EDEN ISS

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Objectives

Sustained human presence in space requires the development of new technologies to maintain environmental control, to manage wastes, to provide water, oxygen, food and to keep astronauts healthy and psychologically fit. Bio-regenerative life support systems, in particular the cultivation of higher plants, are advantageous from this regard due to their ability to be employed for food production, carbon dioxide reduction, oxygen production, water recycling and waste management. Furthermore, fresh crops are not only beneficial for human physiological health, but also have a positive impact on crew psychological well-being.

The EDEN ISS project [Zabel P, et al. (2015)] was a 4.5 M€ European Union Horizon 2020 project (reference number: 636501) supported via the COMPET-07-2014 - Space exploration – Life support subprogramme. It had its official kick-off in March of 2015 and ended in April 2019 after the completion of a year-long Antarctic deployment phase in which the EDEN ISS greenhouse system was installed and operated in the vicinity of the *Neumayer Station III*. The EDEN ISS consortium was comprised of leading European experts (in addition to Canada and the USA) in the domain of human spaceflight and controlled environment agriculture (CEA). The EDEN ISS scientific advisory board consisted of the top scientists in the field of space greenhouses from Russia, USA, Japan, Italy and Germany.

The EDEN ISS greenhouse, or Mobile Test Facility (MTF), has been designed to provide fresh produce for overwintering crews at the *Neumayer Station III* in the Antarctic while at the same time advancing the spaceflight readiness of a number of key plant growth technologies. The greenhouse also serves as a tool to develop operational procedures and select science aims associated with remote plant production. The greenhouse consists of two 20 foot high cube containers, which have been placed on top of an external platform located approximately 400 m south of *Neumayer Station III*. The actual system can be subdivided into three distinct sections:

- Cold porch/airlock: a small room providing storage and a small air buffer to limit the entry of cold air when the main access door of the facility is utilized.
- Service Section (SES): houses the primary control, air management, thermal control, nutrient delivery systems of the MTF as well as the full rack ISPR plant growth demonstrator.
- Future Exploration Greenhouse (FEG): the main plant growth area of the MTF, including multilevel plant growth racks operating in a precisely controlled environment.

The design of the EDEN ISS greenhouse is presented in detail in the following publications [Boscheri G, et al. (2016); Vrakking V, et al. (2017); Zabel P, et al. (2017)].

During the 2018 overwintering period, the EDEN ISS consortium tested essential CEA technologies using an International Standard Payload Rack (ISPR) cultivation system for potential testing on-board the International Space Station (ISS). Furthermore, the FEG was designed with a focus on larger scale bio-regenerative life support systems for planetary

surfaces (e.g. Moon, Mars). In addition to technology development and validation, food safety and plant handling procedures were, and will be, developed and tested in Antarctica. These are integral aspects of the interaction between the crew and plants within closed environments.

Due to the necessity of validating key technologies for space greenhouses under mission relevant conditions and with representative mass flows, the EDEN ISS consortium defined six objectives:

1. Manufacturing a space analogue Mobile Test Facility.
2. Integration and test of an International Standard Payload Rack plant cultivation system for future tests on-board ISS and a Future Exploration Greenhouse for planetary habitats.
3. Adaptation, integration, fine-tuning and demonstration of key technologies.
4. Development and demonstration of operational techniques and processes for higher plant cultivation to achieve safe and high-quality food.
5. Study of microbial behaviour and countermeasures within plant cultivation chambers.
6. Actively advancing knowledge related to human spaceflight and transformation of research results into terrestrial applications.

Although the project officially ended, the German Aerospace Center (DLR) and the Alfred-Wegener Institute agreed to continue operation of the EDEN ISS facility at the *Neumayer Station III* through 2020 and beyond.

Field work

ANT-Land 2018/19 Neumayer Station III summer field season

A detailed overview of EDEN ISS related activities carried out by members of the German Aerospace Center, as well as the University of Florida, during the ANT-Land 2018/19 summer season has been documented in the previous year's ANT-Land report [Vrakking V, et al. (2019)].

Nominal Operations Phase – 2019/20 Neumayer III winter season

For the ANT-Land 2019/20 winter field season, operational activities were carried out by the regular overwintering crew. In the absence of a dedicated operator, scientific activities were reduced throughout the season, in an attempt to limit the required crew effort. Remote support was provided by the consortium partners to assist the overwinterers in the operation of the greenhouse.

The EDEN ISS greenhouse was in dormancy between the departure of the EDEN ISS summer team in February and April 2019. No plants were cultivated in that period. First plants were sown beginning of May and consequently transferred into the cultivation trays. The first harvest took place in June 2019.

Most of the time needed for operations was dedicated to nominal operational and maintenance activities, such as:

- Seeding of various crops,
- Transferring juvenile plants from germination area to cultivation trays,
- Pruning/training of fruiting crops, such as tomatoes and cucumbers,
- Harvesting of various crops, starting with rucola on the 11th of June, 2019,

- Cleaning and disinfection of surfaces, filters and tanks,
- Exchange of consumables (e.g. filters, oxygen tablets, ozone cells),
- Regular (weekly) tele-cons with remote operations team in Bremen,
- Emptying waste water tanks and refilling fresh water tanks,
- Preparation and exchange of nutrient stock solutions,
- Preparation and exchange of acid and base supply,
- Sensor calibration,
- Cleaning and exchange of misting nozzles in the aeroponic plant cultivation trays, and
- Repair and exchange of pumps.

In total 106,5 kg of fresh food was produced for the overwintering crew between May and November 2019. Valuable knowledge was gained about the operation of the greenhouse with non-specialists and non-scientific personnel compared to the previous winter season during which a trained specialist was conduction the operation. This resulted in improved operation procedures, communication and control software. Furthermore, technical issues were observed that need to be improved in order to optimize the operation of the greenhouse, so that more food can be produced with less resources.

In parallel to the operations on-site at Neumayer Station III data evaluation, documentation and publication of the scientific data from the previous winter season were continued by the EDEN ISS partners. Details are provided in a later section.

ANT-Land 2019/20 Neumayer Station III summer field season

During the 2019/20 summer season two project members from the German Aerospace Center traveled to the Antarctic to carry out maintenance and repair work, and to install upgrades to the facility. Although the focus was primarily on routine activities, such as cleaning, sensor calibration, filter exchange and training of the overwintering crew, a number of hardware and software upgrades were conducted as well.

In particular, the misting nozzles in the plant cultivation trays were exchanged with nozzles which have a slightly larger orifice, which should hopefully reduce issues with clogging and cleaning of the nozzles. Additionally, control over the free cooler, the roof-mounted heat rejection unit, was improved by adding control over the fan speed as opposed to the previous on/off control. This measure is expected to reduce the electrical energy demand of the greenhouse.

The EDEN ISS team arrived at the *Neumayer Station III* on the 22nd of December 2019, with flight D9. The last team member left near the end of February 2020. During this time, the following work was carried out with respect to the EDEN ISS project:

- Facility inspection and status documentation,
- Microbial sampling within the facility,
- Harvesting of plants from the Future Exploration Greenhouse (FEG),
- Cleaning of the facility in preparation of maintenance and repair work,
- Cleaning of the Nutrient Delivery System (NDS) piping with hot water,
- Disinfection of the FEG using the TransMADDs system,
- Exchange of consumables (e.g. CO_2 canisters, filters),

- Replacement of the gas concentration measurement system of the EDEN ISS safety system,
- Calibration of the newly installed gas concentration measurement system,
- Testing of the EDEN ISS safety system (gas concentration and smoke sensors),
- Preparation of return freight, and documentation, for ship transport to Europe,
- Installation of Argus control software updates,
- Adjustment of settings for imaging system quality and camera positioning,
- Replace damaged/malfunctioning cameras,
- Preparation of nutrient solution for initial plant cultivation,
- Exchange of cooling fluid in the Thermal Control System (TCS) piping,
- Connection of the SES standalone dehumidifier to the condensate water recovery tubing,
- Preparation of plant scheduling for the summer and winter field seasons,
- Organization of newly arrived cargo,
- Initial teach-in of the 2020/21 winter field season overwinterers,
- Initial seeding of the FEG,
- Replacement of the NDS high pressure pumps,
- Exchange of misting nozzles in the plant cultivation trays with larger orifice nozzles,
- Replacement of NDS sensors and calibration of new sensors,
- Replacement of tubing and connectors for NDS acid and base supply,
- Inspection and cleaning of the Atmosphere Management System (AMS) cooling coil,
- Replacement of AMS condensate water recovery loop UV lamp,
- Preparation of nutrient salt mixtures for the winter field season,
- Repair and installation of the AMS cooling coil UV lamp,
- Inventory of consumables and equipment in the MTF, the multi-purpose laboratory and the various storage areas,
- Repair of insulation around the SES window,
- Filming of activities for outreach (e.g. ZDF),
- Backup of data from the 2018/19 winter field season,
- Maintenance on and repositioning of the energy measurement system in the MTF,
- Setup of the PlantCube plant cultivation system in the Neumayer Station III,
- Installation of speed control for the free cooler fans,
- Preparation of documents for the winter field season (e.g. procedures, task lists),
- Continued training of the winter field season crew,
- Initial harvesting of crops,
- Modifications to the Power Control and Distribution System with the aid of AWI electrician, and
- Safety briefings for the winter field season crew.

For the ANT-Land 2020/21 winter field season, operational activities will be carried out by the regular winter crew. Remote support will be provided by the consortium partners to assist the winter crew with EDEN ISS-related activities.

Preliminary (expected) results

Detailed analysis of the data and samples from the second operations phase is still ongoing. However, some preliminary results have already been collected and are described below.

Data from the 2018 operations phase has already been published, such as the performance of the Plant Health Monitoring system [Zeidler C, et al. (2019)], the impact of plants on crew well-being [Schlacht I, et al. (2019)], crew time measurements [Zabel P, et al. (2019)], biomass production [Zabel P, et al. (2020)], microbiological measurements [Fahrion J, et al. (2019)], and ISPR plant cultivation system performance [Boscheri G, et al. (2019)]. Other data is currently going through the review process prior to being published, one of the topics being the electrical power and energy demand. About 268 kg of fresh edible biomass were harvested between March and November of 2018. A significant amount of fresh biomass was also harvested during the 2018/19 summer season, though this was not tracked as it fell outside of the official operations phase. Figure 1 shows the interior of the FEG just prior to harvesting in the 2018/19 summer season in January of 2019.

Fig. 1: Future Exploration Greenhouse before harvest and cleaning in January 2019

For the 2019 winter season, one objective was to investigate the possibility of running the facility in a stand-by mode for some months and then starting operations remotely. During this stand-by mode, only essential systems were operational, such as the Command and Data Handling System (CDHS) while other subsystems were functioning at reduced capacity.

To allow a remote start of the facility, attempts were made to germinate seeds directly in the plant cultivation trays, as opposed to in a dedicated nursery. Unfortunately, these germination attempts were not successful as the rockwool substrate did not absorb enough moisture from the aeroponic nutrient solution spray. Changes have been made to the design of the 3D-printed rockwool holders to increase the exposure of the rockwool cubes to the nutrient spray, and additional germination tests are planned.

As these germination experiments failed, completely autonomous starting of operations from the remote Mission Control Center was not possible, and the winter crew had to seed plants in the nursery and subsequently transplant them. Nevertheless, the facility ran in a reduced

mode between February and May of 2019 and was then successfully switched to nominal operations mode without issue.

In the initial plant cultivation phase during the 2019 winter season, a large accumulation of microbial contamination occurred, which required a significant crew effort for additional cleaning and decontamination measures. As a similar contamination occurred early on during the 2018 winter season, also following an in-depth cleaning and sterilization process, it is assumed that this rapid growth is due to the reduced microbiome diversity after the cleaning, allowing one or a few micro-organisms to multiply without competitor organisms. Once the plants in the facility reached a higher maturity, the issue resolved itself and microbial contamination was greatly reduced, probably because a stable microbiome was reestablished.

During the 2019/20 summer season the cleaning procedures were adapted, to reduce the use of chemicals during cleaning of the Nutrient Delivery System piping, with the assumption that this would allow the existing microbiome to survive, thereby preventing the initial higher level of contamination which had been observed previously. Based on initial observations, this assumption has been validated.

Biomass production

Table 1 shows the amount of biomass harvested each month during the 2019 operations phass. As mentioned previously, the facility was put in a standby mode until May of 2019, at which time the first seeds were germinated. First harvest occurred in June and the last harvest occurred in November. In preparation of the 2019/20 summer season, only part of the available cultivation area of the MTF was used during the months of October and November in order to reduce crew time demand even further. In total, around 106,5 kg of fresh edible biomass was harvested.

Tab. 1: Monthly fresh biomass harvest during the 2019 winter season

Month	Biomass Yield [kg]
June	4,87
July	14,74
August	25,29
September	26,67
October	23,97
November	11,02

Based on feedback from the first operations phase in 2018, the variety of cultivars available for cultivation in the MTF had been greatly increased for the 2019 winter season. However, for many of these new cultivars no laboratory testing had been done to determine optimal growing conditions and as such some of the new crops did not yield significant edible biomass, thereby reducing the average yield per cultivation area.

Crew time

For the 2019 mission, the overwintering crew of the Neumayer Station III was asked to track the amount of time which was spent on activities related to the operation of the MTF. These activities included regular communication with the project team at DLR, nominal operations in the facility such as cleaning, seeding and harvesting, as well as off-nominal activities in case of, for example, component failures. The maximum amount of time needed by the crew per month during the 2019 winter season was 102,5 hours during both July and August. For the other months, the time was less either due to a reduced amount of plant handling activities and/or fewer off-nominal events.

Only a rough time tracking was carried out during 2019, but for 2020 a Timeular time tracking system has been acquired to improve the precision of the measurements.

Crew time was also tracked for remote operations by the DLR team. Activities carried out by the remote operators involved regular communication with the on-site operators, as well as preparation of the 2019/20 summer season by ordering spare parts and consumables, and preparing logistics and relevant documents for transport to the Antarctic. A maximum of about 50 hours were needed for remote operations in August of 2019.

Microbial contamination

Throughout the first operations phase, samples were taken of harvested biomass, and probes were taken from different surfaces and liquids within the EDEN ISS greenhouse, as detailed in the report for last year's activities [Vrakking V, et al. (2019)]. During the ANT-Land 2019/20 winter field season, no microbial investigations were carried out, to reduce crew time demand for the winter crew. In case of visible contamination, the crew photographed the contamination for analysis by the experts, before cleaning and disinfecting the affected area.

As part of the activities carried out in the ANT-Land 2019/20 summer field season, the team from DLR took a number of samples from within the MTF to enable analysis after return to Europe. The results of these investigations are not yet available.

Psychological investigations

Due to the limited winter crew size of 10 people, the psychological investigations, carried out in 2018, to determine the impact of the greenhouse and fresh produce on crew wellbeing did not yield statistically significant results. Based on anecdotal evidence the general impact of the greenhouse was found to be positive, and in particular the olfactory experience within the greenhouse was explicitly mentioned as a positive aspect.

The ANT-Land 2019/20 winter field season crew participated in a number of psychological and medical investigations and studies. Results from these investigations should add to the data previously collected and allow for more accurate and significant determination of the impact of the EDEN ISS greenhouse on crew wellbeing. Further investigations are planned for future overwinterers as well.

Data management

All data collected and generated by this project will be published in open access journals and/or submitted to a public database (https://zenodo.org/communities/edeniss).

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