Resource Consumption and Waste Production of the EDEN ISS Space Greenhouse Analogue during the 2018 Experiment Phase in Antarctica

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EDEN ISS is a European project focused on advancing bio-regenerative life support systems, in particular plant cultivation in space. A mobile test facility was designed and built between March 2015 and October 2017. The facility incorporates a Service Section which houses several subsystems necessary for plant cultivation and the Future Exploration Greenhouse. The latter is built similar to a future space greenhouse and provides a fully controlled environment for plant cultivation. The facility was setup in Antarctica in January 2018 and successfully operated between February and November of the same year. During this approximately nine month period, 268 kg of fresh edible biomass was produced. The cultivation of crops requires a number of resources like water, nutrients and carbon dioxide, but also consumables such as cleaning agents, gloves and towels. The facility also produces waste in various forms such as waste water from cleaning, paper and plastic. In this paper the solid and liquid waste is compared with the resources needed for optimal crop growth on the approximately 12.5 m² of cultivation area inside the EDEN ISS facility. In total, approximately 18 kg of mineral salts were required to prepare the nutrient solution over this initial experimental period. In addition, more than 2,500 liters of reverse osmosis water was supplied to the facility over this period. The consumable waste from the bins inside the EDEN ISS facility consisted of around 9 kg of dry paper and 5 kg of plastic waste.

Nomenclature

AMS	=	Air Management System
BVAD	=	Baseline Values and Assumptions Document
DTPA	=	Pentetic Acid
FEG	=	Future Exploration Greenhouse
ISPR	=	International Standard Payload Rack
MTF	=	Mobile Test Facility
NDS	=	Nutrient Delivery System
NM III	=	Neumayer Station III
PAR	=	Photosynthetic Active Radiation
RH	=	Relative Humidity
RO	=	Reverse Osmosis
SES	=	Service Section

I. Introduction

The EDEN ISS Mobile Test Facility (MTF) was successfully deployed in Antarctica in January 2018 after three years of design, development and construction. The MTF houses the Future Exploration Greenhouse (FEG), which is a space greenhouse test facility with a cultivation area of 12.5 m² and a Service Section (SES) which contains the subsystems necessary to run the FEG and a work desk including a sink. A detailed description of the design process of the MTF and its components, plant selection and project development can be found elsewhere[1–8].

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The MTF is located 400 meters south of the German Neumayer Station III (70°40´S, 8°16´W) on the Ekström ice shelf in the vicinity of the Atka Bay. The station is operated year-round with a summer (November to February) crew of 50-60 people and a winter (February to November) crew of nine. During the winter period no supply missions are able to reach the station, which means that all supplies (e.g. food, spare parts, tools) need to be delivered during the short summer season. This remoteness makes the Neumayer Station III (NM III) an excellent test area for human space exploration missions.

In 2018 a tenth person complemented the wintering crew to operate the MTF. The operation started in February 2018 and was continued throughout the whole 2018 winter season. The first plants were sown on February 7 and subsequently transferred to the cultivation trays in the following weeks. The plants developed very well and the first harvest occurred on March 20. This harvest included lettuce, radish, Swiss chard and other leafy greens. The first harvest of cucumber (March 29) and tomato (May 16) followed soon after. The last harvest of the 2018 winter season was executed on November 20. Until then a total edible fresh biomass of 268 kg was produced inside the facility[9]. Most of the produce was consumed by the wintering crew except for a small portion that was set aside for scientific measurement and sampling.

Furthermore, a large number of experiments and measurements have been conducted by the on-site operator which included research in the fields of food quality and safety, microbial environment, horticulture, greenhouse subsystem validation, plant health monitoring, impact of the greenhouse on the crew, electrical energy demand, remote operation and crewtime demand[10].

In addition to the aforementioned investigations, the resource consumption and the related waste production due to the operation of the greenhouse was investigated during 286 days of the 2018 experiment phase in Antarctica (February 7 to November 20 2018)[10]. In the following subchapters the water balance, nutrient demand, waste production as well as the carbon dioxide demand are described in detail.

II. Water Balance

A. Mobile Test Facility Water Cycle Description

The water cycle of the EDEN ISS MTF is shown in Figure 1. The fresh water for the MTF is stored in a 250 L tank inside the container. Next to this tank another 250 L tank is used to store the waste water produced in the container. The supply of fresh water from NM III and the removal of waste water to NM III were tracked throughout the year. Two nutrient solution tanks are incorporated in the Nutrient Delivery System (NDS) with one solution tailored to leafy greens (e.g. lettuces, herbs or swiss chard) and the other one adapted for fruit crops (e.g. tomatoes, peppers or cucumbers). After several months of use, both solutions have to be renewed due to imbalances in the solution composition increasing over time. This means emptying and cleaning the tanks and refilling them afterwards with reverse osmosis (RO) water needed for mixing the final nutrient solution. The water removed from the NDS tanks when the nutrient solution was exchanged was also tracked. The water bound in harvested biomass can be extrapolated from the biomass production values and the dry matter content of the crops. The first was measured for all harvested material and the latter was obtained by drying biomass to a point where only small residual amounts of water were left in the plant tissue. The dry mass measurements were not done for all crops, but the existing values can still be used to extrapolate the water removed from the MTF in the form of plant tissue. The water transpired and exhaled by the on-site operator can also be extrapolated using values from NASA's Baseline Values and Assumptions Document (BVAD)[11]. The water lost due to general atmospheric leakage and due to the opening of doors by the on-site personal was not measured and can only be obtained based on assumptions.

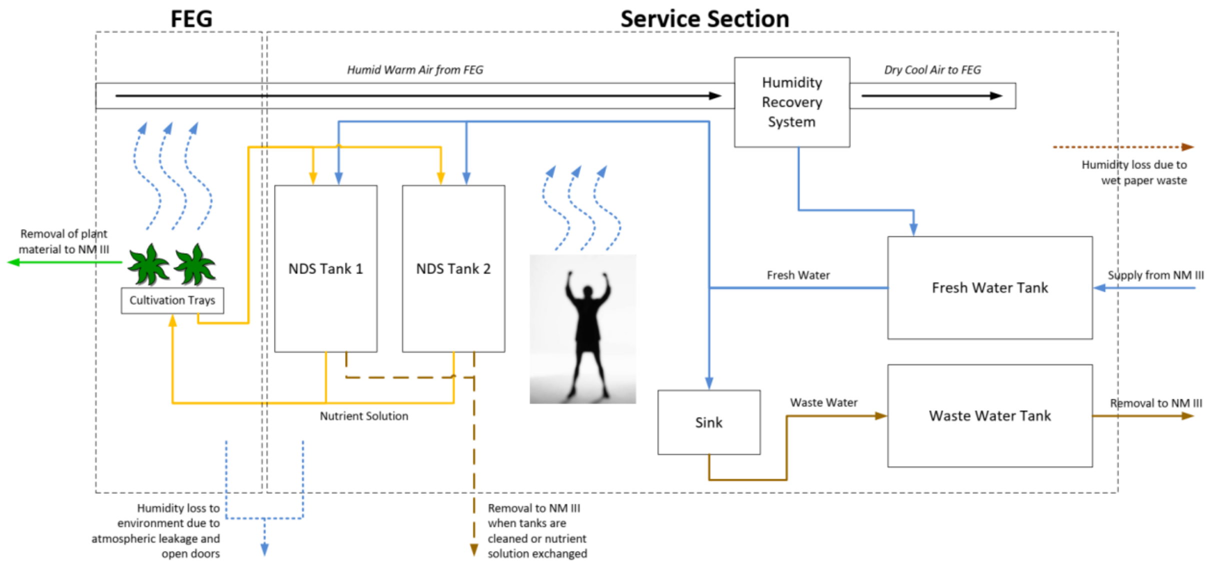

Figure 1. Water cycle, inputs and outputs of the EDEN ISS MTF.

B. Water Balance of the Antarctic Experiment Phase 2018

The water balance of the experiment phase 2018 consists of six components which should sum up to be zero:

$$Water\ balance = Internal\ atmosphere\ water + Tanks + Loss\ due\ to\ biomass + Loss\ due\ to\ wet\ paper\ waste + Water\ from\ crew + Loss\ to\ external\ environment = 0$$

Internal atmosphere water balance

The balance of the water content of the internal atmosphere of the MTF can be calculated by comparing the amount of water vapor present in the air of the MTF at the outset and the completion of the experiment phase. Multiplying the absolute humidity by the internal volume for each section (31.85 m^3 for each of the SES and FEG respectively) of the MTF provides the actual amount of water in the atmosphere. These calculations demonstrated a difference of only several grams and is thus considered negligible with respect to the other components of the water balance.

Water balance of EDEN ISS MTF tanks

Table 1 shows the water balance of the tanks incorporated inside the MTF. Positive values are related to the filling of the tanks and negative values to emptying the tanks or removing water. During the first weeks water was supplied to the humidifier from a separate portable tank. Later the humidifier was filled directly from the fresh water tank and therefore not noted down as a separate position in the table (after March 31). The balance for the NDS tank 1 and tank 2 is negative because the on-site operator manually filled them with a certain amount of RO water from portable tanks (positive values in the NDS tank columns) after emptying them completely (negative values in the NDS tank columns) at the beginning of the experiment phase or after cleaning. This manual process was implemented as using the installed fresh water pump in the MTF to supply the full volume of water to fill the NDS tanks would take too long. After the initial manual filling of the tanks, the NDS would mix the optimal nutrient solution automatically by adding stock solution A and B, acid (diluted nitric acid with a concentration of 1.3%) or base (diluted potassium hydroxide with a concentration of 0.8%) and RO water from the fresh water tank (specific quantities are listed in Table 2 and Table 1). This means 92 kg of RO water wase added by the NDS to NDS tank 1 from the fresh water tank and 124 kg to NDS tank 2. After the experiment phase on 25.11.2018 all tanks in the greenhouse were emptied by the on-site operator for cleaning, in preparation of the next maintenance mission during the following summer season. The water balance of all tanks over the experiment phase amounts to +119 kg (see Table 1).

Table 1. Water balance of EDEN ISS MTF tanks.

Date	Fresh water tank [kg]	Waste water tank [kg]	NDS tank 1 [kg]	NDS tank 2 [kg]	Humidifier [kg]
07.02.2018*	0	0	0	0	0
25.02.2018	160				
26.02.2018			100	100	9
27.02.2018	100				
28.02.2018					9
02.03.2018					9
05.03.2018					9
07.03.2018					9
10.03.2018					9
13.03.2018	80				
24.03.2018	120				
31.03.2018					-3**
18.04.2018	160	-182			
30.04.2018				-154	
30.04.2018				120	
07.05.2018	40				
12.05.2018		-177			
30.05.2018	160				
19.06.2018			-156		
19.06.2018			140		
20.06.2018		-147			
23.06.2018				-153	
23.06.2018				140	
25.06.2018	160				
06.07.2018	-8***				
20.07.2018	160				
21.07.2018		-180			
15.08.2018	160				
28.08.2018		-177			
03.09.2018				-147	
03.09.2018				140	
18.09.2018	160				
19.09.2018			-152		
19.09.2018			140		
09.10.2018		-176			
15.10.2018	160				
25.11.2018	-28	-261	-164	-170	
Balance	**+1,584**	**-1,300**	**-92**	**-124**	**+51**
				Balance total	**+119**

* The experiment phase started with seeding in the nursery on 07.02.2018. The filling of the various NDS tanks started in the facility on 25.02.2018.

** Removed the mobile humidifier with 3 kg of water in the system from the greenhouse. Not needed anymore for keeping the relative humidity level stable in the facility, since plants were big enough.

*** Filled 8 kg of water from the fresh water tank into the International Standard Payload Rack (ISPR).

Taking the values from Table 1 one can see that 2,554 kg of RO water was used in the MTF during the experiment phase. This value splits up in 1,620 kg of RO water as input for the fresh water tank, 380 kg for NDS tank 1 (approximately one refill every three month), 500 kg for NDS tank 2 (approximately one refill every two months) and 54 kg for the FEG humidifier.

On the other hand, 2,435 kg of waste water had to be removed from the system during that time, meaning 36 kg from the fresh water tank, 1,300 kg from the waste water tank, 472 kg from NDS tank 1 and 624 kg from NDS tank 2 as well as 3 kg from the FEG humidifier.

In addition, 40 kg of diluted acid and 12 kg of diluted base were added to the two stock solution tanks. For NDS tank 1 an equal amount of 112 kg was added from stock solution A and B. In case of NDS tank 2 this amount was 128 kg for stock solution A and B. This implies that 532 kg of diluted acid, diluted base and stock solutions (see Table 3) were added to the tanks, increasing the water balance of +119 kg to a total water balance of +651 kg over the experiment phase. It should be noted that Table 3 illustrates the specific date in which the diluted acid, diluted base and stock solution bottles (with a water volume of 4 L each) were brought to the MTF and either attached to the NDS or put into storage for subsequent use (it does not indicate when these volumes were physically added to the main NDS tanks).

Table 2. Acid, base and stock solution input for balance of EDEN ISS MTF tanks.

Date	Diluted acid [kg]	Diluted base [kg]	Stock solution A leafy crops [kg]**	Stock solution B leafy crops [kg]**	Stock solution A fruity crops [kg]**	Stock solution B fruity crops [kg]**
2nd half of February*	8	8	8	8	8	8
01.03.2018			8	8	8	8
31.03.2018			4	4	4	4
06.04.2018	4					
13.04.2018			8	8	8	8
30.04.2018			8	8	8	8
06.05.2018			0	0	8	8
13.05.2018	4					
18.05.2018			8	8	4	4
02.06.2018			4	4	8	8
12.06.2018	4					
15.06.2018			4	4	4	4
22.06.2018			4	4	8	8
23.06.2018	4					
27.06.2018			8	8	4	4
04.07.2018					4	4
23.07.2018	4		8	8	8	8
17.08.2018	4		8	8	8	8
02.09.2018		4	8	8	8	8
14.09.2018			4	4	8	8
27.09.2018			8	8	8	8
18.10.2018	4		8	8	4	4
05.11.2018	4		8	8	8	8
Remaining at end of experiment phase			-4	-4		
Balance	**+40**	**+12**	**+112**	**+112**	**+128**	**+128**
					Total	**+532**

* The experiment phase started with seeding in the nursery on 07.02.2018. The filling of the various NDS tanks started in the facility on 25.02.2018.

** Refer to chapter III for a detailed description of the composition of the stock solutions.

Water loss due to biomass

The balance of the water removed by plant tissue can be derived from the total fresh biomass output. As previously reported an estimate of 268 kg of fresh edible biomass was harvested from the FEG during the experiment phase[9]. Using an assumed average inedible dry weight content of the plants of 6%[9,12] as a representative estimate across the varied high water content crops grown in the facility and an inedible dry biomass of approximately 14,96 kg the inedible fresh biomass of 249 kg can be calculated. This amounts to approximately 517 kg of total fresh biomass, which when considering a percentage dry mass of 6%, equates to 486 kg of water removed from the MTF.

Water loss due to wet paper waste

From Table 5 the loss of water from the system due to wet paper waste can be estimated. Around 4 kg of water was removed by wet paper waste during the 2018 experiment phase.

Water from crew

During the 286 days[10] of experiment phase one person worked between three and five hours a day in the greenhouse. However, on numerous occasions additional crew members also spent some time in the facility, to aid with harvesting for example. For the following calculations it is assumed that a single person spent a daily average of four hours within the MTF. Using a value of 1.9 kg/d per person[11] of water input into the system through human respiration and perspiration the water input can be estimated as 91 kg over this period.

Water loss to the external environment

The water loss to the external environment cannot be reliably tracked or estimated. However, as the water balance equation presented previously should equal zero, the contribution of this loss can be determined from the other water sinks and sources.

When not including the water lost to the environment by opening the entrance door and by general atmospheric leakage, the water balance is roughly -252 kg (see Table 3). Consequently, this should be approximately the amount of water that was lost to the external environment.

Table 3. Water balance summary for the experiment phase 2018.

Source of water	Water balance [kg]
Internal atmosphere balance	~0
Water balance of EDEN ISS MTF tanks	+651
Biomass	-486
Loss due to wet waste	-4*
Water from crew	+91
Loss to environment	-252
Balance	**0 kg**

* Refer to chapter V. Waste Production for detailed calculations regarding the amount of wet waste.

There are some uncertainties in the water balance calculation. In particular, the estimated contribution of 252 kg of water being lost by the opening of the entrance door and by atmospheric leakage seems rather high. It should also be noted that the the evaluation of the fresh inedible biomass comes with some uncertainty due to the variety of crops in the facility and the fact that measurements were not taken on all harvest material as much of the produce harvested from the facility was consumed by the wintering crew. In addition, some of the inedible biomass was harvested wet (e.g. roots and rock wool), some fresh (e.g. radish leaves) and some dry (e.g. withered tomato leaves). Combining all three values into a single figure for all crops is not easy, because the dry biomass ratio is required. Furthermore, some minor conributions related to unaccounted water remaining in the the system piping, sump pump tanks and the condensate tanks could be expected. Finally, the MTF fresh water tank was filled by hand using 20 L water cannisters. It is most likely that some errors in measurement occurred while filling them to the 20 L water mark.

III. Nutrient Demand

The nutrient solution was supplied to the NDS in 4 liter bottles of concentrated stock solution. Each of the two nutrient solutions was a combination of equal parts of two different stock solutions (named A and B). In total 28 bottles each of A and B stock solution were used for the NDS tank 1 which held the leafy crop solution. The fruit crop solution in tank 2 required 32 bottles of A and B each. This amounts to the nutrient demand shown in Table 4 which was needed during the experiment phase 2018 to produce 268 kg of fresh edible biomass. This table also includes the change in nutrient composition for the fruit crop nutrient solution as of the 17th of August 2018.

Table 4. Nutrient demand during the 2018 experiment phase.

Nutrient	Amount of nutrient from leafy crop stock solution demand [g]	Amount of nutrient from fruity crop stock solution demand [g]	Total nutrient consumption [g]
Calcium nitrate ($Ca(NO_3)_2 \cdot 4H_2O$)	2,548.00	4,417.50	**6,965.50**
Ammonium nitrate (NH_4NO_3)	272.72	579.20	**851.92**
Iron chelate DTPA (11.4 %) ($C_{14}H_{19}FeN_3NaO_{10}$)	52.08	80.96	**133.04**
Calcium chloride ($CaCl_2$)	105.00	184.00	**289.00**
Potassium nitrate (KNO_3)	2,374.40	3,192.60	**5,567.00**
Magnesium sulphate ($MgSO_4$)	364.00	870.40	**1,234.40**
Magnesium nitrate ($Mg(NO_3)_2 \cdot 7H_2O$)	193.20	0.00	**193.20**
Potassium sulphate (K_2SO_4)	0.00	572.80	**572.80**
Monopotassium phosphate (KH_2PO_4)	722.40	1,164.80	**1,887.20**
Manganese sulphate ($MnSO_4 \cdot H_2O$)	0.896	11.136	**12.032**
Zinc sulphate ($ZnSO_4 \cdot 7H_2O$)	1.960	7.584	**9.544**
Borax ($Na_2B_4O_7 \cdot 10H_2O$)	7.582	13.184	**20.766**
Copper sulphate ($CuSO_4 \cdot 5H_2O$)	0.473	1.312	**1.785**
Sodium-molybdate ($Na_2MoO_4 \cdot 2H_2O$)	0.274	0.800	**1.074**
		Total	**17,739.261**

IV. Carbon Dioxide Demand

The set point for the CO_2 level inside the FEG during the 2018 experiment phase was 1,000 ppm. The CO_2 graph (see Figure 2) shows that the CO_2 level inside the FEG was always nominally above the set point. The system is only capable of keeping the CO_2 level above the set point, but not of scrubbing out the CO_2 from the air in case of a too high CO_2 level. Due to the influence of the activities of the on-site operator inside the FEG, the CO_2 level was typically much higher than initially planned.

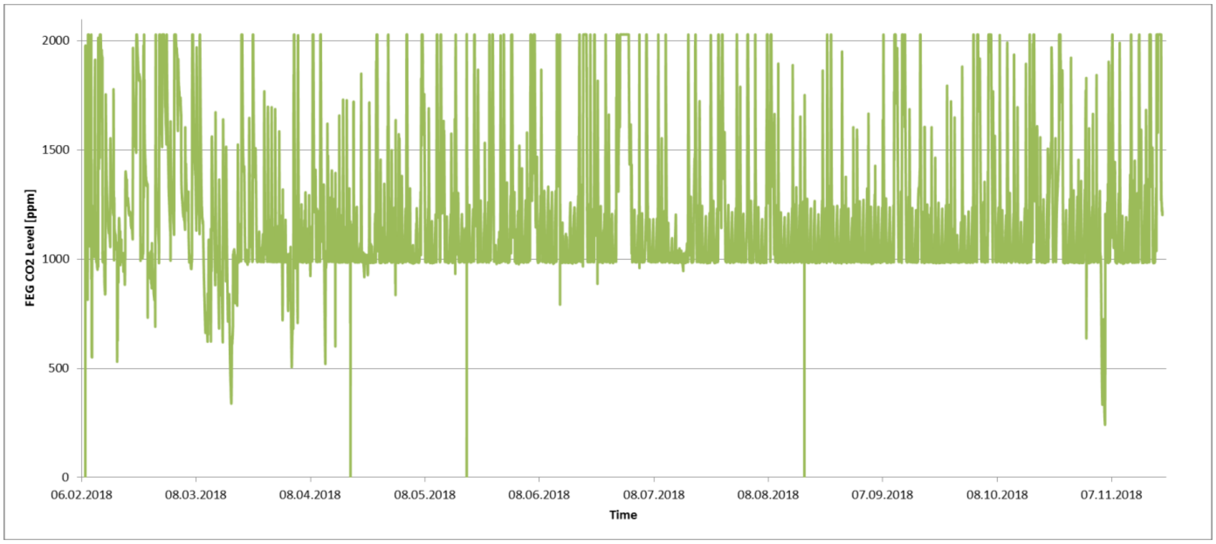

Figure 2. FEG CO_2 level during the experiment phase in 2018. Note: CO_2 sensor range was 0-2,000 ppm. Values above 2,000 ppm were not measured.

Figure 2 shows the CO_2 level for the whole experiment phase. The four peaks going down to 0 ppm in Figure 2 were due to short power outages or connection issues to the control system of the facility (typically of a duration of a few seconds/ minutes). All other peaks going below 1,000 ppm occurred during regular de-icing events of the emergency exit, refilling of the fresh water tank or emptying of the waste water tank. During these events, the emergency exit or the entrance door had to be opened, which resulted in a lowering of the CO_2 level in the facility due to atmosphere exchange with the environment outside the facility.

Figure 3 shows the daily behaviour of the Air Management System (AMS) related to the CO_2 level. Three exemplary days were chosen to show the system's behaviour and are described in the section to follow.

- 27.07.2018: A day without interference by the on-site operator. No human was inside the MTF during that day.
- 08.09.2018: A day without interference by the on-site operator. No human was inside the MTF during that day.
- 10.09.2018: Strong interference by the on-site operator, because of long working times inside the MTF.

The CO_2 level rises during the dark period because CO_2 that was not bound during the photoperiod is released by the plants inside the FEG. When there is no human interference (July 27 and September 8), the CO_2 level drops until it reaches the set point. Then the AMS pumps CO_2 into the air streams from the CO_2 bottles stored on the outside of the MTF. This can be seen in the small fluctuations of the two graphs around the set point. The situation is completely different when there is an operator inside the FEG, which is an additional CO_2 source. The September 10 graph shows an increase in CO_2 starting at around 10:30 and ending at 12:15. During that time the on-site operator performed some tasks inside the MTF. The operator left the MTF at 12:15 for lunch and came back around 13:40 to continue their tasks. This is the second steep increase in CO_2. The operator remained inside the FEG for a while which increased the CO_2 level well beyond the sensor maximum limit of 2,000 ppm. Only at the very end of the day did the CO_2 start to decline below the 2,000 ppm mark.

During the experiment phase in 2018 approximately 50 kg of CO_2 from bottles stored outside of the MTF was used to increase the CO_2 level to the nominal level of 1,000 ppm. This number also includes the CO_2 needed for the container leakage tests[8] during the summer season in the beginning of 2018.

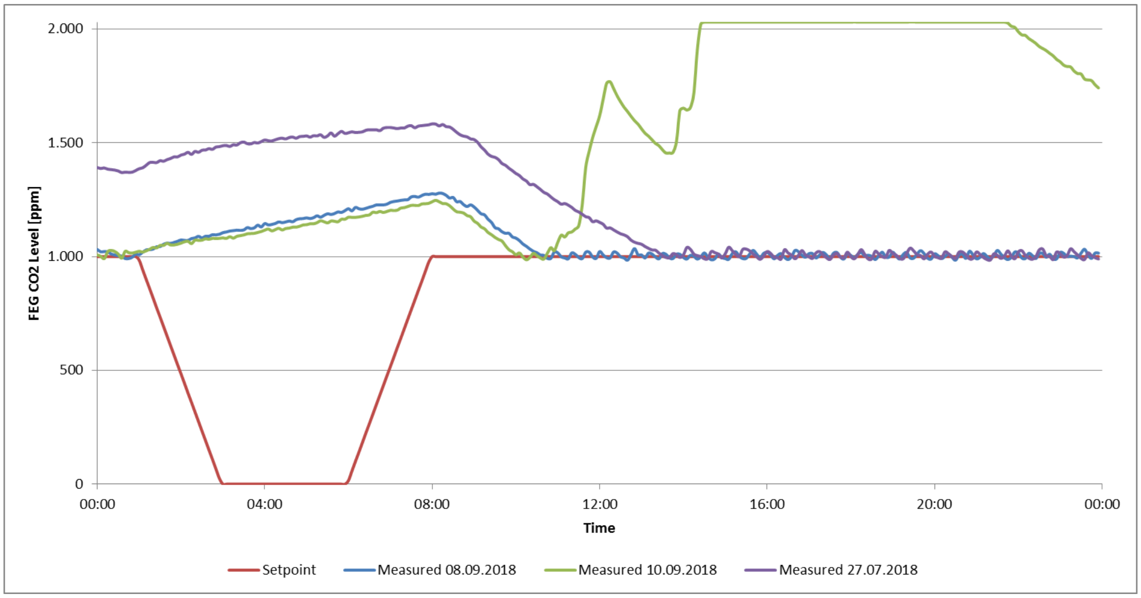

Figure 3. FEG CO_2 level three daily graphs for the three exemplary days during the experiment phase in 2018.

V. Consumable Waste Production

Several of the important waste streams of the MTF were measured and documented during the 2018 experiment phase. The most important waste stream is the one produced by using consumables like gloves or tissue. This waste was collected in the waste bins of the SES and the FEG and removed and weighted on the first day of each month for the month before. Table 5 shows the values of these measurements produced by operations work in the FEG. The paper was often used to clean up for example small spills. Consequently, the paper was often moist when taken out of the MTF. In April, May, July and September the waste was dried completely while in the other months this was not possible. With the assumption that the paper dry mass is about 70% of the total paper wet mass (average value of the measurements in April, May, July and September 2018 of Table 5), the total amount of paper waste (dry) is approximately 8.9 kg and the plastic mass approximately 5.2 kg for the period from February 7 to November 20. The waste for February was not measured since it was mixed with the waste produced during the summer season 2017/2018 and was not representative for the operative work in the greenhouse.

Table 5. Monthly waste removed from the MTF in grams. Black values are measurements and orange marked cells are estimates assuming the dry mass is 70% of the wet mass.

Month	03	04	05	06	07	08	09	10	11
Paper (wet) [g]	1,806.30	1,734.40	2,925.50	1,070.60	1,081.30	785.50	1,108.70	1,040.70	1,303.30
Paper (dry) [g]	1,264.41	1,128.10	2,038.30	749.42	906.40	549.85	598.00	728.49	912.31
Plastic [g]	620.50	523.10	1,018.10	454.80	515.50	435.80	394.40	428.60	773.90

Figure 4 shows an example of monthly trash, in this case May 2018. The plastic waste consisted to a large degree of single-use gloves with small amounts of packaging material. The paper waste was mainly tissues from cleaning tasks and sometimes packaging material (e.g. box of single-use gloves).

Figure 4. Monthly waste May 2018. Left side: Plastic waste. Right side: Paper waste.

Another notable waste stream was the waste produced by science activities. For instance, the taking of samples on surfaces for microbiological investigations produced a lot of waste. This was primarily due to the sterile packaging of the swaps. This activity was performed 9 times during the experiment phase between February 7 and November 20 and each time produced around 400 grams of plastic waste which amounted to 3.6 kg. The taking of plant samples for the microbiologists produced around 830 grams of plastic and 223 grams of cardboard waste per event and was performed 8 times throughout the season. The total amount of plastic waste of this activity is around 6.6 kg and 1.8 kg of cardboard.

Black plastic trays containing the rock wool blocks also produced a notable amount of plastic waste inside the MTF which was not included in the normal monthly waste production described previously. This amount was not thoroughly tracked. It is assumed that this plastic amounts to a few kilograms for the experiment phase 2018.

Within the laboratory in NM III the waste was only partially documented. Most of the waste there consisted of single-use gloves and paper tissues for performing experiments and mixing nutrients. The latter also produced around 2.0 kg of plastic during the experiment phase in the form of empty plastic bottles which contained the various nutrient minerals.

The waste from the EDEN ISS facility is brought to NM III and separated into plastic, paper and bio waste. Plastic and paper waste are subsequently compressed and then stored. During the next summer season the station waste is transported to Cape Town, South Africa by ship for disposal.

VI. Summary

This paper presented an overview of the resource and waste streams observed during the first experiment phase of the EDEN ISS MTF in 2018 at the German Neumayer III Station in Antarctica. During the period from February 7 to November 20, 268 kg of fresh edible biomass was produced in the space analogue greenhouse through the cultivation of pick-and-eat crops, such as lettuce, tomato and cucumber. In order to produce this amount of edible biomass, around 18 kg of nutrient salts, 50 kg of CO_2 from bottles and 2,554 kg of reverse osmosis water were supplied to the facility throughout the experiment phase. In addition, 532 kg of diluted acid, diluted base and stock solutions were added to the two stock solution tanks. In detail this accounts to 40 kg of diluted acid and 12 kg of diluted base. For NDS tank 1 an equal amount of 112 kg was added from stock solution A and B. For NDS tank 2 this amount was 128 kg for stock solution A and B.

Waste byproducts of operating the greenhouse facility consisted of around 2,435 kg of waste water and waste nutrient solution. Furthermore, a significant amount of paper, cardboard and plastic waste, approximately 8.9 kg, 1.8 kg and 17.4 kg respectively, was produced throughout the experiment phase in the form of packaging, cleaning supplies and consumables such as disposable gloves. It should be noted that these values do not account for all waste items produced throughout the year.

A comparison of the waste produced as a result of EDEN ISS operations with other greenhouse facilities or with values from facilities in space, such as the International Space Station, cannot readily be made due to lack of data, as well as the fact that the amount of waste produced is highly dependent on the specifics of both the mission and the facility. The limited data available on waste streams, such as that provided in the NASA Baseline Values and Assumptions Document, typically refers to wastes generated through crew hygiene rather than facility cleaning activities. Estimates for the food and packaging wastes generated through the consumption of prepackaged food are available, but these are not applicable for food production systems.

The data on resource consumption and waste production presented in this paper is in several instances limited in scope and detail, as the on-site operator did not have sufficient time nor accurate enough tools to comprehensively track all the inputs and outputs from the facility. The MTF remains in operation in the Antarctic however, so it is expected that further data will be available in the future.

As the on-site operation of the MTF in 2019 and 2020 will be handled by the regular winter crew of the Neumayer Station III, as opposed to the dedicated EDEN ISS operator who was available during 2018, waste tracking, as well as other non-essential tasks, will not be carried out during these years. However, for 2021 it is planned to once again have a dedicated operator for the greenhouse and it is anticipated that at least partial waste tracking will take place throughout next year's experiment phase. A number of tools have been acquired to allow for more precise measurement of masses, time consumption and other parameters of interest. More importantly, the procedures for various tasks will be updated to incorporate the additional waste tracking tasks.

In addition to the on-site tracking which is anticipated for 2021, significant information is available as a result of the yearly re-supply shipments to the Antarctic over the past few years. The combined data of shipment lists to and from the Neumayer Station III, combined with on-site inventory lists and detailed tracking of on-site waste streams, will allow the data presented in this paper to be refined in the coming years.

Nevertheless, the data presented here provides some initial practical data which can be used for planning of future analogue and actual space missions. In particular, when considering a future space mission, where a greenhouse would most likely be but one part of a larger set of crew infrastructure, it is important to know the inputs and outputs of the greenhouse. Although the amounts of plastic, paper and other waste materials would most likely differ somewhat in such environments, it is nevertheless important to keep in mind that such types of waste will be present and will need to be processed by other systems.

Acknowledgments

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