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

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Highlights:

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

Abstract

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

1. Introduction

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

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

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

2. Closed Environment Agriculture

Whilst efforts are being made globally to mitigate climate change, thus reducing the rate of arable land loss, additional research has been undertaken to actively increase the amount of available space for crop production. This novel thinking has led to the creation of Closed Environment Agriculture (CEA), a term which encompasses a broad range of methods for the production of food within an enclosed environment (Jensen, 2001). The use of closed environments allows for control of many factors in the aerial environment, the root zone, and in irradiation (Rorabaugh et al., 2002). This can optimise plant growth and resource use efficiency whilst also enabling food production in previously unsuitable or unpredictable locations. Comprehensive control of the growing environment also allows for off-season production, eradicating seasonal time restrictions and generating multiple crops per year (Sabir and Singh, 2013). This technology may also provide an alternative agricultural output for areas affected by climate change, industrialisation and urbanisation, and may also reduce reliance on seasonal agricultural labour.

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

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

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

3. History of hydroponics

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

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

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

4. Keeping Control of the Growing Environment

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

Containment has the additional benefit of considerably decreasing the chances of exposure to pests and diseases (Sardare and Admane, 2013). A lack of soil equates to a reduction in the risk of soil-borne plant pathogens (Biebel, 1960). In turn, pesticide and herbicide requirements are reduced, thus minimising environmental pollution and waste production (Sardare and Admane, 2013). However, counter to this, where containment and biosecurity procedures are breached, disease and pest outbreaks can spread rapidly within the facility, as well as leading in turn to risks of their release or escape into the neighbouring natural environment. In some parts of the world, such as in Antarctica, such introductions of alien species and pathogens into ecosystems that currently host no, or few, alien species, are recognised as one of the greatest threats to native biodiversity and ecosystem function, as well as to the regulatory framework governing the continent (Frenot et al., 2005; Greenslade et al., 2006; Hughes and Convey, 2012).

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

5. The Future of Hydroponics

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

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

6. Growing food in remote communities

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

6.1 Pop-up food production in polar regions

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

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

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

Hydroponics has been in use within Antarctica since the 1960s (Scoccianti et al., 2009). Hill (1967) provides a description of an attempt to grow salad crops on the Brunt Ice shelf using hydroponics and motivated by what was possible. From the 1960s onwards more than 46 different crop growth facilities have been or are currently in operation in the Antarctic, with a total of nine research stations still operating hydroponics systems (Bamsey et al., 2015). In the past, crops were also grown within traditional greenhouses and wooden structures, often affixed to the outside of existing buildings (Bamsey et al., 2015), although both these and more formal hydroponics systems have proved repeatedly to be a source of biosecurity concerns, both in terms of alien species being introduced to and existing synanthropically within the facilities, and instances of their escape into the surrounding environment, in some cases further becoming established (Frenot et al., 2005). A good example of a non-native micro-arthropod species being introduced via a hydroponic system and subsequently contained is that of *Xenylla* sp., a collembolan discovered in 2014 at Davis Station, East Antarctica (Bergstrom et al., 2017). The incursion was identified and eradicated, but the event also highlighted the need for several levels of control. The Antarctic Treaty System is the agreed legislative framework for the region. Alongside the Treaty itself, which says little about Antarctic conservation, the Protocol on Environmental Protection to the Antarctic Treaty (entered into force 1998) is the instrument concerned with general Antarctic protection and conservation (Blay, 1992). Mindful of the region’s pristine nature, the low level of species introductions at present, and its importance for scientific research, those negotiating the Protocol set some of the highest legislative standards found globally concerning non-native species (Hughes and Pertierra, 2016). Annex II ‘Conservation of Antarctic Fauna and Flora’ states that non-native plants and animals shall not be introduced to Antarctica without a permit (with the exception of imported foods) and that any species found shall be removed or disposed of unless it is shown that they pose no risk to native biota (ATS, 2009). However, it is not clear whether or how the Protocol applies to species introduced accidentally rather than deliberately, or where liability for consequential costs might lie (see Hughes and Convey, 2014, for discussion of these issues). To help with implementation of Annex II, the Treaty Parties developed the ‘Non-native Species Manual’ in 2011, which was substantially revised in 2017 (ATS, 2017). The manual provided Parties with advice on biosecurity issues generally, and included specific but basic guidelines on how to minimise and contain any biosecurity risks associated with hydroponic systems in Antarctica (Australia and France, 2012; Grewal et al., 2011).

6.2. Food in Space

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

During the 1990s, NASA, in collaboration with the National Science Foundation Office of Polar Programmes, developed a testbed for the CELSS programme. The CELSS Antarctic Analog Project (CAAP) was undertaken at the Amundsen-Scott South Pole Station and was designed to determine feasibility and further develop the technologies for life support systems (Straight et al., 1994). This analogue was chosen due to similarities in developmental and design limitations between polar stations and spacecraft, including energy and resource constraints, biosecurity concerns, and isolation and space limitations (Bubenheim et al., 2003). BPCs contained 20 m^2 of growing area and 113 m^3 of atmospheric volume, which was designed to support only one individual (Wheeler and Sager, 2006). Though innovative at the time, this research highlighted issues surrounding space availability and area-use efficiency. The CAAP was primarily developed to investigate methods by which energy efficiency, productivity and area utilisation could be maximised (Bubenheim et al., 2003). During the 2000s International Space Station crew members have grown edible plants such as peas in a space garden, including in the Lada space greenhouse system in the Russian segment (Sychev et al., 2007). A range of crops for cultivation in space have been suggested including lettuce, tomato, cabbage, radish, carrot, chard, green onion, pepper, strawberry, mizuna and several herbs (Wheeler, 2009). Recently, NASA crew have used a plant growth system called Veggie (Massa et al., 2016) developed by Orbital Technologies Corporation (ORBITEC) to grow such edible plants. The Veggie system is designed to have low power consumption, low launch mass and minimal operator intervention. In addition, therapeutic plant care is likely to be a benefit for crew member health and wellbeing through the restorative effect of contact with nature, as has been reported in studies on Earth (Schebella et al., 2017).

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

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

At an Italian Station at Terra Nova Bay in Victoria Land, lettuce, zucchini and cucumber were grown during the original experiments and were cultivated only during the austral summer, as the station is not a wintering station (Bamsey et al., 2015). Lettuce plants performed well and, during the second trial season, approximately 2.5 kg/m^2 was harvested (Campiotti et al., 2000). Zucchini and cucumber plants grew well but, due to the short period of cultivation (40 days), were unable to fruit (Campiotti et al., 2000). During the 2001–2002 summer season, fruit crops, such as tomatoes and strawberries, were successfully introduced to the system (Scoccianti et al., 2009).

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

It is pertinent to cultivate 'staple' crops which are considered more nutritious and will contribute to a higher proportion of overall dietary requirements (Wheeler et al., 1996). However, higher output requires greater input and so a balance must be achieved between harvest index, nutritional requirements, processing and horticultural needs (Wheeler, 2017). During the course of the CELSS programme, researchers at the Kennedy Space Centre cultivated a mixture of leafy greens, starchy vegetables, grains and fruits. Most commonly used were wheat, rice, potato, sweet potato, soybean, peanut and lettuce (Hoff et al., 1982). Additional benefits of growing crop plants within the Biomass Production Chambers included removal of CO_2, generation of O_2 and waste water purification (Stutte, 2006).

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

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

8.1 Space availability

Space is a major limitation for hydroponic systems in urban areas, and even more so in polar stations and spacecraft. In Antarctica, hydroponics units have ranged from a 0.8 m^2 benchtop system at Scott Base to the 50 m^2 South Pole Food Growth Chamber (SPFGC) at Amundsen-Scott South Pole Station (Bamsey et al., 2015). Space available within the SPFGC was deemed sufficient to provide 100% of the vegetable requirements for 35 over-wintering station staff (Straight et al., 1994). The average size of current systems is approximately 24 m^2 and, although this is not of sufficient size or efficiency to substantially influence a station's logistics, these systems are still considered beneficial (Bamsey et al., 2015).

In addition to the CAAP in Antarctica, research for agriculture in space has been undertaken by numerous countries, all aiming to provide sufficient life support systems within limited space (Wheeler, 2017). During the 1990s, Japanese scientists developed the Controlled Environment Experiment Facility which contained 150 m^2 of growing space, providing sufficient food, air and water supplies for two people and two goats (Tako et al., 2010). Most recently, Chinese researchers at Beihang University were able to provide 100% of oxygen needs and 55% of food requirements for three people using only 69 m^2 of growing space (Fu et al., 2016). These advances in space utilisation were achieved via research into novel technologies such as LEDs, vertical farming, innovative water delivery systems and novel waste recycling processes (Wheeler, 2017). Research into hydroponics in space as well as in terrestrial systems is mutually beneficial for progress with regards to space utilisation practices for both applications (Wheeler, 2017).

8.2 Aeroponics

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

8.3 Bio-intensive Agriculture (BIA)

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

8.4 Intercropping Systems

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

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

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

Alternatively, bioactive root exudates may have allelopathic effects, negatively affecting growth and productivity (Lee et al., 2006; Li et al., 2010; Mortley et al., 1998). Mortley et al. (1998) showed that allelopathic compounds released into the nutrient solution by sweet potato inhibited the growth and yield of peanut plants. Therefore, it is necessary to understand which species are viable companion species when considering multi-culture systems. This information is widely available for traditional agriculture (Cunningham, 2000), but it is yet to be determined whether it is transferrable to hydroponic systems, and so as multispecies plant systems increase in popularity, biocompatibility must be carefully considered (Schuerger and Laible, 1994).

8.5 Root-to-Shoot Diets

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

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

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

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

8.6 Circular economics

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

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

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

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

Growing crops using the minimum of resources to sustain human life clearly has the greatest value and potential impact in economically developing countries. Research is already emerging within such countries using what Orsini et al. (2013) describe as 'simple hydroponics'. In stark contrast to polar and space research, access to advanced growing resources and strategies represents the most significant challenge here (McCartney and Lefsrud, 2018). However, charitable aid could and should be directed specifically towards plant growing facilities (e.g. seeds, containers, LEDs, solar power, indoor systems etc.) or even outdoor systems that use solar radiation.

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

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

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

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

Conclusions

Polar/space research on crop science versus 'simple hydroponics' in economically developing countries may be complete opposites in terms of access to resources and research investment. Clearly space and polar research activities have been historically well resourced but highlight the potential to grow crops in environments limited in resources. The challenge now is to build on this research, to develop technologies, systems and methods that are sustainable, inexpensive and more widely applicable. Hydroponic and LED efficacy and the application of circular economic principles, exploiting local renewable resources and valuing waste can bring new efficiency and opportunity into crop production. BIA principles and intensive planting of 3D arrangements combined with intercropping in hydroponics provides diversity of food and may increase community efficiency in terms of light, water and nutrient utilisation. Plant assemblages of course enhance the possibility of risks from pests and pathogens so this need to considered in relation to system design and operation.

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

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