely cooling via two cooling towers equipped with heat exchangers and fans.

Input variables and boundary conditions for the CFD heat balance simulation

- Air volume flow per fan: 1.600 m³ h^{-1}
- Diameter of the fans: 300 mm
- Cooling water volume flow per cooling tower: l h^{-1}
- Cooling water temperature: 20 °C
- Temperature climatic chamber: 20 °C

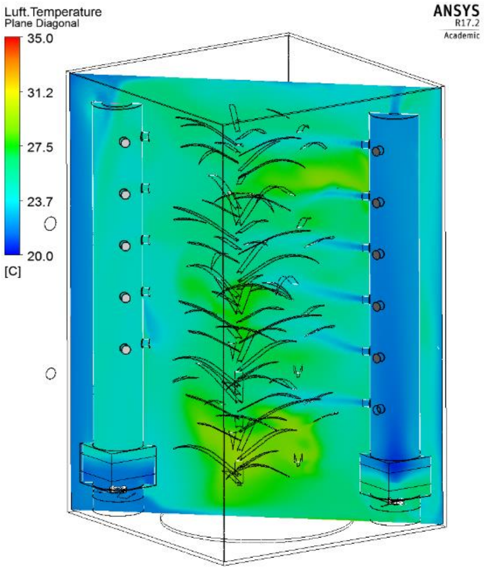

Figure 7: Temperature distribution within the plant chamber for the third and then actually realized cooling concept

Result of the CFD heat balance simulation

The cooling capacity of this system is 655 W K^{-1} of air temperature, which slightly exceeds the required cooling capacity of 640 W K^{-1}. To dissipate the maximum heat load of 3 kW, it would be sufficient to set an average temperature difference between the cooling water and air of 4.6 °C.

Figure 7 shows that there are limited heat zones in the vicinity of the plant, but these can also be found in plants in nature. This cooling concept was assessed as sufficient and implemented.

7 Preparation of supply air

Dried and ultra-pure compressed air (manufacturer: HPS, Düren, Germany) is used to supply air to the plant chambers (residual particles down to 0.01 µm with a separation efficiency of 99.9999 %, dew point: -40 °C, manufacturer of the compressed air fine filters and activated carbon filters: Parker, Bielefeld, Germany). The compressor type is a water-injected oil-free screw compressor for generating oil-free compressed air (manufacturer: compare, Simmern, Germany) in a fully redundant design. The supply air volume flow is adjusted to the requirements of the experiment and the plant per plant chamber (50 ... 1,000 l min^{-1}). After compressed air generation and volume flow regulation, the compressed air is pre-tempered by a heat exchanger to a temperature similar to the desired plant chamber temperature.

The diagram in Figure 8 **Fehler! Verweisquelle konnte nicht gefunden werden.**shows the calculation result for the required supply air volume flow of dry supply air (dew point -40 °C) for drying the plant chamber atmosphere at the maximum transpiration rate of the plant (transpiration rate at 25 °C and 5 m² leaf area: 2.5 mmol m^{-2}s^{-1}, corresponds to 0.45 g H_2O s^{-1}). Example: A volume flow of 1,000 l min^{-1} is required to keep the humidity constant at approx. 60 % rH at 25 °C (Figure 8).

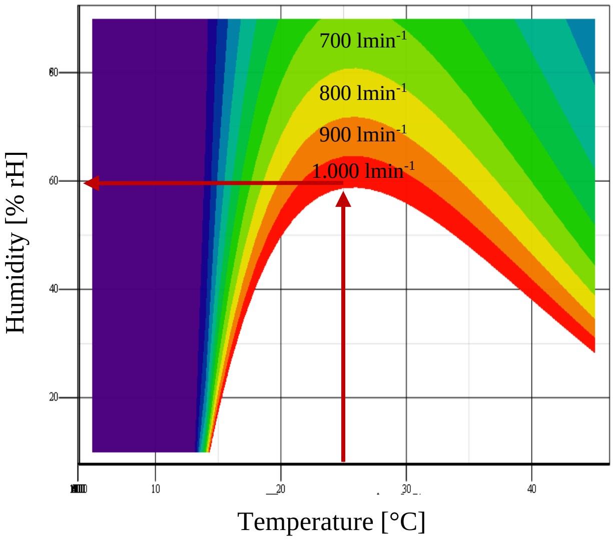

Figure 8: Required supply air volume flow to keep the humidity constant depending on the plant chamber temperature.

8 Humidification

To humidify the supply air of the plant chamber, demineralized water (electrical conductivity $\kappa \leq 0.1$ µS cm^{-1}, concentration of active silicic acid (SiO_2): < 0.02 mg l^{-1}, no chloride ions) is heated together with a small amount of compressed air (5 l min^{-1}) in an evaporator (manufacturer: Institut für Chemische Verfahrenstechnik, Stuttgart, Germany) to form a water vapor-air mixture and fed into the supply air. The mixture then passes through a static impeller mixer for homogenization (supplier: Institut für Chemische Verfahrenstechnik, Stuttgart, Germany). To prevent condensation, all components from the evaporator onwards are heated by a pipe heating system (type: FG200, Wagner GmbH, Wülfrath, Germany). To enable humidity control even at temperatures below freezing, an additional heater ensures that the supply air is at least +3 °C before humidification. The humidified air is mixed with the plant chamber atmosphere inside the plant chamber and cooled there by the cooling towers to the desired temperature, taking the dew point into account. This also enables humidity control at temperatures below the freezing point up to 80 % rH.

In the test shown in Figure 9, the humidity was increased from 19.5 % to 61 % over a period of approx. 3 hours, while the temperature was reduced from 34.5 °C to 19 °C during this period.

Humidity sensor:	Combined sensor for humidity and temperature
Manufacturer/Type:	Rotronic/HC2A-SM
Measurement deviation at 23 °C and ±5 °C:	±0,8 % rH
Control accuracy in this scenario:	±0,5 % rH (see Figure 9)

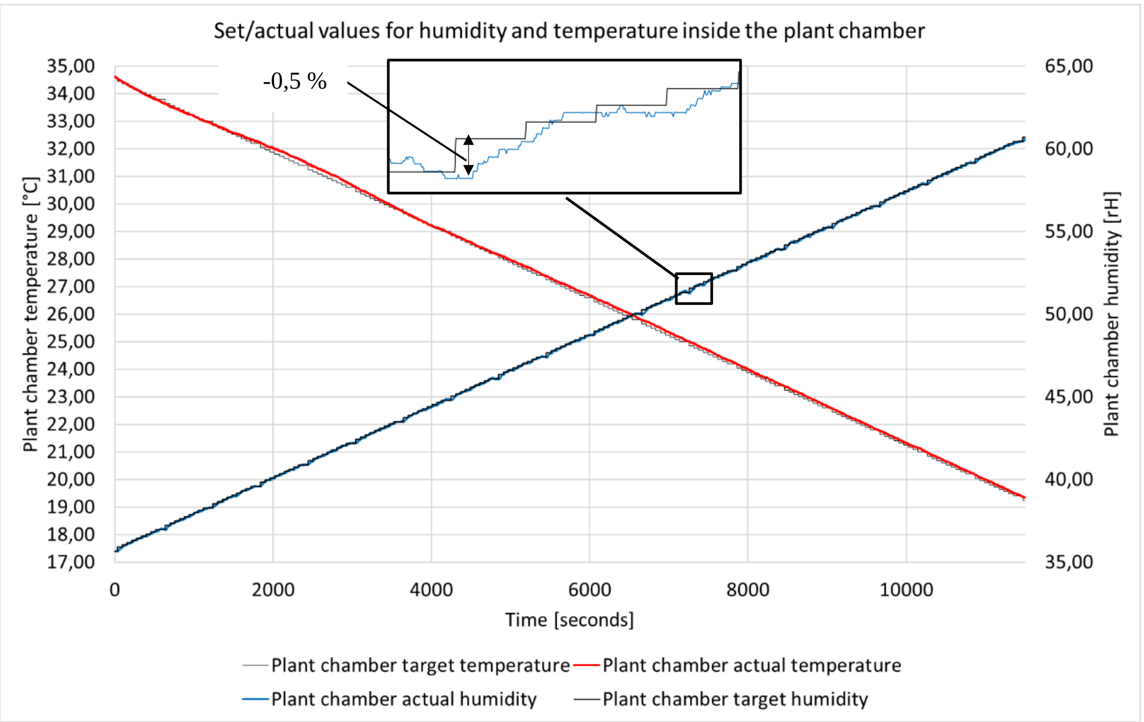

Figure 9: Control accuracy of the plant chamber humidity

9 CO_2 addition

For CO_2 control within the plant chamber, CO_2 (purity grade 4.5 | 99.995 %) is dosed into the supply air using two mass flow controllers (type: EL-FLOW Select, Bronk-horst, Kamen, Germany), mixed with the supply air using a static impeller mixer (Institut für Chemische Verfahrenstechnik, Stuttgart, Germany) and then this mixture is fed into the plant chamber. The CO_2 content is measured both in the supply air and in the plant chamber (type see below) in order to regulate the CO_2 content in the plant chamber and to quantify the influence of the plant on the atmosphere of the plant chamber and the CO_2 uptake/release of the plants.

Figure 8 shows the control accuracy for CO_2. An increase in the CO_2 content from 805 ppm to 827 ppm was specified over a period of approx. 2 hours, whereby significantly larger increases are also possible.

CO_2 Measuring device:	Manufacturer Emerson, Langenfeld, Germany
Type:	X-STREAM (XEPG)
Measurement deviation	≤ ± 15 ppm
Control accuracy:	± 1 ppm (see Figure 8)

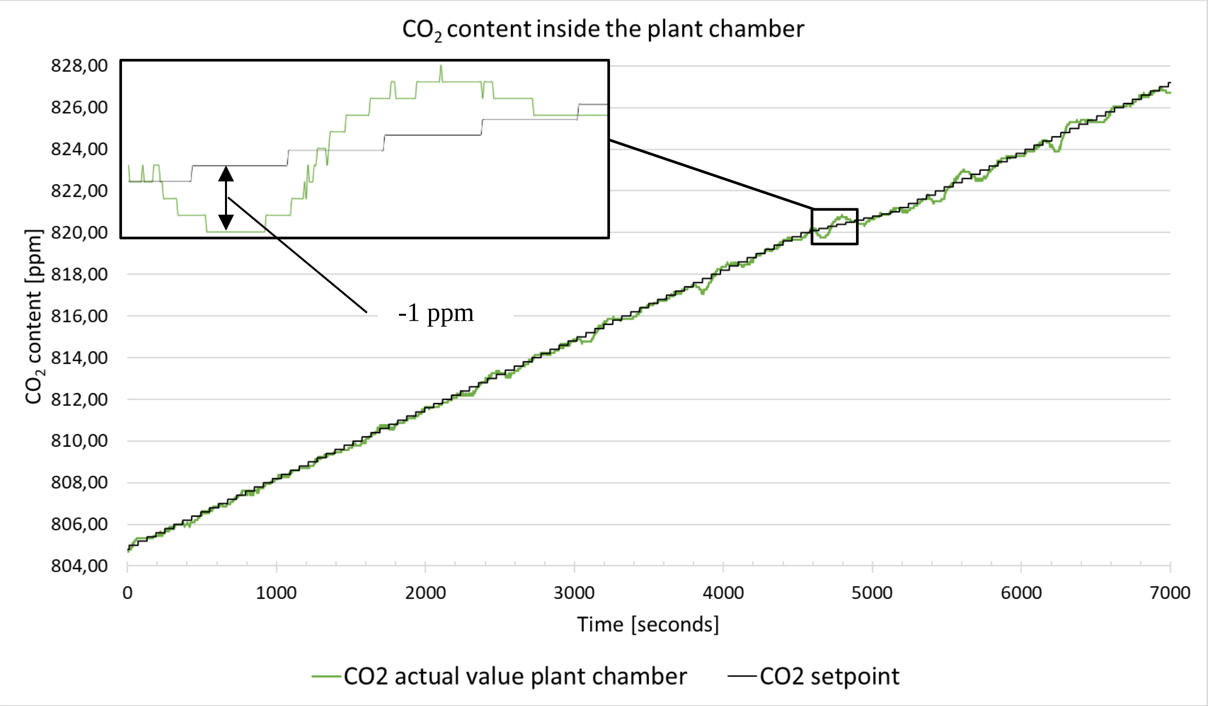

Figure 8: Target/actual comparison of CO_2 control within the plant chamber

10 Air pressure control

The plant chamber is kept under a slight overpressure of 400 Pa to prevent external contamination. The plant chamber pressure must be controlled very precisely (see Figure 9 for control accuracy), as the pressure increase over the surface of the lysimeter results in an apparent additional weight on the soil scale. Weighing provides important information about the water balance in the soil. The lysimeter weight can be used to determine the evapotranspiration, the exact irrigation rate, which is a very important parameter. The measurement accuracy of this weight measurement without the influence of air pressure is ± 50 g (with a mass of the lysimeter including soil of approx. 2.8 t). A pressure fluctuation of ±100 Pa in the plant chamber would result in a weight fluctuation of ±10 kg due to the lysimeter surface area of 1 m², which would make the weight measurement and the resulting irrigation quantity unusable. For this reason, it is essential to regulate and measure the air pressure very precisely as shown in the following table:

Pressure measurement/control

Sensor type:	Differential pressure sensor 266MST
Manufacturer:	ABB, Ratingen, Germany
Sensor measurement deviation:	±0,4 Pa
Control accuracy:	±4 Pa (see Figure 9)

The remaining influence of this small pressure fluctuation (±4 Pa = ±400 g fluctuation of the soil weight) is offset against the measured value of the lysimeter weight, which further increases the accuracy of the weight determination.

The diagram Figure 9 shows the measured plant chamber air pressure and the soil weight over a period of approx. 10 minutes.

Weight measurement

Sensor type:	3 x load cell for a load of 1000 kg each
Supplier:	JR-Aquaconsol, Graz, Austria
Measurement deviation:	± 50 g

- Measuring accuracy due to the pressure control and taking into account the differential pressure measurement between the plant chamber and the environment: ±100 g (see Figure 9)

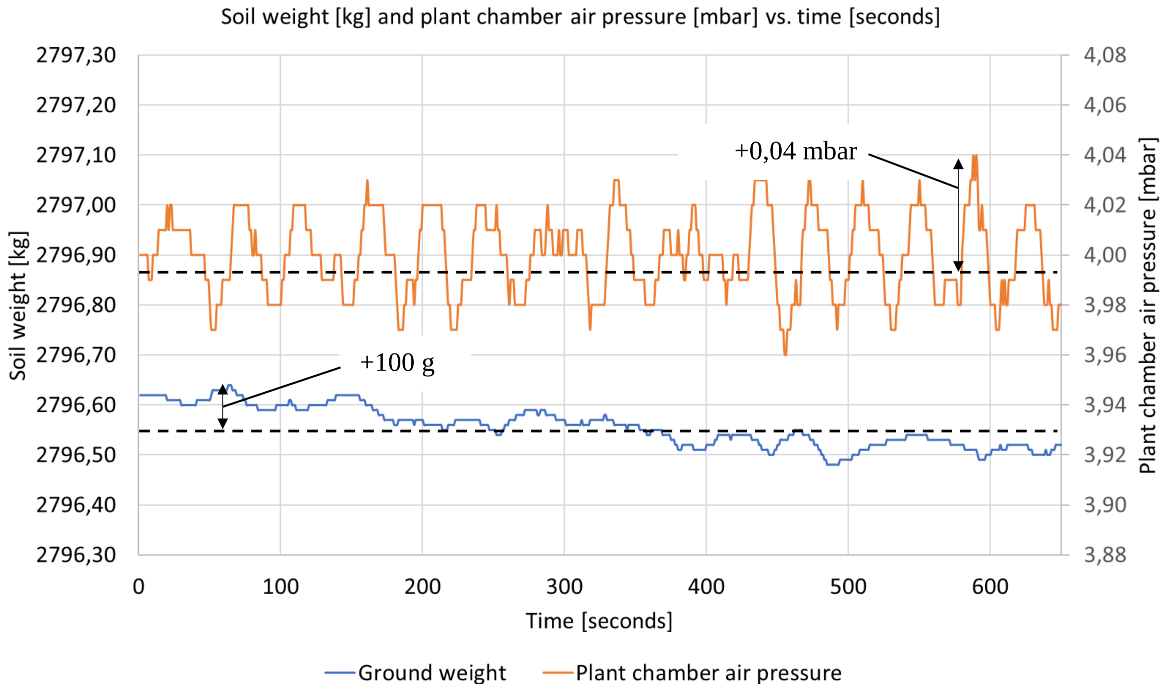

Figure 9: Lysimeter weight and air pressure inside the plant chamber

11 Irrigation

The water for irrigation is produced from demineralized water, minerals and other additives according to the user's specifications in a 1000-liter tank. The water is supplied via pumps (gear pump | manufacturer Iwaki, Willich, Germany | type MDG) and a drip hose (Kärcher, Winnenden, Germany | type: Ø½") based on the specified climate data and is evenly distributed over the soil surface. The irrigation components (such as the hose, the flow meter and the drip hose) are regularly flushed with air to ensure that the irrigation volume is applied as precisely as possible and to prevent standing water from freezing in the hoses at temperatures below the freezing point (at temperatures below freezing point, irrigation no longer takes place). The watering volume can be set between 6 and 48 liters evenly distributed over a time of one hour.

12 Plant lighting

With the plant lighting (manufacturer: Roschwege, Greifenstein, Germany), individual spectra similar to daylight (see Figure 10 for an exemplary spectrum) can be displayed using 12 different LED types (see Table 2). The maximum brightness is 2,500 µmol photons m^{-2} s^{-1}) at a distance of 900 mm from the plant lighting.

	LED-color	Wavelength
1.	UV	365 nm
2.	UV	400 nm
3.	UV	415 nm
4.	UV	430 nm
5.	Blue	470 nm
6.	Turquoise	505 nm
7.	Green	530 nm
8.	Red	660 nm
9.	Red	690 nm
10.	Red	740 nm
11.	Cold white 5000K	-
12.	Warm white 3000K	-

Table 2: ***Wavelengths of the LEDs used***

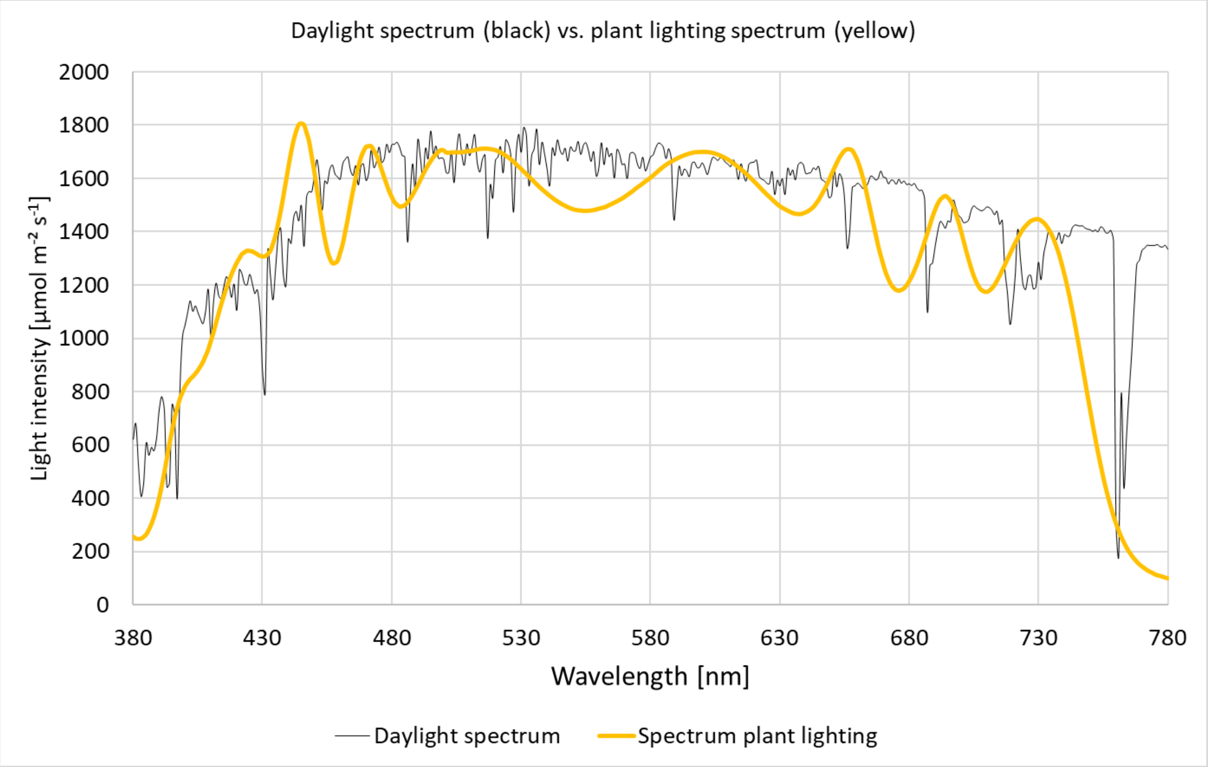

Figure 10: Daylight spectrum compared to an exemplary spectrum of plant illumination at a light intensity of 2,500 µmol photons m^{-2} s^{-1} at a distance of 900 mm from the LED light attachment.

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13 Lysimeter system

The lysimeter system used for Agrasim is based on the technical concept established in TERENO-SOILCan. The lysimeters are stainless steel containers with a surface area of 1 m², a depth of 1,5 m and are filled with a soil monolith (Pütz et al., 2016). To control the hydraulic properties of the lysimeter, the lower boundary condition is set to the desired values using a suction cup rake in combination with a bidirectional pump, a precision tensiometer and a high-precision weighable stainless-steel container with a volume of 100 L to collect the percolate. Water is either pumped into or out of the lower region of the lysimeter. The lysimeters are installed hanging from the cellar ceiling. The high-precision weighing system of a lysimeter consisting of three load cells (model 3510, JR-Aquaconsol, Graz, Austria) and the associated percolate container allow the exact recording of the various measured variables of the water balance equation, such as evapotranspiration, precipitation, dew, percolate and water content change of the soil. In addition, sensors for measuring soil temperature and soil moisture (tensiometer TEROS-41) and TDR-Sensors (Campbell Scientific, Santa Clara, USA), soil potential sensors (CS650, TEROS-21), temperature profile sensors (TH3-S, JR-Aquaconsol) are located at various depths in the lysimeter. The soil solution is sampled using suction cups and a control unit (JR-Aquaconsol). For chemical analysis the percolate is sampled from the downward water flow via an aliquoting unit. The soil temperature is controlled via a heat exchanger loop (JR-Aquaconsol) installed in the lower area of the soil.

14 Gas sampling of lysimeters

An additional system will be used to take gas samples from six depths of the soil from each lysimeter for isotope analysis with a gas analyzer from the company Picarro (Logan, USA). For this purpose, six microporous hoses (outer diameter: 9 mm) are inserted horizontally at different depths (5, 10, 20, 40, 80, 120 cm from the lysimeter upper edge) into the lysimeter through boreholes. Synthetic air (0.5 l min^{-1}) is passed through the microporous hoses as a transport gas. Gaseous substances from the soil can pass through the shell of the microporous hoses and are transferred to the transport gas in the hoses. A total of six lysimeters are sampled in this way, which means that with six samples per lysimeter, a total of 36 gas samples are sequentially switched to the gas analyzer via valves and hose lines. From the outlet of the microporous hose at the lysimeter, the entire hose and valve section must be heated to prevent condensation on the gas-carrying surfaces. In addition, the humidity of the sample can be regulated to the optimum humidity value for the gas analyzer by adding a specific amount of synthetic air before transferring it to the gas analyzer.

The boreholes for the microporous hoses must run precisely through the ground. A specially developed drilling rig is used for this purpose (see Figure 11). It can be aligned and fixed at the lysimeter shell with the aid of cylindrical mounts in the start and target boreholes. With this drilling rig, a drill pipe is pressed into the soil, in which an auger runs and protrudes approx. 20 mm at the end of the drill pipe. The auger loosens the soil in front of the drill pipe and partially removes it so that the drill pipe can be pressed into the ground with less force and the impact on the surrounding soil is small. However, only a finegrained part of the soil can be removed with the auger, which leads to an unavoidable slight compaction of the soil. Once the borehole has been drilled, the microporous tube is pulled in backwards using the drill pipe.

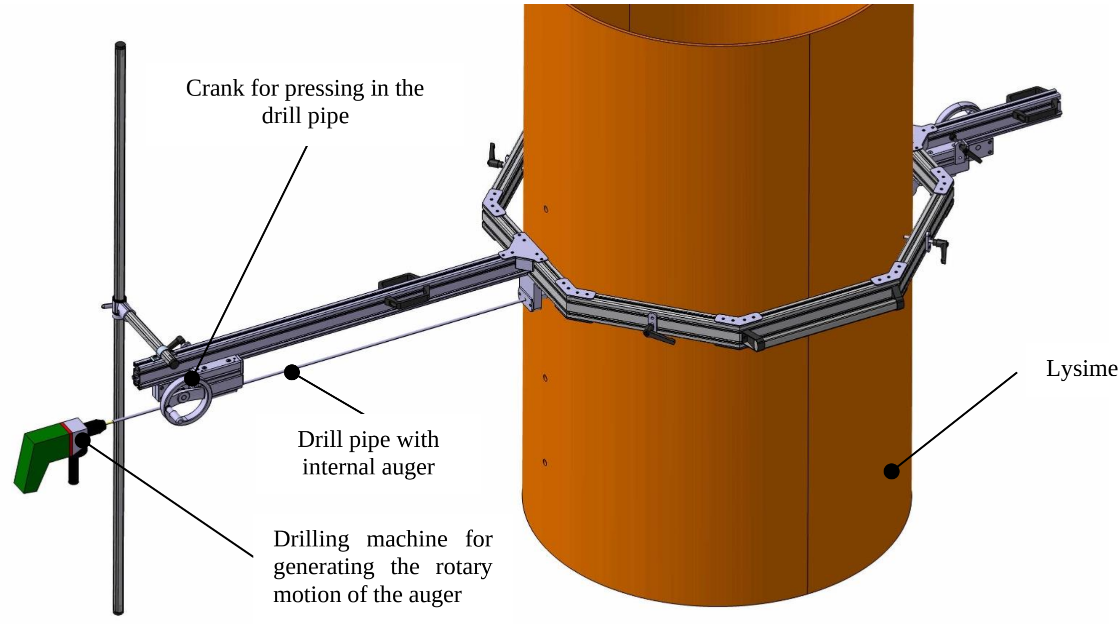

Figure 11: Drilling rig to create the boreholes for the microporous hoses and to pull the microporous hoses into the soil.

15 Gas sampling plant chambers

For the scientific gas analysis of the atmosphere of the plant chambers, one gas sample is taken from the supply air and one gas sample from the exhaust air from each of the six plant chambers. The gas samples are transported at a negative relative pressure of -40 kPa in order to avoid condensation within the transport hoses. The negative pressure must be maintained in all twelve transport lines at all times, which is continuously assured by one of two vacuum pumps. Each of these twelve gas samples is switched to isotope gas analysers via 3/2-way valves and analysed. A second vacuum pump also ensures that the negative pressure is maintained for the gas sample which is switched on the gas measuring device. A filter and an orifice (orifice diameter: 10 µm, heated) are located at the inlet of each transport tube to generate the negative pressure. A volume flow of 0.5 l min^{-1} (based on 20 °C and 1,013 mbar) is required per transport hose in order to generate a negative pressure difference of -40 kPa via this orifice. In addition, reference gases can be switched per 2/2-way valves to the gas measuring device for calibration. Figure 12 shows the corresponding valve terminal.

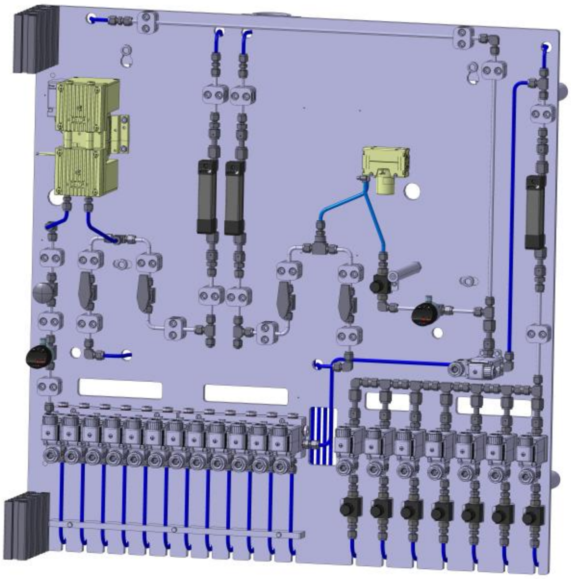

Figure 12: Valve terminal for gas sampling out of the Plant chambers

16 Control system of AgraSim

Programmable logic controllers (PLCs) from the Siemens SIMATIC S7-1500 family are used to control AgraSim. Each of the six AgraSim systems has its own CPU, which ensures the independence of the individual chambers. Furthermore, an additional PLC controls and monitors all infrastructure systems, such as the central gas supply, the central chillers, the compressed air system and the demineralized water treatment (fully desalinated water). The individual chambers can obtain the necessary information from the central control system via a facility-wide IP network and communicate with other control systems in the facility. For example, data is also exchanged with the climate chamber control system, the plant lighting and the lysimeter system. Remote access via VPN server (Virtual Private Network) was implemented via the plant network and a GSM router (Global System for Mobile Communications), which allows various manufacturers of components (e.g. the climate chambers) to gain access to their control system for service purposes without having access to the control systems of other manufacturers. Where possible, the process sensors and actuators are connected to the control system in a decentral manner. This reduces the cabling effort to a minimum and the available installation space can be optimally utilized. By using the IO system of the Siemens SIMATIC ET200SP family, the desired modularity and flexibility of the control system was achieved. Various bus systems are used for communication with the sensors/actuators, e.g., Profinet, Profibus, RS232, Modbus RTU and SDI-12 bus. The system is visualized, fully operated and monitored via a central master computer in a control room.

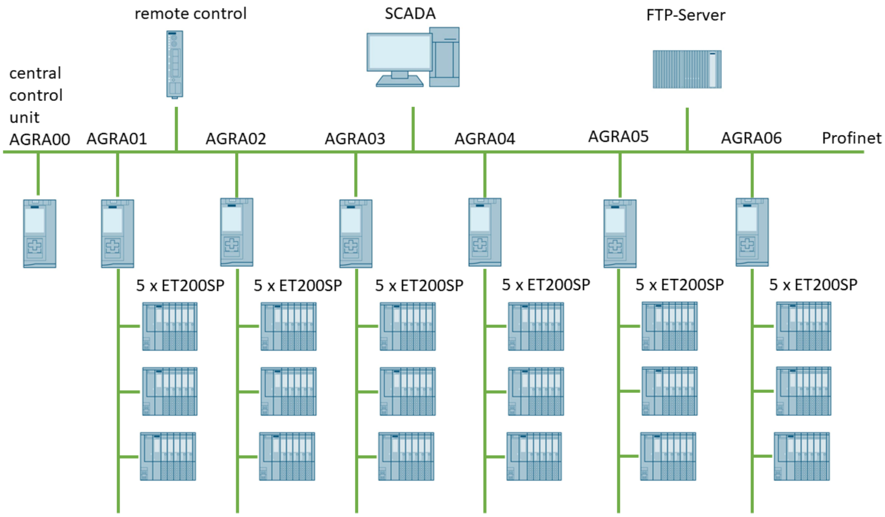

Figure 13: Setup of the network for the entire AgraSim system

The plant chamber atmosphere follows the previously defined default values, such as air temperature, humidity, etc. from climate data profiles. The climate data profiles are based on measurements taken in the field or self-generated data profiles. These profiles cover at least a full year. FTP (File Transfer Protocol) is used as the data protocol in the facility's network to provide the climate data profiles and store all measured values. A separate FTP-server is therefore installed in the network. The control system uses the specified climate data to calculate the set values for the corresponding actuators for precise control of the environmental conditions.

As SCADA system (Supervisory Control and Data Acquisition) Siemens SIMATIC WinCC Professional is used. Visualization was implemented using multi-monitor operation (four 32" monitors). Other SCADA functions include user administration with different operating rights, language switching, event recording, a notification function and measurement data acquisition. Using the Alarm Control Center from Alarm IT Factory GmbH, the events from the SCADA system are transferred to an app for mobile devices. In this way, the system informs the operator about the status of the facility while he is not present.

17 Assembly of the experiment

A prototype was initially built, on which the overall concept, all controllers, sensors and measuring devices were tested. Over 50.000 purchased and manufactured parts were processed for the further construction of the entire system AgraSIM. All components were managed in a database, the order and production statuses were documented and the components were finally sorted and commissioned according to assembly and component ID. The CAD model of the entire system served as the basis for assembly.

18 Summary

The AgraSim large-scale research infrastructure is an experimental simulator consisting of six mesocosms (each mesocosm consisting of an integrated climate chamber-plant chamber and lysimeter system) for studying the effects of future climate conditions on plant physiological, biogeochemical, hydrological and atmospheric processes in agroecosystems, which was designed and built by the Forschungszentrum Jülich.

AgraSim makes it possible to simulate the environmental conditions in the mesocosms in a fully controlled manner under different weather and climate conditions ranging from tropical to boreal climate. Moreover, it provides a unique way of imposing future climate conditions which presently cannot be implemented under real-world conditions. It allows monitoring and controlling states and fluxes of a broad range of processes in the soil-plant-atmosphere system. This information can then be used to give input to process models, to improve process descriptions and to serve as a platform for the development of a digital twin of the soil-plant-atmosphere system.

Each mesocosm consists of a temperature-controlled and weighable soil lysimeter unit with intact soil columns (1 m^2 surface area and 1.5 m depth) and a transparent, fully controllable plant chamber within a temperature-controlled climate chamber with an LED light source that can provide light in the wavelength range of 360-740 nm very similar to the natural solar spectrum with a maximum intensity of 2,500 µmol of photosynthetically active photons $m^{-2} s^{-1}$. With an in-house developed, fully automated process control system, defined climatic and weather conditions as well as air compositions can be set and either kept constant over longer periods of time or varied on the basis of a predefined weather data profile. The implementation involves a considerable amount of in-house development by the Central Institute of Engineering, Electronics and Analytics (ZEA-1) in close cooperation with the Institute of Bio- and Geosciences – Agrosphere (IBG-3) at Forschungszentrum Jülich as well as other institutes and external collaborators, as comparable measuring platforms and experimental simulators do not yet exist.

High demands are placed on the plant chamber and the process technology. The inner surfaces of the plant chambers have the purest and most inert properties possible, with the aim of minimizing interactions between the ambient air of the plants and the chamber wall. Strong LED-based plant lighting provides light conditions similar to daylight, which prevents too large heat input into the chamber. A new concept was developed and implemented to dissipate this heat, which is described in this publication. An important point to consider in the development was to avoid condensation at all times, as condensation dissolves gas molecules from the air in the condensate, changing the isotope composition and thus impeding the atmospheric measurements.

The tasks for the process technology to control the entire system are extensive and varied, which is why an individual, customized solution had to be developed for this purpose. These include precise control of the supply air volume flow, pressure, humidity, CO_2 content, air temperature, light intensity within the plant chamber, soil temperature and irrigation.

19 Outlook

The AgraSim facility is currently in the start-up phase. The soil planned for the future experiments is then selected and placed in the lysimeters. The soil will be excavated with the lysimeters in order to preserve the natural soil structure. Once the lysimeters have been installed in the system, the first experiments will be started.
Each plant chamber is also already prepared for the addition of ozone gas exposure. This would also allow the test plants to be exposed to an increased ozone concentration. However, this system has not yet been implemented. It can be added at a later stage.

The concept described can also be implemented with significant modifications. For example:

- Adapted dimensions and shapes of the atmosphere chamber (plant chamber).
- Adapted air supply, e.g. by mixing the air with various pure gases, adding volatile organic compounds (VOCs), fine particles or similar.
- Adapted pressure conditions, e.g. use of a lower pressure in the chamber.
- Use of other sensor systems to examine the plant and integration of these sensors into the facility control.
- Adapted light spectrum and brightness.

By adapting the concept to the user's requirements, completely different applications are also conceivable, such as the "Cactus" system also planned by ZEA-1 and IEK-8 at Forschungszentrum Jülich. The system provides a defined atmosphere in a small chamber (Ø200 mm, length 1,500 mm) in order to calibrate gas sensors under a variety of conditions. The chamber air is composed of several pure gases, humidified, mixed with volatile organic compounds (VOCs) and fine particles and tempered. Both positive and negative pressure can be set. The chamber itself is inert and clean due to the Silconert-2000 coating.
It would also be conceivable to use AI (artificial intelligence) to evaluate the test data, e.g. to analyze correlations and dependencies. AI could also be an auxiliary tool for controlling the measured variables (e.g., CO_2, temperature, etc.) by using AI to determine the optimum control parameters for each measured variable and the current scenario.

20 Author contribution

The large-scale experiment Agrasim was developed and the construction supervised by the entire team. Project management was the responsibility of JN on the technical side and NB and TP on the scientific side. Simulations and calculations were carried out by JW. The mechanical construction was performed by JH and WM. The electrical planning was implemented by PK and PC, the design and development of the control system was the responsibility of PC. WL was significantly involved in the assembly of the experiment. NH supervises the system in experimental operation and contributed to the development and construction. As institute directors, NG and HV laid the foundations for the development, construction and operation of such a large-scale experiment. The paper was written and conceived by JN, NB, PC, NH, JH, PK, WL, WM, TP, JW, HV and GN.

19 Competing interests

The contact author has declared that none of the authors has any competing interests.

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