Review of Antarctic Greenhouses and Plant Production Facilities: A Historical Account of Food Plants on the Ice

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Antarctic crews have been transporting plants and their supporting infrastructure to Antarctic field sites since as early as 1902. More than 46 distinct plant production facilities have, at one time or another, operated in Antarctica. Production facilities have varied significantly in size, technical sophistication, and operational life. Many of these efforts have been driven by the expeditioners themselves, which clearly demonstrates the fundamental desire that people have to associate themselves with plants while living and working in inhospitable environments. The need for this biological association can be solely psychological, while at other times it is based on the more practical need for fresh food. Although the nature of plant growth activities has evolved with the implementation of increasingly stringent environmental regulations, there remains strong interest in deploying such systems within or near Antarctic stations. Current Antarctic plant growth facilities are predominately organized and administered at the national program level to ensure such regulations are adhered to. Nine hydroponic facilities are currently operating in Antarctica. This paper summarizes historic and existing Antarctic facilities by incorporating information from expeditioners, environmental assessment reports, direct communication with national contact points, as well as published reference documents, unpublished reports, and web-based sources. A description of the country operating the facility, the specific Antarctic station, as well as specific information with regard to the facility size and the nature/type of the deployed systems are provided. Looking towards the future of Antarctic plant growth facilities, a number of previously and currently planned Antarctic facilities are

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also reviewed. The potential for future Antarctic plant production systems are discussed and considered not only for food production but also as bioregenerative life support systems, in that they can provide supplemental station capacity for air and water regeneration. Antarctic testing can also advance the readiness of hardware and operational protocols for use in space-based systems, such as in orbit/transit or on the surface of the Moon and Mars.

I. Introduction

Expeditioners have been bringing plants to the Antarctic since the very early days of Antarctic exploration. Diary and photographic evidence details plants being grown during Scott's Discovery Expedition in 1901-1904 [1, 2]. Dr. Reginald Koettlitz, one of the expedition's surgeons and crew botanist, grew several crops aboard the ship Discovery while it was trapped by the ice in Winter Quarters Bay, McMurdo Sound [3]. Plants were grown during the Austral summer under the wardroom skylight in boxes containing Antarctic soil collected from the nearby hills [2, 4]. The first plants, cress and mustard, were grown in the latter part of 1902 (Figure 1). Other crops such as lettuce, radish, onion and turnip were also planted [5]. Evidence suggests that the crew attempted to grow plants hydroponically by growing them directly on flannel and applying nutrient solution [6]. On November 1, 1902, Koettlitz harvested and served some of the mustard and cress to the crew [2]. This was the first fresh 'green' food that they had eaten for 13 months [2].

Figure 1. October 1902 Discovery Expedition photograph showing the first mustard and cress crop grown on the expedition ship Discovery in boxes under the wardroom skylight (Image credit: [1]).

More sustained growth of food plants in the Antarctic commenced as soon as long-term stations began to be established. Indeed, the first overwintering crew at the newly established South Pole Station had plants with them in 1957, both for visual/psychological purposes but also as an attempt to produce fresh food [7]. Just as plant growth technology has changed since the early days of Antarctic exploration, current facilities utilized to grow plants in the Antarctic are now considerably more sophisticated and include advanced lighting systems, hydroponics, and modern sensor suites. Furthermore, evolving Antarctic environmental regulations have potentially played an even greater role in the appearance and configuration of Antarctic plant growth facilities. In particular, with the implementation of the Antarctic Treaty [8], and later the Madrid Protocol [9], the growth of plants at Antarctic stations requires

adherence to strict requirements aimed at preventing the introduction of non-native species, limiting waste production, as well as greater monitoring and reporting requirements.

This paper represents, to the best of the authors' knowledge, the most comprehensive coverage of the history of Antarctic food production and includes a review of all known past and present Antarctic greenhouses and growth chambers. It should be noted that the authors published a preliminary survey of such facilities [10], but since that time an even wider breadth of facilities and relevant historical details have been found. The initial publication focused primarily on the preliminary design concepts of a planned Antarctic plant production facility, providing only cursory details on historical systems. The current work focuses on providing details on nearly all the Antarctic plant production facilities, both past and present. It is important to note that although the conventional use of the term 'greenhouse' implies growth under at least some natural light, this paper uses 'greenhouse' and 'growth chamber' interchangeably as 'greenhouse' has become a general term in the description of Antarctic plant production systems regardless of the operational mode. Various sources have been utilized in the compilation of information on Antarctic plant production systems and include journal articles, station environment evaluation reports, environmental inspection reports, web-based sources, unpublished reports as well as results of direct communication with facility developers, Antarctic station operators, and numerous national Antarctic institutes.

The authors concede that due to the nature of such historical research, it is probable, if not certain, that some facilities have been overlooked. This is particularly true for early small-scale systems that were expeditioner-driven and not officially documented. Many of the early facilities were not scientifically based, but instead driven by the interest of the expeditioners themselves. The fact that plants have been conveyed by crew members to so many remote Antarctic outposts illustrates the importance they hold. The following quote from the science lead of the first overwintering crew at South Pole, Paul Siple, illustrates this relationship with plants. Although the crew carried a few plants to the station, they did not have the luxury of a sizeable plant production facility capable of providing a measureable fresh produce contribution [11]:

> *"Naturally none could resist dreaming of delightful situations outside, or certain delicacies, such as green salads, that were unobtainable." -- Paul Siple (1960)*

Ample anecdotal evidence exists in the literature regarding the psychological benefit of operating plant production chambers or greenhouses in the Antarctic [12-15]. A South Korean study, conducted after installation of the plant factory at King Sejong Station, not only demonstrated a benefit to physical health, it found that 83% of station crew members found that the produced vegetables were either "very helpful" or "somewhat helpful" to their mental health [16]. Overwintering Antarctic expeditioners are nominally faced with many months of isolation, with no new supplies, and thus no fresh food arriving or available for the duration of this period. Although there is suggestion that yearlong flights to McMurdo Station may soon become a reality [17], most Antarctic aircraft operations are limited to a maximum five-month window, and smaller stations will certainly not have this type of enhancement to their logistics chain for many years. Further, in addition to access to fresh produce, it is also known that the very presence of plants within such remote environments can, in and of itself, provide psychological benefit [18, 19]. Even if controlled environment agriculture technologies do not continue to advance to the point where plant growth systems can be sufficiently efficient and of sufficient size to positively influence a station's logistics chain, there remains considerable benefit in their implementation into Antarctic stations.

The majority of countries operating stations in the Antarctic have at one time or another had plant production facilities operating at one or more of their stations. More than 46 different plant growth facilities have been operated or are presently operating in the Antarctic. Figure 2 illustrates these facilities along with the respective station for which the facility was or is operated.

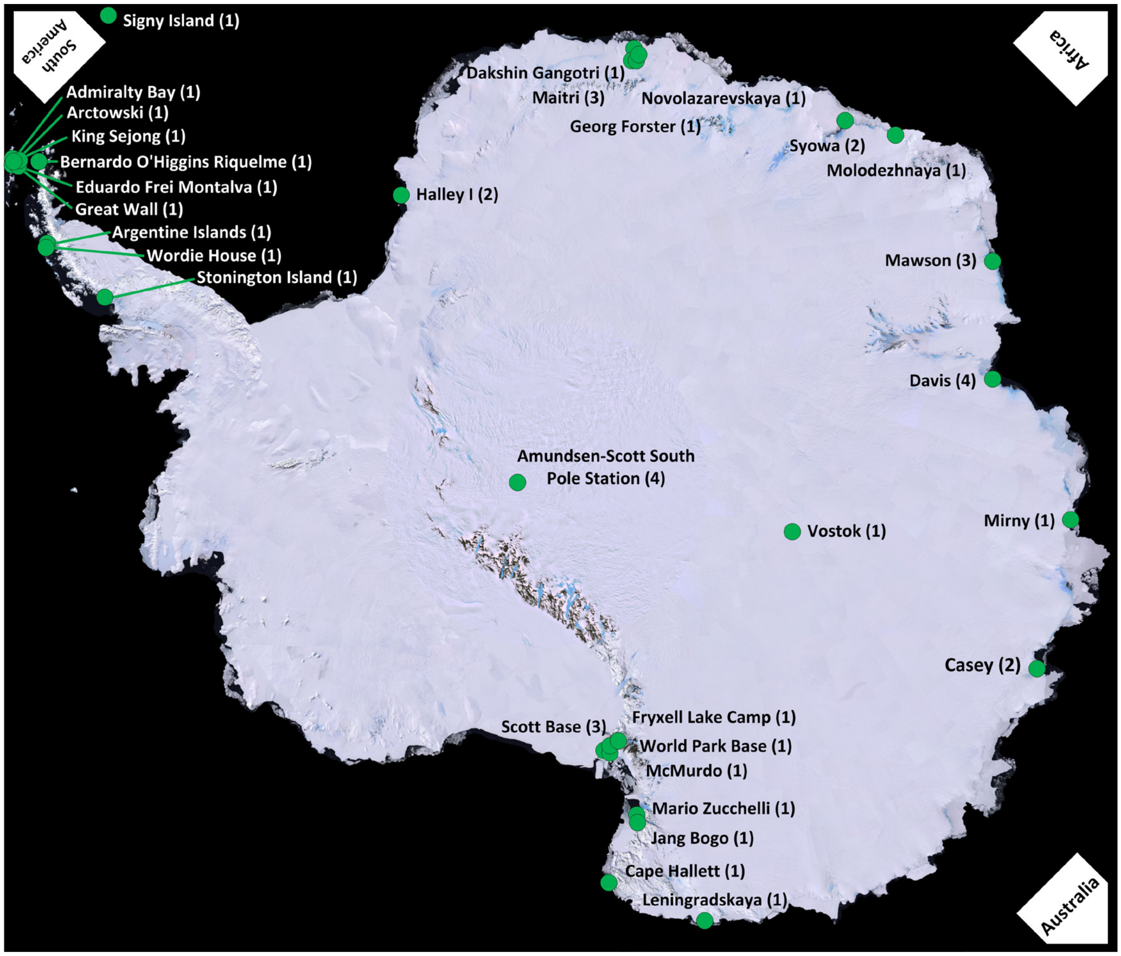

Figure 2. Map depicting documented past and present Antarctic plant production systems. The station (or, in one instance, the camp) at which each facility was installed is indicated. In parentheses are the number of growth facilities operated in the past or currently operating at that given station (outline Antarctic image credit: Landsat imagery courtesy of NASA Goddard Space Flight Center and U.S. Geological Survey).

As is apparent from Figure 2, Antarctic plant production systems have been established primarily in Antarctic coastal areas, with concentrated pockets on King George Island (Admiralty Bay, Arctowski, King Sejong, Eduardo Frei Montalva, Great Wall) and nearby on the Antarctic Peninsula (Bernardo O'Higgins Riquelme), as well as in the Schirmacher Oasis, within Queen Maud Land (Georg Forster, Novolazarevskaya, Maitri and Dakshin Gangotri which itself is on the shelf ice near, but not in the Schirmacher Oasis ice-free plateau) and Ross Island (Scott Base, McMurdo, World Park Base). The location of plant production facilities mirrors the establishment of the main Antarctic bases, which for accessibility and logistics reasons, tend to be near coastal areas that are sea-accessible; areas centered around the Antarctic Peninsula; or around the ring of the continent on or in the proximity of coastal boundaries. Currently there are approximately 40 Antarctic stations that are operated year-round and just over 80 that operate only during the austral summer [19].

More specific information on each of the Antarctic plant production systems is provided in Table 1. For each facility, the national program or country responsible is provided. Station integration information is also provided, including whether the plant production system is included as part of the main station, or is housed in an external building. Further, as a number of the plant growth systems are integrated into sea-containers, the nature of the current system's construction (based on shipping containers or custom-made) is provided. Additional information includes the facility's operational status (i.e., is it currently active), the known timeline of operations, and the approximate size of the facility (specified as the surface area of the entire facility). The references from which this information was obtained are provided in the descriptive information section on each of the respective Antarctic plant production facilities.

Table 1. Summary of documented Antarctic (south of 60°S latitude) plant growth facilities.

National Program	Station Name	Facility Type	Active	Dates of Operation	Full Facility Area**	New Ops. Planned	Note/Description***
Australia	Casey	Int.	No	Opened: 1980 or before. Closed: 1989 or before	6.6 m^2	No	Hydroponic growing room
		Ext.: Container type	Yes	Opened: Summer 2000/2001	27.7 m^2 (2 x 20 ft containers)	N/A	Casey hydroponics facility
	Davis	Int.	No	Opened: 1969. Closed: N/A	N/A (spare donga)	No	Davis indoor garden
		Ext.: Container type	No	Opened: 1984 or before. Closed: 1989 or before	13.9 m^2 (1 x 20 ft container)	No	Container hydroponics garden
		Ext.: Container type	No	Opened: 2001/2002. Closed: 2014	27.7 m^2 (2 x 20 ft containers)	No	Davis hydroponics facility
		Ext.: Container type	Yes	Opened: 2015	13.9 m^2 (1 x 20 ft container)	N/A	Interim hydroponics facility
	Mawson	N/A	No	Opened: 1984 or before. Closed: 1987/1988. Reopened: 1988/1989. Closed: 1989	N/A	No	N/A
		Ext.: Wood building	No	Opened: 1995. Closed: 2000 (non-operational: 1997/1998)	24 m^2	No	Rectangular ISPO hut hydroponics facility
		Ext.: Wood/metal clad building	Yes	Opened: 2001/2002	28 m^2	N/A	L-shaped/Auroral Observatory hydro. facility
Chile	Bernardo O'Higgins Riquelme	Ext.: Specialty constructed	No	Opened: Feb 2005. Closed: N/A	21.57 m^2	No	Módulo Hidropónico Experimental
	Eduardo Frei Montalva	N/A	N/A	Pre-2000?	N/A	N/A	Frei GH
China	Great Wall	Ext:	Yes	Opened: 2014/2015. Full ops. expected 2015/2016	36 m^2	N/A	Great Wall GH
India	Dakshin Gangotri	Int.	No	1986	Small-scale system	No	Small-scale tests
	Maitri	Int.	No	1986	Small-scale system	No	Small-scale tests
		Int.	No	Opened: 1990. Closed: Between 2002-2009	28.2 m^2	No	GH connected to station
		Ext.: Dome	No	Opened: 1991. Closed: N/A	7 m^2 (estimated from [20])	No	Dome GH
Italy	Mario Zucchelli	Ext.: Container type	No	Opened: 1997. Closed: 2002	1997-1999: 13.9 m^2 (1 x 20 ft container) 1999-2002: 31.4 m^2 (2 x 20 ft containers and connecting module)	No	CHGS/PULSA
East Germany	Georg Forster	Ext.: Connected to wood building	No	Opened: ca. 1980. Closed: Early 1990s	Small- to mid-sized system	No	Georg Forster GH
Japan	Syowa	Int.	No	Opened: Early 1966. Closed: Jan 1968	3 x 0.2 m^2 and 3 x 0.29 m^2	No	Plant Boxes
		Int.	Yes	Opened: 2008	~3 m^2	N/A	Plant culture system
Republic of Korea	King Sejong	Ext.: Container type	Yes	Opened: 2010	13.9 m^2 (1 x 20 ft containers)	N/A	Plant factory
	Jang Bogo	Int.	Yes	Opened: 2014	35 m^2	N/A	Plant factory
New Zealand	Scott Base	Ext.: Old insulated water tanks	No	Opened: 1986. Closed: 1999	~15 m^2	No	Water tank hydroponics unit
		Ext.: Container type	No	Opened: 2000. Closed: 2005	27.7 m^2 (2 x 20 ft containers)	No	Scott hydroponics unit
		Int.	Yes	Opened: 2012	~0.8 m^2	N/A	Benchtop hydroponic system
	Lake Fryxell Camp	Ext.: Plastic GH	No	Opened: 1979. Closed: 1983	~10 m^2	No	Lake Fryxell GH
Poland	Arctowski	Int.: In science building	No	Opened: 1978/1979. Closed: Late 1980s. Later reopened and subsequently closed	37.9 m^2	No	Arctowski GH

National Program	Station Name	Facility Type	Active	Dates of Operation	Full Facility Area**	New Ops. Planned	Note/Description***
Russia	Leningradskaya	Int.	No	Opened: N/A. Closed: End 1980s	N/A	No	Leningradskaya GH
	Mirny	Int.	No	Opened: N/A. Closed: End 1980s	N/A	No	Mirny GH
	Molodezhnaya	Int.	No	Opened: N/A. Closed: End 1980s	N/A	No	Molodezhnaya GH
	Novolazarevskaya	Int.	No	Mid-1970s (duration unknown)	Mid- to large-sized system	No	Novo GH
	Vostok	N/A	No	Opened: 1974. Closed: N/A	N/A	No	Vostok GH
UK	Stonington Island – Base E	Int.: GH on side of workshop	No	Opened: 1946. Closed: 1950	2.23 m^2	No	Stonington Island GH
	Wordie House – Base F	Int.: GH on side of station	No	Opened: ca. 1947. Closed: 1953	3.18 m^2	No	Wordie House GH
	Argentine Islands – Base F	Ext.: Wood building	No	Opened: 1968. Closed: Late 1970s?	7.48 m^2	No	Argentine Islands GH
	Admiralty Bay – Base G	Int.: GH on side of station	No	Opened: ca. 1950. Closed: ca. 1954	1.91 m^2	No	Admiralty Bay GH
	Signy Island – Base H	Int.: GH on side of main station. Later on another hut	No	Opened: 1950. Closed: 1952. Newly constructed: 1955 or 1956. Closed: After 1967	2.37 m^2	No	Signy Island GH
	Halley I – Base Z	Int.	No	Opened: 1962. Closed: 1963	0.54 m^2	No	Small-scale radio office system
		Ext.: Wood construction	No	Opened: End 1962. Closed: Early 1963	2.75 m^2 (estimated from [21])	No	External GH
USA	Amundsen-Scott South Pole	Int.	No	Experiments commenced in winter 1957	<1 m^2	No	Basic hydroponic systems
		Ext.: In-station dome (wood construction)	No	Opened: 1990. Closed: 1994	Approx. 3 m^2 (plant growth area)	No	Initial SP GH on ground
		Ext.: In-station dome (wood construction)	No	Opened: 1994/1995. Closed: 2005	Slightly bigger than previous dome GH	No	New SP GH on Annex
		Int.	Yes	Opened: 2004	50 m^2	N/A	SPFGC
	McMurdo	Ext.: Wood building*	No	Opened: 1989. Expanded: 1994. Closed: End 2010-2011 season	50 m^2 before expansion, 66 m^2 after expansion	Yes	McMurdo GH
New Zealand and USA	Cape Hallett	Int.	No	Opened: 1958. Closed: N/A	N/A	No	Dome vegetable garden
Non-Governmental	World Park Base	Int.	No	Opened: 1988/1989. Closed: 1991/1992	~1.2 m^2	No	World Park Base hydroponics system
Previously or currently planned facilities							
Australia	Davis	Ext.: Container type	No	Planned for 2015/2016	~37 m^2 (2 x 20 ft containers and 2 x 10 ft containers)	Yes	Davis four container hydroponics unit
Brazil	Comandante Ferraz	Int.	No	N/A	N/A	N/A	Hydroponic growth chamber
France and Italy	Concordia	Int.	No	N/A	N/A	Previously planned	Concordia GH
Germany	Neumayer III	Ext.: Container type	No	Planned for 2017/2018	27.7 m^2 (2 x 20 ft containers)	Yes	EDEN ISS GH module
UK	Halley VI	Int.	No	N/A	11 m^2	Previously planned	Atrium hydroponic system
USA	Amundsen-Scott South Pole	Int.	No	N/A	Large-scale system	Previously planned	CAAP Hydroponics Unit

Int. = internal, Ext. = external, GH = greenhouse, Ops. = operations. Other abbreviations and acronyms are defined in the text.
*Used old military shipping containers but structure was substantially modified.
**The Full Facility Area column provides the footprint area of the complete facility. Specific plant cultivation areas are provided in later sections (when known).
***The Note/Description column is intended to give the name by which the facility is commonly known in the literature. If a given facility has no name, the table identifies it with a short description.

A number of important observations can be drawn from the list of facilities in Figure 2 and Table 1. In particular, there have been at least 46 different plant production facilities in the Antarctic. The 46 reported facilities are or have been operated by 13 different nations, as well as one non-governmental organization. It is also worthwhile to note that there have been several instances when a particular facility was closed and then subsequently reopened (e.g., facilities at Mawson, Arctowski, Signy Island), or the facility was enlarged or modified in a substantial way (e.g., facilities at McMurdo, Mario Zucchelli). These events have not been included in the aforementioned facility total (i.e., they have been counted as a single facility). Out of the 46 reported facilities, there are nine that are currently operational. These facilities include those at Casey, Davis, Mawson (Australia), Great Wall (China), Syowa (Japan), King Sejong, Jang Bogo (South Korea), Scott Base (New Zealand) and the Amundsen-Scott South Pole Station (USA). It should be noted that the Great Wall Station greenhouse is expected to be fully operational following additional construction activities during the 2015-2016 season [22]. In addition to the countries that confirmed that they currently operate plant production facilities, a number of countries confirmed that they indeed do not presently operate Antarctic plant production facilities at their respective Antarctic stations e.g., India, Norway (nor did it operate any past systems), Poland, Russia [23-26].

From Table 1 it can be seen that roughly half of the plant production facilities have been built within the main station facility, with the remaining being standalone/external units. Whether a facility is internal or external is not always clear from the available data; however, for the purposes of Table 1 'internal' has been defined as a plant production facility that was set up in a nominal, and most often times, already existing station floor area. This includes facilities such as the Maitri greenhouse (India) constructed onto the side of the main station, the South Pole Food Growth Chamber integrated directly into the main South Pole Station (USA), or smaller-scale hydroponic systems that may be setup in an unutilized station room. 'External' has been defined as a facility built into a separate station structure (e.g., to access the facility, expeditioners must go outside). For example, this includes greenhouses built in unused station buildings, specially constructed greenhouses/growth chambers, or those of separate shipping container-based systems. It should be noted that many of the historical United Kingdom station greenhouses have been considered as internal facilities for the purpose of Table 1, as they were accessible without leaving the main station, even though, they were purposefully constructed as external additions to the stations themselves.

Seven of the Antarctic plant production systems have been built into shipping containers. This includes greenhouses located at Casey, Davis (3), Mario Zucchelli, King Sejong and Scott Base. As shipping containers form the backbone of cargo transported by sea to Antarctica, they are either available as empty containers on-site or used as the specific form factor to prefabricate and test a plant production facility prior to shipment to Antarctica. Examples of facilities built within previous on-site containers include Casey and Davis (3) [27-30]. While the Plant-based Unit for Life Support in Antarctica (PULSA) facility at Mario Zucchelli Station and the plant factory at King Sejong Station are examples of plant production facilities fabricated and tested in sea containers prior to shipment to Antarctica [16, 31] (note: other non-shipping container-based systems have undergone integrated testing prior to transport to Antarctica as well: O'Higgins greenhouse, South Pole Food Growth Chamber). Finally, the Scott Base container-based hydroponics unit was something in between the two options, in that it utilized containers that had previously been used in New Zealand, that were shipped to Scott Base in their unmodified state and adapted on-site for use as a hydroponics unit [32]. Other shipping container-based systems are also planned for future deployment [10].

The Protocol on Environmental Protection to the Antarctic Treaty ('Madrid Protocol'), a key aspect of the Antarctic Treaty System, was opened for signature on Oct 4, 1991 and entered into force on Jan 4, 1998 [9]. The protocol provides wide-ranging protection of the Antarctic environment and itself directly shaped Antarctic plant production activities. Indeed, there is a stark contrast between plant production facilities that were installed before the implementation of the Madrid Protocol and those following implementation. Many of the early pre-protocol facilities were developed by expeditioners with supplies and materials found on-site and in many instances used non-native soils or grew non-food crops, both no longer allowed in Antarctica. It has been hypothesized on at least one occasion that a pre-protocol facility was one of the vectors in which a non-native species (e.g., *Poa annua* – annual bluegrass) established itself in the Antarctic [33]. Although no longer acceptable, pre-protocol facilities are included in this review as they represent an important piece of the history of growing plants in the Antarctic. Post-protocol facilities have increased in automation, sophistication, and in the use of controlled environment agriculture technologies. Such technologies aid station operators in meeting environmental regulations (minimizing wastes) while enhancing crop yields.

As evident in Table 1, there are several instances where information is lacking related to the listed plant production facilities. This is primarily a result of many of the early plant growth activities in the Antarctic being ad-hoc in nature. Early expeditioners would develop systems on-site, primarily for their own personal interest. In certain cases, documentation may not exist and thus the findings provided in Table 1 should not be considered

comprehensive, rather a summary of the best available information. Illustrative examples of systems alluded to in the literature but not included in this review/count include a precursor greenhouse at the Argentine Islands Station which was positioned in the same location as the latter-built facility, single-plant pots positioned by windows in stations such as Bellingshausen and Georg Forster, and a number of undocumented plant growth activities at Australian stations Mawson, Casey and Davis [30, 34, 35].

In addition to the Antarctic facilities depicted in Figure 2, there are a number of other facilities that were either planned but never implemented, or are active projects that are still under development. Information on these proposed hydroponic facilities is included in Table 1 and more specific details are provided in the sections that follow the detailed description on past and current plant production facilities.

II. Facilities by Country

A. Australia

Various horticultural activities have been conducted at Australian stations since the late 1960s [36, 37]. However, all plant growth activities at Australian stations were suspended in 1989 due to concerns over the introduction of non-indigenous species and ever more stringent environment regulations [38, 39]. When Australia decided to suspend plant production activities at its stations, an open letter appealing this decision and elaborating on the psychological benefit of in-situ production was drafted and signed by approximately 20 past Australia Antarctic crew members [39]. The closure of these facilities permitted Australia to implement a very organized hydroponic program that, once the ban was lifted (1991), better ensured compliance with environmental regulations. It also included strong commonality between growth systems operating at Australia's three stations and its subantarctic Macquarie Island Station [14, 40]. The importance of plant growth activities at Australia's Antarctic stations is further evidenced by the fact that Australia maintains an active training program for expeditioners (i.e., prior to deployment) and a 'hydroponics manual' [14, 38].

1. Casey Station

Australian activity in proximity to the current Casey Station involved the use of Wilkes Station and the later-constructed Repstat ('replacement station') which was officially opened and renamed Casey Station in 1969 [41]. The original Casey Station was later abandoned in the 1980s when the current Casey Station was built and officially opened in 1988 [42]. Casey is one of three permanent Australia Antarctic stations and serves an overwintering crew of approximately 20 [43]. Initial documented expeditioner-driven plant growth at Casey Station started as early as 1969 when a small-scale natural-light plant growth system was installed beside a north-facing window of the cosmic-ray telescope (not included in Table 1) [34]. A small hand-watered one-gallon tin full of soil was used to plant tomatoes during the southern summer. A larger facility was initiated in 1980 in which a small station room of 3 m x 2.2 m was converted into a growing room [29]. A number of growing modules were lined with plastic, filled with scoria that served as the inorganic growth substrate, installed on a table and fed with recirculating nutrient solution. Plants were illuminated with a height-adjustable bank of 7 to 8 fluorescent lamps [29]. The system experienced a number of difficulties, including insufficient light and water supply, and was later closed [29].

The first long-term plant production activities at Casey commenced in the 2000-2001 austral summer, as Australia was reintroducing hydroponic production at its Antarctic stations. Casey was the first of the Australian stations to receive such 'purpose-built' facilities [27]. The facility was contained within two adjoined 20 ft shipping containers connected along their longitudinal axis and including a small cold porch (Figure 3A). The stand-alone nature of the Casey hydroponics facility, and of other Australian-station facilities, met an important constraint placed upon the newly reintroduced facilities regarding limiting the spread of any detected disease or infestation [38]. The insulated containers had their interior lined with stainless steel to simplify cleaning. The facility has grown a wide variety of crops including tomatoes, lettuce, herbs (basil, parsley, chives, dill, and thyme), cucumbers, onions, snow peas and silver beet [27].

Figure 3. Australian Antarctic growth chambers. (A) Casey exterior 2012 (Image credit: Australian Antarctic Division). (B) Davis exterior 2011 (Image credit: Bernd Kaifler). (C) Mawson exterior 2005 (Image credit: M. Smith, Australian Antarctic Division).

2. Davis Station

Davis Station was founded in 1957 and presently serves approximately 20 overwintering expeditioners [43]. The first documented plant growth activities at Davis date back to 1969 during which an indoor garden and a glasshouse were constructed [36]. The internal system was constructed within a spare donga and permitted year-round growth of cress, radish, lettuce, onions, cabbage and tomatoes [36]. The basic hydroponic system included a growth substrate made up of a mixture of sand, gravel and vermiculite, while lighting was provided by ten fluorescent lamps [36]. The external glasshouse included a sloping roof constructed of double-glazed panels. Watering was done by hand. The facility permitted the growth of a wide variety of crops. It is not known if the operation of either of these facilities was continued in the years to follow.

Although there are documented plant growth activities at Davis prior to 1984, that year expeditioners achieved year-round plant growth through the use of a larger 'growth chamber' (distinguished here from a greenhouse) [44]. The facility was installed within a container (6 m x 2.4 m x 2.3 m) and utilized a hydroponics system with mineral wool as a support substrate fed with a liquid nutrient solution and illuminated with fluorescent light tubes [29]. It is reported in that same year that a crew member installed a small plant production chamber in his bedroom (not included in total facility count) [44]. Although the 1985 Davis team had the desire to continue the very successful plant growth activities of 1984, the sea container in which the growth chamber was installed was returned to its owners and the hydroponic systems removed [44]. At the time that Deprez (1990) published reports and images of production at Davis, he commented that, to the best of his knowledge, there had never been any successful, concerted effort to have a continuous, permanent, hydroponics facility at any of the Australian Antarctic stations. However, there is anecdotal and photographic evidence of potential past systems, including a facility (Figure 4) operating at David Station in 1982 [30].


Figure 4. 1982 image of a Davis hydroponics facility (Image credit: Australian Antarctic Division).

The Davis hydroponics facility (Figure 3B) was the second of the Australian facilities established in the early-2000 time period to incorporate the latest growth system technologies and to realize a greater growth area. The Davis facility was installed in 2001-2002 and its design was similar to the unit installed at Casey but included a number of minor modifications based upon early experience with the Casey facility [27]. The system was composed of two 20 ft containers bolted together with a small cold porch on one side [28]. Like Casey, the Davis hydroponics facility has been used to grow a wide variety of crops including lettuce, chilies, cucumbers, tomatoes, silverbeet, celery and various herbs [45]. Although not noted to be the highest yield recorded at Davis, the facility produced a total edible yield of 237 kg between Dec 1, 2012 and Oct 16, 2013 [45]. For reference, during the same period a total of 420 kg of total green matter and an additional 240 kg of clay balls and perlite were put through the station's incinerator [45]. During the 2014 winter, the hydroponics facility experienced a springtail infestation [30]. The facility was cleaned and shut down to prevent the spread of the invertebrates. Rather than recomissioning the facility, it was decided to return it to Australia. This decision was based on the fact that the facility had, over years, suffered snow/ice damage and had a number of cold paths that resulted in heat loss and condensation issues [30, 45].

A large hydroponics facility is planned to replace the facility that closed in 2014 [30]. In the interim, a hydroponics unit has been setup within a disused 20 ft container (previously used as a cheese/dairy store). The plant growth hardware was sent to Davis in February 2015 with seeds first sowed at the end of April 2015 [30]. The plant growth system itself has a footprint of approximately 9 m^2 and employs fluorescent and high pressure sodium lighting in conjunction with a nutrient film technique (NFT) irrigation system. The facility is planned to operate only during the austral winter [30].

3. Mawson Station

Mawson, Australia's first Antarctic station, was established on February 23, 1954 [46]. The year-round station supports approximately 20 overwintering crew members [43]. Documented evidence shows a Mawson hydroponics building operating at least as early as 1984 [47, 48]. This facility was likely operated continuously in the years to follow, aside from an idle period in 1987/1988 [39]. The facility was recommissioned for one additional overwinter (1988/1989) before once again being shut down when all Australian Antarctic hydroponic activities were halted in 1989 [14, 39]. Following the lifting of the prohibition of Australian hydroponics, production was resumed at Mawson in 1995 [14, 27]. This facility operated until the 1999/2000 season [49] (although it is likely that it was not operated consecutively during this period as it was observed that the facility did not operate in 1997/1998 [30]). The facility was installed within an exterior fully insulated plywood building that was initially the Ionospheric Prediction Service Organisation (IPSO) hut, and then utilized for expeditioner accommodation and subsequently as a sauna and gym (Figure 5) [49, 50]. The building measured 8 m x 3 m and included a cold porch at one end. The interior of the facility was lined with reflective foil and included ten small double-glazed windows with internal shutters [49]. As the facility was not connected to station services, water was transported weekly to the facility in a large drum on the back of a truck. Nutrient solution was made up on-site using two-part powder salts and recirculated within the facility to the extent possible. The facility used clay balls, perlite and vermiculite as growth substrate and NFT for the growth of certain crops [49].

Figure 5. Mawson Station hydroponics facility utilized in the period of approximately 1995 to 2000 (Image credit: John Gillies taken in 2001).

In the austral summer of 2001-2002 a vacated paint storage unit, which was previously used for the Auroral Observatory, was refurbished and became the current Mawson hydroponics growth system (Figure 3C). The building is comprised of a two-room L-shaped building including a 6 m x 3 m and a 4 m x 2.5 m room and a cold porch [14]. The building is of wood-stud construction with polyurethane insulation and sheet-metal cladding (Zincanneal) [34]. The Mawson system is outfitted with similar plant growth systems and lighting as those employed within the current Casey and Davis systems [38]. The continued use of this building as a hydroponics facility is planned for the long-term [51].

B. Chile

1. Bernardo O'Higgins Riquelme Station

The Bernardo O'Higgins Riquelme Station is a permanently crewed research station and is one of the longest continuously operated stations on the continent having been established in 1948. A greenhouse was installed at the station in February 2005 (Figure 6). The development of the Módulo Hidropónico Experimental – M.H.E ('Experimental Hydroponics Module') was conducted under a collaborative agreement between the University of Chile and the Chilean Army, not under a Chilean national science program [52, 53]. The initial project had four primary activities that included: 1) the installation of the laboratory at O'Higgins Base, 2) the initiation of the hydroponic cultivation system and data acquisition and control systems to collect environmental data at regular intervals, 3) the training of the Chilean Army to operate the facility, and 4) conduct of a series of growth tests in the first calendar year of operation [52]. The facility was deployed near the main entrance of the original O'Higgins Station building. The dimensions of the module were approximately 9.7 m x 2.52 m x 2.80 m (h), of which a small floor space (approximately 1.46 m x 2.50 m) was utilized as a vestibule area, which separated the sole exit door from the main plant growth area [52, 54]. This left approximately 19.02 m^2 for the cultivation area [53]. The greenhouse used natural light via 16 windows covering the bulk of three sides of the module [52]. During winter operations the system was outfitted with 16 x 250 W high pressure sodium lamps [53]. The hydroponics system was based on two separate but identical NFT systems each comprised of seven PVC gutters 3 m in length, each NFT system permitting the growth of 81 plants. The test phase included the production of various lettuce cultivars; data from these tests has been presented previously [52]. At the time this project was active there was interest between Chilean Antarctic Institute and the Polish Academy of Sciences to collaborate in the area of Antarctic plant production and associated controlled environment agriculture technology [55].

Reference has also been made to a greenhouse facility that operated at Eduardo Frei Montalva Station and small-scale hydroponics unit that was operating at Villa Las Estrellas [40, 56].

Figure 6. O'Higgins Station experimental hydroponics module (white/windowed building indicated with arrow) installed near the main entrance of the original station building (Image credit: Ejército de Chile).

C. China

1. Great Wall Station

Great Wall Station, located on King George Island, was the first Chinese station to be established in Antarctica. The year-round station opened in 1985 and has an overwintering crew size of approximately 14 [43]. A greenhouse is being constructed during the 2014/2015 Antarctic summer, with construction expected to continue through the 2015/2016 season (Figure 7) [22]. The greenhouse will utilize a combination of natural and electric lighting composed of LED and high pressure sodium lamps [57]. The symmetric double pitched roof and walls are composed of a transparent (polymethyl methacrylate) skin material installed within a steel structural frame (Figure 7). The building has an area of 36 m^2 and will produce approximately 60 kg of vegetables per month [57]. The facility will focus on, but not limited to, crops such as lettuce, cucumber, cherry tomatoes, and peppers. The facility has been developed with a design lifetime of 15 years [57]. The greenhouse will utilize a maximum electrical load of 8.5 kW [57]. The hydroponic growth system is a stacked ebb and flow design. Waste nutrient solution and other small sources of wastewater are sent to the Great Wall Station sewage treatment system, while the inedible plant waste is first dried and then sent to the station's high-temperature incinerator. The greenhouse includes a condensate-recovery system which helps to offset greenhouse generated station water demand. There are presently no plant growth facilities operating at other Chinese stations [22].

Figure 7. Great Wall Station hydroponic food production system just following construction in the 2014/2015 austral summer (Image credit: Chinese Arctic and Antarctic Administration).

D. India

The first documented Indian food production activities in the Antarctic occurred during the 5th Indian Antarctic Expedition in 1986 [58, 59]. These early experiments focused on assessing indoor cultivation under the local temperature, illumination and space constraints at Dakshin Gangotri and Maitri stations. These experiments grew a number of salad crops using various materials including local soils, soil transported from India, snowmelt water and lake water [58]. Artificial illumination was employed at Dakshin Gangotri, while sunlight was used at Maitri. Although these experiments provided encouraging results, they confirmed that neither sunlight nor the electric lighting systems were adequate for productive plant growth under the configurations used [58].

1. Dakshin Gangotri Station

Dakshin Gangotri was the first permanent Indian station and was established during the third Indian expedition to Antarctica in 1983-1984; the first overwintering crew was stationed there in 1984 [60]. The initial soil-based plant growth facility was constructed in 1986 on the second floor of the two-storey station and installed in the A block mezzanine above the generator room and repair shops [58, 60]. At that time there was no access to sunlight nor temperature control in the A block of Dakshin Gangotri. Coarse temperature control (temperature approx. 13°C to 21°C with humidity nominally between 16% to 30%) was achieved by the construction of a makeshift enclosure around the plants using metal-foil-clad foam polystyrene blocks and utilizing generator waste heat [58]. Lighting was provided by four 40 W cool-white fluorescent lamps and plants were grown within soil in wooden packing

cases and plastic bags [58]. The authors could not find any documentation of horticultural activities at Dakshin Gangotri after the cursory studies of 1986 up to the station's closure in 1990 due to an excessive snow load.

2. Maitri Station

Plant growth activities were initiated at Maitri in 1986, even before Maitri became the second of India's full-year Antarctic stations in 1989 [58]. The initial experiments conducted in the temporary Maitri camp were only 11 days in duration; essentially they were germination studies to determine if local soil collected from the nearby Lake Priyadharshini was suitable for plant production at the station [58]. Soil-filled bags were located next to a window on the first floor of the kitchen hut. Radish, spinach, methi (fenugreek), tomato and cucumber were planted. Interestingly, the cucumber seeds were provided by the local Russian, Novolazarevskaya Station [58]. As the Maitri camp was being closed for the season, the bags containing the seedlings were transported by the exiting expeditioners to Dakshin Gangotri, during which approximately half of the plants perished due to the freezing temperatures. Those that survived the trip continued to grow well at Dakshin Gangotri [58].

The larger, long-term Maitri greenhouse was installed during the 9th Indian Antarctic expedition which opened in 1990; the greenhouse facility was capable of year-round operation [12, 61]. The greenhouse shown in Figure 8 was built onto the side of the main Maitri Station and benefited from natural light for plant growth. Although issues arose during construction, including an injury that required repatriation, the facility became operational during the overwintering period [61]. The greenhouse itself measured 10.6 m x 2.66 m. Natural light was provided by glass windows installed over the maximum possible area. Fluorescent and high pressure sodium lamps provided electric light [61, 62]. Translucent curtains were used to provide a day/night cycle during 24-hr polar summer days [12]. Although plants were grown in soil, the greenhouse included a nutrient reservoir with on-line monitoring and adjustment of pH and electrical conductivity (EC), as well as its own environmental control system [12, 13]. An on-site constructed NFT system and Rockwool were also employed within the facility's hydroponic system [13]. The greenhouse was utilized to grow a wide variety of crops and the assessment of their growth was quantitatively evaluated on several occasions [12, 13]. It is not known precisely when the long-term greenhouse at Maitri was closed but various Antarctic inspection reports suggest that it was operational in 2001, but reports from 2009, 2012 and 2013 do not reference its operation or status [63-66].

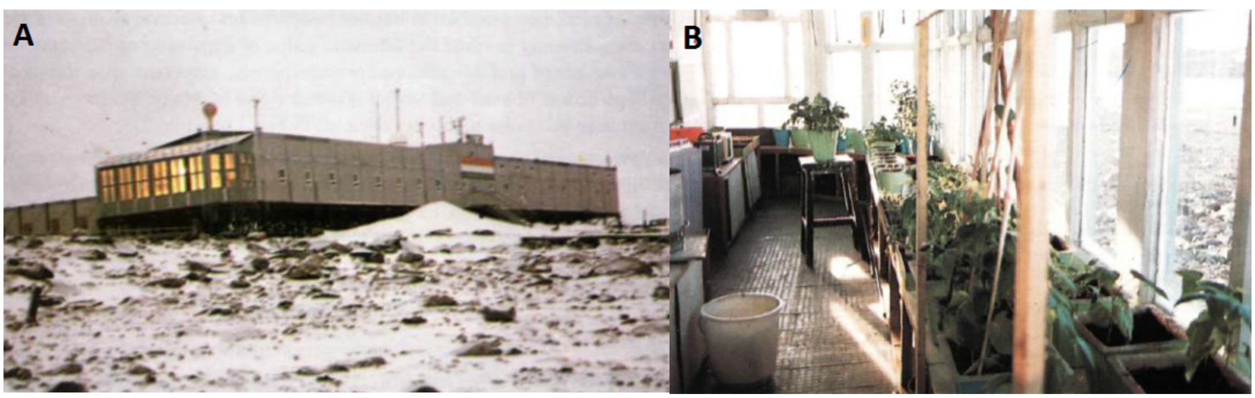

Figure 8. (A) Maitri Station showing the illuminated greenhouse installed on the side of the station (early 1990s). (B) Internal view of the Maitri greenhouse (Image credits: [12]).

Another smaller and shorter-term greenhouse facility was constructed at Maitri in an external dome in 1991 during the 10th Indian Antarctic expedition [20]. The external dome (Figure 9) was made of steel tubes, nodal joints and a transparent fiberglass reinforced plastic panel cladding [67]. The dome and its internal racks and facilities for hydroponics were constructed over a period of six days and provided an estimated internal area of 7 m^2 [20, 67, 68]. It has been confirmed that India does not presently operate hydroponic plant production facilities at any of its Antarctic stations [23].

Figure 9. Early 1990s image of the Maitri dome greenhouse (Image credit: [20]).

E. East Germany

1. Georg Forster Station

The East German station located in close proximity to the Soviet Novolazarevskaya Station was opened in 1976. It was later named the Georg Forster Station, but was decommissioned in 1993. During its operational period, the crew constructed and operated a year-round greenhouse (Figure 10) [58, 69]. Sometime between the late 1970s and early 1980s (the exact years are not known) the greenhouse was constructed onto the side of the station's power plant, an external building as shown in Figure 10 [68, 69]. The greenhouse was not used for scientific investigations, but instead for the psychological benefit of crew [70]. As this facility was constructed before the Madrid Protocol, like many before it, it used soil brought from outside of the Antarctic. The facility grew lettuce, cucumbers, tomatoes, strawberries, herbs, flowers, as well as many other species. Natural and electric lighting was employed to permit growth throughout the austral winter. Its walls consisted of three layers, of which the top layer could be easily replaced when damage from the high solar UV became too great and reduced the transmission of photosynthetically active radiation [70]. At the time of station decommissioning, all station-building materials (including those for the greenhouse) and all the soil used in the greenhouse, were transported off of Antarctica and properly disposed of [70]. Records also suggest the existence of pre-protocol plant growth activities at Neumayer I and Neumayer II stations [70].

Figure 10. Georg Forster Greenhouse. (A) Georg Forster Station during the polar night showing the illuminated greenhouse to the right side of the image (Image credit: Günter Stoof - image taken during the 37th Soviet Antarctic Expedition in 1992). (B) Interior of the Georg Forster Greenhouse (Image credit: Günter Stoof).

F. Italy

1. Mario Zucchelli Station

Mario Zucchelli Station is a large Italian station located at Terra Nova Bay that serves approximately 90 expeditioners seasonally (no overwintering) [43]. In 1997 a standard 20 ft shipping container containing a prototype greenhouse module was deployed to the station [71]. The container included a curved 18 mm thick polymethyl

methacrylate panel to permit the use of natural light. This facility was developed by ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development) and called the Closed Hydroponic Greenhouse Module (CHGM) [71, 72]. It was later renamed PULSA (Plant-based Unit for Life Support in Antarctica). It was operated and further developed over four campaigns conducted from 1997-1998 to 2001-2002 [73]. The greenhouse module underwent large modifications in 1999 during which a second standard 20 ft container was added and linked to the first by way of a smaller bridge unit (1.50 m × 2.46 m × 2.59 m (h)) that was used as a service area (Figure 11A) [73]. As with the initial 20 ft container, the added container had transparent panels along its longitudinal wall. All walls were well insulated and their interior surfaces were designed to permit daily cleaning with a sterilizing agent [73].

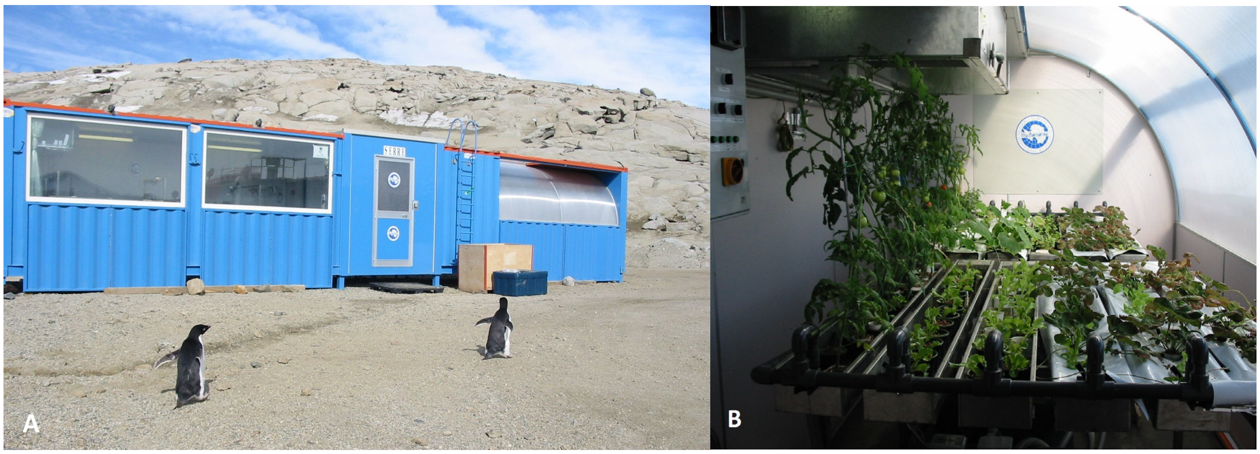

Figure 11. PULSA greenhouse module. (A) External view of PULSA displaying the initial CHGM container (unit A) with curved transparent panel in the right side of the image and the 1999-added service module and additional growth systems (unit B) in the left side of the image (Image credit: Carlo Alberto Campiotti). (B) Internal view from unit A of PULSA (Image credit: Carlo Alberto Campiotti).

The initial PULSA (unit A) container included a closed NFT system comprised of two benches with six gullies each sized 1.60 m (l) x 0.20 m (w) x 0.12 m (h). The system included a mixing tank with online pH and EC measurement and control [73]. The added growth module (unit B) included a substrate based plant growth system with five gullies each measuring 4.00 m (l) x 0.19 m (w) x 0.07 m (h), with manual adjustment of the nutrient solution pH and EC [73]. Unit A employed an air heater/cooling system while an air heater/cooling system including a dehumidifier was installed in unit B. Each system had a maximum power draw of 5.0 kW and temperature was maintained between 15°C and 30°C and humidity between 40% and 70% [73]. The overall PULSA system also included two fans, each with an air-exchange capacity of 1200 m^3/h [73].

Although the main focus of PULSA was on leafy green crops (three cultivars of lettuce: Yatesdale, Great Lakes and Iceberg), tall fruiting crops such as tomato, strawberry and cucumber were also trialed (Figure 11B) [31, 73]. The entire PULSA facility could be easily operated and maintained by one person, without significant experience in soilless cultivation [31]. Although the PULSA project focused on growth during the austral summer using only natural light, studies and designs were conducted regarding the incorporation of electric lights and other enhancements to permit year-round operation [73]. In addition, this project stimulated a number of associated research projects related to multilevel hydroponic units, LED lighting, a biomass production model for controlled environment lettuce growth, and a unit to purify spent nutrient solution and recycle residual biomass produced in such remote facilities [31, 74, 75].

G. Japan

1. Syowa Station

Built in 1957, Syowa Station is located on East Ongul Island in Queen Maud Land. As Japan's sole year-round station it includes an overwintering crew of approximately 28 members [43]. The first known deployment of plant growth hardware to a Japanese station occurred in the mid-1960s when small Japanese-developed 'plant boxes' were sent to the Syowa Station (Figure 12A). In addition to the hardware which was installed in Syowa Station, plant growth hardware was set up in the Japanese Antarctic resupply ship 'Fuji' that carried the plant boxes to Syowa [76]. The overall ship-based growth system was of 1.3 m x 1.3 m x 1.0 m (h) in size and provided a cultivation area

of 2.7 m^2 [76]. It included 16 fluorescent lights that provided 3500 lx at the cultivation surface. The system operated on board the Antarctic resupply ship from November 20, 1965 until its return to Tokyo on April 8, 1966 [76].

Following the arrival of the resupply ship at Syowa, the six plant boxes (3 x NEC-type and 3 x Toshiba-type) were installed at the station. Operations commenced in early 1966 [76, 77]. Each Toshiba plant box provided a 0.2 m^2 cultivation area and had dimensions of 0.70 m x 0.40 m x 0.55 m (h) [76, 78]. Each included four fluorescent lights providing 3500 lx at the cultivation surface. The culture medium was a 60:40 mix of pearlite and shale substrate [76]. Each NEC-type plant box had a 0.29 m^2 cultivation area with overall dimensions of 0.66 m x 0.66 m x 0.365 m (h) and utilized fluorescent lighting to supply 4200 lx at the cultivation surface [78].

The Syowa plant growth boxes were operated over winter to provide fresh green vegetables to the 7th Japanese wintering party (1965-1966) and continued though the 8th wintering party (1966-1967) until their operations ceased in January 1968 [76]. Crop yields from both the NEC and Toshiba provided units were monitored throughout the duration and both systems were found to provide very satisfactory results [76, 78].

Figure 12. (A) One of three Toshiba plant boxes transported on the S.S. Fuji Japanese Antarctic vessel and subsequently installed at the Syowa Antarctic Station (Image credit: Motoi Imajo). (B) 2010 image of the five-level internal hydroponics growth system at Syowa Station (Image credit: National Institute of Polar Research, Japan).

In 2008 Japan installed a new hydroponic plant growth system at Syowa Station [79]. The facility was installed on the 2nd floor of the generator building within a 2.046 m x 1.5 m x 2.092 m (h) enclosure [80]. Within the chamber, a cultivation area of approximately 3 m^2 is made available through the use of a five-tier growth system as shown in Figure 12B [80]. The system was developed by Mirai Co. (Tokyo, Japan). The facility initially included fluorescent lights and more recently has incorporated LEDs [81]. A CO_2 concentrator maintains an approximate 1500 ppm CO_2 concentration in the airtight acrylic-panel growth chamber [80]. Although other crops have been grown in the facility, the system is primarily being used to provide leafy green vegetables such as lettuce. During the operational period from April 2008 to January 2009, 18.8 kg of lettuce was harvested from the multilevel system [80]. Unused volume (i.e., not part of the stacked growth system) has also been used to grow other crops (e.g., bean sprouts) [80]. In addition to providing some fresh produce over winter, it is claimed by the station operators that the in-situ plant growth activities at Syowa provide a psychological benefit to the crew [80].

H. Republic of Korea

1. King Sejong Station

King Sejong Station was established on King George Island in February 1988. The year-round station has an overwintering crew of approximately 18 personnel [43]. A plant factory (Figure 13), one of the most advanced plant production systems to be installed in the Antarctic, was sent to the station at the end of 2009 and officially opened in January 2010 [82, 83]. The facility was developed by PARU Co., Ltd. (Suncheon, South Korea). The growth chamber is based around a 20 ft shipping container, which further demonstrates the popularity of basing systems on established transportation form factors [82, 84]. Polyurethane insulating panels of 15-20 cm thickness were installed on the inner walls. The three-level hydroponic cultivation system permits the installation of 72 trays, each 60 cm x 30 cm, within the chamber, providing an average of more than 1 kg of fresh vegetables per day; this is sufficient to provide the full station crew with fresh salads and vegetables, at least once per week, during the entire winter [16]. The plant factory utilizes both LED and fluorescent lighting deployed in such a way as to permit a moderate amount of light-quality manipulation to suit specific crops [16]. Further, reflective panels are employed to maximize light

delivery to the plants. During a 2012 inspection, the facility was being used to grow crops such as lettuce, peppers and cabbage [85]. At the time, all waste, including growth substrates and plastic plant trays, were being sent to Chile for disposal [85].

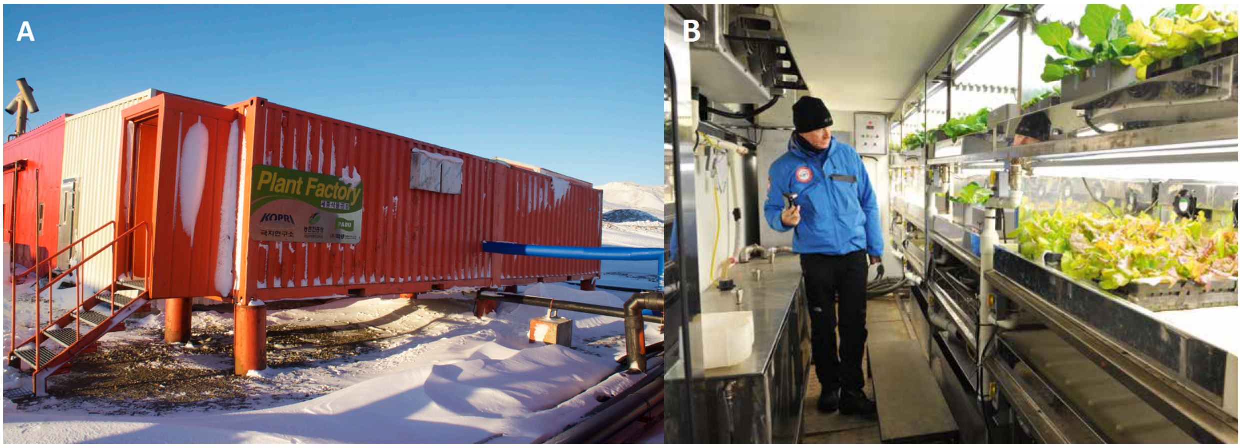

Figure 13. (A) External view of the King Sejong Station plant factory (Image credit: KOPRI). (B) King Sejong Station plant factory during a 2012 site inspection (Image credit: [85]).

2. Jang Bogo Station

Jang Bogo Station, located in Terra Nova Bay, was officially opened in February 2014. It is the second of South Korea's permanent Antarctic stations, accommodating up to 15 overwintering personnel, and it is the first of South Korea's stations to be located on the Antarctic mainland [86]. The plant growth facility at the station commenced operations in late March 2014 [87]. The Jang Bogo facility was also developed by PARU and incorporates the same controlled environment agriculture technologies as those of the King Sejong plant factory. That said, unlike the system based on shipping containers at King Sejong Station, the 35 m^2 Jang Bogo facility is situated within the main building of the station [87]. The plant production components of the facility are divided into two separate rooms (Figure 14A). The first including four single-layer grow shelf systems incorporating drip irrigation. The other, shown in Figure 14B, includes four three-layer bottom-watering systems. Each year, one of the overwintering crew members from Jang Bogo is put in charge of the operation and management of the facility [87]. The remainder of the station staff also receive training from PARU before being deployed to Antarctica.

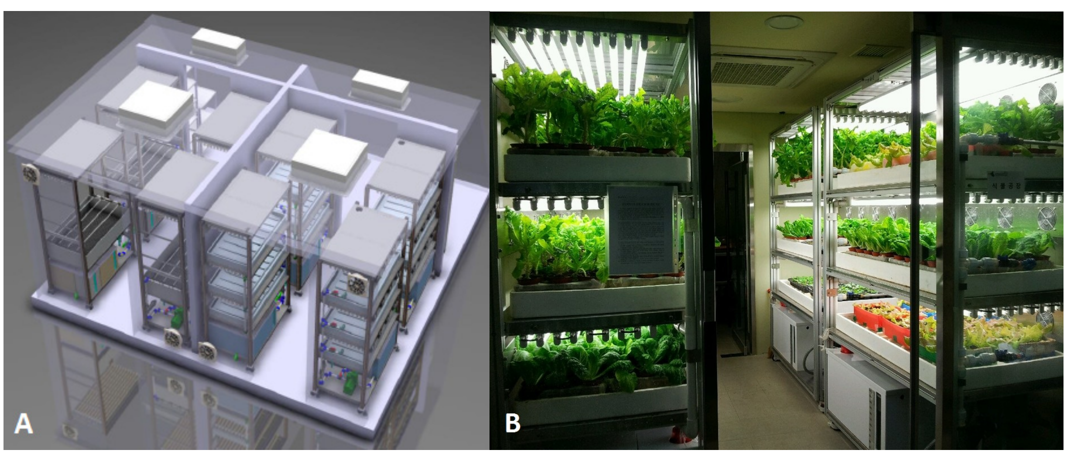

Figure 14. (A) Computer model of the now operational Jang Bogo Station internal plant factory showing the two separate controlled environments and multilevel growth systems (Image credit: KOPRI/PARU). (B) January 2015 internal image of one of the rooms of the Jang Bogo Station plant growth facility showing the multilevel growth system and bottom-watering system (Image credit: KOPRI).

I. New Zealand

1. Scott Base

Scott Base is New Zealand's permanent Antarctic station and was opened on the southern part of Ross Island in McMurdo Sound in 1957. The base was initially built to support the Commonwealth Trans-Antarctic Expedition and International Geophysical Year of 1956-1959. Today, the station can accommodate 85 people over the summer and approximately 10 overwintering crew members [43]. Although not known if it was installed, it has been reported that Sir Edmund Hillary took a greenhouse with him to the Antarctic as part of the Commonwealth Trans-Antarctic Expedition of 1955-1958 [88]. Hillary had announced that he intended to grow cress, mustard and a number of other fast-growing vegetables within a transparent structure in soil transported to Antarctica from New Zealand [89].

In 1986 two large insulated external water tanks at Scott Base were joined with a newly constructed intermediate section including entry door [90] (Figure 15). Soon after, the facility was outfitted with basic hydroponic plant growth hardware and grew crops such as tomato, lettuce, other leafy greens and various herbs under fluorescent lights [90, 91]. The facility operated until 1999 [32].

Figure 15. (A) External image of the Scott Base hydroponics unit (shown to the right of the image) constructed in two insulated water tanks (Image credit: Keith Martin ©Antarctica New Zealand Pictorial Collection [ANZSC0235.2] [1986-1987]). (B) Interior view of the water-tank-based hydroponics unit (Image credit: Chris Rudge ©Antarctica New Zealand Pictorial Collection [ANZSC0191.20] [1987-1988]).

From 2000 to 2005, Scott Base operated a container-based hydroponics unit (Figure 16) [37]. The system included two 20 ft containers and provided a total facility area of approximately 27.7 m^2 [92]. The containers were previously-used freezer units purchased using the Scott Base recreation fund for the specific use as a hydroponic plant growth system [32]. Upon shipment from New Zealand to Antarctica, they were modified for use by the on-site crew. The facility was situated near the main powerhouse to take advantage of waste heat from the power plant and the growing area could be accessed through a porch via a landing connected to the main base [92]. In addition to new lighting systems, lights from the previous water-tank-based hydroponics unit were transferred and used within the new container-based system [32]. This resulted in a system that used fluorescent, metal halide and high pressure sodium lighting [32]. Four NFT systems and an ebb and flow system were used for irrigation. These systems were purposely constructed to operate separately and in a fairly manual way so as to minimize the risk of failure [32]. The facility produced a large variety of food crops (herbs, lettuce, tomato, snow peas, cucumber, zucchini, chili peppers, strawberries, squash, spinach and Swiss chard) and a range of flower crops [92]. Grow media was typically a mixture of perlite and vermiculite and the ebb and flow system used expanded clay [32]. Following the detection of a springtail infestation in 2002, all plant material was destroyed, the hydroponics unit was dried and then disinfested with bleach, and cooled down rapidly (springtails rarely pose a threat to plants themselves but action was required in this instance due to the potential concern of Antarctic non-native species introduction) [92, 93]. Once no further signs of the springtails were evident, the unit was re-initialized and a regular inspection protocol was put in place. Two years later, the facility was once again infested. A similar cleaning process was undertaken; however, the facility was not reinitiated because of two concerns: the risk of introducing exotic species into the environment, and for energy consumption considerations [32, 92]. The facility was initially used as an informal storage area and then removed to make way for the wind farm frequency converter, after which the containers were employed to support the conservation team working on Scott's and Shackleton's historic huts [32, 37, 92, 94].

Figure 16. Exterior of Scott Base (ca. 2000/2001) showing the 2000-2005 containerized hydroponics unit (1) beside the main powerhouse (2). The door and landing to the hydroponics unit are on the far side of the unit and are not visible in the image (Image credit: Johno Leitch).

In 2012, documentation including a risk analysis and standard operating procedures were drafted for the operation of a new small-scale hydroponics unit at Scott Base [37]. The operating procedures specified that the system would only be operated during the winter and provide growth for a maximum of ten individual plants [37]. A small (approximately 0.8 m^2 growth area) tabletop hydroponics unit with two hanging grow lights now operates at Scott Base (Figure 17) [95]. The system is based upon a commercial off-the-shelf NFT hydroponics unit that is assembled only after the departure of the last flight of the summer season [96]. Following operations during the winter, the unit is disassembled, thoroughly cleaned (sodium metabisulphite) and stored over the summer [96]. The unit is set up in the mess hall along the west wall near the entry of the lounge [96]. Antarctic best practice suggest that hydroponic units should be separate from areas where food is prepared and/or stored, or high human traffic areas; however, the mess hall site was selected to enhance visual monitoring by all staff and to ensure a rapid response should any incident occur [96].

Figure 17. Benchtop hydroponics unit at Scott Base (Image credit: Antarctica New Zealand).

2. Lake Fryxell Field Camp

A plastic greenhouse was constructed in 1979 at New Zealand's Lake Fryxell field camp (77° 36' S, 163° 7' E) [97]. The facility was used for the experimental growth of garden vegetables as well as for the storage of some field equipment due to the warm temperatures within [98]. During the 1979 field campaign, the facility was used to grow numerous crops (e.g., green beans, sugar peas, tomatoes, and cornflowers) in local soil and soil transported from New Zealand [6]. Similar to the camp itself, the greenhouse was only operated during the austral summer and removed at the completion of each field campaign [97]. The initial facility was constructed using a small metal A-

frame covered with double-layered bubble plastic. The greenhouse was expanded in the austral summer of 1980/1981 by the addition of a second A-frame section (Figure 18). In 1982/1983 the Lake Fryxell camp plant growth facilities where further elaborated by constructing a larger semicircular cross-section greenhouse. All facility equipment and structures were later removed from the Lake Fryxell site.

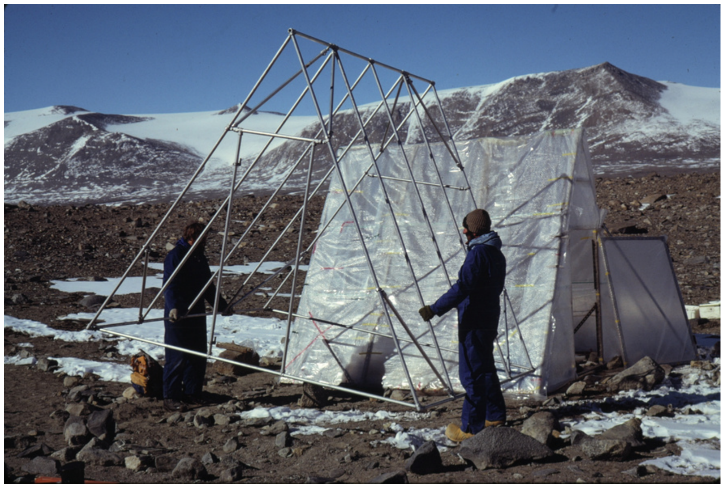

Figure 18. Lake Fryxell greenhouse expansion during the 1980/1981 austral summer (Image credit: ©Antarctica New Zealand Pictorial Collection [ANZSC0976.12] [1980-1981]).

J. Poland

1. Arctowski Station

The greenhouse at the Polish Arctowski Station was one of the most well-known Antarctic greenhouses (Figure 19). The Arctowski Station was opened in 1977 and the greenhouse constructed soon after in the 1978-1979 timeframe [99, 100]. The plant production facility operated until the late 1980s [101]. It was subsequently reopened and once again closed and now houses scientific equipment [85, 102]. The large greenhouse facility had an approximate area of 38 m^2 and provided both natural and artificial lighting (high pressure sodium) [25, 103]. Plants were originally grown in soil transported from Poland. Later, a mixture of local sand (flushed with fresh water) and diluted guano was utilized [25]. Poland presently does not operate any Antarctic plant production systems [25].

Figure 19. (A) External view of the Arctowski Station greenhouse in 1978/1979. (B) Internal view of the Arctowski Station greenhouse in 1978/1979 (Image credits: Boguslaw Molskie, Department of Antarctic Biology, Institute of Biochemistry and Biophysics, Polish Academy of Sciences).

K. Russia

There is very little published documentation on plant growth activities conducted at Russian stations. One of the first possible examples may well be when a pilot grew onions under natural and artificial light at Mirny Station in 1958/1959 [104]. Another reference exists relating to flowers, produced in the Russian Vostok Station greenhouse, being gifted to visiting American expeditioners in the mid-1970s [105]. This facility is reported to have opened in 1974, and in addition to flowers, grew tomatoes and radishes using hydroponic means [106]. A relatively large greenhouse is known to have operated at the Russian Novolazarevskaya Station during the mid-1970s [70]. Crew members at the East German Georg Forster Station received tomatoes grown in this greenhouse as a gift from a 1976 overwintering Novolazarevskaya crew member [70]. This facility, or one operating just before it, was reported to have produced 50 kg of tomatoes, cucumbers, onions, chives and several types of flowers during the 1972-1973 season [107]. Additionally, indoor cultivation under natural light was performed at the Russian Novolazarevskaya Station during the 1980s [58]. A 2001 reference points to a number of plants being observed in Novolazarevskaya Station, including a station greenhouse, during an Antarctic inspection tour [63]. Similarly, a hydroponics system was observed at Leningradskaya Station in the mid-1980s [48]. It has been reported that Russia closed down greenhouses operating at Mirny, Leningradskaya and Molodezhnaya stations in the late 1980s [26]. Russia does not presently operate any specifically designed plant production facilities at its Antarctic stations nor do they have plans to reinitiate any of the aforementioned facilities in the near future [26].

L. United Kingdom

1. Stonington Island Station – Base E

The United Kingdom's Base E on Stonington Island, located at the southern end of Marguerite Bay, was established in 1946 [108]. The base was closed in 1950, reoccupied for one year in 1958-1959, before being officially reopened in 1960. It was rebuilt in 1961 with the original base used as a source of construction material. It was operated continuously until its closure in 1975. A lean-to type greenhouse (Figure 20) was built onto the side of the station workshop in 1946 [109]. Entrance into the greenhouse was possible without exiting the station via a door between the greenhouse and the workshop. The greenhouse was heated by natural light, station heat entering through this door as well as a set of 2" diameter pipes carrying heat from a stove in the workshop. The greenhouse had a 6 ft x 4 ft footprint with the roof sloping from 6 ft in height at the side of the station to 4.5 ft [109]. The use of natural light was enabled via double-glazed windows with a 2.5" airspace. The remainder of the greenhouse was of wood construction and all internal non-glass wall areas, as well as the floor, were lined with aluminum foil to maximize light reflection. On sunny summer days it was often necessary to shade the facility [109]. A metal structure including a 1/2" wire mesh netting was constructed external to the greenhouse to protect the greenhouse glass. Plants were grown hydroponically in a substrate composed of locally collected volcanic ash and sand. The hydroponic solution was mixed using nutrient salts brought specifically for this purpose. Lettuce, radish, carrots, cabbage, spring onion, cress and pansies were grown [109].

Figure 20. 1949 image of Base E, Stonington Island. The lean-to greenhouse is visible near the center of the image (Image credit: Colin C. Brown, March 5, 1949. Reproduced courtesy of the British Antarctic Survey Archives Service. Archives ref. AD6/19/3/C/E4).

2. Wordie House – Base F

Wordie House (first Argentine Islands Station, but listed separately here) on Winter Island in the Wilhelm Archipelago was established in January 1947 [110]. The hut was constructed on the foundations of a previous hut established during the British Graham Land Expedition. The station was permanently occupied from its construction until May 1954 when the new Argentine Islands base was opened on the neighbouring Galindez Island [111]. A wood and glass lean-to type greenhouse was used at Wordie House from ca. 1947 until 1953. The greenhouse (Figure 21) was installed on the north wall of the main hut [110]. It had a footprint of 7'1" by 4'10" and was used to grow salad vegetables.

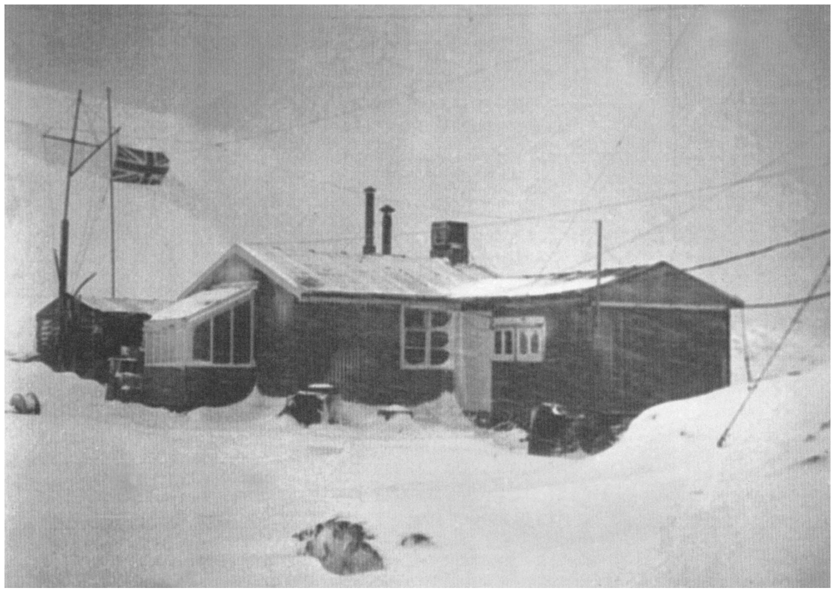

Figure 21. Wordie House greenhouse visible on the left side of the image (Image credit: Henry George Heywood, 1950. Reproduced courtesy of the British Antarctic Survey Archives Service. Archives ref. G25/1/1).

3. Argentine Islands Station – Base F

Argentine Islands Station was moved to Galindez Island in 1954, and was renamed Faraday Station in 1977 [111]. In 1968 a greenhouse was constructed on a platform on the side of the main hut (Figure 22A). Prior to this, it was reported that this same platform had been used to support a previous greenhouse, but no details could be found on this earlier facility [112]. The newly constructed facility measured 10'6" by 7'8" and was 7'5" high [112]. The wooden structure initially included a single layer of glass but was found to result in too much heat loss and its walls were subsequently insulated and the glass replaced by double-glazed glass [113]. These 1969 structural enhancements also included improvements to the greenhouse electrical system. The greenhouse used both natural and electric lighting [112]. The lights were installed on pulleys to allow their height to be adjusted for different crops [112]. The multilevel growth arrangement (Figure 22B) permitted plants on the bottom level to be grown under artificial light year-round, while plants on the upper shelves could be grown under natural light in the summer. Additional window surface area was added in 1969, increasing natural light levels in the greenhouse, while aluminum foil was also used to maximize light reflection [113]. Plants were grown hydroponically as well as in soil [114]. The greenhouse was known to have produced vegetables including lettuce, tomatoes, cucumbers, radishes, mustard and cress. During periods of high productivity, the facility was known to provide every station crew member a salad meal on a frequency from once every one to two weeks [114]. The greenhouse was used actively until 1976 but is also mentioned in station reports as late as 1979.

Figure 22. (A) Exterior of the Argentine Islands Station greenhouse in 1968. (B) The interior of the greenhouse in 1968 illustrating the multilevel growth system with only the bottom level in operation (Image credit: Photographer unknown. 1968. Reproduced courtesy of the British Antarctic Survey Archives Service. Archives ref. AD6/2F/1968/C1).

4. Admiralty Bay Station – Base G

The Admiralty Bay Station located on King George Island was constructed in 1947. Although the specific dates of operation are unclear, a greenhouse appears in records at the station between 1950-1954 [115]. The facility (Figure 23) was of a wood and glass lean-to construction with a footprint of 4'9" by 4'4". Vegetables as well as flowers were known to be grown in the summer, while the greenhouse was used as a dog kennel in the winter [116].

Figure 23. Admiralty Bay Station building with an arrow indicating the station greenhouse on the rear-facing side (Image credit: Roger Anthony Todd-White, 1951. Reproduced courtesy of the British Antarctic Survey Archives Service. Archives ref. AD6/19/2/G176).

5. Signy Island Station – Base H

Signy Island Station located on Signy Island within the South Orkney Islands was first occupied in 1947. A lean-to greenhouse (Figure 24) with a footprint of approximately 6'3" by 4'1" was active between 1950 and 1952. The wood and glass structure built onto the original accommodation hut, Clifford House, was destroyed by strong winds in 1952. The greenhouse (or same size equivalent) was reconstructed in 1955 or 1956 onto the side of the recently built generator/boat shed. In 1958, the greenhouse was used to grow mustard, cress, radish, onion and lettuce [117]. In 1963 the base commander reported that the greenhouse was successfully growing daffodils, mustard and cress in soil, but had less success with other crops such as radish, lettuce and spinach [118]. At the time, it was suggested that the fumes from the diesel generators or high temperatures could have been the reason for these difficulties [118]. Photographic evidence suggests that the greenhouse existed until at least 1967 [119].

Figure 24. Early 1950s Signy Island Station greenhouse installed on the side of Clifford House. The greenhouse is indicated with an arrow (Image credit: William Joseph Sladen, 1950. Reproduced courtesy of the British Antarctic Survey Archives Service. Archives ref. AD6/19/3/C/H1).

6. Halley I – Base Z

In mid-1962 the overwintering radio operator at UK Halley I Station constructed an internal hydroponic growth system in the station radio office [21]. The project was not part of any ongoing scientific program. Rather it was expeditioner-driven. Plants were grown over a period of a year and included tomato, lettuce, radish, mustard, cress, and peas [21]. Growth was conducted under fluorescent light (natural light was unavailable because the hut was approximately 9 m below the surface of the snow). Nutrients were provided hydroponically with plants growing in a mixture of gravel and vermiculite. Four trays measuring 45 cm x 35 cm x 15 cm (h) were filled with the gravel and vermiculite and watered via both drip-feed and flood-and-drain techniques at various times over the operational life of the system [21]. Several other plants were grown in empty cigarette tins under drip-irrigation.

With increasing day length (Sep-Oct 1962) the construction of a small outdoor greenhouse was initiated [21]. The facility (Figure 25) was a standalone building with wooden walls filled with fiberglass insulation. Double-glazed windows that covered approximately half the total surface area of the exterior walls permitted the use of natural light. The construction of the facility was completed at the end of 1962. Plants were grown in empty cereal tins of the same length and width, but of slightly greater depth than those used in the station's internal hydroponics system. A 60:40 gravel and vermiculite mixture was used and water was primarily provided by ebb and flow irrigation. Operational and environment control challenges, in the form of low relative humidity and inadequate cooling capabilities during periods of strong sunlight proved difficult to overcome. Even with outdoor temperatures well below freezing, temperatures inside the greenhouse rose above 35 °C [21].

Figure 25. Halley I external greenhouse (Image credit: R. Lee, 1962. Reproduced courtesy of the British Antarctic Survey Archives Service. Archives ref. G100/1/1).

M. USA

1. Amundsen-Scott South Pole Station

Located at the Geographic South Pole, the construction of the original South Pole Station began in November 1956. The first hydroponic garden at the original South Pole Station was constructed in 1957 from a large baking pan covered by a clear plastic lid [7]. Within the pan were three breadbasket trays that contained sweet potatoes, philodendron, cress seeds, radishes and clover. In conjunction, the first documented plant to survive an entire year at South Pole (1957) was a potted philodendron plant kept under artificial light by the station's scientific lead Paul Siple. Interestingly, this was a plant that made the entire trip to Antarctica from the United States after it was given to Siple by a neighbour [7]. In addition to these informal plant growth experiments, in 1960/1961 the first detailed (non-native) plant production 'science' was conducted at the South Pole (and McMurdo) in which a number of plants, insects and small animals were studied to assess the influence of the rotation of the Earth on their biological clocks [120]. The common bean (*Phaseolus vulgaris*) was utilized as the test organism and grown in a simple growth unit illustrated in Figure 26 [120]. In the years to follow, a number of expeditioner developed gardens were episodically used at South Pole Station [121].

Figure 26. Overwintering crew member tends to plants as part of a biological experiment conducted at South Pole station during the 1961 summer/winter (Image credit: US Navy).

The first long-term sustained greenhouse at South Pole was constructed in 1990 out of a former paint/do not freeze storage building [122]. The building was placed under the South Pole Station dome, stripped, reinsulated and then outfitted in time for the overwintering crew to use during that first year (Figure 27A). The approximately 3 m^2 plant growth area system included heaters, walls lined with aluminum foil, electric lighting, a single nutrient reservoir, and a two-tier, vermiculite-based, hydroponic plant growth system [122, 123]. A substantial number of upgrades were made to the South Pole Station greenhouse during the 1991-1992 austral summer based on deficiencies found during the initial run. These deficiencies included inadequate lighting, poorly designed trays, and lack of knowledge with respect to the operation of the facility [124]. Accordingly, modifications included the installation of new trays, additional lighting, a heat exchanger, and improved insulation. At the time of the upgrades, the following plants (number of plants in parentheses) were planned for growth within the facility: tomato (4), pepper (4), sweet pepper (5), cucumber (2), spinach (30) and lettuce (90) [124]. Lighting was provided by high pressure sodium lamps [125].

Operations continued until 1994 when the internal systems were transferred to a different station building with slightly more interior space situated on the roof the Annex (still under the dome) as shown in Figure 27B [122, 125]. Operations continued in this facility until it was closed in 2005 when the greenhouse, along with a number of other of the dome buildings, were dismantled as part of the shutdown/removal of the South Pole Station dome [126].

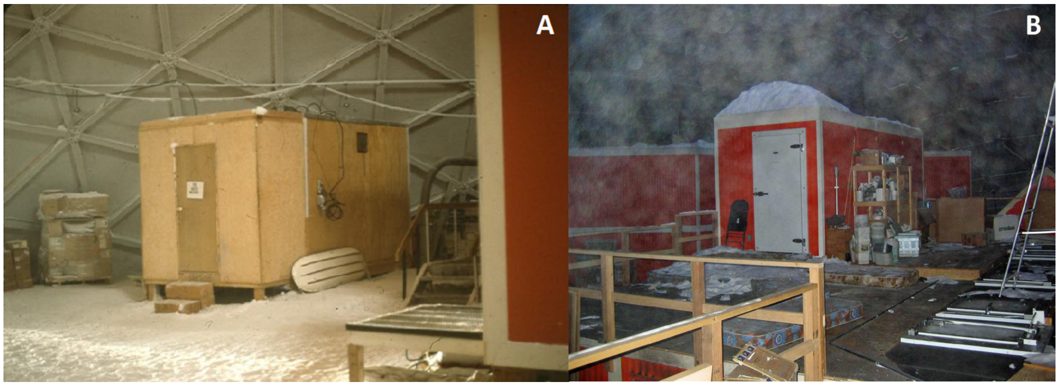

Figure 27. (A) Original greenhouse under the South Pole dome (1990-1994) (Image credit: Phil Sadler). (B) New greenhouse located on roof of Annex under the dome (1994/1995 to 2005) (Image credit: Bill Spindler).

One of the best documented and well-known Antarctic plant growth chambers is the South Pole Food Growth Chamber (SPFGC). The facility, shown in Figure 28, was developed under funding from the National Science Foundation by the University of Arizona in cooperation with Sadler Machine Company (Tempe, Arizona). In 2001 the contract was provided to design, construct, test and support the operation of the SPFGC, which was planned for installation within the new elevated South Pole Station [123]. Unlike many other Antarctic plant production facilities that are constructed for the first time on-site, the SPFGC was first assembled and extensively tested at the University of Arizona before shipment and reassembly at South Pole [123]. Installation and startup of the food chamber was undertaken by Raytheon Polar Services Company and operation of the facility commenced in 2004; it remains operational today. Since the facility has been active it has been used to grow a wide variety of crops including lettuce, cucumber, tomato, herbs, cantaloupe and pepper, among others [123]. Due to the high elevation of the Amundsen-Scott South Pole Station, the nominal atmospheric pressure is approximately 68 kPa with a typical station interior temperature of 16 °C and a relative humidity of approximately 10% [127].

Figure 28. The South Pole Food Growth Chamber plant production room in March 2013 (Image credit: Felipe Pedreros Bustos, National Science Foundation).

The SPFGC is based upon a cubical insulated refrigerator box that was equipped to contain a plant production room of 5.60 m x 3.91 m x 2.50 m (h) and a 2.35 m x 3.91 m x 2.50 m (h) environmental room [123]. Between the rooms is a glass wall (including door) that separates the two atmospheres. The environmental room is known to be a place where station crew members enjoy relaxing in their downtime [128, 129]. The facility includes a utility room, located adjacent to the other rooms, that contains the computer control systems, electrical hardware, pumps and various plant-nutrient feed components. Primary lighting of the plant production room is based upon glass jacketed

high pressure sodium lamps. The SPFGC incorporates soilless hydroponic systems using NFT and deep flow nutrient techniques [123]. Yields from the SPFGC have reached as high as 45 kg of fresh vegetables per week with typical yields of approximately 27 kg per week [127]. During 2006 operations, the average facility electrical power-draw during the 17 hour photoperiod was approximately 16 kW and 3 kW during the dark period [127]. The SPFGC, although maintained primarily by nominal on-site station personnel, can be monitored and control remotely via satellite link [127].

2. McMurdo Station

McMurdo Station is located on Ross Island near Scott Base in McMurdo Sound. Established in 1955, McMurdo is the largest station in the Antarctic with approximately 1000 summer and 250 overwintering personnel [43]. The same biological clock studies conducted at South Pole Station were also conducted at McMurdo during 1960-1961 [120]. The well-known McMurdo greenhouse was opened in 1989 [123]. The relatively large (approximately 50 m^2) hydroponics facility was initially constructed out of two military shipping containers that were to be burned [125]). The containers were connected, interior walls removed, and the exterior sheeted and painted [125]. The interior of the greenhouse was constructed using parts available on-site, including 6” PVC pipes that were originally to be used for the general station but deemed unusable and subsequently repurposed for the McMurdo greenhouse [125]. In 1994 the all-electrically illuminated ‘greenhouse’ facility was expanded: a glasshouse was built on its side using double-pane windows that were repurposed from another station building (Figure 29) [130]. The addition provided an area of approximately 16 m^2 that could take advantage of the continuous sunlight during the austral summers and, with the employment of fitted Styrofoam covers, growth continued in the entire facility under electrical light during the dark austral winters [123, 130]. A few years after its operation as a summer greenhouse, the glasshouse section was converted to an electrically illuminated growth chamber configuration using high pressure sodium and metal halide lamps [130, 131]. The McMurdo greenhouse used NFT hydroponics and included 11 independent hydroponic systems within the greenhouse [131]. Although a new McMurdo hydroponics facility will be considered in the development of the McMurdo Station long-range plan, the McMurdo greenhouse was closed at the end of the 2010-2011 season [37].

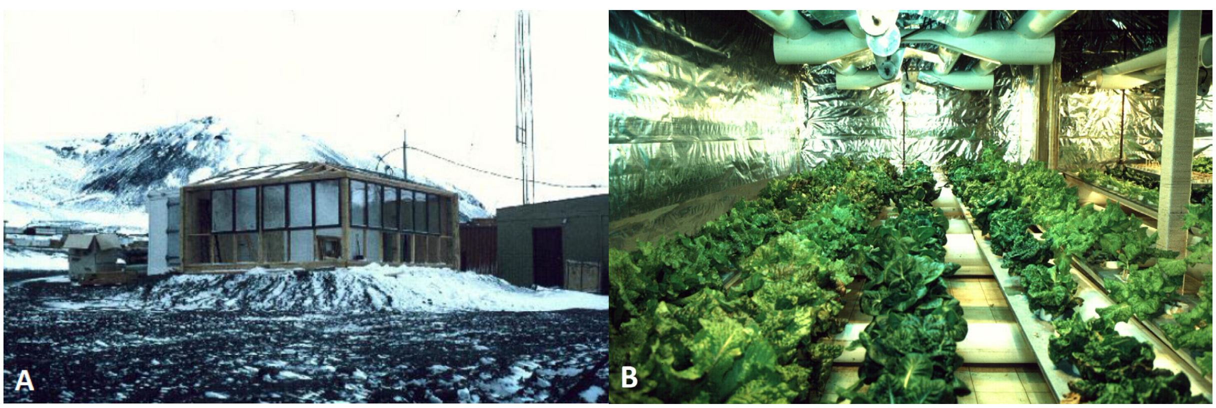

Figure 29. (A) McMurdo greenhouse showing the glasshouse expansion being added in 1994 (Image credit: Phil Sadler). (B) Internal view of the McMurdo greenhouse ca. 1990 (Image credit: Phil Sadler).

N. New Zealand and USA

1. Cape Hallett Station

Cape Hallett Station was a joint New Zealand - United States base completed in February 1957 [132]. The station was occupied year-round until 1964 when it converted to summer-only operations. The base was abandoned in 1973 but has been subsequently visited for cleanup and remediation activities. It has been reported that a vegetable garden was installed within the station’s radar weather-balloon tracking dome (Figure 30) [133]. This purely expeditioner-driven hobby garden was first described in 1958 [132, 133]. It grew plants in soil that was transported from the USA to Antarctica [132]. The facility produced radishes that were served to the station crew for Christmas dinner in 1958 [132].

Figure 30. Cape Hallett Station in 1961-1962 showing the elevated radar weather-balloon tracking dome that was reportedly used for plant growth as early as 1958 (Image credit: John Cranfield ©Antarctica New Zealand Pictorial Collection [ANZSC0163.2][1961-1962]).

O. Non-Governmental

1. Greenpeace – World Park Base

The international environmental organization Greenpeace constructed the year-round World Park Base on Ross Island, which opened in the austral summer of 1986/1987 to serve primarily as a platform for environmental monitoring in the Antarctic. The base was designed to permit the overwintering of four crew members and operated for five years [134]. A hydroponic plant growth system was set up in the 1988/1989 austral summer and operated until the station closed in 1991/1992 [134, 135]. The hydroponics system was installed in the station's main common room to one side of the dining/kitchen area [135]. As illustrated in Figure 31, the system was built around eight 1.5 m long, 4" pipes held in place by two wood-frame ladder support structures. The pipes were angled slightly to permit the flow of the nutrient solution downward through the system [135].

Figure 31. (A) World Park Base hydroponics system showing its full height in comparison to a crew member (Image credit: Keith Swenson). (B) Close-up of several system grow pipes with installed plant pots at approximately 6" spacing (Image credit: Keith Swenson).

A reservoir containing between 30-40 L of nutrient solution was installed at the base of the system. A pump circulated the solution from the reservoir through the topmost pipes from where it flowed down and through the lower pipes. Plants were installed within small vermiculite-containing plant pots fitted within pre-drilled holes at approximately 6” intervals [135]. Light was provided by fluorescent lights installed above each row of 4” pipes. Lights were operated for approximately 20 hours a day. Seeds were started in a plant flat filled with soil [135]. Sprouts/seedlings were subsequently transferred to the small plant pots which were installed within the main system grow pipes. The starter soil was kept in a sealed container, and like the vermiculite and all other hydroponic system hardware, was removed to New Zealand when the World Park Base station was dismantled [135]. The system was mainly used to grow leafy vegetables, including a variety of lettuce, kale and spinach (small plum tomatoes were also grown at various periods) and provided each of the four station personnel a small salad every few days [135]. Station crew members reported that trickling water and the sight of a leafy green wall created a soothing ambience [135].

III. Previously Planned or Currently Planned Facilities

Table 1 also presents Antarctic plant growth systems that were planned but never built, or are currently planned to be implemented at some point in the future. More details on these facilities are provided in the sections to follow.

A. Australia – Davis Station

Planning is underway for a new Davis Station hydroponics system to replace the larger system that was shut down in 2014 [30]. The new facility will be constructed using 2 x 20 ft and 2 x 10 ft containers to form a building with external dimensions of approximately 30 ft by 16 ft. The facility is planned for deployment in 2015/2016. The containers will be cut and modified (i.e., removal of walls, cladding) prior to shipment and assembled on-site in Antarctica [30].

B. Brazil – Comandante Ferraz Station

Brazil’s only permanent Antarctic station, Comandante Ferraz Station, was almost completely destroyed during a fire in 2012 [136]. Plans continue for the construction of a new, highly advanced station. One of the proposed design implementations (although not selected) included a hydroponic growth system within the primary structure of the station [137].

C. France-Italy – Concordia Station

The joint French-Italian operated Concordia Station, located inland at Dome C on the Antarctic Plateau, was opened 2005. Although the facility has often been proposed as a test-bed for advanced life support technologies [138], there is no documentation of it including a greenhouse/growth chamber. That said, following the initial success and development of the PULSA facility at the Italian Mario Zucchelli Station, there were discussions in the mid-to-late 1990s related to the setting up of such a facility at Concordia Station [72]. Design discussions explored the concept of installing a greenhouse on top of one of the two cylindrical modules [139]; however, this facility was never built.

D. Germany – Neumayer Station III

Planning is currently underway for the development and deployment of a shipping container-based growth chamber to the German Neumayer Station III. The greenhouse will include two 20 ft adjoined containers installed upon an elevated platform situated some distance away from the main station [10]. The facility will be composed of a section devoted to testing International Space Station form-factor plant growth systems, a larger-scale high density plant production system, as well as a devoted service section. In addition to providing Neumayer III crew members with fresh produce year-round, the system will help advance the technology readiness of a number of controlled environment agriculture technologies and their associated operational protocols for use on-orbit or in future space-based plant production systems. In this sense, the station and the plant production system are Moon and Mars operational analogues. The facility, being developed under a European Union funded project named EDEN ISS, is planned for deployment to the Antarctic at the end of 2017.

E. United Kingdom – Halley VI Research Station

The new Halley VI Station includes eight transportable modules sitting on skied stilts. The station became operational in 2012. A large design competition was initiated for the new Halley VI Station in 2004 and the winning design from Faber Maunsell and Hugh Broughton Architects was selected in 2005 [140]. These designs included the

incorporation of an 11 m^2 hydroponics plant growth unit within the atrium of the station's main module (Figure 32) [140-142]. Unfortunately, the construction of the hydroponics facility was eventually terminated based on cost-benefit grounds [143].

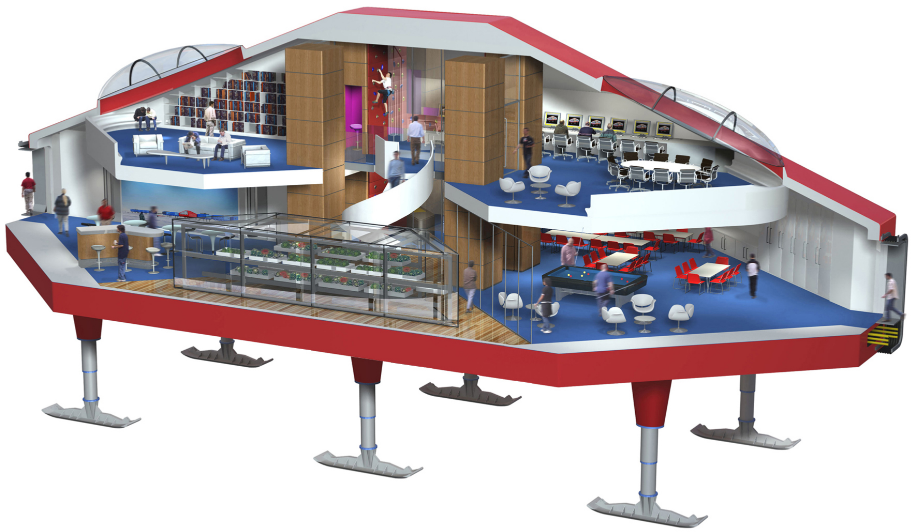

Figure 32. Computer model of the central module of the Halley VI Research Station illustrating its originally proposed trapezoid-shaped hydroponics unit in the main floor space of the atrium (Image credit: Hugh Broughton Architects/7-t Limited).

F. USA – Amundsen-Scott South Pole Station

During the same time that the SPFGC was being designed, another plant production facility for the South Pole was under study. The CELSS (Controlled Ecological Life Support System) Antarctic Analog Program (CAAP) was a project based out of NASA Ames Research Center and included a crop production system as part of a larger advanced life support test-bed design planned for deployment into the Amundsen-Scott South Pole Station. This test-bed also included integrated aquaculture and waste treatment facilities [144-147]. The project had a phased approach but the final hydroponics system, optimized for food production, was to be sized to provide 100% of the vegetable requirements for a 35-person overwintering crew [144, 145]. Because the SPFGC was eventually selected by the National Science Foundation for installation within the station during the South Pole rebuild, CAAP plant production hardware was not implemented at the station.

G. Future Antarctic Plant Production System Outlook

With the implementation of the Antarctic Treaty and the associated Madrid Protocol, the days of utilizing non-native soils, penguin guano and the general construction of expeditioner-driven/makeshift Antarctic plant production systems has come to a close [40]. Unlike past stories such as the McMurdo greenhouse designer being gifted a sum of only $75.00 USD for the development of the initial McMurdo greenhouse [130], new systems such as those recently implemented and operating at Antarctic stations operated by Australia, China, Japan, New Zealand, South Korea, United States as well as those planned for development in the coming years will be based upon a high level of controlled environment agriculture technology, extensive standard operating procedures, and monitoring programs. Meeting the Madrid Protocol's environmental protection requirements, although necessary and invaluable, has driven up the cost of deployment.

The Madrid Protocol is in many ways an operational analogue to current planetary protection regulations being developed for planetary exploration. The protocol, combined with the challenges imposed by the remoteness, harsh environment, and typical overwintering crew systems in place at Antarctic stations, further enhance Antarctica's utility as a test-bed for technologies applicable to future space-based missions [138, 148, 149]. The Antarctic serves as a highly useful test-bed for life support technologies and specifically bioregenerative life support systems. It can be argued that the unique analogue system provided by Antarctica is underutilized for space exploration activities. As the international community makes strides towards long-term habitation of the Moon and Mars, it is hoped that this will improve.

IV. Conclusion

It is certain that this review has not captured all the plant production systems that have ever existed in Antarctica. However, at least 46 facilities have been implemented at one time or another, a remarkable total. This demonstrates a fundamental human need to have plants present when establishing a long-term or even permanent presence in harsh environments. The complexity of the Antarctic plant production systems has varied considerably, with many early systems being smaller and more expeditioner-driven in nature. Over time and as a direct result of more stringent environmental regulations, the construction and operation of plant production facilities has evolved considerably. Currently, operating facilities no longer import non-native soils nor utilize local soils. Rather, they are required to use hydroponic systems to limit the risk of accidental introduction of non-native species. Prior to the Madrid Protocol, plant production activities could be conducted at the sole discretion of an individual crew member. Post-Madrid Protocol operations now require considerable documentation, planning and training for station crews that support on-site plant production activities.

There are presently nine plant production systems operating in nine different Antarctic stations. These systems often employ some combination of (or all) advanced lighting technology, environmental and plant health monitoring sensors, and control and monitoring systems. They attempt to improve yield while reducing waste production per unit area by using stacked-growth systems. Although the Antarctic logistics chain will become more robust with time, it is more likely that local in-situ production of food at Antarctic stations will continue to expand, not just for the provision of fresh produce for dietary and menu diversity reasons, or even crew psychological well-being, but also to take advantage of the Antarctic as a unique long-term operational analogue and test-bed for technologies that will be used on future long duration spaceflight missions. There is a basic human need to be surrounded by other higher living organisms; for humans this translates to shepherding plants with us as we, as a species, explore new environments, whether it be in Antarctica, on board spacecraft, or on the surface of other planetary bodies in our solar system.

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additional Antarctic plant production facilities to communicate with the authors, so that this important historical information can be appropriately captured in the future.

References

[1]Scott, R. F., *The voyage of the 'Discovery' - Vol. 1*, Charles Scribner's Sons, New York, NY, 1905.

[2]Skelton, J., and Skelton, R., *The Antarctic journals of Reginald Skelton - 'Another little job for the Tinker'*, Reardon Publishing, Cheltenham, UK, 2012.

[3]New Zealand Antarctic Society. "Round up of United States activities," *Antarctic*, Vol. 3, No. 11, 1964, pp. 485-487.

[4]Savours, A., *The voyages of the Discovery: The illustrated history of Scott's ship*, Seaforth Publishing, Barnsley, UK, 2013.

[5]Bernacchi, L., "The South Polar Times." 1903.

[6]New Zealand Antarctic Society. "New Zealand season - Ellsworth Mountains to Horlicks," *Antarctic*, Vol. 9, No. 1, 1980, pp. 2-6.

[7]Siple, P., *90 degrees south: The story of the American South Pole conquest*, G.P. Putnam's Sons, New York, NY, 1959.

[8]Antarctic Treaty. "Antarctic Treaty," Washington, D.C., 1959.

[9]Antarctic Treaty. "The protocol on environmental protection of the Antarctic Treaty," Madrid, Spain, 1991.

[10]Bamsey, M. T., Zabel, P., Zeidler, C., Poulet, L., Schubert, D., Kohlberg, E., and Graham, T., "Design of a containerized greenhouse module for deployment to the Neumayer III Antarctic station," ICES, ICES-2014-122, Tucson, AZ, 2014.

[11]United States Antarctic Projects Officer. "A day at the South Pole Station," *Bulletin of the U.S. Antarctic Projects Officer*, Vol. 2, No. 3, 1960, pp. 5-7.

[12]Pathak, R. C., and Gangadhara, R. S., "Some constructional, environmental control and plant growth aspects of green house at Indian Antarctic station 'Maitri'," *Scientific Report: Ninth Indian Expedition to Antarctica*. Vol. 6, Department of Ocean Development, 1994, pp. 299-311.

[13]Joshi, R. P., "Polar horticulture report of Tenth Antarctic Expedition," *Scientific Report: Tenth Indian Expedition to Antarctica*. Vol. 8, Department of Ocean Development, New Delhi, India, 1995, pp. 231-249.

[14]Australian Antarctic Division. "Initial environmental evaluation of the proposal to introduce hydroponic operations at Australian Antarctic stations," Amended 2/10/98 ed, Australian Antarctic Division, 1994.

[15]Haeuplik-Meusburger, S., Paterson, C., Schubert, D., and Zabel, P., "Greenhouses and their humanizing synergies," *Acta Astronautica*, Vol. 96, 2013, pp. 138-150.

[16]Korea Fruit Growers Association. "2012 modularization of Korea's development experience: White revolution of agriculture in Korea: The achievement of year-round production and distribution of horticultural crops by the expansion of greenhouse cultivation ", 11-7003625-000060-01, Ministry of Strategy and Finance, Republic of Korea, 2013.

[17]Rejcek, P., "Year-round access - USAP prepares to test plan for regularly scheduled winter flights to McMurdo," *The Antarctic Sun*, National Science Foundation, Oct 31, 2014.

[18]Bates, S., Gushin, V., Bingham, G., Vinokhodova, A., Marquit, J., and Sychev, V., "Plants as countermeasures: A review of the literature and application to habitation systems for humans living in isolated or extreme environments," *Habitation*, Vol. 12, 2010, pp. 33-40.

[19]U.S. Antarctic Program Blue Ribbon Panel. "More and better science in Antarctica through increased logistical effectiveness – Report of the U.S. Antarctic Program Blue Ribbon Panel," Washington, D.C., 2012.

[20]Bhatia, S., "Report on R&DE(E) tasks during Tenth Antarctic Expedition," *Scientific Report: Tenth Indian Expedition to Antarctica*. Vol. 8, Department of Ocean Development, 1995, pp. 293-297.

[21]Hill, J., "An experiment in growing salad vegetables at an Antarctic station," *British Antarctic Survey Bulletin*, Vol. 13, 1967, pp. 47-69.

[22]Chinese Arctic and Antarctic Administration. *Personal Communication*, Great Wall Station plant production, 2014.

[23]National Centre for Antarctic and Ocean Research - India. *Personal Communication*, Indian Antarctic hydroponic activities, 2015.

[24]Norwegian Polar Institute. *Personal Communication*, Norwegian Antarctic hydroponic activities, 2015.

[25]Polish Academy of Sciences. *Personal Communication*, Polish Antarctic hydroponic activities, 2015.

[26]Arctic and Antarctic Research Institute/Russian Antarctic Expedition. *Personal Communication*, Soviet/Russian station plant production facility history, 2015.

[27]Australian Antarctic Division. "New hydroponics facilities for Australia's Antarctic stations," *Australian Antarctic Magazine*. Vol. Spring 2001, Australian Antarctic Division, Kingston, Tasmania, Australia, 2001.

[28]Kaifler, B., *Personal Communication*, Davis hydroponics system description, 2015.

[29]Hanger, B., "Hydroponics in Antarctica," *Practical Hydroponics and Greenhouses*. Vol. 10 Casper Publications, Sydney, Australia, 1993.

[30]Australian Antarctic Division. *Personal Communication*, Australian station hydroponic history, 2015.

[31]Campiotti, C. A., Balducchi, R., Dondi, F., Alonzo, G., Catanese, V., Incrocci, L., and Bibbiani, C., "The PULSA (Plant-based Unit for Life Support in Antarctica): A sustainable plant food production technology for remote and isolated environments," *Acta Horticulturae*, Vol. 801, 2008, pp. 417-424.

[32]Leitch, J., *Personal Communication*, Scott Base hydroponics system description, 2015.

[33]Chwedorzewska, K. J., Gielwanowska, I., Olech, M., Molina-Montenegro, M. A., Wódkiewicz, M., and Galera, H., "*Poa annua* L. in the maritime Antarctic: an overview," *Polar Record*, 2014, pp. 1-7.

[34]Gillies, J., *Personal Communication*, Casey Station plant production - 1969, 2014.
[35]Hughes, K. A., Pertierra, L. R., Molina-Montenegro, M. A., and Convey, P., "Biological invasions in terrestrial Antarctica: What is the current status and how can we respond?," *Biodiversity and Conservation*, Vol. 24, No. 5, 2015, pp. 1031-1055.
[36]Parker, D., "A salad machine vegetable project, Davis 1969," *Aurora Journal*. ANARE Club, Melbourne, Australia, 1970, June, pp. 30-31.
[37]ATCM. "Use of hydroponics by national Antarctic programs," *Antarctic Treaty Consultative Meeting XXXVI*. IP 31, CEP 10c, Brussels, 2013.
[38]Australian Antarctic Division. "Australian Antarctic Division - Hydroponics Manual 2013-2016," Rev. 3, Kingston, Tasmania, Australia, 2013.
[39]Orchard, B., "Letters to the Editor: A cable addressed to the Editor from Mawson, 13.12.1989," *Aurora Journal*. ANARE Club, Melbourne, Australia, 1990, March.
[40]United States. "Report of the United States Antarctic inspection," United States Department of State, 2001.
[41]Mackenzie, R., "From Wilkes to Casey," *Australian Antarctic Magazine*. Australian Antarctic Division, Kingston, Tasmania, Australia, 2008, pp. 24-26.
[42]Bowden, T., "Founding Davis and Casey stations," *Australian Antarctic Magazine*. Australian Antarctic Division, Kingston, Tasmania, Australia, 2012, pp. 20-21.
[43]COMNAP. "Main Antarctic facilities operated by National Antarctic Programs in the Antarctic Treaty Area (South of 60° latitude South)," Feb 13, 2014 ed, Council of Managers of National Antarctic Programs, 2014.
[44]Deprez, P., "Hydroponics at Davis," *Aurora Journal*. ANARE Club, Melbourne, Australia, 1990, March.
[45]Sheehy, B., "Hydroponics report Davis 2013," Australian Antarctic Division, 2013.
[46]Bowden, T., "Founding Mawson: Australia's first Antarctic station," *Australian Antarctic Magazine*. Australian Antarctic Division, Kingston, Tasmania, Australia, 2012, pp. 16-19.
[47]New Zealand Antarctic Society. "Microlites and Copepods," *Antarctic*, Vol. 10, No. 7, 1984, p. 276.
[48]New Zealand Antarctic Society. "Microlites and Copepods," *Antarctic*, Vol. 10, No. 5, 1984, p. 172.
[49]Rocke, G., and Vinycomb, D., "Growing challenges in Antarctica," *Practical Hydroponics and Greenhouses*, Vol. 56, January/February, 2001.
[50]Rando, S., "Mawson Station heritage assessment," Australian Antarctic Division, Hobart, Australia, 1995.
[51]Commonwealth of Australia. "Mawson Station Heritage Management Plan 2014-2019," Department of the Environment, Canberra, Australia, 2014.
[52]República de Chile Comisión Nacional del Medio Ambiente Dirección Ejecutiva. "Calificación ambiental de la evaluación preliminar de impacto ambiental del proyecto estudios en ecofisiología vegetal en un laboratorio 'Módulo hidropónico experimental' en Base O`Higgins," Resolución Exenta Nº 240, Santiago, Chile, 2005.
[53]Tapia, M. L., Riquelme, A., and Mella, R., "First Chilean 'experimental hydroponics module' in the Antarctic: Stress ecophysiological research program of vascular domestic plants," *II Simposio Latinoamericano Sobre Investigaciones Antárticas y VI Reunión Chilena de Investigación Antártica*. INACH - La Prensa Austral Impresos, Concepción, Chile, 2006, pp. 313-317.
[54]Tapia, M. L., "Consolidado de observaciones al proyecto estudios en ecofisiología vegetal en un laboratorio 'módulo hidropónico experimental' en base Antártica O'Higgins," *Servicio de Evaluación Ambiental*, 2005.
[55]Tapia, M. L., "Evaluacion preliminar de impacto ambiental proyecto cientifico - Estudios en ecofisiología vegetal en un laboratorio 'Módulo Hidropónico Experimental' en Base Antártica O'Higgins," Ejército de Chile, Universidad de Chile, 2005, p. 7.
[56]El Mercurio. "Chilenos hacen soberanía en Villa Las Estrellas," [online document], http://www.emol.com/mundografico [cited Apr 22, 2015].
[57]Tongji University. "Initial environmental evaluation - Construction and operation of the new hydroponic food production system at Chinese Great Wall Station, Fildes Peninsula, Antarctica," Chinese Arctic and Antarctic Administration, 2014.
[58]Joshi, M. C., and Banerjee, B. K., "Prospects of horticulture in Antarctica," *Scientific Report: Fifth Indian Expedition to Antarctica*. Vol. 5, Department of Ocean Development, 1988, pp. 473-487.
[59]Dhaulakhandi, A. B., Joshi, R. P., and Joshi, M. C., "Growth and yield of fenugreek (*Trigonella foenum graecum* L.), spinach (*Spinacea oleracea* L.), coriander (*Coriandrum sativum* L.) and lettuce (*Lactuca sativa* L.) under continous daylight conditions in Antarctica," *Scientific Report: Tenth Indian Expedition to Antarctica*. Vol. 8, Department of Ocean Development, 1995, pp. 195-208.
[60]Nair, P. K., and Gupta, H. K., "Dakshin Gangotri: The Indian permanent station in Antarctica," *Scientific Report: Third Indian Expedition to Antarctica*. Vol. 3, Department of Ocean Development, 1986, pp. 15-18.
[61]Ravindra, R., "The Ninth Indian Scientific Expedition to Antarctica – Events & Achievements," *Scientific Report: Ninth Indian Expedition to Antarctica*. Vol. 6, Department of Ocean Development, 1994, pp. 1-20.
[62]Dhaulakhandi, A. B., Joshi, R. P., and Joshi, M. C., "Optimisation of greenhouse climate and PAR at Maitri," *Scientific Report: Tenth Indian Expedition to Antarctica*. Vol. 8, Department of Ocean Development, 1995, pp. 187-193.
[63]Norway. "Report of the Norwegien Antarctic inspection under Article VII of the Antarctic Treaty and Article 14 of the Protocol on Environmental Protection to the Antarctic Treaty," 2001.
[64]Japan. "Japanese inspection report 2010: Inspections under Article VII of the Antarctic Treaty and Article 14 of the Protocol on Environmental Protection," IP 4, ATCM 11, CEP 10, ATCM, 2010.

[65]United States and Russia. "U.S.-Russian report of inspections under Article VII of the Antarctic Treaty and Article 14 of the Protocol on Environmental Protection," United States Department of State, 2012.
[66]Germany and South Africa. "German-South African report of inspections under Article VII of the Antarctic Treaty and Article 14 of the Protocol on Environmental Protection," 2013.
[67]Defence Research and Development Organisation. "Dome shelter," *Technology Focus - Bulletin of Defence Research and Development Organisation*, Vol. 5, No. 5, 1997, p. 10.
[68]Sharma, S. S., *Breaking the ice in Antarctica: The first Indian wintering in Antarctica*, New Age International Publishers, New Delhi, India, 2001.
[69]United States. "Report of the United States observer team in Antarctica - Report of inspections under Article VII of the Antarctic Treaty," United States Department of State, 1983.
[70]Alfred Wegener Institute. *Personal Communication*, H. Gernandt: Georg Forster Station and Novolazarevskaya Station greenhouse history, 2015.
[71]Campiotti, C., Balducchi, R., Incrocci, L., Pardossi, A., Popovski, K., and Popovska, V., "Hydroponics technology as a tool for plant fresh food support in Antarctica," *Acta Horticulturae*, Vol. 554, 2001, pp. 279-284.
[72]Campiotti, C. A., Balducchi, R., Taggi, R., and Tognoni, F., "The hydroponic greenhouse module for plant fresh food produce in Antarctica," *VIII Symposium on Antarctic Logistics and Operations*. Council of Managers of National Antarctic Programs. Standing Committee on Antarctic Logistics and Operations, Concepción, Chile, 1998, pp. 71-81.
[73]Campiotti, C., Dondi, F., Scoccianti, M., Di Carlo, F., Bibbiani, C., Alonzo, G., and Incrocci, L., "Technology for plant food support in Antarctica," *Acta Horticulturae*, Vol. 893, 2011, pp. 453-460.
[74]Campiotti, C. A., Di Bonito, R., Papalia, B., Alonzo, G., Incrocci, L., Piccolo, F., and Bornisacci, V., "Integration of Antarctica hydroponics as option for food plant life support in space," Moon Base Workshop, Moscow, Russia, 2006.
[75]Campiotti, C., Alonzo, G., Belmonte, A., Bibbiani, C., Carlo, F. D., Dondi, F., and Scoccianti, M., "Renewable energy and innovation for sustainable greenhouse districts," *Analele Universităţii din Oradea Fascicula de Energetică*, Vol. 15, No. 2, 2009, pp. 196-201.
[76]Shinagawa, J., Imajo, M., and Hanada, T., "PLANTLUX, Newly designed fluorescent lamp for plant growth," *Toshiba Review*, Jan-Mar, 1967. pp. 5-10.
[77]Geographical Survey Institute. "50 years of Antarctic research expeditions by the Geographical Survey Institute Planning Department, Geodetic Department, and Topographic Department," *Bulletin of the Geographical Survey Institute*, Vol. 54, 2007, pp. 1-24.
[78]Matsuda, T., Hoshiai, T., Kikuchi, C., Shiraishi, H., "The electrical lighting vegetable cultivation at Syowa Station, Antarctica," *Journal of the Illuminating Engineering Institute of Japan*, Vol. 53, No. 241, 1969, pp. 1-2.
[79]Government of Japan. "Expanding 'vegetable factories' to meet the world's food needs," *Highlighting Japan*, Vol. 24, No. July 2009, 2009, pp. 25-27.
[80]National Institute of Polar Research Japan. *Personal Communication*, Current plant culture chamber at a Japanese Antarctic Station, Syowa operated by the Japanese Antarctic Research Expeditions (JAREs), 2015.
[81]National Institute of Polar Research Japan. "Vegetable cultivation - April 18, 2010," *Where is the field research team - Showa base now?* ; [online document], http://www.nipr.ac.jp/jare-backnumber/now/back51/20100418.html [cited Jan 25, 2015].
[82]Choul-woong, Y. "Agricultural technology with IT convergence," [online document], URL: http://koreaittimes.com/story/9974/agricultural-technology-it-convergence [cited Feb 13, 2014].
[83]PARU. "Plant Factory - PARU Plant Factory Information." Suncheon, South Korea, 2011.
[84]Um, Y. C., Oh, S. S., Lee, J. G., Kim, S. Y., and Jang, Y. A., "The development of container-type plant factory and growth of leafy vegetables as affected by different light sources," *Journal of Bio-Environment Control*, Vol. 19, No. 4, 2010, pp. 333-342.
[85]United Kingdom, Netherlands, and Spain. "Antarctic Treaty Inspections Programme Report 2012. Report of Antarctic Treaty inspections undertaken jointly by the United Kingdom, the Netherlands and Spain in accordance with Article VII of the Antarctic Treaty and Article 14 of the Environmental Protocol," United Kingdom, 2013.
[86]Korea Polar Research Institute, and Korea Environment Institute. "Final comprehensive environmental evaluation: Construction and operation of the Jang Bogo Antarctic Research Station, Terra Nova Bay, Antarctica," 2012.
[87]Korea Polar Research Institute. *Personal Communication*, King Sejong Station and Jang Bogo Station plant production facility description, 2014.
[88]New Zealand Antarctic Society. "Antarctic miscellany," *Antarctic*, Vol. 1, No. 6, 1957, p. 150.
[89]New Zealand Antarctic Society. "The Trans-Antarctic Expedition - New Zealand's part," *Antarctic News Bulletin*, Vol. 19, 1955, p. 6.
[90]Antarctica New Zealand. "Antarctica New Zealand - ADAM," [online document], http://antarctica.recollect.co.nz/ [cited Apr 2, 2015].
[91]New Zealand Antarctic Society. "Successful airdrop breaks winter routine for 11 New Zealanders," *Antarctic*, Vol. 13, No. 6, 1994, pp. 226-229.
[92]Jack, G., "Hydroponic food production at Scott Base," *Graduate Certificate in Antarctic Studies*, University of Canterbury, Christchurch, New Zealand, 2007.
[93]Antarctica New Zealand. "Annual Report 2002 - 2003," New Zealand Government, 2003.
[94]Antarctica New Zealand. "Development, management and execution of the New Zealand Antarctic Programme 2008/09 - Initial Environmental Evaluation," 2008.
[95]Antarctica New Zealand. *Personal Communication*, Scott Base hydroponic system history, 2015.

[96]Poirot, C., "Scott Base Winter Hydroponics - Standard Operating Procedure," Version: 1.6, SOP Code: BS-004, Antarctic New Zealand, 2012.
[97]Committee for Environmental Protection. "Management plan for Antarctic specially protected area No. 131 – Canada Glacier, Lake Fryxell, Taylor Valley, Victoria Land," Measure 1 – Annex C, 2006.
[98]New Zealand Antarctic Society. "University projects in McMurdo Sound," *Antarctic*, Vol. 9, No. 3, 1980, pp. 82-85.
[99]Rakusa-Suszczewski, S., and Krzyszowska, A., "Assessment of the environmental impact of the 'H. Arctowski' Polish Antarctic Station (Admiralty Bay, King George Island, South Shetland Islands)," *Polish Polar Research*, Vol. 12, No. 1, 1991, pp. 105-121.
[100]United Kingdom, Italy, and Korea. "Report of a joint inspection under Article VII of the Antarctic Treaty by United Kingdom, Italian and Korean Observers. January - February 1993," 1993.
[101]Greenpeace International. "Greenpeace 1992/93 Antarctic Expedition Report," Greenpeace International, Amsterdam, The Netherlands, 1994.
[102]Majewski, R., "27th Polish Antarctic Expedition to Arctowski Station (King George Island, Antarctica), 2002/2003," *Polish Polar Research*, Vol. 25, No. 1, 2004, pp. 97-102.
[103]Swołek, W., "Rzut Budynku Szklarni Laboratorium - Polska Stacja Antarktyczna - Rysunek." Zakład Biologii Antarktyki - Warszawa, Warsaw, Poland, 2005.
[104]Rubin, M., "The Mirny Diary - 12 Feb.1958 - 7 Feb.1959," The Antarctican Society, 1959.
[105]Spindler, B. "How we got there...via McMurdo... (South Pole Station)," [online document], http://www.southpolestation.com/pole/howwegotthere2.html [cited Feb 10, 2014].
[106]New Zealand Antarctic Society. "Navy Hercules flights to Soviet stations," *Antarctic*, Vol. 8, No. 1, 1977, pp. 20-22.
[107]Vane, G., "Soviet Antarctic research, 1972-1973," *Antarctic Journal of the United States*, Vol. 8, No. 6, 1973, pp. 325-331.
[108]Antarctic Treaty Secretariat. "Visitor site guide - Stonington Island," 2014.
[109]Bingham, E. W., "A greenhouse in the Antarctic," *Polar Record*, Vol. 6, No. 43, 1952, pp. 392-393.
[110]Morrison, M., "Station F Wordie House Winter Island - Heritage survey report," UKAHT, BAS and FCO, 2008.
[111]British Antarctic Survey. "British research stations and refuges - History," [online document], http://www.antarctica.ac.uk/about_bas/our_history/stations_and_refuges/index.php [cited May 19, 2015].
[112]Unpublished Report - Burns, P., "Appendix to building report - Greenhouse," British Antarctic Survey Archives Service reference AD6/2F/1968/C1, 1968.
[113]Unpublished Report. British Antarctic Survey Archives Service reference AD6/2F/1969/C, 1969.
[114]British Antarctic Survey. "Extract from oral history interview with Allan Wearden, cook at Base F, Galindez Island, 1969-70," *British Antarctic Oral History Project*. Archives ref: AD6/24/1/168/3, 1972.
[115]Unpublished building and base commanders reports. British Antarctic Survey Archives Service reference AD6/2G series.
[116]Unpublished building report. British Antarctic Survey Archives Service reference AD6/2G/1954/C, 1955.
[117]Unpublished Report. British Antarctic Survey Archives Service reference AD6/2H/1958/A, 1958.
[118]Unpublished Report. British Antarctic Survey Archives Service reference AD6/2H/1963/A, 1963.
[119]Ward, P. "Cool Antarctica - Signy gallery - Base H," [online document], http://www.coolantarctica.com/Bases/Signy/thumbs1.htm [cited May 20, 2015].
[120]United States Antarctic Projects Officer. "UCLA team studies 'biological clocks'," *Bulletin of the U.S. Antarctic Projects Officer*, Vol. 2, No. 9, 1961, pp. 1-2.
[121]United States Antarctic Projects Officer. "Brief notes of interest from U.S. Antarctic stations," *Bulletin of the U.S. Antarctic Projects Officer*, Vol. 5, No. 3, 1963, p. 7.
[122]Spindler, B. "South Pole History and Trivia Files - Pole: The 90's," [online document], http://www.southpolestation.com/trivia/90s/pole90s.html [cited Feb 5, 2014].
[123]Patterson, R. L., "Description, operation and production of the South Pole Food Growth Chamber (SPFGC)," *Department of Agricultural and Biosystems Engineering*. Masters of Science, University of Arizona, Tucson, AZ, 2011.
[124]National Science Foundation. "Environmental Action Memorandum (Hydroponics project at Amundsen-Scott South Pole Station)," File: opp93065, National Science Foundation, 1992.
[125]Sadler, P., "The history of the US Antarctic greenhouse project (1988-2004)," 2006.
[126]Spindler, B. "Winter Photos - Annex Redux," [online document], http://www.southpolestation.com/0607/06wphotos1a.html [cited Feb 10, 2014].
[127]Giacomelli, G. A., Patterson, R. L., and Sadler, P. D., "Telepresence technologies and practises for enabling remote semi-autonomous CEA food production," *Acta Horticulturae*, Vol. 761, 2007, pp. 21-31.
[128]Patterson, R., Giacomelli, G., and Sadler, P., "Resource and production model for the South Pole Food Growth Chamber," ICES, 2008-01-2011, 2008.
[129]MacGregor, S., "Cropping up - MacGregor returns to the Ice to work in the South Pole growth chamber," *The Antarctic Sun*, National Science Foundation, May 20, 2011.
[130]Sadler, P., *Personal Communication*, McMurdo and South Pole Station plant production facility history, 2015.
[131]Nelkin, J., "Supporting science in Antarctica with fresh produce," *University of Arizona Lecture*. Controlled Environment Agriculture Center, University of Arizona, 2006.
[132]United States Antarctic Projects Officer. "Hallett Station - From idea through the IGY," *Bulletin of the U.S. Antarctic Projects Officer*, Vol. 6, No. 5, 1965, pp. 21-31.
[133]New Zealand Antarctic Society. "U.S. and N.Z. co-operation at Hallett Station," *Antarctic*, Vol. 1, No. 2, 1958, pp. 283-284.

[134]Greenpeace International. "Greenpeace World Park Base - Antarctica 1987 - 1992. Treading lightly: A minimal impact Antarctic station ", Greenpeace International, Amsterdam, The Netherlands, 1994.
[135]Swenson, K., *Personal Communication*, World Park Base hydroponic system, 2015.
[136]Interministerial Commission for Sea Resources. "Brazilian Antarctic Program - PROANTAR," [online document], https://www.mar.mil.br/secirm/proantar-i.html [cited Jan 15, 2015].
[137]Ferraro Choi and Associates Ltd. "Case studies: Comandante Ferraz Antarctic Station," [online document], http://www.ferrarochoi.com/casestudies/Ferraz-Antarctic-Station/index_Ferraz-Antarctic-Station-CaseStudy.html [cited Feb 3, 2014].
[138]Lasseur, C., Angerer, O., Schmitt, D., Rebeyre, P., Amblard, P., Lasserre, J. C., Demey, D., Doulami, F., and Michel, N., "Life test validation of life support hardware in Concordia Antarctic base," ICES, 2004-01-2352, Colorado, CO, 2004.
[139]Campiotti, C. A., *Personal Communication*, Possible plant growth system at Concordia Station, 2015.
[140]British Antarctic Survey. "Proposed construction and operation of Halley VI Research Station, and demolition and removal of Halley V Research Station, Brunt Ice Shelf, Antarctica - Final Comprehensive Environmental Evaluation," 2007.
[141]Broughton, H. G. K., "Antarctic research stations: Parallels for interplanetary design," ICES, AIAA 2010-6106, 2010.
[142]New Zealand Antarctic Society. "Halley Station designs," *Antarctic*, Vol. 23, No. 2, 2005, pp. 22-23.
[143]British Antarctic Survey. *Personal Communication*, Status of Halley VI plant growth activities, 2014.
[144]Flynn, M. T., Bubenheim, D. L., Straight, C. L., and Belisle, W., "The Controlled Ecological Life Support System Antarctic Analog Project: Analysis of wastewater from the South Pole Station, Antarctica - Volume 1," NASA-TM-108836, NASA Ames Research Center, 1994.
[145]Flynn, M. T., Bubenheim, D., and Straight, C., "Development of an advanced life support testbed at the Amundsen-Scott South Pole Station," ICES, 941610, 1994.
[146]Bubenheim, D. L., and Flynn, M. T., "The CELSS Antarctic Analog Project and validation of assumptions and solutions regarding regenerative life support technologies," ICES, 961589, 1996.
[147]Bubenheim, D. L., Schlick, G., Wilson, D., and Bates, M., "Performance of the CELSS Antarctic Analog Project (CAAP) crop production system," *Advances in Space Research*, Vol. 31, No. 1, 2003, pp. 255-262.
[148]Anderson, D. T., McKay, C. P., Wharton, R. A., and Rummel, J. D., "An Antarctic research outpost as a model for planetary exploration," *Journal of the British Interplanetary Society*, Vol. 43, 1990, pp. 499-501.
[149]Anderson, D. T., McKay, C. P., Wharton, R. A., and Rummel, J. D., "Testing a Mars science outpost in the Antarctic Dry Valleys," *Advances in Space Research*, Vol. 12, No. 5, 1992, pp. 205-209.