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Growing fresh food on future space missions: Environmental conditions and crop management

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ABSTRACT

This paper deals with vegetable cultivation that could be faced in a space mission. This paper focusses on optimization, light, temperature and the harvesting process, while other factors concerning cultivation in space missions, i.e. gravity, radiation, were not addressed. It describes the work done in preparation of the deployment of a mobile test facility for vegetable production of fresh food at the Neumayer III Antarctic research station. A selection of vegetable crops was grown under varying light and temperature conditions to quantify crop yield response to climate factors that determine resource requirement of the production system. Crops were grown at 21 °C or 25 °C under light treatments varying from 200 to 600 μmol m^{-2} s^{-1} and simulated the dusk and dawn light spectrum. Fresh food biomass was harvested as spread harvesting (lettuce), before and after regrowth (herbs) and at the end of cultivation.

Lettuce and red mustard responded well to increasing light intensities, by 35–90% with increasing light from 200 to 600 μmol $m^{-2}s^{-1}$, while the other crops responded more variably. However, the quality of the leafy greens often deteriorated at higher light intensities. The fruit biomass of both determinate tomato and cucumber increased by 8–15% from 300 to 600 μmol $m^{-2}s^{-1}$. With the increase in biomass, the number of tomato fruits also increased, while the number of cucumber fruits decreased, resulting in heavier individual fruits. Increasing the temperature had varied effects on production. While in some cases the production increased, regrowth of herbs often lagged behind in the 25 °C treatment. In terms of fresh food production, the most can be expected from lettuce, cucumber, radish, then tomato, although the 2 fruit vegetables require a considerable amount of crop management. Spread harvesting had a large influence on the amount of harvested biomass per unit area. In particular, yield of the 3 lettuce cultivars and spinach was ca. 400% than single harvesting. Increasing plant density and applying spread harvesting increased fresh food production. This information will be the basis for determining crop growth recipes and management to maximize the amount of fresh food available, in view of the constraints of space and energy requirement of such a production system.

1. Introduction

Production of food is essential in order to realize successful space missions for extended periods of time. As staple crops can be preserved dried for a long time, a priority is production of fresh vegetables, which has also been shown to have beneficial psychological effects for the crew members (Koga and Iwasaki, 2013; Odeh and Guy, 2017). The purpose of the EU-funded EDEN ISS project (Ground Demonstration of Plant Cultivation Technologies and Operation in Space) is to develop a growing system for fresh vegetables, that can operate under the constraints of a space mission. However, plant cultivation during space missions must cope with factors like gravity and radiation, which are difficult to properly address in plant cultivation on earth.

As deep space is still far away, the EDEN ISS project is limited to design and build a mobile test facility (MTF) in which crops can be cultivated for at least one full year, that will be deployed to the Neumayer III Antarctic research station (Zabel et al., 2016). The use of Antarctica as analogue for deep space lies particularly in the hostile external environment, being physically isolated and the limited resources available in terms of crew time, energy and volume. Therefore, it is necessary to define growth conditions and crop management that maximise the productivity of both space and energy, that is electricity to power artificial light and air conditioning. For instance, in order to maximize light use efficiency (LUE) of lettuce, Poulet et al. (2014) made use of targeted lighting, illuminating only the photosynthetic plant tissue. This was achieved by having the plants in fixed spots, which entails a large fraction of unused space during the early stage of the crops. Space is also a very limited resource in space missions, and to

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mimic this, the cultivation space in the MTF will be 40 racks of 40 × 60 cm, of which 22 are 30 cm high (cultivation space between the top of the rack and lamp), 16 are 80 cm and 2 are 160 cm. The issue is therefore to develop crop growing and management recipes that maximise productivity of both electricity and space. This requires some knowledge of the marginal value (in term of additional production) of both. That was the purpose of the work described here, which was carried out in climate rooms equipped similarly to the growing cabinets of the MTF. The development of these crop growth recipes may also be employed in vertical farming.

The first step is, rather obviously, the selection of suitable crops. While the aspect of human nutrition is obviously an important element in space farming, it has been expressed in earlier studies (Hoff et al., 1982, Massa et al., 2015). Due to the fact that the physical space for plant growth is very limiting in space missions, the focus was placed on the psychological component of a limited amount of fresh food. The desirable characteristics of ready-to-eat fresh vegetable products for their well-being have been expressed by former astronauts and crews that have over-wintered on Antarctica (Mauerer et al., 2016,We developed an objective selection method that differently prioritizes "hard" constraints (for instance, space) and "soft" constraints (such as harvest index or even spiciness) (Dueck et al., 2016). The method resulted in a diverse set of vegetable crops, each with their own specific requirements for optimal growth and production, like light intensity, light spectrum, temperature and humidity.

With a knowledge of the edible biomass that can be harvested per unit area per cultivation cycle of the individual crops, it becomes possible to set-up a crop plan (sowing and harvest dates) to maximise space utilisation; food production and diet variety.

Whereas light intensity (and spectrum) can be adapted in each single tray of the growing unit in the MTF, there will be one temperature and humidity set point. Therefore, the overall objectives of this work were:

- Determine the "marginal" value of resources (light and temperature) in terms of [fresh] yield.
- Collect suitable information for crop management planning that maximises productivity of the unit and ensures a varied diet.

2. Methods

Their limited size and high harvest index, ensure that leafy greens are always at the top of any list for "space vegetables" for fresh food (Hoff et al., 1982; Wheeler, 2004; Chunxiao and Hong, 2008; Massa et al., 2015). Our list was not an exception, although it did include a dwarf variety of tomato and a cocktail cucumber (as fruit crops) and radish as root crop. Besides different cultivars of lettuce, spinach, red mustard, Swiss chard and herbs were included for more taste and quality aspects. Two experiments were conducted to determine the influence of light intensity, and the influence of temperature at 2 different light levels on the growth of the vegetables and regrowth of some crops, harvested during or at the end of the growth period.

2.1. Influence of light intensity on crop growth

2.1.1. Plant material and growth conditions

Two consecutive trials were conducted to accommodate 9 different crops. Five crops were grown in the first trial: lettuce 'Expertise' (type Crispy Green; Rijk Zwaan, de Lier, NL) and 'Outredgeous' (type red Romaine; Johnny Seeds, Winslow, ME), red mustard 'Frizzy lizzy' and radish 'Lennox' (Bayer/HILD, DE), and chives 'Staro' (Johnny Seeds, Winslow, ME). In the second trial the following crops were grown: lettuce 'Othilie' (type Batavia; Rijk Zwaan, de Lier, NL), rocket 'Rucola Cultivated' (Seeds from Italy, Harrow, UK), Swiss chard 'Red ruby' (Johnny Seeds, Winslow, ME) and spinach 'Golden Eye' (Rijk Zwaan, de Lier, NL). Seeds were sown directly onto 2 cm rock wool plugs and were

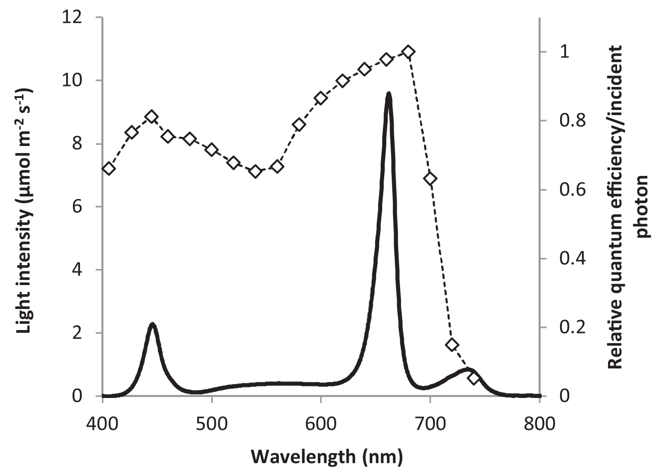

Fig. 1. Spectrum of the 4 channel LED lighting assembly at a light intensity of 300 µmol m^{-2} s^{-1} (line), and the relative quantum efficiency per incident photon (symbols) (Paradiso et al., 2011).

later transplanted into 7 × 7 cm rock wool blocks, or directly onto smaller rock wool blocks (4 × 4 cm) depending on the estimated final plant size. They were placed in 40 × 60 × 10 cm open trays and were given a nutrient solution with an ebb and flow system. The nutrient solution with an EC 1.7 and pH 5.8 was composed of, in mmol l^{-1}: 11.5 NO_3-, 1.0 SO_4-, 1.25 P-, 1.0 NH_4^+, 6.75 K^+, 2.63 Ca^{2+}, 0.25 Cl- and 1.0 Mg^{2+}; and in µmol l^{-1}: 20 Fe, 25 B, 10 Mn, 5 Zn, 0.75 Cu and 0.5 Mo. The climatic conditions entailed a day/night temperature set points of 21/19 °C, a day/night relative humidity of 75/85%, 750 ppm CO_2 and a 17 h photoperiod. The realised climate was 20.7/18.9 °C day/night; 76/83% RH day/night and 744 ppm CO_2 during the light period.

2.1.2. Experimental design

Each trial took place within a period of 6 weeks in 2 climate chambers, the first in May/June, followed by the second trial in July/August 2016. Artificial light was supplied by LED lighting modules from Heliospectra AB, Götenburg, Sweden, with 4 programmable channels of blue (446 nm), red (663 nm), far red (736 nm) and white LEDs (5700 K) (Fig. 1). As Fig. 1 shows, the red and blue peak of the lamps correspond with peaks in the relative quantum efficiency of roses (Paradiso et al., 2011) earlier established by McCree (1972) for multiple crops. A choice was made to use one spectrum that covered photosynthetic active radiation (PAR), with relatively more red light than in sunlight and included far red radiation. A large number of studies have been performed with basic red and blue (RB) LED lighting, but recent research (Mazza and Ballaré, 2015; Massa et al., 2016; Park & Runkle, 2017) has indicated that the addition of far red and white or green light enhances plant growth and production in an environment without sunlight. Lin et al. (2013) and Cocetta et al. (2017) have also reported that a spectrum including more wave lengths than only RB also enhanced the plant quality (i.e. crispness, sweetness and shape). Thus a spectrum was chosen of 17% blue (400–500 nm), 12% green (500–600 nm), 71% red (600–700 nm) and 35 µmol m^{-2} s^{-1} far red radiation (Fig. 1), which is similar to that in the Advanced Plant Habitat (APH) designed to fly to the ISS in 2017 (Massa et al., 2016).

The four treatments consisted of various light intensities, 200, 300, 450 and 600 µmol m^{-2} s^{-1}. The average realised light intensities over all shelves and experiments at crop level (and standard deviation) were 198 ± 11, 292 ± 17, 436 ± 25 and 582 ± 42 µmol m^{-2} s^{-1}. The standard deviation represents the horizontal distribution in the trays. The light intensity was weekly adjusted to maintain the same intensity at the top of the plant canopy.

Light was increased in 2 steps during the first hour of the photoperiod to the desired intensity, and decreased again at the end of the photoperiod. Sunrise and sunset were simulated with a natural a red:far