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Can the optimisation of pop-up agriculture in remote communities help feed the world?

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1 **Can the optimisation of pop-up agriculture in remote communities help feed the**
2 **world?**

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24 **Highlights:**

- 25 • Crops can potentially be grown in extreme and remote locations, including polar bases
26 and possibly even space stations.
- 27 • Indoor soil-less crop production systems developed must adopt near zero waste
28 principles.
- 29 • This efficiency culture can help deliver crop production systems that can respond to
30 future food security threats.
- 31 • Time to 'cross pollinate' high technology soil-less approaches with emergent pop up
32 agriculture in developing countries.

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45 **Abstract**

46 Threats to global food security have generated the need for novel food production
47 techniques to feed an ever-expanding population with ever-declining land resources.
48 Hydroponic cultivation has been long recognised as a reliable, resilient and resource-use-
49 efficient alternative to soil-based agricultural practices. The aspiration for highly efficient
50 systems and even city-based vertical farms is starting to become realised using
51 innovations such as aeroponics and LED lighting technology. However, the ultimate
52 challenge for any crop production system is to be able to operate and help sustain human
53 life in remote and extreme locations, including the polar regions on Earth, and in space.
54 Here we explore past research and crop growth in such remote areas, and the scope to
55 improve on the systems used in these areas to date. We introduce biointensive agricultural
56 systems and 3D growing environments, intercropping in hydroponics and the production of
57 multiple crops from single growth systems. To reflect the flexibility and adaptability of these
58 approaches to different environments we have called this type of enclosed system 'pop-up
59 agriculture'. The vision here is built on sustainability, maximising yield from the smallest
60 growing footprint, adopting the principles of a circular economy, using local resources and
61 eliminating waste. We explore plant companions in intercropping systems to supply a
62 diversity of plant foods. We argue that it is time to consume all edible components of plants
63 grown, highlighting that nutritious plant parts are often wasted that could provide vitamins
64 and antioxidants. Supporting human life via crop production in remote and isolated
65 communities necessitates new levels of efficiency, eliminating waste, minimising
66 environmental impacts and trying to wean away from our dependence on fossil fuels. This
67 aligns well with tandem research emerging from economically developing countries where
68 lower technology hydroponic approaches are being trialled reinforcing the need for 'cross-
69 pollination' of ideas and research development on pop-up agriculture that will see benefits
70 across a range of environments.

72 **1. Introduction**

73 An expanding global population is the root cause of fundamental environmental
74 challenges faced today. Global population estimates predict a 35% increase from 7.3
75 billion to 11.2 billion by 2100 (UNDESA, 2014). With increases in population come
76 amplified anthropogenic pressures on the environment (Harte, 2007), increased pollution
77 (Cole and Neumayer, 2004) and reduced per capita land and resource availability (Sheikh,
78 2006; Vörösmarty et al., 2000). The cumulative impact of these issues is likely to
79 negatively affect the sustainability of global resources and in turn the longevity of the
80 human population.

81 By 2050 it is estimated that 66% of the global population will live in urban regions
82 (UNDESA, 2014). In the UK, the Office for National Statistics documented an 8.1%
83 increase in urban populations between 2001 and 2011 (Gower et al., 2013). Urbanisation
84 in western societies further decreases available land as a result of developmental pressure
85 from cities into surrounding agricultural areas (Despommier, 2010).

86 Anthropogenic climate change compounds the above issues as many tropical and
87 sub-tropical countries, more vulnerable to the impacts of global warming, may see
88 reductions in viable arable land due to the consequences of desertification and sea level
89 rise (Le Houérou, 1996; Rosenzweig et al., 1994; Zhang and Cai, 2011). It is therefore
90 pertinent that innovative and efficient food production techniques are implemented at a
91 significant scale in order to mitigate the disparity between population growth and food
92 production.

93 **2. Closed Environment Agriculture**

94 Whilst efforts are being made globally to mitigate climate change, thus reducing the rate of
95 arable land loss, additional research has been undertaken to actively increase the amount
96 of available space for crop production. This novel thinking has led to the creation of Closed
97 Environment Agriculture (CEA), a term which encompasses a broad range of methods for

98 the production of food within an enclosed environment (Jensen, 2001). The use of closed
99 environments allows for control of many factors in the aerial environment, the root zone,
100 and in irradiation (Rorabaugh et al., 2002). This can optimise plant growth and resource
101 use efficiency whilst also enabling food production in previously unsuitable or
102 unpredictable locations. Comprehensive control of the growing environment also allows for
103 off-season production, eradicating seasonal time restrictions and generating multiple crops
104 per year (Sabir and Singh, 2013). This technology may also provide an alternative
105 agricultural output for areas affected by climate change, industrialisation and urbanisation,
106 and may also reduce reliance on seasonal agricultural labour.

107 Soil-less culture is enveloped within the umbrella term of CEA, and consists of
108 aeroponic, aquaponic and hydroponic technologies. The latter pertains to a system of
109 horticulture by which water is used as the primary growth medium, supplied with controlled
110 concentrations of nutrient solution (Jensen and Collins, 1985). Hydroponics is not a novel
111 technology, however, consistent and ongoing research is increasingly revealing the full
112 potential of its applications. More specifically, hydroponics has been identified as a
113 technology for the future as a tool for long-duration space travel (MacElroy et al., 1987;
114 Smith et al., 2005) and disaster relief, as well as aiding climate change mitigation efforts
115 (Despommier, 2013).

116 Hydroponic techniques vary in design, though the general principles remain similar.
117 As an alternative to soil, plants are cultivated in a water-based solution containing the
118 nutrients essential for plant growth. Aggregate systems replace the traditional medium of
119 soil, with an inert substrate used for structural support and its water retentive properties
120 (e.g. coconut coir, Rockwool, vermiculite, sand, gravel) (Jensen, 1997). Alternatively, liquid
121 (non-aggregate) systems have no supportive growing medium and roots are directly
122 exposed to the nutrient solution (Marr, 1994).

123 The most commonly employed hydroponic techniques include Deep Flow Techniques
124 (DFT) and Nutrient Film Technique (NFT). Within DFT systems, crops are grown within
125 raft-like structures on the surface of aerated nutrient solution, allowing for complete
126 submersion of the root zone (Rodríguez-Delfín, 2011). The benefit of this approach is the
127 simplicity of the design and therefore relative ease of implementation. DFT is an 'open
128 system' of hydroponics where nutrient solutions are actively replaced at regular intervals.
129 In contrast, NFT is referred to as a 'closed system' due to the automatic filtration and
130 recirculation of nutrient solutions (Rodríguez-Delfín, 2011). Here we extend the concept of
131 CEA and soil-less culture systems to develop the concept of pop-up agriculture. Such
132 agriculture is flexible in that crops can be grown in relatively small areas as determined by
133 particular environmental limitations such as polar research stations, space capsules,
134 remote offshore platforms or even school canteens, but the approach is not limited to small
135 area agriculture. Pop-up agriculture embodies the aspiration to maximise the potential
136 advantages of a more controlled environment to produce a more efficient circular system in
137 which waste is limited and/or re-used where possible and crops are grown and utilised to
138 achieve maximal nutrient output for minimal resource input.

139 **3. History of hydroponics**

140 Originally, hydroponic techniques were developed for use within botanical research,
141 though not initially known by this name. William F. Gericke coined the term "hydroponics"
142 in the 20th Century after successful cultivation of tomatoes within a simple system
143 comprised of buckets filled with nutrient solution (Gericke, 1937). This innovation inspired
144 the idea that food production via hydroponics was viable on a larger scale. The
145 development of computerised systems during the 1980s allowed for the ultimate control of
146 the enclosed environment, thus leading to the realisation of hydroponics as a commercially
147 viable food production technique (Sardare and Admane, 2013; Sengupta and Banerjee,
148 2012).

149 Today, the most common theme in hydroponic research is the development of the
150 technology for efficient control of the microclimate in order to increase productivity and
151 reduce costs (Jensen, 1997; Scoccianti et al., 2009). Nested within this general trend lies
152 research regarding the specific elements of climatic control, including lighting systems
153 (Ebisawa et al., 2008; Genovese et al., 2008; Martineau et al., 2012; McAvoy and Janes,
154 1983), nutrient solution composition and pH (Sardare and Admane, 2013; Tyson et al.,
155 2008; Velázquez et al., 2013), aerial and root zone temperature (Bugbee and White, 1984;
156 Papadopoulos and Tiessen, 1983; Sakamoto and Suzuki, 2015; Wu and Kubota, 2008)
157 and electrical conductivity (Cornish, 1992; Velázquez et al., 2013; Wu and Kubota, 2008).
158 This research couples technological advances with knowledge of plant physiology to
159 produce the most efficient and productive systems.

160 Use of an enclosed environment is both a strength and a weakness; the privilege of
161 being able to control environmental variables exhaustively necessitates the use of
162 advanced computer systems and sensory technology as well as provision of lighting,
163 heating and/or cooling, potentially equating to high energy costs (Jensen, 1997). Careful
164 and accurate regulation of environmental variables can produce yields of up to 20 times
165 that of traditional Open Field Agriculture (OFA) (Jensen, 1997). However, in order to
166 achieve the full benefits of ultimate environmental control, hydroponic systems require
167 significant capital investment to deliver such high yields (Ferguson et al., 2014; Sengupta
168 and Banerjee, 2012). There are, therefore, concerns that hydroponic systems may not
169 currently be economically viable on a larger scale and cannot compete with OFA methods
170 (Jensen, 1997; Martineau et al., 2012). However, OFA is not an option in certain areas of
171 the world or in certain seasons. Hydroponic systems allow the growing of higher value
172 horticultural produce in areas of otherwise poor quality land, or indoors. Also OFA and
173 Hydroponics need to be compared in relation to their carbon footprint and environmental
174 sustainability particularly as we try to wean away from our dependence on fossil fuels.

175 **4. Keeping Control of the Growing Environment**

176 Research and technological advancements ultimately aim to offset the costs of such
177 intensive systems via increases in efficiency, productivity and quality of produce (Jensen,
178 1997; Scoccianti et al., 2009). Much research has been undertaken into how to control
179 individual variables most efficiently in order to generate the highest crop value (Buck et al.,
180 2004; Martineau et al., 2012; Park and Kurata, 2009). Artificial lighting systems are
181 perhaps the most energy-demanding element of hydroponic cultivation (Martineau et al.,
182 2012), and have generated a considerable body of research. In the past, High Pressure
183 Sodium (HPS) light treatments were used to extend photoperiod and increase yields;
184 however, a large amount of waste heat was generated (McAvoy and Janes, 1983). More
185 recently, LED lighting systems have been highlighted as a means of reducing energy costs
186 (Brown et al., 1995; Martineau et al., 2012) and may also benefit crop growth (Chin and
187 Chong, 2012; Sabzalian et al., 2014). Martineau et al. (2012) reported energy savings of
188 up to 33.8% being achieved through use of LEDs. The ability to control light intensity and
189 photoperiod eliminates seasonality, allowing for year-round crop production (Rodríguez-
190 Delfín, 2011). In addition, aerial environmental factors, such as temperature and humidity,
191 must be regulated consistently to complement lighting regimes. The effective interaction of
192 these elements can enhance crop quality, growth and yields (Buck et al., 2004).

193 Containment has the additional benefit of considerably decreasing the chances of
194 exposure to pests and diseases (Sardare and Admane, 2013). A lack of soil equates to a
195 reduction in the risk of soil-borne plant pathogens (Biebel, 1960). In turn, pesticide and
196 herbicide requirements are reduced, thus minimising environmental pollution and waste
197 production (Sardare and Admane, 2013). However, counter to this, where containment and
198 biosecurity procedures are breached, disease and pest outbreaks can spread rapidly
199 within the facility, as well as leading in turn to risks of their release or escape into the
200 neighbouring natural environment. In some parts of the world, such as in Antarctica, such

201 introductions of alien species and pathogens into ecosystems that currently host no, or
202 few, alien species, are recognised as one of the greatest threats to native biodiversity and
203 ecosystem function, as well as to the regulatory framework governing the continent (Frenot
204 et al., 2005; Greenslade et al., 2006; Hughes and Convey, 2012).

205 The consistency and efficiency of regulation of the microclimate will be subject to the
206 robustness of containment of the system. Such systems also often require ventilation and
207 gas exchange to the outside and this must be considered when implementing such
208 technologies in areas where the climate is considered to be unsuitable for food production.
209 The design of the system will vary dependant on location as no one system is cost
210 effective for every climate (Jensen, 2001). Its structural integrity must be sufficient to
211 provide protection from the elements, factors that are specific to each location. If
212 inadequate consideration is given to maintaining structural integrity and optimum
213 environmental conditions, then the system will not be economically viable (Jensen, 2001).

214 **5. The Future of Hydroponics**

215 Maximising efficiency and productivity is key for the successful future of hydroponic
216 technology. Although primarily a technique for high value food production, applications are
217 still expanding, providing solutions to issues far removed from the general principles of the
218 technique. For instance, it has been suggested that hydroponic cultivation could be the key
219 to large-scale implementation of urban vertical farms (Despommier, 2013; Martellozzo et
220 al., 2014). Vertical farming in itself is a novel concept whereby crops are grown within
221 stacked hydroponic units, hence utilising the large amounts of vertical space within urban
222 areas where ground space is limited (Martellozzo et al., 2014). This concept aims to
223 provide an alternative source of food into the future and reduce, possibly drastically, the
224 need for reliance on traditional agriculture (Despommier, 2013). Despommier (2010) also
225 suggested that this approach may clear surplus agricultural land leading to increased
226 biodiversity levels and attenuating global warming through higher carbon sequestration.

227 A number of studies have also suggested that governmental inputs would benefit
228 the advancement of hydroponic technology (Jensen, 1997; Sardare and Admane, 2013;
229 Sengupta and Banerjee, 2012). Jensen (1997) explains the role of the US government in
230 assisting co-generation projects where excess heat from power generation plants was
231 used to heat greenhouses. A number of facilities were considered but development was
232 constrained by the complexity of such integration.

233 **6. Growing food in remote communities**

234 Each natural environment presents its own specific challenges. Therefore, it is the
235 overarching aim of CEA technology to be a sufficient and consistent method of food
236 production within a range of environments. Current research ultimately aims to reduce
237 resource requirements by means of educated system design and integration of the
238 technology with the surrounding environmental conditions. Capitalising on the beneficial
239 aspects of a given climate (e.g. greater light intensity) and using these gains to offset and
240 minimise antagonistic aspects (e.g. low water availability) will allow development of
241 economically viable systems which may minimise resource use and, in turn, the associated
242 environmental impacts.

243 **6.1 Pop-up food production in polar regions**

244 Conventional agriculture is not possible within the polar regions due to unfavourable soil
245 conditions, temperature limitations and highly variable seasonal light conditions.
246 Indigenous populations have survived within the Arctic on a hunter-gatherer diet since
247 soon after the retreat of the northern ice sheets after the last ice age, living a more
248 nomadic lifestyle to ensure the sustainability of food sources (Kuhnlein and Receveur,
249 1996). Nowadays, a shift in food availability and supply logistics has led to a divergence
250 from a traditional diet to one which is mostly imported from lower latitudes, and traditional
251 food sources now account for only 10-36% of the average adult diet (Kuhnlein et al., 2004).
252 In the Canadian Arctic, this has been accredited to colonialism and the introduction of

253 Hudson's Bay stores in the late 19th Century (Kuhnlein et al., 2004). In turn, there has
254 been a lifestyle shift to a more sedentary way of living, also generating diet-related health
255 concerns (Young, 1996).

256 Unlike the Arctic, the Antarctic has no history of indigenous human population. Human
257 exploration of the continent and surrounding isolated islands commenced in the last 1-3
258 centuries, with human occupation associated with research stations starting after the
259 Second World War. Contemporary human presence on the continent relies entirely on
260 imported food, including fresh fruit and vegetables. Due to extreme environmental
261 conditions during the austral winter, resupply ships are only able to bring food and other
262 resources to the continent within a maximum 5 month window during the summer (Bamsey
263 et al., 2015). After the final resupply of the summer season, overwintering staff must
264 survive on mostly frozen, canned and dried foods once fresh food stores have been
265 depleted (Potter, 2010). In some stations, this diet is supplemented by greenhouse or
266 hydroponically grown produce (Potter, 2010). Hydroponics systems in these stations not
267 only provide benefits to physical health via the availability of fresh food, but also aid mental
268 wellbeing during the dark isolated winter months (Bates et al., 2009).

269 Hydroponics has been in use within Antarctica since the 1960s (Scozzianti et al.,
270 2009). Hill (1967) provides a description of an attempt to grow salad crops on the Brunt Ice
271 shelf using hydroponics and motivated by what was possible. From the 1960s onwards
272 more than 46 different crop growth facilities have been or are currently in operation in the
273 Antarctic, with a total of nine research stations still operating hydroponics systems
274 (Bamsey et al., 2015). In the past, crops were also grown within traditional greenhouses
275 and wooden structures, often affixed to the outside of existing buildings (Bamsey et al.,
276 2015), although both these and more formal hydroponics systems have proved repeatedly
277 to be a source of biosecurity concerns, both in terms of alien species being introduced to
278 and existing synanthropically within the facilities, and instances of their escape into the

279 surrounding environment, in some cases further becoming established (Frenot et al.,
280 2005). A good example of a non-native micro-arthropod species being introduced via a
281 hydroponic system and subsequently contained is that of *Xenylla* sp., a collembolan
282 discovered in 2014 at Davis Station, East Antarctica (Bergstrom et al., 2017). The incursion
283 was identified and eradicated, but the event also highlighted the need for several levels of
284 control. The Antarctic Treaty System is the agreed legislative framework for the region.
285 Alongside the Treaty itself, which says little about Antarctic conservation, the Protocol on
286 Environmental Protection to the Antarctic Treaty (entered into force 1998) is the instrument
287 concerned with general Antarctic protection and conservation (Blay, 1992). Mindful of the
288 region's pristine nature, the low level of species introductions at present, and its
289 importance for scientific research, those negotiating the Protocol set some of the highest
290 legislative standards found globally concerning non-native species (Hughes and Pertierra,
291 2016). Annex II 'Conservation of Antarctic Fauna and Flora' states that non-native plants
292 and animals shall not be introduced to Antarctica without a permit (with the exception of
293 imported foods) and that any species found shall be removed or disposed of unless it is
294 shown that they pose no risk to native biota (ATS, 2009). However, it is not clear whether
295 or how the Protocol applies to species introduced accidentally rather than deliberately, or
296 where liability for consequential costs might lie (see Hughes and Convey, 2014, for
297 discussion of these issues). To help with implementation of Annex II, the Treaty Parties
298 developed the 'Non-native Species Manual' in 2011, which was substantially revised in
299 2017 (ATS, 2017). The manual provided Parties with advice on biosecurity issues
300 generally, and included specific but basic guidelines on how to minimise and contain any
301 biosecurity risks associated with hydroponic systems in Antarctica (Australia and France,
302 2012; Grewal et al., 2011).

303 **6.2. Food in Space**

304 During the 20th Century, it was suggested that hydroponics may be used within space
305 travel and habitation (MacElroy et al., 1987). Food for crew members aboard the
306 International Space Station (ISS) is pre-prepared, packaged and then sent in unmanned
307 resupply vessels along with scientific equipment and other necessary supplies. It is vitally
308 important that the nutritional requirements of crew members are met via a varied diet,
309 especially for future long-duration space missions (Smith et al., 2005). Long-duration space
310 missions will not have the luxury of regular resupply, and systems such as hydroponics will
311 necessarily form part of life-support systems, providing dietary support as well as water
312 recycling, atmospheric regeneration and waste processing (Mitchell, 1994). Biosecurity,
313 health and food standards are clearly implicit in the design and development of such
314 systems to mitigating any possible risks. For plant production, hydroponic crop generation
315 is integrated with supplementary life support systems, improving system sustainability and
316 reliability (Wheeler et al., 1996). Such systems are known as Bioregenerative Life Support
317 Systems (BLSS) and were initially studied by the U.S. Air Force during the 1950s and
318 1960s (Wheeler and Sager, 2006). The National Aeronautics and Space Administration
319 (NASA) began conducting research within this field independently during the 1960s and by
320 1985 had initiated their Controlled Ecological Life Support System (CELSS) project
321 (Wheeler and Sager, 2006). The CELSS project involved the use of atmospherically sealed
322 containers, formerly hypobaric test chambers, for simulated bio-regenerative crop
323 production (Prince and Knott III, 1989) known as Biomass Production Chambers (BPCs).

324 During the 1990s, NASA, in collaboration with the National Science Foundation
325 Office of Polar Programmes, developed a testbed for the CELSS programme. The CELSS
326 Antarctic Analog Project (CAAP) was undertaken at the Amundsen-Scott South Pole
327 Station and was designed to determine feasibility and further develop the technologies for
328 life support systems (Straight et al., 1994). This analogue was chosen due to similarities in
329 developmental and design limitations between polar stations and spacecraft, including

330 energy and resource constraints, biosecurity concerns, and isolation and space limitations
331 (Bubenheim et al., 2003). BPCs contained 20 m² of growing area and 113 m³ of
332 atmospheric volume, which was designed to support only one individual (Wheeler and
333 Sager, 2006). Though innovative at the time, this research highlighted issues surrounding
334 space availability and area-use efficiency. The CAAP was primarily developed to
335 investigate methods by which energy efficiency, productivity and area utilisation could be
336 maximised (Bubenheim et al., 2003). During the 2000s International Space Station crew
337 members have grown edible plants such as peas in a space garden, including in the Lada
338 space greenhouse system in the Russian segment (Sychev et al., 2007). A range of crops
339 for cultivation in space have been suggested including lettuce, tomato, cabbage, radish,
340 carrot, chard, green onion, pepper, strawberry, mizuna and several herbs (Wheeler, 2009).
341 Recently, NASA crew have used a plant growth system called Veggie (Massa et al., 2016)
342 developed by Orbital Technologies Corporation (ORBITEC) to grow such edible plants.
343 The Veggie system is designed to have low power consumption, low launch mass and
344 minimal operator intervention. In addition, therapeutic plant care is likely to be a benefit for
345 crew member health and wellbeing through the restorative effect of contact with nature, as
346 has been reported in studies on Earth (Schebella et al., 2017).

347 **7. What to Grow in Antarctica, and in Space?**

348 Few stations currently operate hydroponics units within Antarctica; however, between them
349 a wide range of crops are cultivated. The Australian Antarctic Division (AAD) currently
350 operate three of the nine existing hydroponics systems at their Casey, Mawson and Davis
351 research stations. These facilities grow a range of crops including lettuce, celery,
352 cucumbers, tomatoes, chillies, onions, silver beet and a variety of herbs (Bamsey et al.,
353 2015). During the austral summer of 2012–2013, the Davis facility produced a total edible
354 yield of 237 kg. However, 420 kg of green waste was also incinerated (Sheehy, 2013; as
355 cited in Bamsey et al., 2015).

356 At an Italian Station at Terra Nova Bay in Victoria Land, lettuce, zucchini and
357 cucumber were grown during the original experiments and were cultivated only during the
358 austral summer, as the station is not a wintering station (Bamsey et al., 2015). Lettuce
359 plants performed well and, during the second trial season, approximately 2.5 kg/m² was
360 harvested (Campiotti et al., 2000). Zucchini and cucumber plants grew well but, due to the
361 short period of cultivation (40 days), were unable to fruit (Campiotti et al., 2000). During the
362 2001–2002 summer season, fruit crops, such as tomatoes and strawberries, were
363 successfully introduced to the system (Scoccianti et al., 2009).

364 The vast majority of crops cultivated within Antarctica are tall fruiting crops, lettuce
365 varieties, leafy greens and herbs, due to their ease of cultivation. Although these provide
366 vital minerals and vitamins to staff, a lack of crops high in carbohydrates and fat means
367 that current produce serves primarily as a supplement to a mostly canned and dry food
368 diet. Though this does not pose much of an issue for staff on Antarctic research stations, in
369 order for these systems be viable for space missions, further advances must be made in
370 order to reduce the high inputs required for more nutritionally valuable crops.

371 It is pertinent to cultivate 'staple' crops which are considered more nutritious and will
372 contribute to a higher proportion of overall dietary requirements (Wheeler et al., 1996).
373 However, higher output requires greater input and so a balance must be achieved between
374 harvest index, nutritional requirements, processing and horticultural needs (Wheeler,
375 2017). During the course of the CELSS programme, researchers at the Kennedy Space
376 Centre cultivated a mixture of leafy greens, starchy vegetables, grains and fruits. Most
377 commonly used were wheat, rice, potato, sweet potato, soybean, peanut and lettuce (Hoff
378 et al., 1982). Additional benefits of growing crop plants within the Biomass Production
379 Chambers included removal of CO₂, generation of O₂ and waste water purification (Stutte,
380 2006).

381 During the CAAP program, crops were chosen based on nutritional content,
382 versatility and processing requirements (Bubenheim et al., 2003). Crop lists for these
383 experiments varied slightly from previous BLS experiments, consisting primarily of leafy
384 vegetables, herbs and salad vegetables with minimal carbohydrate contribution. Two
385 hydroponic studies were undertaken within the CAAP testbed crop production chamber
386 which both aimed to demonstrate production capacity of the system; the first was a
387 batched lettuce crop trial and the second a continuous mixed crop trial (Bubenheim et al.,
388 2003). Results of these two studies suggested that although the lettuce crop had a greater
389 production efficiency, the high diversity of the mixed crop trial offered an increased calorific
390 contribution, offsetting the lower yields (Bubenheim et al., 2003). This suggests that the
391 nutritional benefits offered by a higher variety crop list would offset the reduced yields.

392 **8. Learning to produce more with less: a blueprint for the future**

393 **8.1 Space availability**

394 Space is a major limitation for hydroponic systems in urban areas, and even more so in
395 polar stations and spacecraft. In Antarctica, hydroponics units have ranged from a 0.8 m²
396 benchtop system at Scott Base to the 50 m² South Pole Food Growth Chamber (SPFGC)
397 at Amundsen-Scott South Pole Station (Bamsey et al., 2015). Space available within the
398 SPFGC was deemed sufficient to provide 100% of the vegetable requirements for 35 over-
399 wintering station staff (Straight et al., 1994). The average size of current systems is
400 approximately 24 m² and, although this is not of sufficient size or efficiency to substantially
401 influence a station's logistics, these systems are still considered beneficial (Bamsey et al.,
402 2015).

403 In addition to the CAAP in Antarctica, research for agriculture in space has been
404 undertaken by numerous countries, all aiming to provide sufficient life support systems
405 within limited space (Wheeler, 2017). During the 1990s, Japanese scientists developed the
406 Controlled Environment Experiment Facility which contained 150 m² of growing space,

407 providing sufficient food, air and water supplies for two people and two goats (Tako et al.,
408 2010). Most recently, Chinese researchers at Beihang University were able to provide
409 100% of oxygen needs and 55% of food requirements for three people using only 69 m² of
410 growing space (Fu et al., 2016). These advances in space utilisation were achieved via
411 research into novel technologies such as LEDs, vertical farming, innovative water delivery
412 systems and novel waste recycling processes (Wheeler, 2017). Research into hydroponics
413 in space as well as in terrestrial systems is mutually beneficial for progress with regards to
414 space utilisation practices for both applications (Wheeler, 2017).

415 **8.2 Aeroponics**

416 A variation of hydroponics called aeroponics, in which the water and nutrient solution is
417 delivered to the plant root system as an aerosol, was reviewed for crop growth by Gopinath
418 et al. (2017). The advantage of such a system being that the root zone remains highly
419 aerated and no separate aeration system is required. Aeroponics has received attention in
420 areas such as the development of seed potatoes where aeroponics allows the advantages
421 of hydroponics in developing tubers in a clean nutritious environment with fewer potential
422 soil borne contaminants while not requiring tubers to be immersed in water (Buckseth et
423 al., 2016; Margaret Chiipanthenga, 2012). Aeroponics shares the improvement in water
424 use efficiency attributed to hydroponic systems (Barbosa et al., 2015), and of particular
425 note for efficient production of crops in pop-up systems, aeroponics allows spatial flexibility
426 in the design of growth areas with the possibility to improve crop density. In particular in
427 combination with flexible point sources of illumination, such as that possible using LEDs,
428 the delivery of water by aerosol allows plants to be grown across different shaped
429 surfaces, for instance an early example of aeroponics illustrated growing plants on two
430 sides of a triangle (Abou-Hadid et al., 1994). Such flexibility will allow different spatial
431 orientations of plants and lights to be optimised, in particular such designs have the

432 potential to provide highly novel solutions for crops grown under microgravity in space
433 capsules.

434 **8.3 Bio-intensive Agriculture (BIA)**

435 BIA is one method which uses space-saving agricultural techniques and mixed planting to
436 maximise space use efficiency (Jeavons, 2001). A similar approach is taken in SPIN (small
437 plot intensive) farming for use in backyards and small (less than one acre) urban spaces
438 (Christensen, 2007), and may be traced back to prehistoric intensive midden cultivation
439 (Guttmann, 2005). Although BIA is a soil-based technique, several of the broader
440 principles are transferable to hydroponics, including companion planting, intensive planting
441 arrangements and 3D structuring (Jeavons, 2001). This design has shown great potential,
442 and was described by Glenn et al., (1990) during the Biosphere II trials. These principles
443 are not novel and originated from Alan Chadwick's 'Biodynamic French Intensive Method'
444 during the 1960's (Chadwick, 2008).

445 **8.4 Intercropping Systems**

446 An additional method for maximising productivity is the space utilisation method of
447 intercropping. This technique describes the cultivation of two or more crop species together
448 in the same space (Li et al., 2014). Shorter crops, such as lettuce varieties, can be planted
449 interspersed between taller crops, such as tomatoes, utilising the space between larger
450 plants which would usually remain unoccupied. The interspecific interactions between
451 intercropped plants have been suggested to positively influence below-ground resource
452 use efficiency (Hauggaard-Nielsen and Jensen, 2005) and pest management (Fagan et al.,
453 2014; Parker et al., 2013) in addition to space utilisation. However, the vast majority of
454 investigations in this area has involved traditional soil-based systems, with little reference
455 to hydroponics.

456 Certain crops have been shown to either positively or negatively affect the growth
457 and survival of neighbouring plants. Commercial horticultural texts provide basic

458 information on which combinations of crops work best when planted together but do not
459 provide the underlying scientific principles behind such companionships. Information is
460 largely based on circumstantial evidence with little academic evidence. However, there has
461 been an increase in research since the turn of the century to more comprehensively
462 determine the credibility of these suggestions (Bomford, 2009; Li et al., 2014; Parolin et al.,
463 2015). With regards to hydroponics, these effects may be encountered when utilising
464 recirculating or dual-culture hydroponic systems. These systems reduce environmental and
465 economic costs via recycling and recirculation of the nutrient solution (Bugbee, 2004). In
466 some cases, the production of bioactive root exudates may offer the benefit of increased
467 growth (Stutte, 2006).

468 Organic compounds exuded by plant roots may increase the uptake of
469 micronutrients by other plants (Mackowiak et al., 2001); however, the mode of action of this
470 process remains little understood (Stutte, 2006). For example, a bioactive compound
471 produced in hydroponically grown potatoes, known as TIF (Tuber Inducing Factor), was
472 found to enhance the harvest index of several crop species, showing potential within dual
473 culture systems (Edney et al., 2001). Similarly, research conducted by Schuerger and
474 Laible (1994) on the biocompatibility of wheat and tomatoes within a dual-culture system
475 showed that there were no significantly adverse effects on either species. Their results
476 indicated that intercropping of multiple species is a viable space utilisation method. It was
477 also suggested that root zone competition may have led to a slight increase in wheat yield.
478 Mixed cropping has also been assessed for space exploration and no negative effects
479 detected when growing radish, lettuce and bunching onion together hydroponically (Edney
480 et al., 2006).

481 Alternatively, bioactive root exudates may have allelopathic effects, negatively
482 affecting growth and productivity (Lee et al., 2006; Li et al., 2010; Mortley et al., 1998).
483 Mortley et al. (1998) showed that allelopathic compounds released into the nutrient

484 solution by sweet potato inhibited the growth and yield of peanut plants. Therefore, it is
485 necessary to understand which species are viable companion species when considering
486 multi-culture systems. This information is widely available for traditional agriculture
487 (Cunningham, 2000), but it is yet to be determined whether it is transferrable to hydroponic
488 systems, and so as multispecies plant systems increase in popularity, biocompatibility must
489 be carefully considered (Schuenger and Laible, 1994).

490 **8.5 Root-to-Shoot Diets**

491 In Antarctic hydroponic units a large proportion of green waste is produced, generating
492 losses in productivity and additional practical challenges and costs in disposal (Bamsey et
493 al., 2015). All waste (with the exception of sewage and grey water) must be either
494 incinerated (which uses fuel) or stored and then removed from the Antarctic Treaty area. In
495 order to maximise the output it is beneficial to minimise biological waste via the cultivation
496 of crops which are high in edible biomass. Cultivation of high edible value crops such as
497 lettuce varieties, cabbages, leafy greens and herbs would maximise the productivity of
498 hydroponic systems. However, as mentioned previously, these crops have a lower overall
499 nutritional contribution to diets than fruiting crops and root vegetables (Bubenheim et al.,
500 2003). Alternatively, green waste could be reduced via consumption of edible by-products
501 which would traditionally be disposed of. This "Root to Shoot" ideology addresses the need
502 to reduce commercial and domestic food waste, and aims to find novel uses for what are
503 typically regarded as 'waste products' (Youngman, 2016).

504 Many food crops have secondary edible parts in addition to the commonly edible
505 portion, which are not generally consumed due to comparatively unfavourable flavour or
506 texture (Stephens, 2005). This includes stems, leaves, flowers and roots. Culinary
507 professionals invent novel ways in which to incorporate these by-products into the common
508 diet to increase their palatability (Youngman, 2016). However, some plant parts may be
509 inedible and possibly even poisonous. For example, vegetables of the 'Nightshade'

510 (*Solanaceae*) family, including tomato, potato, eggplants and peppers, contain toxic
511 glycoalkaloids (Carman Jr et al., 1986). Also referred to as solanine, concentrations of this
512 chemical are lowest in the fruits/tubers and so are non-toxic; however, high concentrations
513 are present in the foliage which should therefore not be consumed (Slanina, 1990). In
514 contrast, the phenolic compounds found in the roots, stalks and leaves of some plants are
515 high in antioxidants (Otles and Yalcin, 2012). For example, nettle roots (*Urtica dioica*) have
516 high phenolic and antioxidant activity (Otles and Yalcin, 2012). The same is true for the
517 Indian pennywort (*Centella asiatica*), native to Asian wetlands and used to treat a range
518 of ailments including kidney problems, cancer and bronchitis (Jaganath and Ng, 2000;
519 Kan, 1986; Zainol et al., 2003).

520 The "Root to Shoot" principle needs further investigation and is particularly attractive
521 in hydroponics as all plant components are clean and accessible. During space
522 exploration, uneaten plant parts could have considerable potential for conversion to bio-
523 based materials or use as a feedstock for bioreactors. There is significant scope to harvest
524 and utilise biomass and plant components that would otherwise be discarded, and even
525 scope for bioprospecting novel compounds. However, detailed analyses of nutrition,
526 potential toxicity and contamination are required in order to minimise any potential risks to
527 human health.

528 **8.6 Circular economics**

529 Recent innovations in energy, nutrient solutions and lighting sensors can now be exploited
530 to assemble automated crop growing systems based on the principles of the circular
531 economy. Circular economics was first introduced by David Pearce and R. Kerry Turner in
532 1990 (Pearce and Turner, 1990) and attempts to integrate the energy and resource cycling
533 principles of natural systems into industrial and economic systems (Geng and Doberstein,
534 2008) . A link is created between waste and primary resources in a similar way to that of
535 natural systems; for example, nutrient recycling of waste plant biomass back into the soil.

536 These techniques have been developed in an effort to promote resource minimisation and
537 generate more environmentally sustainable development (Andersen, 2007). This principle
538 revolves around the notion that a closed system is one in which resources can be more
539 sustainably maintained than that of traditional linear industrial systems.

540 Antarctic research stations operating during the austral winter represent the ideal
541 model for closed systems. They have limited access to the outside world and the importing
542 of goods and exporting of waste are both largely impossible. Circular economic principles
543 implemented at the stations can optimise resource use during the winter, and this also
544 applies within hydroponic facilities. For temperature control, intelligent building design
545 could be used to exploit heat sources and sinks (Agoudjil et al., 2011). Waste water could
546 be filtered recirculated using the Nutrient Film Technique (NFT) which is a closed system
547 of hydroponics (Rodríguez-Delfín, 2011). In addition, local precipitation could be harvested
548 and recycled (Helmreich and Horn, 2009; Kurunthachalam, 2014) and even integrated
549 energy could be captured locally (e.g. solar, wind). This can be combined with efficient
550 LED technology which has high energy efficiency a long life-cycle and low maintenance
551 costs (Singh et al., 2015) and provides a safe working environment with no glass
552 coverings, low touch temperatures and no mercury to dispose (Massa et al., 2016).

553 **9. How we share and exploit this knowledge to design crop production systems**
554 **that respond to food security threats in economically developing countries?**

555 Growing crops using the minimum of resources to sustain human life clearly has the
556 greatest value and potential impact in economically developing countries. Research is
557 already emerging within such countries using what Orsini et al. (2013) describe as ‘simple
558 hydroponics’. In stark contrast to polar and space research, access to advanced growing
559 resources and strategies represents the most significant challenge here (McCartney and
560 Lefsrud, 2018). However, charitable aid could and should be directed specifically towards

561 plant growing facilities (e.g. seeds, containers, LEDs, solar power, indoor systems etc.) or
562 even outdoor systems that use solar radiation.

563 Hydroponics is space and water efficient but energy inefficient compared to soil-
564 based horticulture (Barbosa et al., 2015). The balance of cost benefit in adopting popup
565 systems will likely depend on which resources are limiting and/or costly in the local
566 environment and which can be provided, perhaps by sustainable technologies. Therefore
567 equatorial regions with low water availability, degraded soils and high sunlight may favour
568 a form of hydroponics/aeroponics if solar panels can be used for energy. McCartney and
569 Lefsrud (2018) also recently reviewed protected agriculture systems in extreme
570 environments and highlight the need for cooling and ventilation systems in tropical regions
571 but heating in polar regions (McCartney and Lefsrud, 2018).

572 Social capital is high in economically developing countries so some technological
573 aspects of plant husbandry might be by-passed via human collaboration. However, there is
574 a need for knowledge to be communicated about the value of hydroponic systems. Also
575 the control of such systems often relies on information and communications technology
576 (ICT). There is evidence that mobile phones are being used widely as the core ICT in
577 economically developing countries. For example, in a study of 202 South African
578 universities, 36% of students tested used a mobile phone for health information (Cilliers et
579 al., 2017). Also a study in Uganda showed that in women there was a link between mobile
580 phone ownership and dietary diversity and empowerment (Sekabira and Qaim, 2017).
581 Research is also emerging from developing countries on the use of mobile phones to
582 operate sensors for hydroponics (Ibayashi et al., 2016; Peuchpanngarm et al., 2016;
583 Ruengittinun et al., 2017; Sihombing et al., 2018). Hence, mobile phone technology may
584 be a central vehicle that facilitates information about new crop production systems also
585 useful for sensor and system control in economically developing countries.

586 A further challenge to growing crops in economically developing countries is access
587 to inorganic sources of fertilizer. This is not an issue for polar and space crop production
588 but finding alternative sources of nutrients is a necessity if crop production systems are
589 ever to become sustainable. Fertilizers from organic origin (animal and even human
590 sources) represent a resource to grow plants and aligns well with the principle of circular
591 economics promoted in this review. Research in economically developing countries already
592 highlights the potential of exploiting animal manures in hydroponics for plant growth (Abd-
593 Elmoniem et al., 2001; Capulín-Grande et al., 2000). Further, human urine may be
594 exploitable as a plant fertilizer (Andersen, 2007; Andersson, 2015; Chrispim et al., 2017;
595 Mnkeni et al., 2008).

596 For both polar/space and economically developing countries there is a need to
597 focus more on staple crops. Previously the CELLS space programme tested some starchy
598 vegetables including potato. Crops high in carbohydrate would also be particularly valuable
599 in economically developing countries and some research has already developed looking at
600 potato and yam propagation in aeroponic systems (Margaret Chiipanthenga, 2012; Maroya
601 et al., 2014). Further, research is also needed on the use of hydroponics to deliver high
602 protein crops (e.g. pulses and legumes) and there may even be benefits if plants can fix
603 their own nitrogen. For economically developing countries, crops high in proteins could
604 potentially supplement the use of livestock maybe using manure as a plant resource.

605 **Conclusions**

606 Polar/space research on crop science versus 'simple hydroponics' in economically
607 developing countries may be complete opposites in terms of access to resources and
608 research investment. Clearly space and polar research activities have been historically well
609 resourced but highlight the potential to grow crops in environments limited in resources.
610 The challenge now is to build on this research, to develop technologies, systems and

611 methods that are sustainable, inexpensive and more widely applicable. Hydroponic and
612 LED efficacy and the application of circular economic principles, exploiting local renewable
613 resources and valuing waste can bring new efficiency and opportunity into crop production.
614 BIA principles and intensive planting of 3D arrangements combined with intercropping in
615 hydroponics provides diversity of food and may increase community efficiency in terms of
616 light, water and nutrient utilisation. Plant assemblages of course enhance the possibility of
617 risks from pests and pathogens so this need to considered in relation to system design and
618 operation.

619 Tandem research emerging from economically developing countries highlights how
620 some elements of technology could be by-passed or even replaced to grow soil-less crops
621 in such regions. These including using human effort in place of automation, mobile phones
622 for ICT and organic sources of nutrients. The time is now ripe to look for 'cross-pollination'
623 of ideas on soilless crops, novel 'pop up' growing systems, finding value in all edible crop
624 components, using simple and accessible technologies and turning our waste into
625 resource. Our future depends on our capacity to innovate, to challenge what we see as
626 agriculture, and learn to get more from less by living and what we have.

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