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Comparison of two pilot cropping systems for vertical cultivation of lettuce

Jämförelse av två pilotodlingssystem för vertikal odling av sallat

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Självständigt arbete vid LTJ-fakulteten, SLU
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Abstract

Commercial cultivation of greenhouse crops is today dominated by horizontal hydroponic cropping systems. But with greater demand for local food production, increased urbanization and expanding cities creates an interest of improved space utilization and crop optimization per square meter. This study was initiated to investigate the possibility of vertical cultivation of lettuce. Two pilot cropping prototypes, P1 and P2, designed for vertical cultivation of lettuce were compared to define the potentials and limitations for commercial lettuce production. Results look promising and both P1 and P2 showed potential production of lettuce (*Lactuca sativa, Lollo rosso,* cv. fortress) with respect to canopy fresh weight. Lettuce with acceptable commercial size was produced. The results also showed that light intensity is the limiting factor in terms of crop size and to produce a uniform crop in vertical cropping systems. Conclusion is that both prototypes P1 and P2 are interesting candidates for cultivation of lettuce in vertical hydroponic cropping systems, but they need improvements regarding irrigation strategy and for a more even irradiation.

Keywords: Greenhouse production, Hydroponics, *Lactuca sativa*, Lettuce, Vertical cropping systems.

Sammanfattning

Yrkesodlingen av växthusgrödor domineras idag av horisontella odlingssystem. Med en större efterfrågan på närodlad mat samtidigt som urbaniseringen ökar och städerna växer skapas ett behov att effektivisera ytanvändningen. Denna studie initierades för att undersöka möjligheterna av vertikal odling för sallad. Två pilotprototyper för vertikal hydroponisk odling jämfördes för att undersöka potentialen och begränsningarna för odling av sallad. Resultaten visade att båda prototyperna, P1 och P2, har en potential för produktion av sallad (Lactuca sativa, *Lollo rosso*, cv. fortress) med hänsyn till plantvikt - plantor med kommersiellt accepterad storlek producerades. Resultaten visade också att ljusintensiteten är den begränsande faktorn vad gäller plantstorlek och plantsymmetri i vertikala odlingssystem. Slutsatsen är att båda prototyperna P1 och P2 är intressanta kandidater för odling av sallad i vertikala hydroponiska system men att det behövs förbättringar vad gäller belysning.

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1 Introduction

With increasing migration from rural to urban areas all over the world, the cities expand their area on the expense of arable land. This leads to reduced and impaired food production in the vicinity of the peri-urban and urban areas. The problem with densely populated cities is evident in developing countries, where migration to cities often leads to a life in poverty and malnutrition (Fecondini et al. 2009, FAO 2006, Aldous 2007, Orsini et al. 2009). Cities cover approximately 2% of the earths surface. However 89% of the population live in cities and consume 75% of resources. Food crop production in and around the cities could improve the quality and sustainability of the urban life style (De Zoysa 2007).

Urban horticulture is defined as an alternative solution to increase food production and establish jobs in cities of the developing countries (Fecondini et al. 2009). Also in developed countries, the interest is large for urban food production due to environmental awareness and questioning the origin of their food (Luykx and van Ruth 2008). Urban horticulture is particularly interesting for products with limited shelf life intended for fresh consumption such as berries, vegetables, and culinary herbs.

High- and low-tech cropping systems may turn non-arable areas such as roofs, facades, small spaces between buildings and inside buildings to functioning food production areas. New cropping areas are needed, as well as the crop production has to be intensified for optimal use of resources (Fresco 2009) and supply the citizens with crops produced during the whole year (Pardue 2010). With peri-urban or urban horticulture there is more benefits then just improved food production (Fecondini et al. 2009). Others are reduced transportation, the potential use of wastewater in the nutrient solution (Mavrogianopoulos et al. 2002). Aldous (2007) also highlighted potential health benefits. When restrictive and expensive areas are used as arable land, it is important to have efficient space utilization to maximize yield (Raviv and Lieth 2008). Hydroponic cropping systems in particular have the potential to meet the challenges of urban horticulture (Domurath et al. 2009). Intensive cultivation in vertical hydroponic cropping systems can be one alternative for efficient space utilization.

Vertical cropping systems are relatively new and few commercially products are available until now. Various problems have to be solved, among these uneven distribution of light, water and nutrients (Linsley-Noakes et al. 2006). In the framework of this BSc-thesis, two prototypes of vertical cropping systems, designed at the Department of Horticulture, SLU, Alnarp in collaboration between Beatrix Alsanius, Johan Ljungquist, Rickard Strömblad, Mikael Olenmark and Thomas Eriksson were compared.

1.1 Purpose of study

Purpose of this study was to compare two prototypes for vertical hydroponic cropping systems, Prototype 1 (P1) and Prototype 2 (P2), according to their potentials and limitations for lettuce production.

1.2 Hypothesis

1. The vertical hydroponic cropping systems prototype P1 and P2 are appropriate for cultivation of lettuce
2. Light is the main limiting factor for lettuce in vertical systems
    a) P1 will suffer more from reduced light condition
3. Water and nutrient supply affects plant performance
    a) Biomass production differs between prototypes due to water and nutrient supply
    b)Root length and root biomass differs between prototypes due to differences in water and nutrient availability
    c) Biomass production will be better in P1 due to its constant water availability in containers

2 Background

2.1 Hydroponic cropping systems

Gericke (1937) used the term hydroponics (Savvas and Passam 2002) to describe all methods of growing plants in liquid media for commercial purposes. Steiner (1967) introduced the soilless cultures to a commercial scale, motivated by increased productivity and better efficiency (Raviv and Lieth 2008). In the 1970s, soilless culture in greenhouses using mineral wool expanded commercially (Verwer 1978) due to technical innovations in fertilization and irrigation leading to a more optimal plant growth (Raviv and Lieth 2008). Hydroponic systems are today a common method for cultivation in several countries of the world. Liquid and solid culture is often the two different ways of describing the differences in hydroponics (Jensen and Collins 1985). Liquid culture is commonly named as water cultures and substrate cultures describe cropping systems using different types of growing media. There are various types of systems that have evolved over time. Some of the techniques available are Deep Flow Technique (DFT), Nutrient Film Technique (NFT), plant plane hydroponics and aeroponics; these systems will be described in more detail for understanding the variety of hydroponic cropping systems. Hydroponic cropping systems are considered to be safe, profitable and have the opportunity for a sustainable crop production. In hydroponic systems the plants are grown directly in the nutrient solution, or with one or another substrate. Examples of growing media can be gravel, sand, rockwool, pumice, or various types of organic growing media. The systems can be closed, recirculating nutrient solution to minimize both water and nutrient use, or open systems where nutrient solution is wasted after it passed the crop. The advantage of open systems is that the risk for dispersal of pathogens is lower if nutrient solution does not pass the plants several times. The disadvantages are considerable costs for the grower and emissions to the environment. Hydroponic systems also differ in use of technology. There are low-tech systems which often are open and thereby do not require electricity or pumps. The high-tech systems vary a lot in designs with all from simple designs where the nutrient loop is closed, to very complex designs with several pumps, sensors, mixing device and surveillance systems. Liquid hydroponics employ a minimum of growing media and require continuous flow of nutrient solution, such as nutrient film technique (NFT) and deep flow technique (DFT). Whereas growing media are used in solid hydroponics, growing with intermittent supply of water and nutrients.

Savvas and Passam (2002) stated some guidelines for reaching a successful hydroponic system. "(i) Avoid a significant fluctuation of nutrient concentration in the culture solution, (ii) Maintain the solution pH and EC at the desirable levels, (iii) Provide a continuous oxygen

supply to the root system, (iv) be economically feasible, and (v) be easily adapted to a wide-range specifications of soil and climate conditions".

There are many different hydroponic cropping systems. Some of them are described below:

2.2 Deep flow technique (DFT)

DFT systems were first used for commercial cultivation by Gericke (1929). Plant roots are fully or partially submerged (Savvas and Passam 2002, Raviv and Lieth 2008). The depth of DFT schemes varies (15-30 cm) (Savvas and Passam 2002) and 5-15 cm (Raviv and Lieth 2008). Common width are 100-130 cm (Raviv and Lieth 2008).The plants can either be fixed in pots or floating on the nutrient solution, plants can be fixed in growing medium or directly into the container or without growing medium. DFT systems can be closed or open the closed systems have a larger initial investment since they preferably need to have a monitored nutrient solution and need more techniqual devices (Savvas and Passam 2002). The large amount of water in DFT systems makes it easier to control the nutrient solution and avoid large fluctuations (Raviv and Lieth 2008). The large water buffer also decreases the fluctuation in temperature making the systems practical in regions with large temperature changes (Park et al. 2001). Biggest drawbacks in DFT systems are that water tends to become too stagnant, thereby causing lack of oxygen. There is a considerable risk for dispersal of pathogens between plants. This problem has been attempted to solve with different types of aeration. From an ergonomic perspective, DFT are – due to their high weight hard to handle (Savvas and Passam 2002).

2.3 Nutrient film technique (NFT)

Dr. Allen Cooper developed NFT systems in the late 1960s -, this system has led to several modified systems used primarily for commercial production of leafy vegetables (Savvas and Passam 2002). NFT systems are based on a small but continuous flow of nutrient solution that passes the plants roots (Savvas and Passam 2002, Raviv and Lieth 2008). The plants are often fit into gutters with an inlet at one end has an inlet and an outlet at the other end. NFT systems basically work as follows; nutrient solution is pumped up from a container to the gutters, and runs back to the container after the passage through the gutters (Savvas and Passam 2002). The roots need to be kept moist but the layer of nutrient solution should be as thin as a film. Width of the gutters varies between crops and for lettuce gutter width 4-8 cm is suitable. Water flow for lettuce are optimal between 3-8 l m^{-2} h^{-1}(Raviv and Lieth 2008). NFT systems make it easier to monitor the composition of the nutrient solution since less water is used compared to the DFT systems. The nutrient solution can be computer-controlled which makes it easier to match the needs of the crop during different growth periods (Savvas and Passam 2002). Disadvantages with the NFT systems are that the small amount of nutrient solution in the system cannot buffer sufficiently and fluctuations in pH and EC might occur. The recirculation of nutrient solution and involuntary interruption in water supply raise the risk for spreading of

pathogens (Savvas and Passam 2002, Raviv and Lieth 2008). Another disadvantage is the high investment cost for these kinds of high-tech systems (Savvas and Passam 2002).

2.4 Plant plane hydroponics

Plant plane hydroponics can be used as open or closed systems. The plant seeds are placed between two polyester fleece layers which also work as growing media. The fleece layers are covered by plastic sheeting. The nutrient solution flows through the polyester fleece and provides the plant roots with nutrients and water (Schroeder and Goehler 1989).

2.5 Aeroponics

In the aeroponic system, the plant roots are in an environment that is intermittently saturated with small drops of nutrient solution. The water molecules cleaved ultrasonically and produce a fine mist (Savvas and Passam 2002, Raviv and Lieth 2008). Aeroponics is not yet commercially viable and is an expensive investment (Savvas and Passam 2002). There is a big risk by using aeroponics in commercial farming due to technical issues; there is no water buffer and no growing medium to retain moisture. If the production of mist fails, the plant will dehydrate quite quickly (Savvas and Passam 2002, Raviv and Lieth 2008).

2.6 Growing medium based hydroponic cropping systems

Hydroponic cropping systems incorporating solid growing media can either be open or closed. Often an inert growing medium is used to support the crop. Most crop species can be grown in solid media based systems and most common placement of growing media is in different types of mats, containers or pots. Common irrigation strategy is sub- or drip irrigation and individual irrigation is to prefer in case of disease. Advantages with incorporation solid growing media is; stability for the crop, maintained moisture and aeration around the roots. There is a wide range of commonly used growing media in commercial cropping systems such as; sand, perlite, mineral wool, pumice, polyurethane foam and natural organic medium (Savvas and Passam 2002).

2.7 Horizontal cultivation/vertical cultivation

Hydroponic cropping systems are commonly today implemented in different types of horizontal cropping systems, especially vegetables, ornamentals, berries and culinary herbs. The vertical cropping systems are an attempt to optimize space utilization and to maximize yield (Raviv and Lieth 2008). Very few vertical cropping systems are described in scientific articles, and the described ones mainly focus on vertical strawberry production (Linsley-Noakes et al. 2006, Linardakis and Manios 1990). Vertical cropping systems need to solve uneven light distribution which leads to that the upper plants get more light than the lower ones (Raviv and Lieth 2008), another risk in a vertical cropping system

according Leoni et al. (1994) is that plants such as lettuce might grow in a crooked shape depending on which angle the light comes from.

2.8 City planning perspective

One term that is used frequently in the public conversation today is the term “sustainability”. Sustainable city was coined by Register (1987) and describes cities that minimized their ecological footprint (Shakouri and Yazdi 2010). Sustainable city encourage plant cultivation in the cities. The cultivation is intended both for recreation, health benefits and for food production (Aldous 2007). However, most of the articles published about plant cultivation in the peri-urban- and urban areas both the scientifically and none scientifically articles are about future visions and literature studies for the sustainable cities. Very few publications deal with experiments, where cultivation strategies, crop quality and possible systems are evaluated for the potential use of cities as food production sites.

3 Materials and Methods

3.1 System Design

Two prototypes of vertical cropping systems prototype, P1 and P2, were evaluated during the project (see appendix, page 34 and 35). Both are closed and based on growing medium. They were designed for growing low (approximately 23 cm of height and 21 cm of width) plants, e.g. lettuce, herbs or strawberries. The prototypes are intended for pumice as growing medium because of its ability to buffer moisture (Sahin et al. 2002) and for simplify the root handling with less root losses at harvest (Wilson 1983). During this evaluation the nutrient solution was not disinfested.

P1 is a suspended, cone-shaped (80° inclination) unit with separate irrigation and drainage to each pot. It consists of 68 pots (0.8 dm^3 each), is 2.5 m high and occupies a surface area of 0.8 m^2 (Appendix, page 34). Each pot is mounted on its own drainage pipe which is connected to a central pole that carries the prototype. A tank (0.1 m^3) with nutrient solution was placed underneath the prototype. Nutrient solution was pumped (GARDENA model 2000/1) up from the tank through a hose (TORO 13 mm) inside the central pole and spiraling down on the outside of the prototypes, giving the fluid a natural fall. From this main hose, smaller hoses (GARDENA 4.6 mm) connected with a dripping nozzles (GARDENA ~2 l/h) distributes water to each pot. Each small hose had a natural fall and distributes nutrient solution to one pot. The drainage water runs from each pot into the center pole where the water runs down and back to the nutrient solution container. The drainage pipe in each pot was placed 20 mm above the bottom displaying a small water reservoir for each plant. The unit can be equipped with a motor in the suspension if rotation is desired.

The prototype P1 was divided into four levels from the bottom to the top based on distance from light source. The first level consisted of 20 pots, the second level of 23 pots, and the third level of 17 pots and the fourth level of 8 pots.

P2 is an A-shaped (80° inclination), floor-bound framework which consists of 18 vertically rotating NFT gutters with space for seven pots (0.37 dm^3 each) in each gutter (Appendix, page 35). The gutters measured 85/50/1760 mm (width/height/length). The construction was based on two chains that rotate on three axes with two cogwheels in the ends of each axis. The prototype is suspended on one side of the framework leaving the other side free for connecting irrigation and drainage. The nutrient solution was pumped (GARDENA model 2000/1) from a tank (0.1 m^3), and added in one end of each gutter through a rotating system connected to the chains and drained in the other end in similar way. Each gutter had a rotating suspension in both upper ends, and along with the growing medium in each pot this gave the gutters a low centre of gravity preventing the gutters tipping. It was 2.5 m high and occu-

pied 1.5 m^2. The rotating mechanism was not used during this experiment but can hypothetically be set in intervals to even out insufficient light intensity.

The prototype P2 was divided into six levels from the bottom to the top based on distance from light source. The first level consisted of 21 pots, the second level of 14 pots, the third level of 28 pots, the fourth level of 42 pots, the fifth level of 14 pots and the sixth level of 7 pots.

The fundamental difference between the two prototypes, other than the design itself, was that the plant roots in each gutter were in contact with each other in P2, while the roots in P1 were isolated from each other, making it suitable for crops that are particularly sensitive to root pathogens. Another difference was the irrigation strategies, where P2 had an intermittent NFT irrigation, and P1 had intermittent drip irrigation with a buffer in the pot bottom.

Schematics of the prototypes are found in Appendix.

3.2 Crop Management

The evaluation was conducted in the experimental greenhouse at SLU Alnarp (55,660297° N 13,077318° E), Sweden between October 2009 and February 2010. Two experiments were conducted (crop 1 and crop 2). Temperature was set at 21° C. Due to the poor natural light conditions in Sweden during winter, high pressure sodium (HPS) lamps were used during the experiment as complementary illumination. The HPS lamps (Philips SON/T, 400 W) were controlled by digital timers, and the prototypes were illuminated for 8 h per day between 08.00 and 16.00. The lamps were placed on each side of the prototypes with a displacement in one direction, giving the prototypes an artificial shadow effect. Humidity was not registered during the experiment due to technical errors (computer did not register).

As a model plant *Lactuca sativa* (*Lollo Rosso*, cv. Fortress) was used. The lettuce seeds were grown in perlite for three weeks (21 days) and then transplanted to the prototypes where they were grown for four weeks (28 days) during the first crop and for six weeks (42 days) during the second crop, before harvest. In both prototypes non fertilized, crushed pumice (Ø 2-8 mm, Hekla pimpsten®, Bara Mineraler) was used as a growing medium. During the first crop, the transplanted seedlings had an average fresh weight of 0.110 g (±0.024) and an average dry weight of 0.023 g (±0.009). During the second crop the average fresh weight was 0.094 g (±0.022) and the average dry weight was 0.020 g (±0.008) of the transplanted seedlings. The weight was measured from 20 randomly chosen seedlings before planting.

The nutrient solution composition was adapted according to recipes developed by Sonneveld and Straver (1994) with an extra addition of silica (Table 1) for an increased natural defense and stress relief in plants (Currie and Perry 2007). Once a week water samples were sent for analysis to LMI AB whereupon the nutrient solution was balanced according to the analysis. Twice a week electrical conductivity (EC) and pH was measured and balanced if necessary through dilution or addition of nutrient solution (EC), and addition of appropriate acids or bases (pH). EC was measured with an EcoScan CON5 (EUTECH Instruments) and pH was measured with a SevenGo Pro SG8 (Mettler Toledo). The nutrient solution naturally held ambient temperature (21° C).

Table 1. Nutrient recipe from Sonneveld (1989) with addition of silica and nutrient concentration in tap water from SLU Alnarp which was used in the calculation of nutrient solution

Nutrients	Sonneveld (mmol/l)	Sonneveld (mg/l)	Tap Water (mg/l)
pH	5.8-6.2	5.8-6.2	7.5
EC (ms/cm)	2.61	2.61	0.45
NO_3-N	19	266	2.91
P	2	61.9	0.115
K	11	430	3.1
Mg	10	24.3	3.18
S	11.3	36.1	28.6
Ca	45	180	60
Mn	0.005	0.275	0.037
B	0.03	0.324	0.015
Cu	0.00075	0.0477	0.022
Fe	0.04	2.23	0.002
Zn	0.004	0.262	0.258
Mo	0.0005	0.048	0.0006
Si	0.5	14	0.411
NH_4-N	1.25	17.5	0.1

The irrigation in P1 was set at 15 min every second hour with a flow of 1.71 l h^{-1} (±0.340) from 06.00 to 18.00 and for 15 min at 22.00 and 02.00. The irrigation in P2 was set at 5 min every hour with a flow of 43.3 l h^{-1} (±5.23) from 08.00 to 16.00 and for 5 min at 00.00.

3.3 Analyses

3.3.1 Plant analyses

After planting, the width and height of all plants were measured weekly, as well as the number of leaves along with the number of dead leaves which were removed at each time of measurement. The height was measured from the base of the plant to the tallest leaf, and the width was measured at the widest point of each plant. The number of dead plants was also registered during each time of measurement.

After the last measurement the plants were harvested and carefully removed from the pots along with the pumice. The roots were cut off at the base of the canopy whereupon the roots were rinsed and all pumice was removed. Root length, canopy fresh weight and root fresh weight was measured. For dry weight determination canopies and roots were dried at 70° C for 72 h. The drying temperature was chosen so that the samples can be sent for plant analysis for further evaluation if necessary.

Twenty and thirty plants were randomly chosen from P1 and P2 respectively, for further measurements of leaf color, leaf area and fluorescence. Leaf color was measured with a chromameter (CR-200, Minolta, Japan), parameter analyzed were hue angle (H°) indicating color differences, H° is divided in 0°/360° in the color wheel (McGuire 1992), translated to color terms 0°/360° (red/purple), 90°(yellow), 180°(bluish/green) and 270°(blue). Leaf area was measured with an area meter, model LI3100 (LI-COR, USA). Fluorescence was measured with a Handy PEA (Hansa Instruments,

England) after a dark-period of 20 min according to instructions. Parameter analyzed is Fv/Fm which is used for its sensitive indication of plant photosynthetic performance with a maximum value around 0.85, lower values of Fv/Fm indicates biotic or abiotic stress for the plants (Handy Pea operations manual 2006)

3.3.2 Analyses of environmental factors

Light intensity was measured in each pot of the prototypes with a light meter; model Li-189 (LI-COR, USA). The instrument was held in the center of each pot against the substrate were the light was measured before planting. The light intensity was also measured at various distances (every 10 cm from 10 to 260 cm) from the light source to obtain reference values to the plants distances from the light source.

3.3.3 Chemical analyses

After the harvest of each crop, growing medium (pumice) from three randomly chosen pots (total 1 dm^3) in the top half respectively bottom half (prototypes was divided in two halves). Growing medium was sent for chemical analysis at LMI AB. All pumice in the prototypes was reused during the second culture.

The TOC in the nutrient solution was analyzed from samples (200 ml) taken after each of the four crops. The analyses was conducted by the expulsion method according to standard procedures and instruction to the LANGE LCK385 (Hach-Lange, USA) (3-80 mg l^{-1}) determinator which was used in the analyses. The LANGE TOC-X5 (Hach-Lange, USA) (shaker), the LANGE LT200 (Hach-Lange, USA) (thermostat) and the LANGE XION$^{\Sigma}$500 (Hach-Lange, USA) (analyzer) were used during this analyzed according to the standard procedures and instructions.

3.3.4 Microbiological analyses

Microbial assessment was conducted with respect to the bacterial and fungi flora using R2A (product number: 218263) (BD Difco, USA) and malt extract agar (MA) (6 g of malt extract (product number: 211220) (BD Difco, USA) 12 g of bact agar (product number: 218263) (BD Difco, USA) and 1000 ml of distilled water). From each prototype, two samples (each 150 ml) were collected with two replicates. The nutrient solution was serially diluted in 0.85% NaCl solution and 100 µl were inoculated on the agar plates. Plates were incubated for 96 h in 25°C for R2A and MA respectively.

3.3.5 Statistical Analysis

Statistical analyses were carried out using univariate ANOVA (UNIANOVA) to test the differences between the prototypes dependent on the light intensity (covariate) for each plant. One way ANOVA followed by Tukey`s test were used for statistical analyses regarding canopy fresh weight and light depending on level within the prototypes P1 and P2 and for statistical analyses of differences in the microbiological assessment. Independent samples T-test followed by Levines test. Statistical analyses were carried out in the statistical program SPSS Statistics 19 (IBM, USA).

4 Results

4.1 Plant results

Prototype 1 (P1) and prototype 2 (P2) were appropriate for lettuce *Lactuca sativa* (*Lollo rosso, cv. fortress*) production, both crop 1 and crop 2 generated lettuce plants (Fig. 1A-B). The plant survival was greater in P1 than in P2 in both crops but the differences were only significant in crop 2.
In crop 1 95.6 % of the plants survived in P1 and 88.1 % in P2. In crop 2 80.9 % of the plants survived in P1 and 52.4 % in P2. There were no significant differences between P1 and P2 in repetition 1 ($p>0.05$) but significant differences occurred in repetition 2 ($p<0.001$) according to independent samples T-test followed by Levines test.

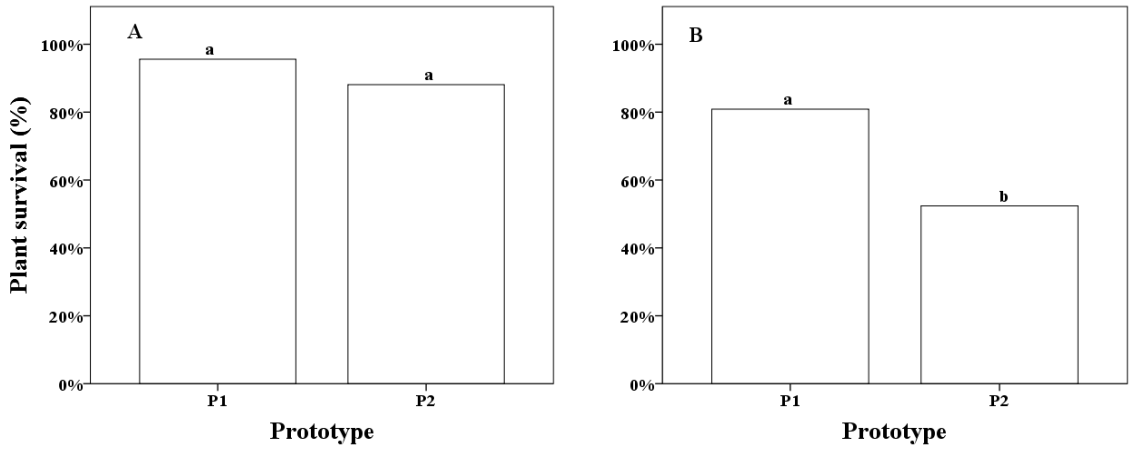

Figure 1. Survival (%) of lettuce (*Lollo rosso*) that survived until harvest in the two prototypes. Lettuce was grown in two prototypes of vertical cropping systems, P1 and P2, with either drip (P1) or sub-irrigation (P2). The experiment was repeated once. A: repetition 1: November – December, (P1; n=68, P2; n=126); B: repetition 2: December – January (P1; n=68, P2; n= 126). Bars labeled with different letters were significantly different according to independent samples T-test followed by Levines test ($p<.0.001$).

The canopy fresh weight varied within the prototypes P1 and P2 related to their position (Fig. 2A-D). The overall average canopy fresh weight in crop 2 was higher. Canopy fresh weight differed significant within P1 and P2 respectively dependant on position in both crop 1 and crop 2. Variations were larger in crop 2 (C-D) than in crop 1 (Fig. A-B).

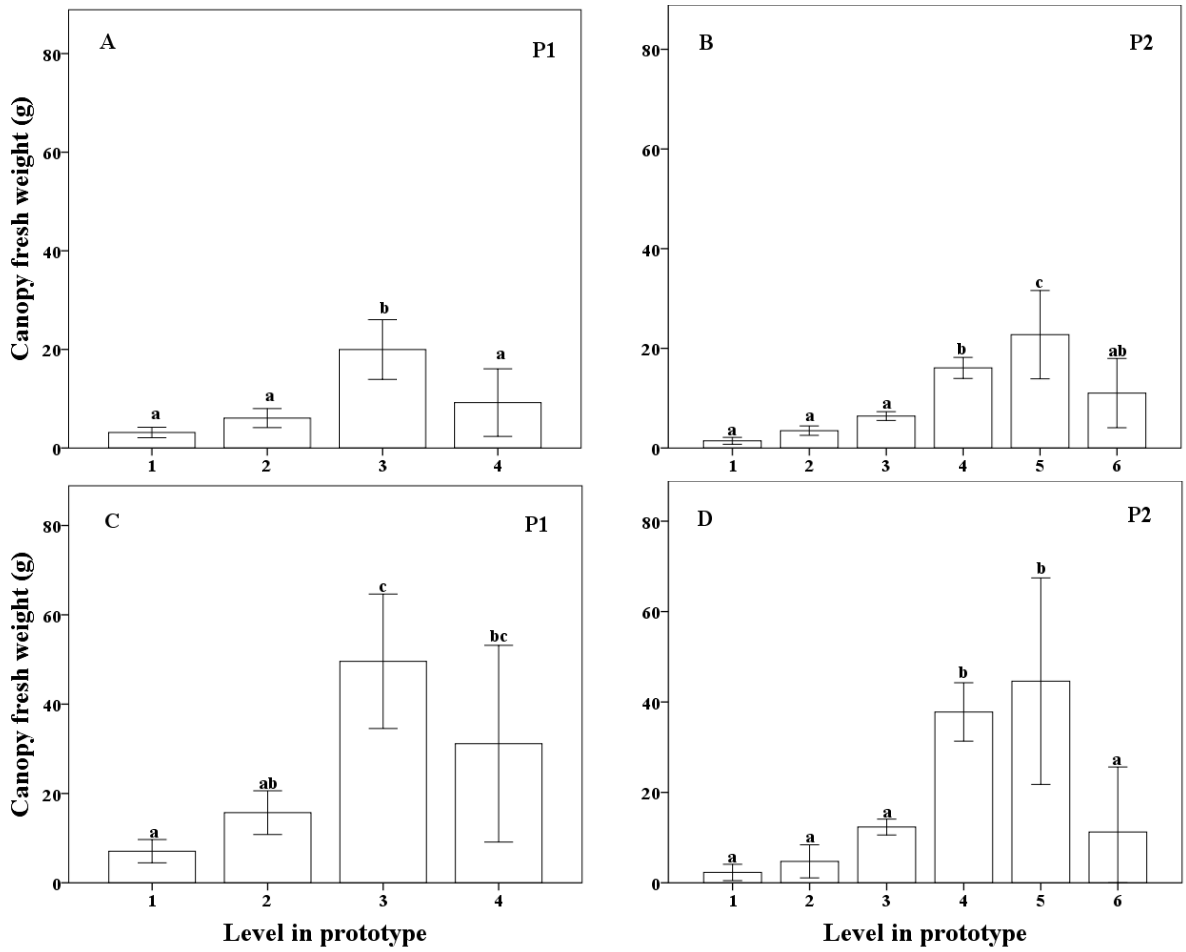

Figure 2. Average canopy fresh weight (g) of lettuce (*Lollo Rosso*) at different levels in the prototypes. Lettuce was grown in two prototypes of vertical cropping systems, P1 and P2, with either drip (P1) or sub-irrigation (P2). The experiment was repeated once. A (P1) and B (P2): repetition 1: November – December, (P1; n=65, P2; n=80); C (P1) and D (P2): repetition 2: December – January (P1; n=55, P2; n= 66). Bars labeled with different letters were significantly different according to ANOVA followed by Tukey`s test (p<.0.05)

4.2 Environmental results

Distribution of light was uneven between level location in P1 and P2 (Fig. 3A-B). There were significant differences in light intensity between the levels within P1 and P2 respectively. Even within levels there were large variations of light intensity, especially level 2 and 3 in figure 5 A and level 3 in figure 3 B.

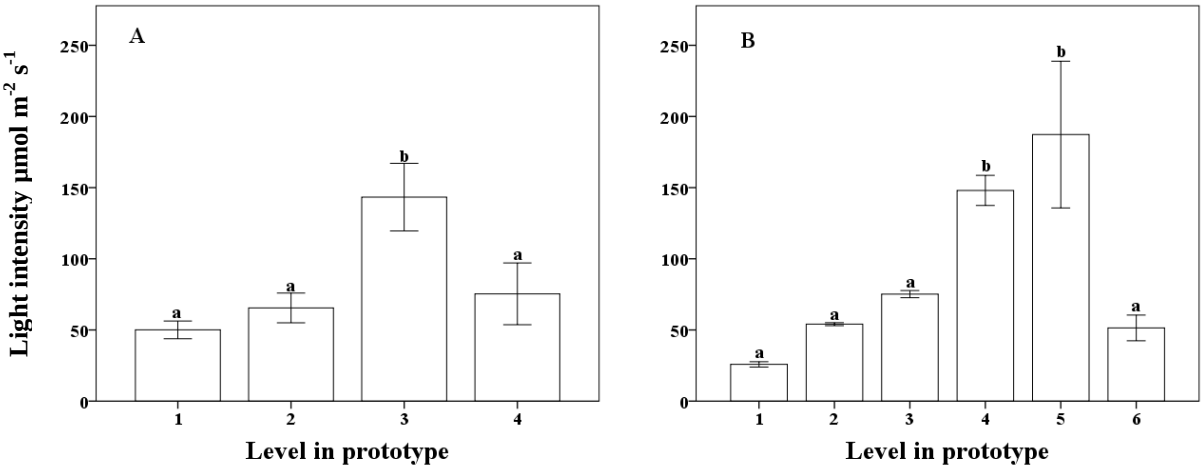

Figure 3. Average light intensity (µmol m^{-2} s^{-1}) from light source (Philips SON/T, 400 W) at different levels in the prototypes. Measurements were made (beginning of November) pot specific in the two different prototypes P1 (A; n=68) and P2 (B; n=80), pots were divided into levels due to distance from light source. Bars labeled with different letters were significantly different according to ANOVA followed by Tukey`s test (p<.0.05).

The decline of light intensity is clearly shown in figure 4. Light intensity steeply dropped due to the greater distance from light source. There was only approximately 2 % left of the initial light intensity 2.5 m away from light source and the distance where lettuce (*Lollo rosso*) get optimal light conditions 200-250 µmol m^{-2} s^{-1} is only about 15 cm. Light intensity decreases rapidly and between 10 cm and 20 cm distance light intensity drops 56.5 %. 2.5 meters from light source only 1.85 % of the intensity remains.

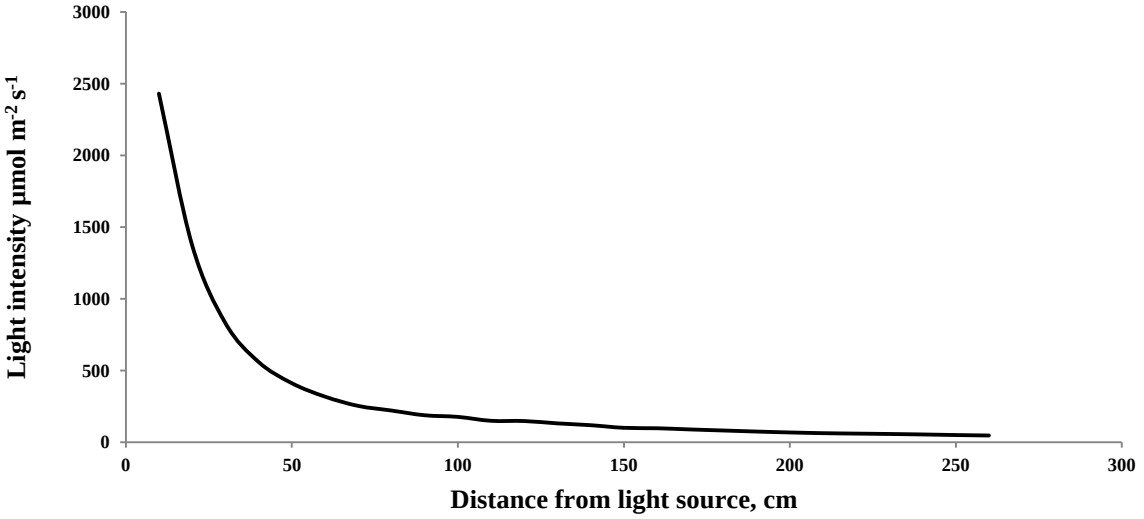

Figure 4. Light intensity (µmol m^{-2} s^{-1}) as affected by distance from light source (Philips SON/T, 400 W). Measurements were made (beginning of November) with 10 cm intervals from light source, starting at 10 cm and ending at 260 cm.

Canopy fresh weights in prototype P1 and P2 were correlated with light intensity (Fig. 5 A-B) in crop 1 (A) and crop 2 (B) respectively. There is a tendency in crop 1 that plants grown in P1 were heavier than plants in P2 at comparable light intensity, but differences were not significant. However in crop 2

(B) there is a significant difference between the prototypes P1 and P2 regarding canopy fresh weight affected by light intensity.

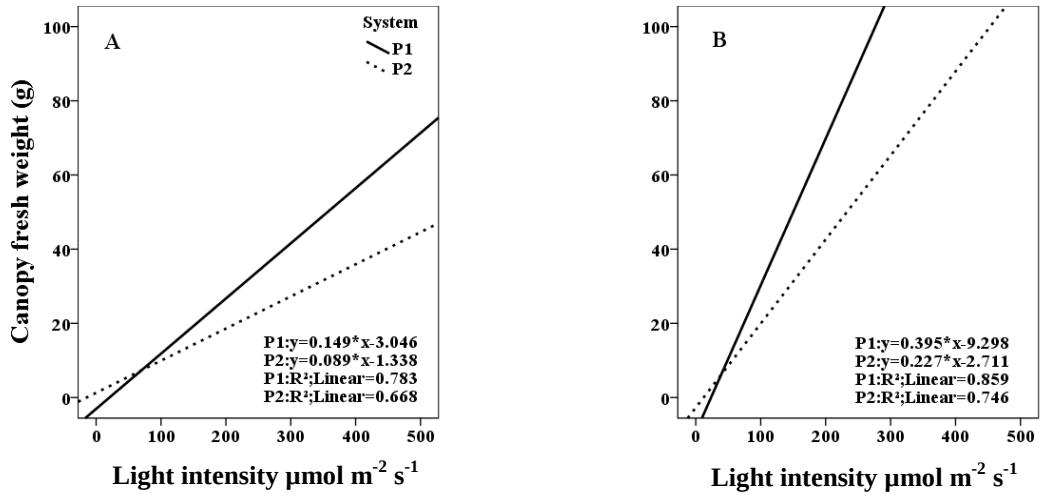

Figure 5. Canopy fresh weight (g) of lettuce (*Lollo Rosso*) as affected by light intensity (µmol m^{-2} s^{-1}). Lettuce was grown in two prototypes of vertical cropping systems, P1 and P2, with either drip (P1) or sub-irrigation (P2). The experiment was repeated once. A: repetition 1: November – December, (P1; n=65, P2; n=80); B: repetition 2: December – January (P1; n=55, P2; n= 66). There were no significant differences between P1 and P2 in repetition 1 ($p>0.05$) but significant differences occurred in repetition 2 ($p<0.001$) according to UNIANOVA

Canopy dry weight (Fig. 6 A-B) followed the same pattern as canopy fresh weight with correlation between canopy dry weight and light intensity for plants grown in prototype P1 and P2. But canopy dry weight showed significant differences between prototypes P1 and P2 in both crops respectively.

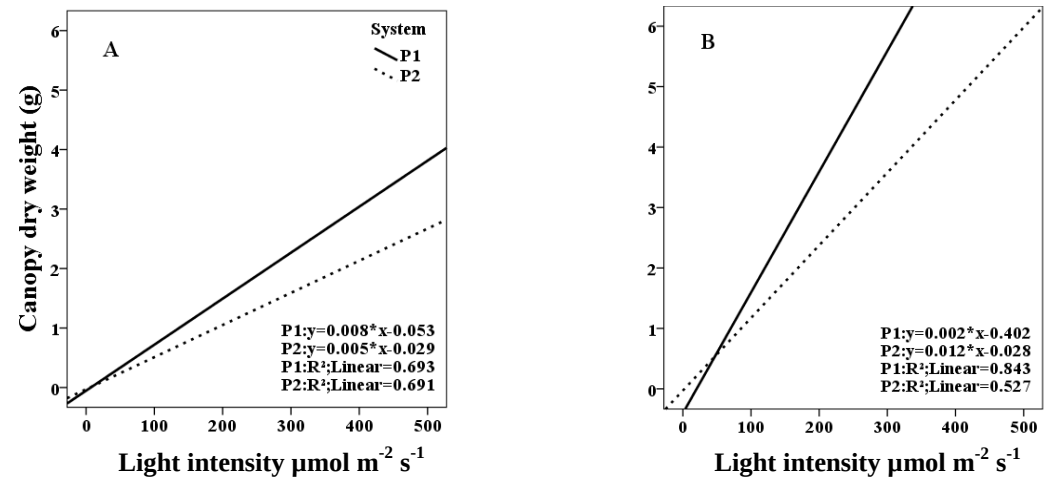

Figure 6. Canopy dry weight (g) of lettuce (*Lollo Rosso*) as affected by light intensity (µmol m^{-2} s^{-1}). Lettuce was grown in two prototypes of vertical cropping systems, P1 and P2, with either drip (P1) or sub-irrigation (P2). The experiment was repeated once. A: repetition 1: November – December, (P1; n=63, P2; n=80); B: repetition 2: December – January (P1; n=55, P2; n= 66). There were significant differences between P1 and P2 in repetition 1 ($p<0.001$) and in repetition 2 ($p<0.05$) according to UNIANOVA

Leaf area was correlated to light intensity in crop 1 and crop 2 respectively (Fig. 7 A-B). No significant differences were shown in crop 1 between the two prototypes P1 and P2, but in crop 2 significant differences occurred between prototypes.

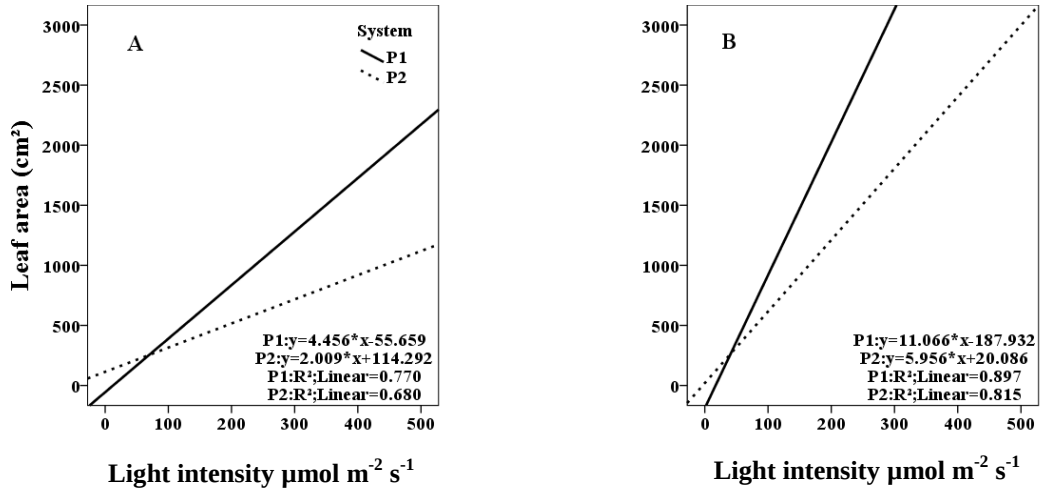

Figure 7. Leaf area (cm²) of lettuce (*Lollo Rosso*) as affected by light intensity (µmol m^{-2} s^{-1}). Lettuce was grown in two prototypes of vertical cropping systems, P1 and P2, with either drip (P1) or sub-irrigation (P2). The experiment was repeated once. A: repetition 1: November – December, (P1; n=20, P2; n=30); B: repetition 2: December – January (P1; n=20, P2; n= 28). There were no significant differences between P1 and P2 in repetition 1 ($p>0.05$) but significant differences occurred in repetition 2 ($p<0.01$) according to UNIANOVA.

Fluorescence measurements of Fv/Fm values had a green spot in the data handling program which indicates no stress, a UNIANOVA showed that no significant difference were found between the prototypes P1 and P2 in crop 1 and crop 2 respectively ($p=>0.05$). Leaf color (H°) measurements analyzed showed significant differences between P1 and P2 in crop 1 according to UNIANOVA ($p<0.01$), correlations between light intensity and color (H°) were however weak. In crop 2 color measurements showed no significant differences between P1 and P2 according to UNIANOVA ($p>0.05$), also here no correlation were found.

Root fresh weight (Fig. 8 A-B) showed significant differences between prototypes P1 and P2 and correlations between root fresh weight and light intensity were stated.

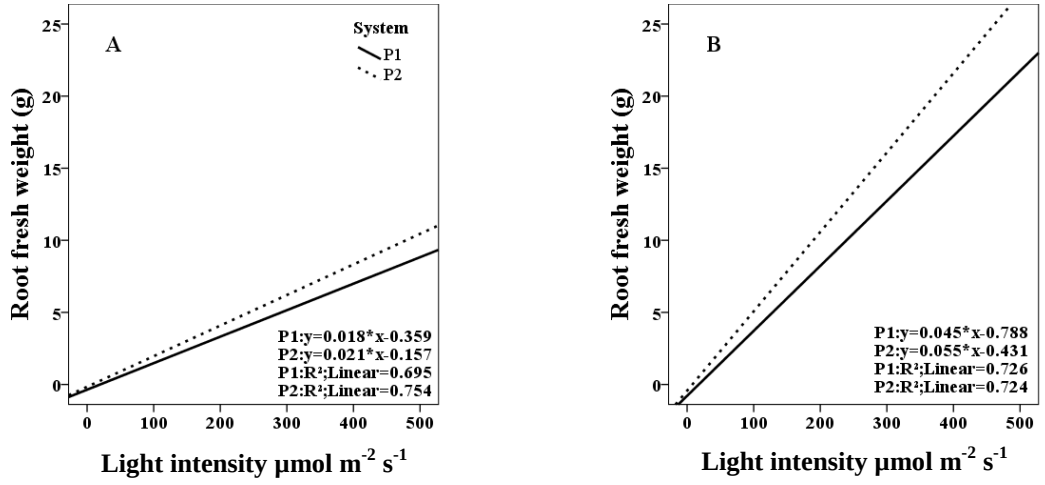

Figure 8. Root fresh weight (g) of lettuce (*Lollo Rosso*) as affected by light intensity (µmol m^{-2} s^{-1}). Lettuce was grown in two prototypes of vertical cropping systems, P1 and P2, with either drip (P1) or sub-irrigation (P2). The experiment was repeated once. A: repetition 1: November – December, (P1; n=65, P2; n=80); B: repetition 2: December – January (P1; n=55, P2; n= 66). There were significant differences between P1 and P2 in repetition 1 and 2 ($p<0.01$) according to UNIANOVA.

In crop 1root dry weight (Fig. 9A-B) showed no significant differences between prototypes P1 and P2. In crop 2 root dry weights differed significant between prototypes P1 and P2. Correlations between root dry weight and light intensity were detected in both crops (Fig. 9A-B).

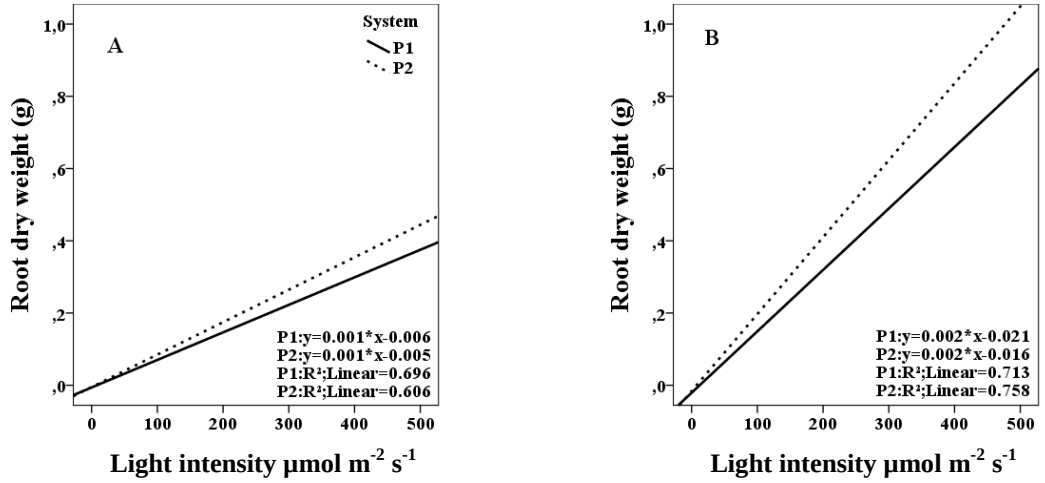

Figure 9. Root dry weight (g) of lettuce (*Lollo Rosso*) as affected by light intensity. Lettuce was grown in two prototypes of vertical cropping systems, P1 and P2, with either drip (P1) or sub-irrigation (P2). The experiment was repeated once. A: repetition 1: November – December, (P1; n=59, P2; n=79); B: repetition 2: December – January (P1; n=55, P2; n=64). There were no significant differences between P1 and P2 in repetition 1 ($p>0.05$) but significant differences occurred in repetition 2 ($p<0.01$) according to UNIANOVA.

Root length (Fig. 10 A-B) differed significant between prototypes P1 and P2 in both crops ($p<0.001$). No strong interaction between root length and light intensity was found.

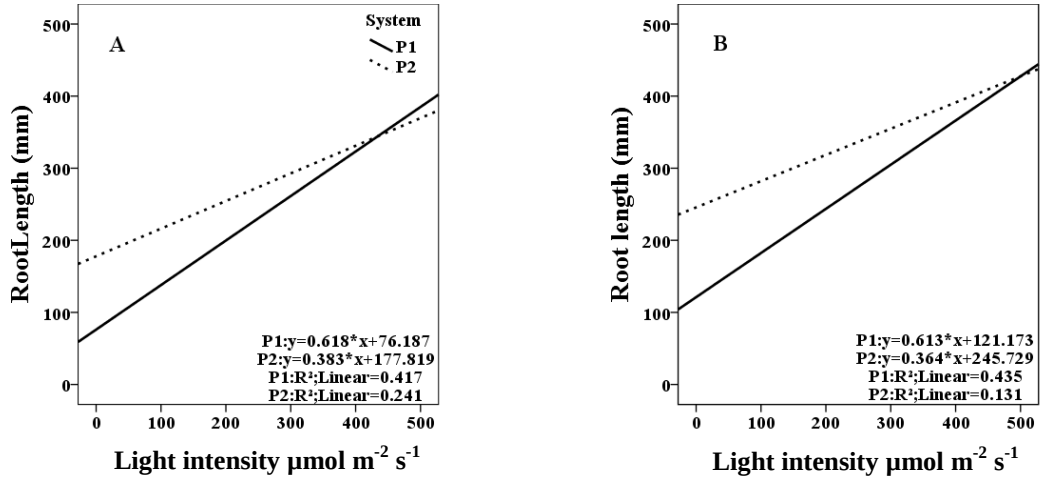

Figure 10. Root length (mm) of lettuce (*Lollo Rosso*) as affected by light intensity (µmol m^{-2} s^{-1}). Lettuce was grown in two prototypes of vertical cropping systems, P1 and P2, with either drip (P1) or sub-irrigation (P2). The experiment was repeated once. A: repetition 1: November – December, (P1; n=65, P2; n=80); B: repetition 2: December – January (P1; n=54, P2; n=66). There were significant differences between P1 and P2 in repetition 1 and 2 ($p<0.001$) according to UNIANOVA.

4.3 Chemical analyses

Variations in water parameters based on analysis from LMI AB are displayed in table 2. Na, Cl and Al were not included in Sonnevelds recipe (Table. 1) but were detected in the analyses.

Table 2. The chemical analyses were made at LMI AB. Minimum and maximum values of nutrients (mg/l) in the drained nutrient solutions in prototype 1 (P1) and prototype 2 (P2) during repetition 1 (crop 1) and repetition 2 (crop 2).

Nutrient (mg/l)	*Prototype 1* Crop 1 min. - max.	*Prototype 2* Crop 1 min. - max.	*Prototype 1* Crop 2 min. - max.	*Prototype 2* Crop 2 min. - max.
pH	4.90 - 5.80	5.30 - 6.10	5.50 - 6.20	6.00 - 6.30
EC (mS/cm)	3.15 - 3.51	3.06 - 3.43	2.86 - 3.25	2.75 - 3.05
NO_3-N	268 – 315	261 - 296	267 – 302	246 - 282
P	50.9 - 89.0	61.8 - 100	27.1 - 61.0	33.5 - 61.5
K	410 – 495	423 - 501	375 – 474	322 - 429
Mg	31.4 - 33.8	29.9 - 33.9	23.8 - 25.9	23.8 - 24.8
S	86.3 - 94.3	86.7 - 101	56.1 - 76.8	57.7 - 82.8
Ca	269 – 315	263 - 298	224 – 267	201 - 283
Na	20.7 - 25.8	15.5 - 20.5	15.0 - 27.2	16.7 - 29.5
Cl	30.3 - 35.9	16.2 - 21.6	15.4 - 20.8	18.0 - 29.6
Mn	0.0860 - 0.425	0.0440 - 0.206	0.0240 - 0.425	0.042 - 0.229
B	0.365 - 0.408	0.333 - 0.354	0.257 - 0.296	0.239 - 0.296
Cu	0.239 - 0.282	0.267 - 0.378	0.138 - 0.196	0.117 - 0.535
Fe	1.16 - 1.44	0.888 - 1.46	0.922 - 1.59	0.942 - 1.46
Zn	0.611 - 1.02	0.891 - 1.64	0.264 - 0.613	0.260 - 1.15
Mo	0.0170 - 0.0500	0.031 - 0.038	0.00400 - 0.0560	0.0500 - 0.0170
Al	0.0500 - 0.0880	0.013 - 0.048	0.0140 - 0.256	0.0110 - 0.199
Si	13.2 - 24.1	2.37 - 11.2	1.36 - 27.2	1.36 - 11.6
NH_4-N	5.75 - 21.1	13.2 - 22.9	0.127 - 34.3	1.50 - 31.9

Nutrient content, pH and EC in the growing medium are displayed in table 3. In general there was a higher content of nutrients in crop 2 than crop 1 both at top- and bottom half. There were also higher nutrient content in the top halves compared to bottom halves. Some nutrients increased extremely from crop 1 to crop 2. Small variations in pH were detected (6.2-6.4). EC on the other hand had much higher variations (1.9-8.9 mS/cm). In general EC were higher in crop 2 than in crop 1 in both top- and bottom halves.

Tabel 3. pH, EC and nutrient content in the growing medium (pumice). Prototypes were divided in two (top half; bottom half). Growing medium from pots positioned in top- respectively bottom half in prototype P1 and P2 were collected. One sample at each half was analyzed. Experiment were repeated once (crop 1 and crop 2)

Nutrient (mg/l)	P1				P2			
	Crop 1		Crop 2		Crop 1		Crop 2	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
pH	6.3	6.2	6.3	6.4	6.3	6.3	6.3	6.2
EC(mS cm^{-1})	3.8	3.0	8.4	6.2	2.4	1.9	9.6	6.6
NO_3-N	388	308	748	659	282	199	980	592
NH_4-N	6	6	20	12	3	5	8	12
P	35	33	54	43	39	31	55	33
K	561	456	1140	958	388	324	1370	863
Mg	55	46	76	67	40	29	91	54
S	103	98	172	146	93	62	251	140
Ca	385	338	669	583	358	249	930	519
Na	97	80	96	84	56	43	109	670
Cl	86	66	62	55	27	27	50	33
Mn	0.9	0.8	23	1.8	0.8	0.6	2.5	1.7
B	0.4	0.3	0.6	0.5	0.3	0.2	0.8	0.4
Cu	0.6	0.5	n/a	n/a	0.6	0.4	n/a	n/a
Fe	12	11	n/a	n/a	16	13	n/a	n/a
Zn	2	2	n/a	n/a	3	3	n/a	n/a
Mo	0.08	0.08	n/a	n/a	0.1	0.07	n/a	n/a
Al	7	6.7	n/a	n/a	5.9	6.2	n/a	n/a

Analyses of TOC content (mg l^{-1}) in the nutrient solution did not show any large variations between prototypes in both crops. TOC in P1 was 14.5 mg l^{-1} in crop 1 and 11 mg l^{-1} in crop 2. TOC in P2 was 12.2 mg l^{-1} in crop 1 and 13.6 mg l^{-1} in crop 2.

4.4 Microbiological results

Analyses of the microbiological assessment stated significant differences ($p<0.05$) between prototype P1 and P2 colony-forming unit (cfu) bacteria and fungi. Prototype P2 had higher abundance of bacteria and fungi in the nutrient solution in both crops.

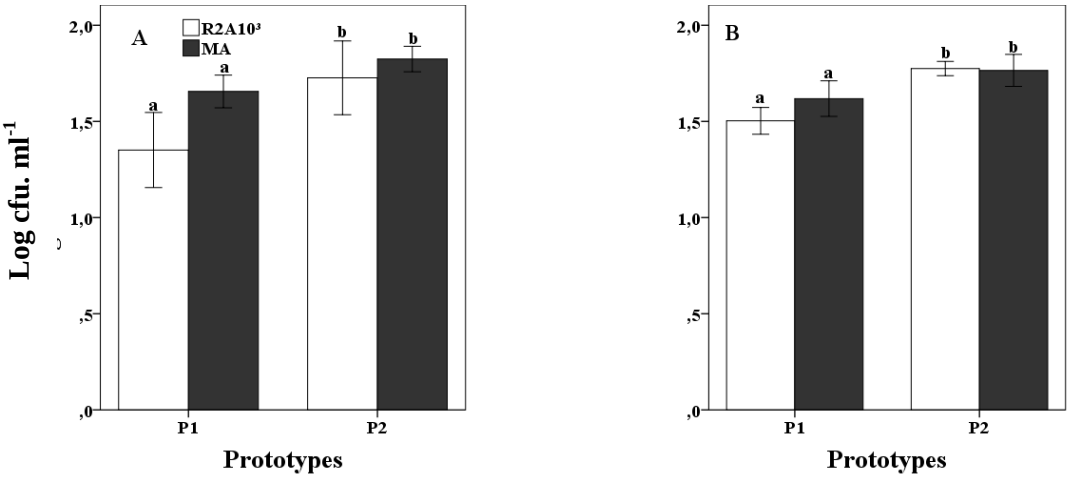

Figure 11. Viable count of bacteria (cfu; R2A) and fungi (MA)in the two prototypes for vertical cropping systems. Lettuce (*Lollo Rosso*) was grown in two prototypes of vertical cropping systems, P1 and P2, with either drip (P1) or sub-irrigation (P2). Nutrient solution were collected and inoculated on agar plates. The experiment was repeated once. A: repetition 1: November – December, (P1; R2A 10^3; n=6, P2; R2A 10^3 n=6); (P1; MA; n=12, P2; MA; n=12). B: repetition 2: December – January (P1; R2A 10^3; n=6, P2; R2A 10^3 n=6); (P1; MA; n=12, P2; MA n=12). Bars labeled with different letters were significantly different according to ANOVA followed by Tukeys test (p<.0.05)

4.5 Statistical results

A consolidation of statistical results is shown in table 5.

Table 5. Summary of statistical results showing significances between prototypes P1 and P2 divided in crop 1 and crop 2

	Difference between prototypes	
Measurements	Crop 1	Crop 2
Root Length	p<0.001 (***)	p<0.001 (***)
Plant fresh weight	p>0.05 (No sig.)	p<0.001 (***)
Plant dry weight	p<0.001 (***)	p<0.01 (**)
Root fresh weight	p<0.01 (**)	p<0.01 (**)
Root dry weight	p>0.05 (No sig.)	p<0.01 (**)
Leaf area	p>0.05 (No sig.)	p<0.01 (**)
Fluoroscence	p>0.05 (No sig.)	p>0.05 (No sig.)
Leaf color (c)	p<0.001 (***)	p>0.05 (No sig.)

5 Discussion

Development of vertical cropping system is an essential step for implementation of urban horticulture. In the present study, two prototypes were tested with one replicate each. The study was repeated once. The gathered results give an insight about limitations of the systems, which is an important step at this stage of the development. For evaluation of the systems, a more thorough scrutiny has to be performed.

There are only few vertical cropping systems and even less has been assessed in a scientific way. Therefore, the possibilities for comparison are limited and horizontal cropping systems for production of lettuce in greenhouses are used for comparison in the present stage. Considering plant survival (Fig. 1A, B) both prototypes were appropriate for lettuce production. With respect to achieved plant weight, both prototypes displayed a potential for production of lettuce (*Lollo rosso*). However, as few plants had a commercially acceptable size about 100 g (Engström 2011), further improvements have to be done. We therefore conclude that both prototypes are potential candidate systems for vertical cropping systems.

Variations between the prototypes were substantial with respect to canopy fresh weight (Fig. 5 A, B). Also, considerable variations in canopy fresh weight within both prototypes were observed (Fig. 2 A-D).

Light intensity was identified as a dominant factor. This supports hypothesis 2. Lettuce (*Lactuca sativa*) is a light demanding crop (Karlsson and Werner 2009) and is a challenge to grow in vertical systems. Shadow effect is a common problem in vertical cropping systems who often suffer from it (Linsley-Noakes et al. 2006). The shadow effect leads to that crop just few inches away from each other can have totally different light conditions, this is shown in figure 3 A-B where the light intensity in level 3 and 4 in P1 and level 5 in P2 shows large variance within the same level.

In our experiment, light was supplied from above. It is common sense that light intensity decreases by increasing distance from the light source. Furthermore, a stronger shadow effect may be expected depending on the position of the light source, as opposed to horizontal cropping systems. We therefore conclude that the position of the light source should be altered from top illumination to crop stand illumination. When adopting energy saving light sources, this would also lead to a heat gain for the crop.

In the present comparison, light intensities varied between 17–435 µmol $m^{-2}s^{-1}$. Despite of these variations, no stress response in photosystem II was detected based on fluorescence measurements (Maxwell and Johnson 2000). Fluorescence measurements can never be used for comparison between leaves or plants without additional measurements such as gas ex-

change analysis (Maxwell and Johnson 2000) making it difficult to draw any conclusions based on results.

Leaf color is another important variable growing *Lollo rosso* because of its sharp red color. In general, light conditions during subarctic winters are not suitable for production of leaf lettuce in greenhouses (Karlsson and Werner 2009).

In the present case we used *Lollo rosso* as an indicator plant for plant performance in relation to light conditions. In crop 1 there were significant differences between P1 and P2 regarding leaf color (H°), however crop 2 did not show any significant difference between the prototypes. These findings demonstrate that prototype 2 is more sensitive to low light conditions as compared to prototype 1. The absence of strong reddish canopies is probably linked to that illumination strategy of 8 hours of complementary illumination wasn't enough.

The significant differences in canopy fresh weight are explained in figure 5 A-B were a correlation between canopy fresh weight and light intensity is shown. Crop grown in P2 where more similar in size and gradually increased or decreased in size depending on light intensity.

Both prototypes were based on intermittent irrigation strategies. However, in P1 a certain container volume was retained for buffering of water and nutrients. Instead, the irrigation interval in P2 was shorter. Both prototypes used the same recipe of nutrient solution from Sonneveld and Straver (1994) and no disinfection occurred. The hypothesis 3a and 3c "Biomass production differs between prototypes due to water and nutrient supply" and "Biomass production will be less affected in P1 due to constant water availability" cannot be supported from the present data. But water and nutrient supply have an impact on plant performance (Raviv and Lieth 2008). Changes in pH, EC, salinity and nutrient concentration can all have considerable impacts in crop nutrient uptake and thereby affect yield and crop size (Savvas and Passam 2002). Optimal plant performance and nutrient uptake for lettuce according Sonneveld and Straver (1994) occurs with a pH 5.8-6.2 and an EC value around 2.6 mS cm^{-1}. No large variations in pH and EC occurred during none of the experiments (table 2). However nutrient concentrations shown in Table 2 displayed large variations between minimum and maximum levels of specific nutrients. Periods with nutrient deficiency and skewed nutrient distribution might affect crop growth negatively.

Light intensity also affect water and nutrient relations and is a major factor affecting photosynthesis (Savvas and Passam 2002) and in general water and nutrient uptake increases with increased light intensity (Raviv and Lieth 2008). However, crop grown in P1 intend to grow larger than in P2 even under similar light conditions (Fig. 5A-B) this could be deduced to better water and nutrient supply strategy in P1. Also the significant differences between P1 and P2 according to leaf area (Fig. 7B) state that crop grown in had better water availability than crop grown in P2 this according to Williams et al. (1999) that showed a correlation between reduced leaf area and dehydration.

Hypothesis 3b"Root length and root biomass differs between prototypes due to differences in water and nutrient supply" can be supported, significant differences between the prototypes regarding root length (Fig. 10 A-B), root fresh weight (Fig. 8 A-B) and root dry weight (Fig. 9 B) occurred. Root length intends to increase due to water stress (Henry et al. 2011) and it is shown that crop grown in P2 have both longer and heavier roots than crop grown in P1 even though the canopy fresh weight were higher in P1. This means that crop grown in P2 puts

more energy in root growth than crop grown in P1. We conclude that crops grown in P2 to some extent were affected by water shortage.

There was a significantly higher microbial growth of bacteria and fungi in P2 than in P1 (Fig. 11 A-B). Obtained viable counts for bacteria or fungi were low, which is in line with viable counts in experimental and commercial settings with lettuce (Delaquis et al. 1999). Differences might depend on the system design with open channels in prototype 2 as compared to drip irrigation in prototype 1. The observed differences were not reflected in the total organic carbon content assessed at the end of the experiments. This might indicate that the organic carbon was used to in a limited extent. Reasons for limited use of carbon in hydroponics may depend on (i) non-mineralisation of organic compounds originated from the incoming water and/or released by roots, substrate or technical devices, (ii) non-solubility of the organic compound in the nutrient solution, (iii) no match between the site where the organic compound is present with the site where microorganisms able to degrade this compound are present or (iv), inability of the resident microflora to produce enzymes to degrade the organic compound in question and/or incapacity to induce such enzyme complexes as described by Alsanius and Jung (2004). Distribution of nutrient solution in closed hydroponics is an important factor for spread of root and water borne pathogens. With respect to this issue, the single container approach in prototype 1 might be less conducive to plant diseases than the set up of in prototype 2. In extension, prototype 1 might be more suitable when sensitive crops are grown.

6 Conclusion

We conclude that;
i) prototypes 1 and 2 are interesting candidates for vertical production of lettuce.
(ii) both prototypes need improvements.
(iii) light is a limiting factor when provided as top irradiation. Crop stand irradiation appears to be a more appropriate way of distributing light to crops grown in these prototype systems.
(iv) P2 needs irrigation improvements.

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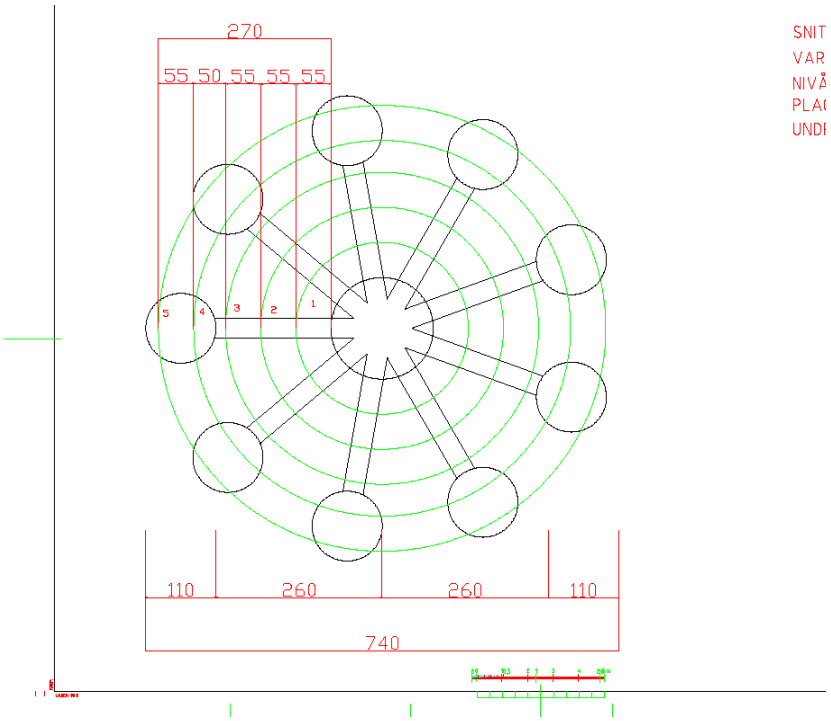
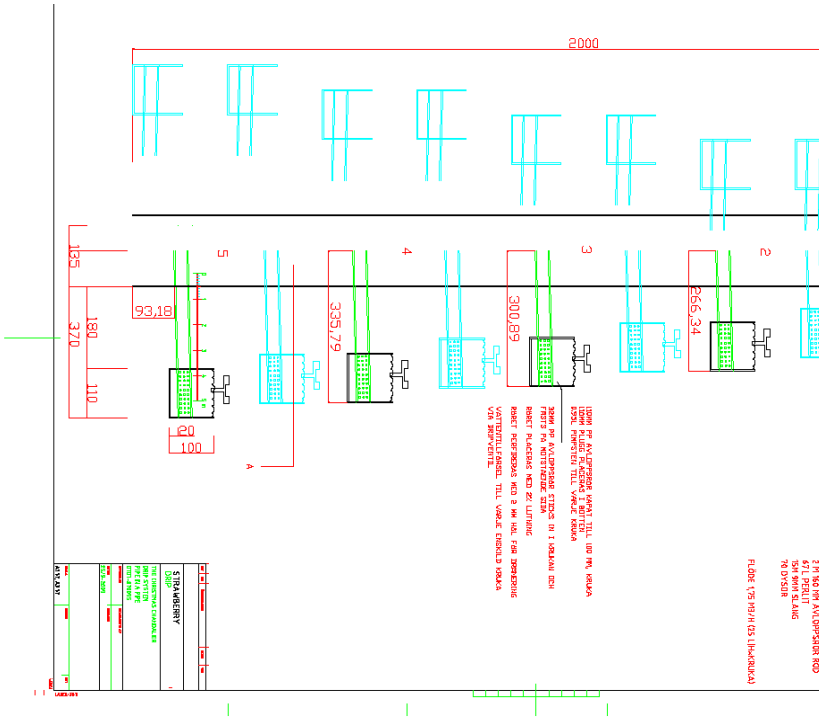
9 Appendix

Schematics of prototype P1 and P2.

Prototype P1.





Prototype P2.