Comparison of Light Emitting Diode and High Pressure Sodium Light for Hydroponics Growth of Boston Lettuce

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Abstract

Sustained developments in light emitting diode (LED) technology have brought their irradiance to a suitable level for being considered as a replacement to traditional high pressure sodium (HPS) lamps in hydroponics growth environments. LED lamps are anticipated to replace HPS lamps in most applications due to their reduced electricity consumption, improved quality of light and the possibility for customization of the light spectrum for increased yields. While equipment costs are still high, as is the case with most new technologies, greenhouse growers across the world stand to substantially decrease their energy use which directly translates into reduced costs and reduced carbon emissions from the energy stand point.

We have compared the effects of LED lamps (LED Innovation Design, TI-SL600) made by LED Innovation Design (Terrebonne, Quebec) against HPS lamps (ballast: Philips Advance Model 71A85F5; Bulb: General electric, model LU600X0PSLT40) used at HydroSerre Mirabel (Mirabel, Quebec) for the growth of Boston lettuce (*Lactuca sativa* var. *capitata*) for both biomass yields and nutrient content. The light treatments were applied for eight hours after sunset to extend the photoperiod to sixteen hours. Wet and dry masses of plants and roots were weighed on a weekly basis during the course of the experiment. On average, optimum HPS light treatment produced statistically similar masses compared to optimum LED light treatment even though the LED lamps provided roughly half the amount of moles of light per meter^2 compared to the HPS lamps at final harvest time (71.3moles/m^2 for HPS and 35.8moles/m^2 for LED over four weeks).

There was no statistical difference between the samples taken from LED and HPS optimum light treatments, regular HPS greenhouse levels and control (no supplemental light) treatment for both wet and dry masses. However, LED light treatments showed improved homogeneity of plant mass across the entire area while HPS light treatment showed potential for elevated production in limited areas. Dry ratios of plant mass (in grams) by artificial irradiation (in moles per plant) normalized by the percentage of supplemental light versus total light were of 0.54 g/mol/plant and 0.35 g/mol/plant for

both HPS experimental replications and of 0.59 g/mol/plant and 0.26 g/mol/plant for both LED experimental replications. This indicates that while there is an intensity difference between both light treatments, plant mass production remained similar.

Health benefits are linked with increased consumption of β-carotene and other phytochemicals present in vegetables, such as lettuce. Photomorphogenesis may enable increased concentrations of those healthy compounds at little cost to the growers. However, contrary to expected results, chemical analysis of LED-treated samples showed the smallest concentrations of β-carotene, chlorophyll a and b, neoxanthin, lutein, antheraxanthin and violaxanthin. Both control replications are significantly more concentrated in xanthophylls and chlorophylls than the samples taken from the HPS plots, which were also more concentrated than the samples harvested from LED plots. Additional research needs to be performed to optimize the LED-based photomorphogenesis process.

Résumé

Les développements récent et continus dans la technologie des lampes à Diodes Électro-Luminescentes (DEL) ont permis à leur intensité d'atteindre un niveau suffisant pour être considéré comme un remplacement pour les lampes traditionnelles au sodium à haute pression (HPS) dans les environnements de croissance hydroponique. On anticipe que les lampes DEL remplaceront les lampes HPS dans la plupart des applications à cause de leur consommation réduite en électricité, de l'augmentation de la qualité de la lumière et pour les possibilités de modification du spectre lumineux pour augmenter les rendements. Bien que les coûts d'équipement soit encore élevés, comme il est le cas avec les nouvelles technologies, les producteurs en serres à travers le monde pourront réduire de façon importante leur consommation d'énergie; ce qui se traduit par une réduction des coûts et des émissions de gaz à effet de serre.

Nous avons comparés des lampes DEL (LED Innovation Design, TI-SL600) faites par LED Innovation Design (Terrebonne, Québec) avec des lampes HPS (Ballaste: Philips Advance Model 71A85F5; Bulbe: General Electric, modèle LU600X0PSLT40) utilisées chez HydroSerre Mirabel (Mirabel, Québec) pour la croissance des laitues Boston (*Lactuca sativa* var. *capitata*) dans le but de déterminer le rendement de biomasse ainsi que le contenu nutritionnel des plantes. Les traitements lumineux ont été appliqués pendant huit heures après le coucher du soleil pour étendre la photopériode jusqu'à seize heures. Les masses humides et sèches des plantes et des racines ont été pesées à chaque semaine pendant l'expérience. En moyenne, le traitement optimal HPS à produit des masses statistiquement similaire à celle produite par les traitements DEL même si les lampes DEL ont produit approximativement la moitié des moles de lumières par mètre carrés comparativement aux lampes HPS (71.3moles/m^2 pour HPS et 35.8moles/m^2 pour DEL pendant quatre semaines).

Il n'y avait pas de différence statistique entre les échantillons prélevés des traitements DEL et HPS optimaux, HPS niveau régulier et contrôle (pas de lumière supplémentaire) pour les masses sèches et humides. Par contre, le traitement DEL a démontré une homogénéité accrue de masses de plante au travers de toute la section du bassin traitée

pendant que le traitement HPS a démontré un potentiel pour une production supérieure pour de petites sections localisées. Les ratios secs de masse de plante (en grammes) par l'irradiation artificielle (en moles par plante) normalisée par le pourcentage de lumière supplémentaire par rapport à la lumière totale étaient de 0.54 g/mol/plante et de 0.35 g/mol/plante pour les deux réplications HPS expérimentales et de 0.59 g/mol/plant et 0.26 g/mol/plante pour les deux réplications DEL expérimentales. Ceci indique que bien qu'il existe une différence d'intensité entre les deux traitements, la production de masse végétale reste semblable.

Des bénéfices pour la santé sont reliés à la consommation de β-carotène et d'autres produits phytochimiques présent dans les légumes comme la laitue. La photomorphogenèse pourrait permettre d'augmenter la concentration de ces composés bénéfiques à peu de coûts pour les producteurs. Par contre, contrairement aux résultats attendus, l'analyse chimique des échantillons traités aux DEL démontre la plus faible des concentrations de β-carotène, chlorophylle a et b, noexanthine, lutéine, anthéraxantine et violaxanthine. Les deux réplications de contrôle sont beaucoup plus concentrées en xanthophylles et en chlorophylles que les échantillons des parcelles traitées aux lampes HPS qui étaient aussi plus concentrés que les échantillons des parcelles traitées aux lampes DEL. Des recherches additionnelles sont donc requises pour optimiser le processus de photomorphogenèse à base de lampes DEL.

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Chapter 1. Literature Review

This literature review follows a simple framework. First, information regarding lighting technologies relative to both general and agricultural applications is presented. Following those topics, information is presented regarding Boston lettuce, hydroponics growth systems and other promising avenues of research where advanced lighting techniques could be used. Finally, information relevant to the impact of lighting technologies on nutrient content within the plant tissue is presented. Relevant information is given on phytochemicals and their associated pathways.

1.1 Background on LED lights

The acronym LED stands for Light Emitting Diode. Invented by Nick Holonyak Jr. in 1962 (Holonyak and Bevacqua, 1962) while working at General Electric Company, one of the initial usage for LED lights was as indicator lamps in electronic devices. A LED lamp generates light based on a process called electroluminescence, with the output wavelength determined by the energy gap of the semiconductor material as seen in figure 1.1. Electroluminescence happens when an electric current passes through a material, like the semiconductor found in a LED, and the electrons emit photons when changing energy from one energy state to the next (Mueller et al., 1999).

The luminous efficiency was quite low for the first generation of GaAsP (Gallium arsenide phosphide) red LED lamps. Holonyak's former graduate student, M. George Craford, was the first to improve the LED technology by a factor of ten in the 1960s with the addition of isoelectronic hydrogen to GaP (Gallium phosphide) (Logan et al., 1968) and GaAsP (Groves et al., 1971) in the red through green wavelengths. These GAP:N and GaAsP:N technologies became excessively easy to manufacture, driving unit prices down to pennies. AlGaAs (aluminium gallium arsenide) red LEDs was the following technological step in the 1980s to be commercially important (Alferov et al. 1975). In the 1990s, newer AlInGaP devices (Kuo et al., 1991) in red, orange and yellow colors were increasingly used for lighting applications in various domains, both indoor and outdoor at an intensity 1000 times higher than the first LED created fifty years ago (Steranka et al., 2002). Most recently, InGaN-based LED systems (indium gallium nitride**)** have been demonstrated. While this nitride system has been investigated since the 1970s, technical difficulties in the growth process of the substrate hindered progress. In 1993, blue and green high performance diodes were finally commercialised by Nichia, based in Tokushima, Japan (Mueller et al., 1999). This latest breakthrough enabled LED lamps to output over the entire visible spectrum at intensities over that of conventional incandescent white lamps.

Some advantages of this technology include reduced energy cost, higher conversion of electricity into light energy and reduced heat output, which are all beneficial in the scope of academic research due to increased reliability, repeatability and portability of LED lamps (Tennessen et al., 1994).

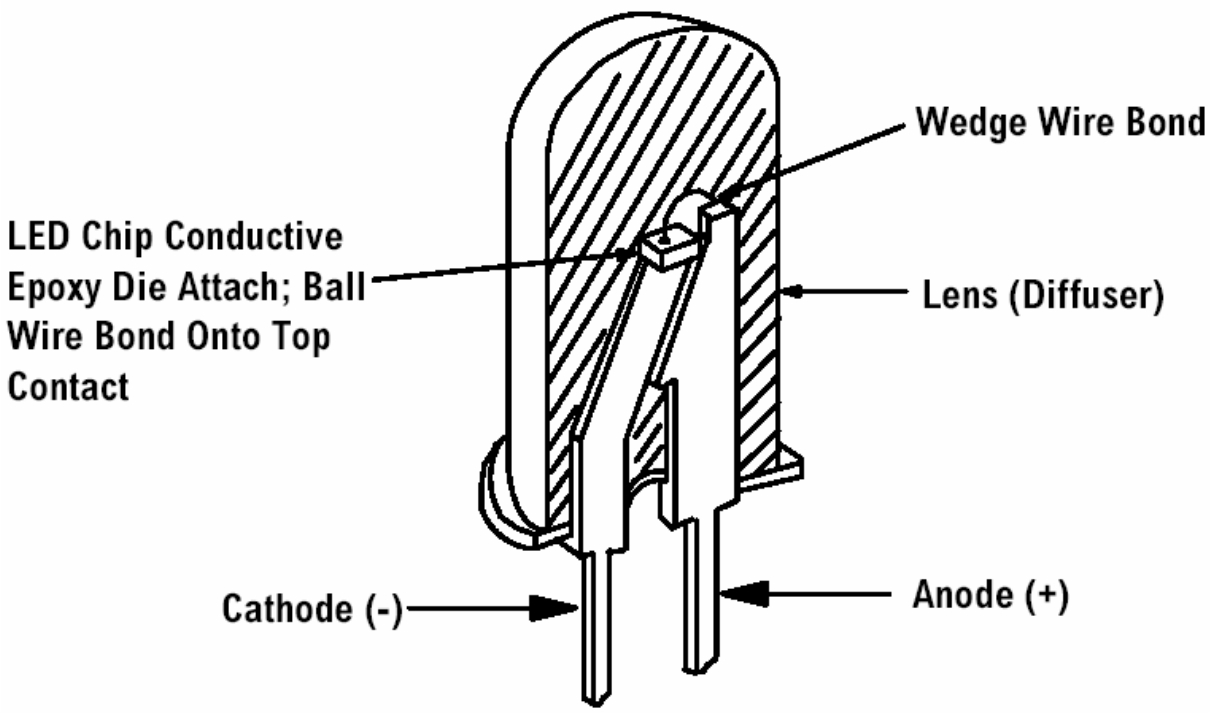

Figure 1.1: Transection of a LED 5mm package (Mueller et al., 1999).

1.1.1 For agricultural use

In the recent years, many efforts were made to quantify the effect of LED light quality on plants (Zhou et al., 2008) along with the effects of changing the light balance, for example reducing the blue spectrum (Dougher and Bugbee, 2001), increasing the green wavelength (Kim et al., 2006) or changing the blue to red ratio (Yanagi et al., 1996, Okamoto et al., 1997). *Lactuca sativa* 'Greenwave' (lettuce) and other greens have been prime candidates for experimentation (Shimizu, 2010). These efforts were also extended to several other plants species such as *Capsicum annuum* (pepper plants) (Schuerger, 1996), *Triticum aestivum* 'USU-Super Dwarf'(wheat plants) (Goins et al, 1997) and *Solanum tuberosum* 'Benimaru' (potato plantlets) (Miyashita et al., 1995). Most experiments were done in controlled environments to determine specific plant

parameters, such as research aimed at finding the cause of photo inactivation (Oguchi et al, 2008). Some experiments were designed to lead to potential applications in space exploration (Goins, 2001) and there are also conceptual designs for high density biomass production systems available (Shotipruk et al., 1999). This lighting technology seems well suited for advanced life support systems through intra-canopy design, where the lamps are placed in the canopy to increase light penetration, according to experiments performed at NASA (Massa et al., 2005).

The industry of commercial flowers has also been subject to LED experiments. An experiment has been done to compare the effects of incandescent, fluorescent cool white and blue, compact discharge, low pressure sodium (LPS) and LED lamps with a red color on *Euphorbia pulcherrima* 'Angelika' (poinsettia) and *Callistephus chinensis* 'Kometa pink' (China aster). This experiment was done with intensities of 0.1 to 2 μmol $m^{-2}s^{-1}$. All lamps performed well except for blue incandescent light which performed worst (de Graaf-van der Zande and Blacquière, 1992).

Another experiment compared the effect of monochromatic red, monochromatic blue, blue plus red and fluorescent light for 10-12 hours a day for the *Cyclamen persicum* 'Dixie White' variety. Red light alone improved flower stalk length while doubling flowering length compared to fluorescent light. Blue and red LED treatments showed a potential for controlling flowering and growth of cyclamen (Heo et al., 2003).

1.1.2 For other uses

LED lamps are currently being marketed in every conceivable niche market (Craford, 2005). The expected energy savings make them strong candidates for road lamps, portable computers, more efficient vehicle lights (Young et al., 1996) and even road-to-vehicle communication technology (Wada et al., 2005). Other plant based research has been performed to determine if different lighting technologies could alter the ability of foliage plants to remove chemical contaminants such as toluene (Matsumoto et al., 2007). Some of the more advanced use of LED lamps is in cancer therapies and wound healing treatments as discussed by NASA researchers (Whelan et al., 1999, 2000, 2001)

1.2 Overview of other competing technologies

1.2.1 CCFL

The term CCFL means Cold Cathode Fluorescent Lamp and this type of lamp is part of the Gas Discharge group of lamps. The technology was initially patented in 1936 (Farnsworth, 1936) and 1944 (Hansell, 1944). It was intended to be for electron generators and oscillation generator tubes. The cold cathode is named as such because the cathode is not independently heated. A cathode is considered to be an element that emits electrons and it is the negative electrode in a tube filled with a gas that can be ionized.

Traditionally, CCFL have been used in applications where shaped light sources, such as luminous outdoors signs are required. Current applications range from backlights in liquid crystal displays (LCD) and as light sources for customized computer cases. They can be used inside or outside, even below freezing point. While cold cathode lamps operate at high voltage, they cannot be dimmed without experiencing a drastic shortening of their lifespan.

Depending on the gas used in the tube, CCFL can give out a wide range of wavelengths. Typical fluorescent lamps will emit short-wave ultraviolet (UV) light when mercury vapour is used as the plasma gas source. This reaction causes the phosphorus to fluoresce, which in turn produces visible light.

The ballast required to regulate the flow of electricity in CCFL lamps requires an initial cost that is higher than alternative technologies. However, it is more energy efficient than incandescent lamps and energy savings can be realized over the entire lifespan of the lamp.

One of the advantages of CCFL lights in their use for plant growth is the uniform distribution of photosynthetic photon flux density (Tanaka et al, 2009). Another

advantage is the low heat generation of the lamp. This characteristic enables plant growers to place the bulb and ballast very close to the plant in an effort to increase the effective photon flux.

1.2.2 HPS

HPS stands for high pressure sodium, a type of sodium vapour lamp using sodium as an ionized gas to produce light. It was initially patented by General Electric Company in 1966 (Shmidt, 1966). This type of lamp is considered to be part of the high intensity discharge lamps. HPS lamps usually contain additional elements such as mercury. Several improvements were made over the initial patented design, such as the use of pulses between 500 and 2000 Hertz to improve color rendition (Osteen, 1979). Typical applications range from street lamps to security lamps and they are also used for supplemental lighting in agricultural applications. HPS are usually smaller than their counterpart, the low pressure sodium lamp. They are quite efficient and produce a large color spectrum which is found to be desirable in indoor plant growing operations. Experiments using HPS lamps to supplement greenhouse tomato growth have been successful since 1983 (McAvoy, 1984) and earlier for greenhouse grown roses in 1974 (White, 1974). A HPS lamp, like many others, is dependent on an electronic controller, called ballast, to regulate power levels through control of the voltage, current and frequency. Some characteristics of importance for the design of good ballasts include high-voltage ignition system, dimming capabilities and the ability to perform cold and hot starts (Ben-Yaakov, 2002).

1.2.3 LPS

LPS stands for low pressure sodium and is a type of sodium vapour lamp using sodium as an ionized gas to produce light. The lamp is usually made of a straight or U-shaped section filled with small quantities of neon and argon along with solid sodium that is enclosed into a vacuum tube to improve thermal insulation and efficiency with an approximate conversion of electrical energy into visible light of 35%. The main

wavelength output occurs at 589nm which is close to the peak sensitivity of the human eye, making this type of lamp very efficient for lighting purpose in human environments. However, the narrow spectrum prevents the use of this lamp in situation where color rendition is required. Street lamps however are a prime example of a use for LPS lamps (Jack and Vrenken, 1980). In a situation where light pollution is required to be very low, such as nearby observatories, LPS are recommended because the narrow band light emitted can be easily filtered out (Garstang, 1989).

1.2.4 Others

Other available types of lighting systems include xenon lamps, sulfur lamps, carbon arc lamps, plasma lamps and organic light emitting diodes. These lamps are either not suited or too costly for agricultural related use and are therefore not detailed in this text.

1.3 Light absorbance curves

1.3.1 History

When the first light sensors were invented, precision of ±10% on solar radiation measurements were very difficult to obtain (McCree, 1966). Although several different types of illumination units existed, they typically were not optimal for agricultural purposes. Lighting engineers were primarily concerned about quantifying light as it would appear to a human observer (with concepts such as nits, candles, lumens, etc) while physicists were interested in quantifying the energy levels of light. This led to the birth of a simple system, useable by applied plant scientists, for measuring the light which is active in plant growth. The instrument used to measure light for plant growth is the quantum light sensor, which measures light from 400nm to 700nm range, called the photosynthetically active radiation (PAR). This PAR range is the wavelengths that chlorophyll is most efficiently able to convert solar energy into chemical energy (Biggs et all., 1971). This sensor uses silicon photodetectors and a filter to remove any incident light outside of the 400-700nm band (McPherson, 1969).

The PAR response curves for an average plant, with sufficient accuracies for practical purposes, was then created using technology available in the early 1970s. This seminal work on PAR response curves by McCree is the current industry standard. Research has been done to validate the concept of PAR curves for many different plants, herbs and trees (Inada, 1976) as shown in figure 1.2. However, with the increasing availability of powerful single band LED lights, work is being done to update these curves at higher light intensity levels, perhaps even up to saturation, and very specific wavelengths and combinations of wavelengths (Lefsrud et al., 2006, 2007, 2008).

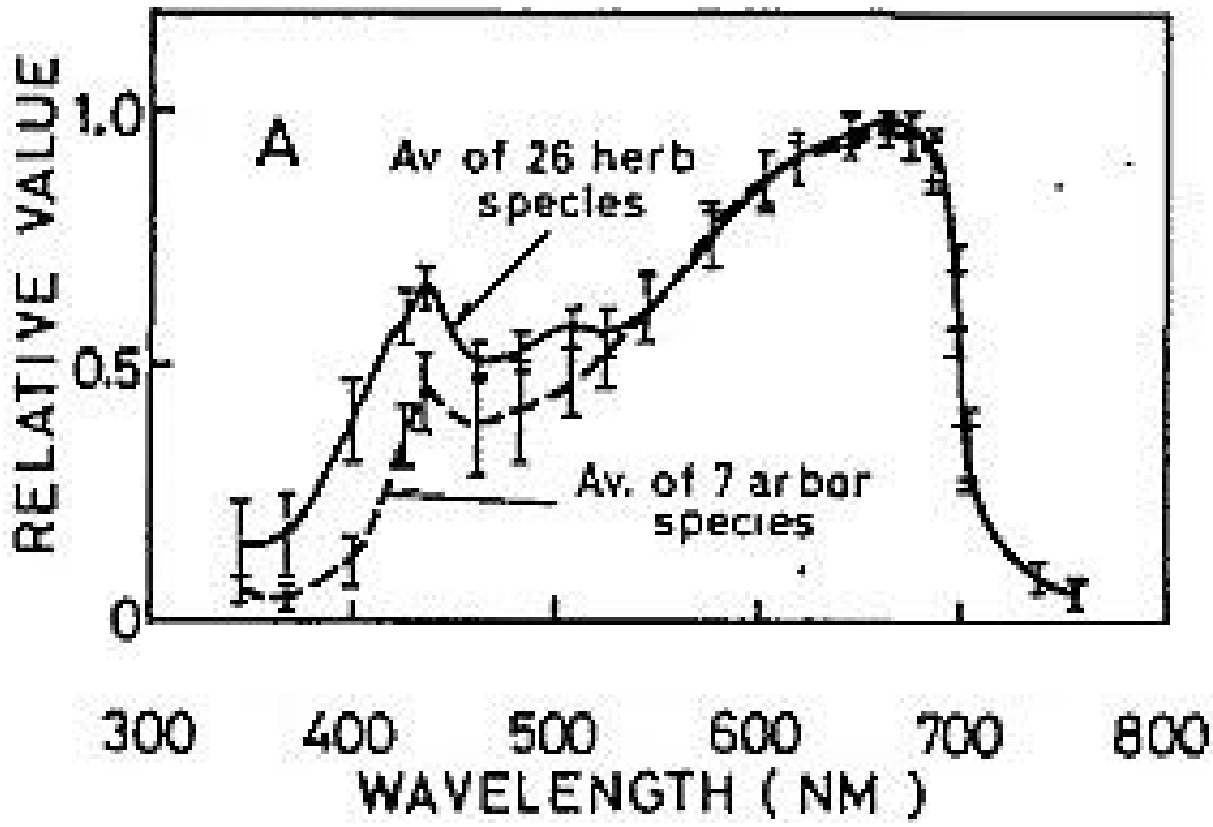

Figure 1.2: Average action spectra curve for unit incident energy, for 26 herb species and 7 tree species (Inada, 1976). Vertical lines indicate the standard deviations.

1.3.2 Light Explained: PAR, Lumens, Footcandle, Watts, µmol s^{-1} m^{-2}

PAR as defined earlier refers to the spectral range between 400 and 700 nm where optimal photosynthesis occurs. It is also relatively close to the spectral range perceived by the human eye (~390 – 780nm). The energy level of a single particle of light (called a photon) is high enough to allow photosynthesis to occur but low enough that no tissue or cell damage is incurred in the plant.

The concept of PAR is important because it bridges spectral distribution of the incident light to the spectral response of the plant and by extension, the sensor (Federer and Tanner, 1966). The unit of PAR is µmol photons m^{-2} $second^{-1}$ and represents a quantity of photons per area and time period or alternatively, it can be explained as being the

photosynthetic photon flux density (PPFD). PPFD has been showed to have an impact on plant growth both for the current flux reaching the plant and the PPFD of the previous year (Welander and Ottoson, 1997) for perennial plants.

Illuminance can be quantified in footcandle (fc, non-SI unit) and lux (lx, SI unit). The Lux is based on the flux of lumens, which is the photometric unit based on the brightness response of the human eye. A footcandle is defined as a flux of one lumen of light over a surface of one squared foot. Another is the irradiance in watts per area, usually squared meters, which is indicative of the flux of radiant power over a pre-defined waveband (W m^{-2}). The unit of choice for PAR is the flux of a quanta (in micro Einstein, which is also equivalent to µmol photons m^{-2} $second^{-1}$) of absorbed photons, usually in the 400 to 700nm band (McCree, 1972).

1.3.3 PAR response curve

The PAR action spectrum can be drawn for any given organism by measuring the photosynthesis rate and plotting it against the wavelength of the light used in the process. Neales et al. (1968), describes leaf photosynthesis rate as being the net CO_2 exchange (P) or the dry mass accumulation per unit leaf area (E). This rate may be greatly influenced by external factors such as radiation flux density, ambient CO_2 concentration, leaf temperature and wind speed over the leaf surface (Gaastra, 1959).

Usage of PAR levels can be the characterisation of ecosystem productivity (Frolking et al., 1998) and estimation of crop growth through modelling. Indeed, models usually require leaf area index (LAI) or absorption of radiation which are tedious and time-consuming to acquire. It was stated that PAR is a better indicator of yield than LAI for several different soil types, planting densities and planting dates (Gallo et al., 1985).

1.4 Information on Lettuce plant

1.4.1 Background

Lettuce (*Lactuca sativa*) was amongst the first vegetables brought to the new world by Columbus and it has been grown in North America since the first settlers (Davis et al., 1997). The industry has grown to be a multi-billion dollar industry across the continent.

The United States is the second largest producer of lettuce behind China, which dominates world production. In 2004, China produced approximately 10.4 million metric tons while U.S. production was at 4.4 million metric tons (FAO, 2005). The Chinese produce 48% of the global supply but consume most of it internally while the U.S. produces 20% of the world's supply (Boriss et al., 2005). Lettuce production in the USA in 2004 amounted to slightly more than two billion United States dollars (USD) while exports were approximately worth $275 million USD (FAO, 2005).

The vegetable greenhouse industry of Quebec was valued at approximately 50 million dollars in 1999 with 12 hectares dedicated to lettuce, representing approximately 12% of the total greenhouse area that year (Carrier, 1999). Production areas for lettuce by hectares using 2003 data places Quebec first with 80% of the national acreage (9.87 ha); British Columbia second with 11% (1.36 ha) and Ontario third with 9% (1.12 ha). Nova Scotia produces about 0.13 ha or 1.0 % of the national acreage and there is a small amount produced in Alberta (Pesticide Risk Production Program, 2006).

Greenhouse production started in the province in 1987 with the construction of 3.9 ha of artificially lit greenhouses for tomato, cucumber and pepper production (Papadopoulos et al., 2000). Initially, there was a lack of experience in the supplemental lighting field. This led to problems with gray mould and flies in the winter harvests, resulting in losses of up to 60% according to Papadopoulos et al. (2000). Within years, best management practices were established to improve yields and correct recurring issues.

The current situation for vegetable growers in Canada and Quebec is challenging because of added competition from southern growers. Expected advances in genetically engineered cultivars, specifically designed for soil-less media, promise increases in yields and quality (Papadopoulos et al., 2007).

1.4.2 Growing specification

Lettuce growth can be modified by various parameters. Research has been done to determine the effects of temperature (Scaife, 1973) and phosphorus and nitrogen concentrations (Azcón et al., 2003). There is a link between the head structure of the lettuce head and the nutritional content of the plant (Mou et al., 2004) which seems to indicate that open lettuce heads tend to be more nutritious. The effects of supplemental light on phytochemicals present in lettuce leaves seem to indicate that red light can increase most phenolic concentrations, blue light increases directly anthocyanin concentrations while far red can increase biomass at the cost of reduced nutrient concentrations (Li et al., 2009).

Some greenhouses have carbon dioxide management systems. Those systems have been shown to have a beneficial input on yields when properly configured in function of PAR (Both et al., 1997). However, the relationship between PAR levels and carbon dioxide has not been studied as extensively for LED lamps, compared to Both et al. (1997) study with HPS lamps.

1.4.3 Xanthophyll Cycle

When low light conditions are present, the plant must utilize light in the most efficient fashion. In excessive light conditions, the plant must also be able to limit over-excitation to prevent cell damage. The xanthophyll cycle enables the plant to shed excess light energy. It is present in thylakoid membranes of all higher plants, ferns, mosses and several algal groups. There are two variants, the violaxanthin cycle being the most

common and found in higher plants while the diadinoxanthin cycle is found in some algal groups. There are three main xanthophylls involved in the cyclic process. First, violaxanthin is de-epoxidated into antheraxanthin and then it is de-epoxidated again into zeaxanthin, as shown in figure 1.3. This reaction is driven by ascorbate oxidation and catalyzed by two different enzymes called violaxanthin de-epoxidase (VDE) and zeaxanthin epoxidase (ZE). When there is excess light being absorbed by chlorophyll, violaxanthin is converted into zeaxanthin; the opposite reaction happens in low light conditions (Eskling et al., 1997). The photosynthetic pigments are bound to specific pigment-protein complexes (Siefermann-Harms, 1990). This is true for both chlorophyll (Markwell et al., 1979) and carotenoids (Siefermann-Harms & Ninnemann, 1979). In contrast to chlorophyll a which occurs in all pigment-protein complexes of the thylakoid membrane, α- and β-carotene are located in the reaction centers and their closely associated antennae complexes, whereas chlorophyll b and the xanthophylls are located in the more peripheral antennae complexes, especially in the light-harvesting chlorophyll-a/b-protein complex of Photosystem II (Siefermann-Harms, 1985). Due to this pigment organization, changes in the stoichiometry of the pigment-protein complexes should result in changes in the ratio of different pigments. Violaxanthin and zeaxanthin appear to be less strongly bound to proteins than the other carotenoids (Siefermann-Harms, 1984).

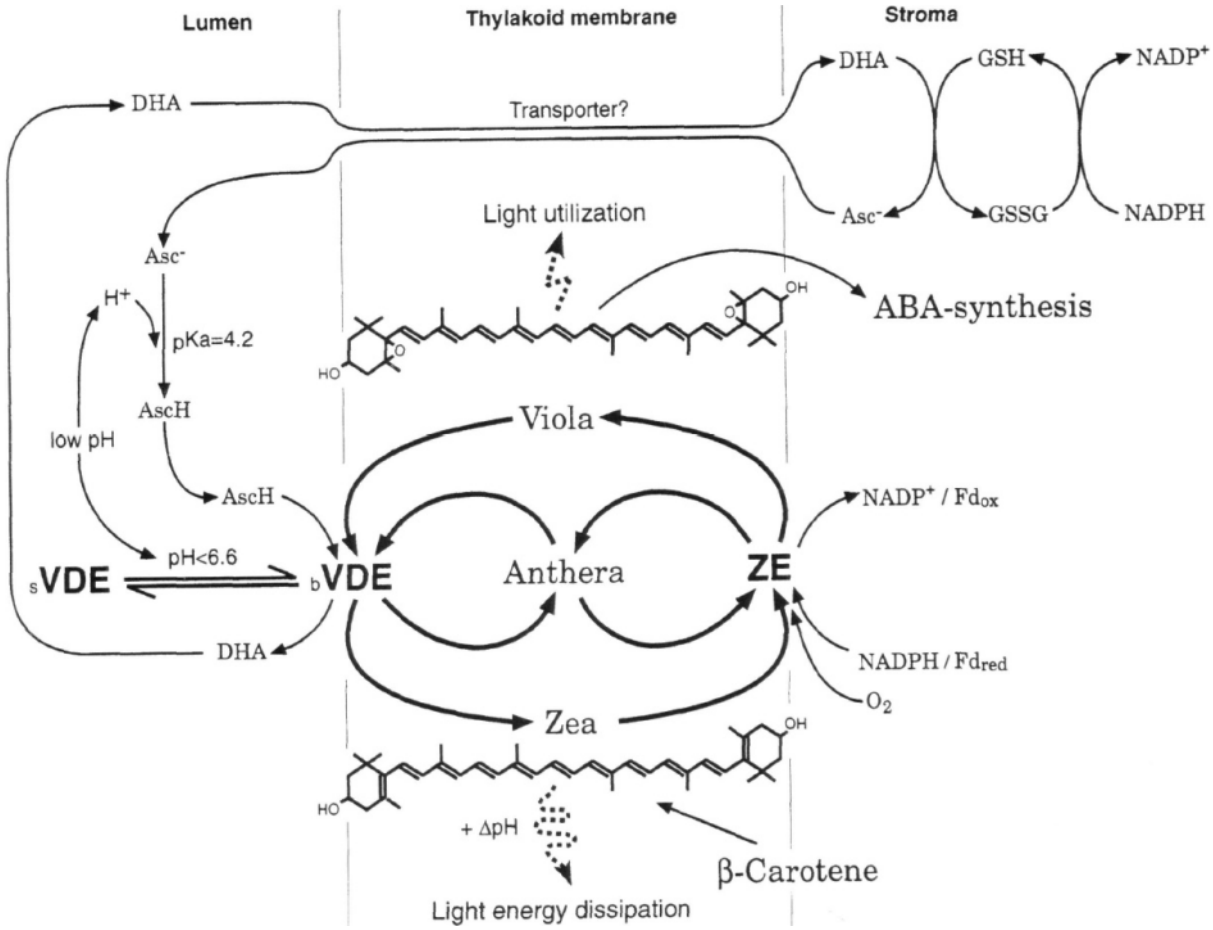

Figure 1.3: Model of the Xanthophyll Cycle and its relation to abscisic acid (ABA) synthesis.
VDE, violaxanthin de-epoxidase; sVDE, soluble VDE; bVDE, bound VDE; DHA, dehydroascorbate; Asc-, ascorbate; AscH, ascorbic acid; GSH, glutathione; Viola, violanxanthin; Anthera, antheraxanthin; Zea, zeaxanthin; Fd, ferrodoxin. (Eskling et al., 1997)

The research done on the xanthophyll cycle is somewhat recent. This is due to the lack of a specific role for this cycle up until an experiment made the link between zeaxanthin formation and dissipation of excess light energy in the late 1980s (Demmig et al., 1987). There are other functional aspects which have been reviewed and discussed by Yamamoto and Bassi (1996), Demmig-Adams et al. (1996) and Gilmore (1997).

Some of the more promising aspects of lutein and zeaxanthin are their use as powerful antioxidant mechanism and chemopreventive agents in the fight against cancer (Khachik et al., 1995).

1.4.4 Past relevant experiments

There are several parameters of interest, with varying connection to light treatments, which have been studied on lettuce plants. For example, stomatal conductance (Kim et al., 2004), mass in function of red and blue light ratios (Yanagi et al., 1996), effects of pulsed white light (Yasuhiro et al., 2002) and seed germination (Borthwick et al., 1954). Hypocotyl elongation has also been studied in lettuce as a function of red and far-red wavelengths (Evans et al., 1965).

A study on light quality and its impact on lettuce quality in terms of nutrient content, vitamins and harmful chemicals such as nitrates and oxalic acid showed that gains can be made if blue or red/blue supplemental light is used (Ohashi-Kaneko et al., 2007).

1.4.5 Potential gains with LED light

As previously discussed, LED light enables a much finer control on the spectrum of light available to plants during growth. Research has been done to quantify the impact of increased blue light on nutrient uptake and photosynthetic characteristics on rice leaves (Matsuda et al., 2004).

In terms of plant morphogenesis control, light response is called photomorphogenesis. Increased levels of red light tends to suppress stem elongation and promote lateral branching while far-red light tends to do the opposite and promote stem elongation (Moe et al., 1990). The addition of yellow light has been shown to inhibit lettuce growth (Dougher et al., 2001). Blue light seems to darken the leaves while reducing plant height; yellow light inhibits growth; and green light seems to discolour the leaves (Mortensen et al., 1987).

Chapter 2. Comparative Study

2.1 Introduction

The established practice for greenhouse growers interested in supplemental lighting technologies is to install high pressure sodium (HPS) lamps and use them to extend the photoperiod of the crops and increase yields (McAvoy, 1984). However, this practice can be onerous for large installations, both in equipment and energy costs. Some other disadvantages of HPS lamps include heat generation and sub-optimal spectrum for photosynthesis. Light emitting diode (LED) lamps are a promising technology that has the potential to improve upon those issues (Tennessen et al., 1994). Research has been done to test the impact of light from LED lamps (Zhou et al., 2008) in several specific wavelengths, notably far-red, red, blue and ultra-violet (Dougher et al., 2001, Yanagi et al., 1996, Okamoto et al., 1997). More recently, brighter diodes enabled their use as a potential replacement for traditional HPS systems in the 600 - 1000 watts category of lamps (Steranka et al., 2002). Claims of 50% energy savings for similar biomass yields are now common in the marketplace (Craford, 2005). The following experiment aims to verify if LED lamps can produce similar biomass levels compared to those of HPS lamps at reduced energy cost for lettuce grown in a hydroponics setup. The experimental site has the capacity to produce 10 to 14 crops annually (Carrier, 1999) according to the established provincial average.

2.1.1-Hypothesis

The initial hypothesis of this experiment is that lettuces grown under LED light treatment will have equivalent wet and dry masses and visual properties (color, shape, size) compared to lettuces grown under HPS treatment, regular HPS treatment (based on Hydroserre Mirabel's production levels) and control light treatment (no supplemental light).

2.2 Materials and Methods

2.2.1 Plant Culture

The Boston head lettuce (*Lactuca sativa* var. *capitata*) was provided by Hydroserre Mirabel (Mirabel, Quebec, Canada). Lettuce plants were cultured and germinated according to HydroSerre Mirabel proprietary methods. After the initial transplant in the experimental block, plants were grown under light treatments for approximately 30 days till plant maturity.

2.2.2 Test Installation

Each plot measured 28 feet by 36 feet (8.53m by 10.97m). Spacing between experimental areas was at least twenty-eight feet (8.53m) with no artificial lighting used in those buffer zones, as seen in figure 2.1. No experimental area was within twenty-eight feet (8.53m) of the end of the pool. Neighbouring light pollution was limited by using shading cloths on the sides of the experimental bays as seen in figure 2.2.

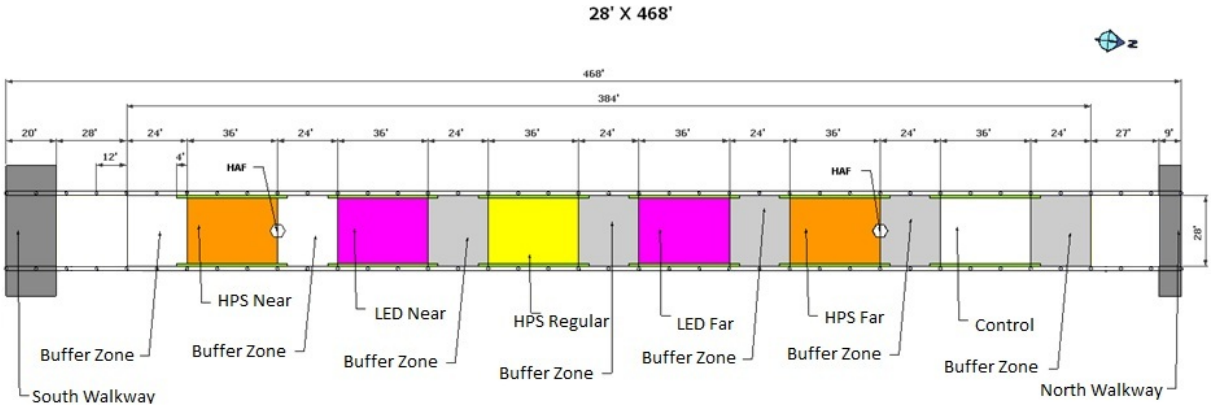

Figure 2.1: Experimental map.
Top view of the experimental area with dimensions in feet.

Sensors were calibrated and tested before being installed in the six experimental plots. Data loggers and ground temperature sensors were laid on floating trays as to cause minimum shading to neighbouring lettuces. The floating trays were approximately 4.5 feet by 2.5 feet (1.37m by 0.76m) and held 18 lettuce plants each, as seen in figure 2.5.

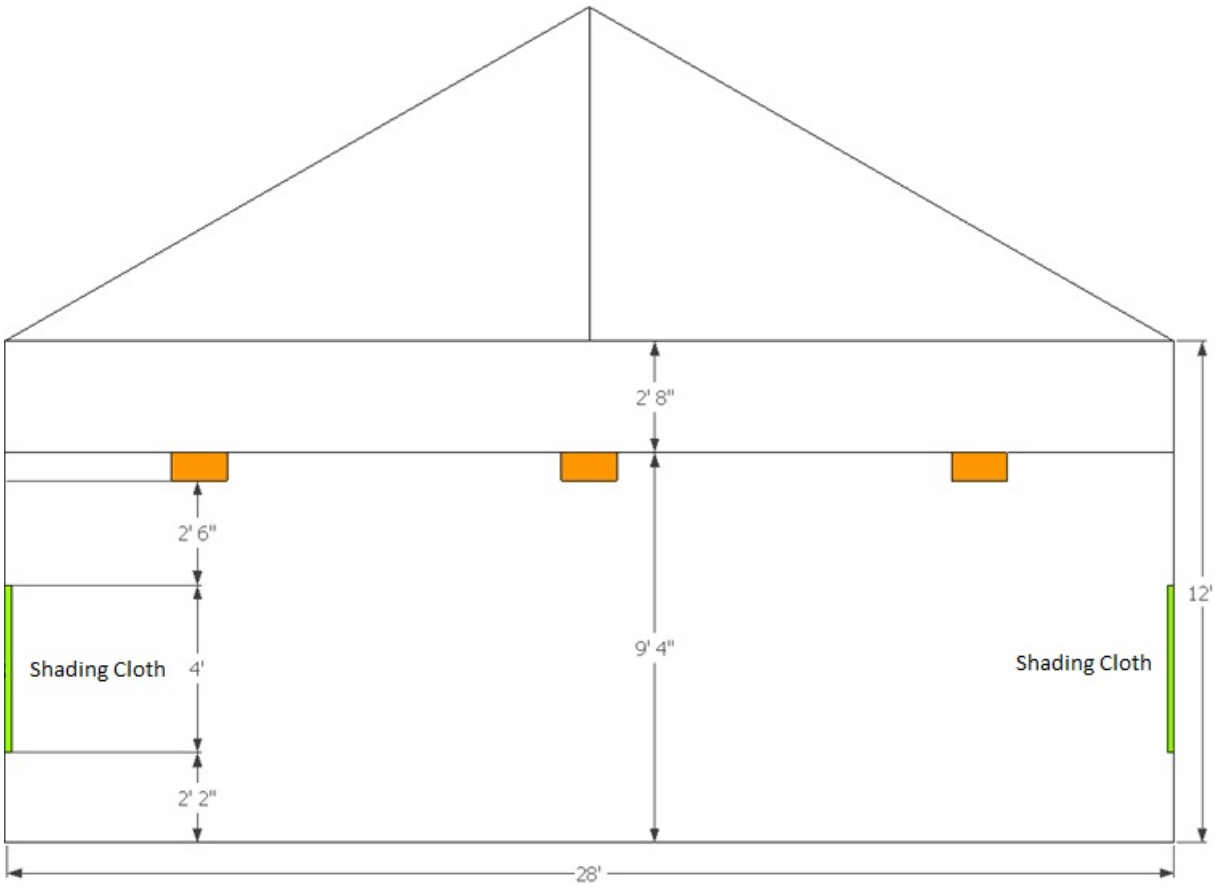

Figure 2.2: Side View of Shading Cloth.
Approximate position of shading cloth and lamps in the test plot.

The placement of LED lamps (LED Innovation Design, TI-SL600) was selected in function of an effective radius of four feet two inches (1.28m) per lamp. Twenty four LED lamps are used on each plot as shown in figure 2.3. The HPS plots (ballast: Philips Advance Model 71A85F5; Bulb: General electric, model LU600X0PSLT40) had eighteen lamps spaced approximately six feet from (1.83m) each other, as demonstrated in figure 2.4 while the regular HPS plot had only four lamps each spaced to cover a quarter of the plot. The control plot had no lamps at all.

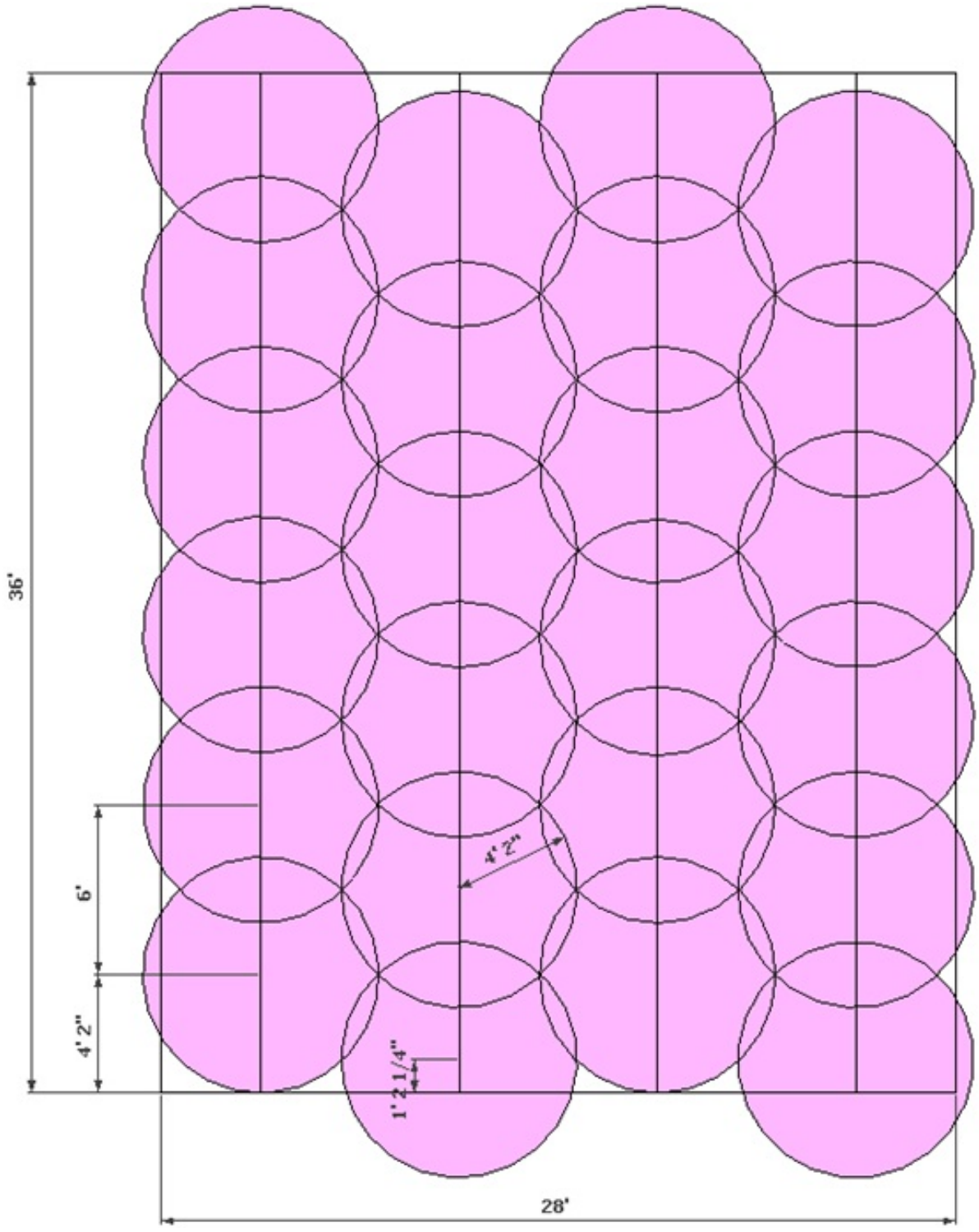

Figure 2.3: Top View of LED Lamp Placement.
LED lamp placement with distances in feet for LED plots.

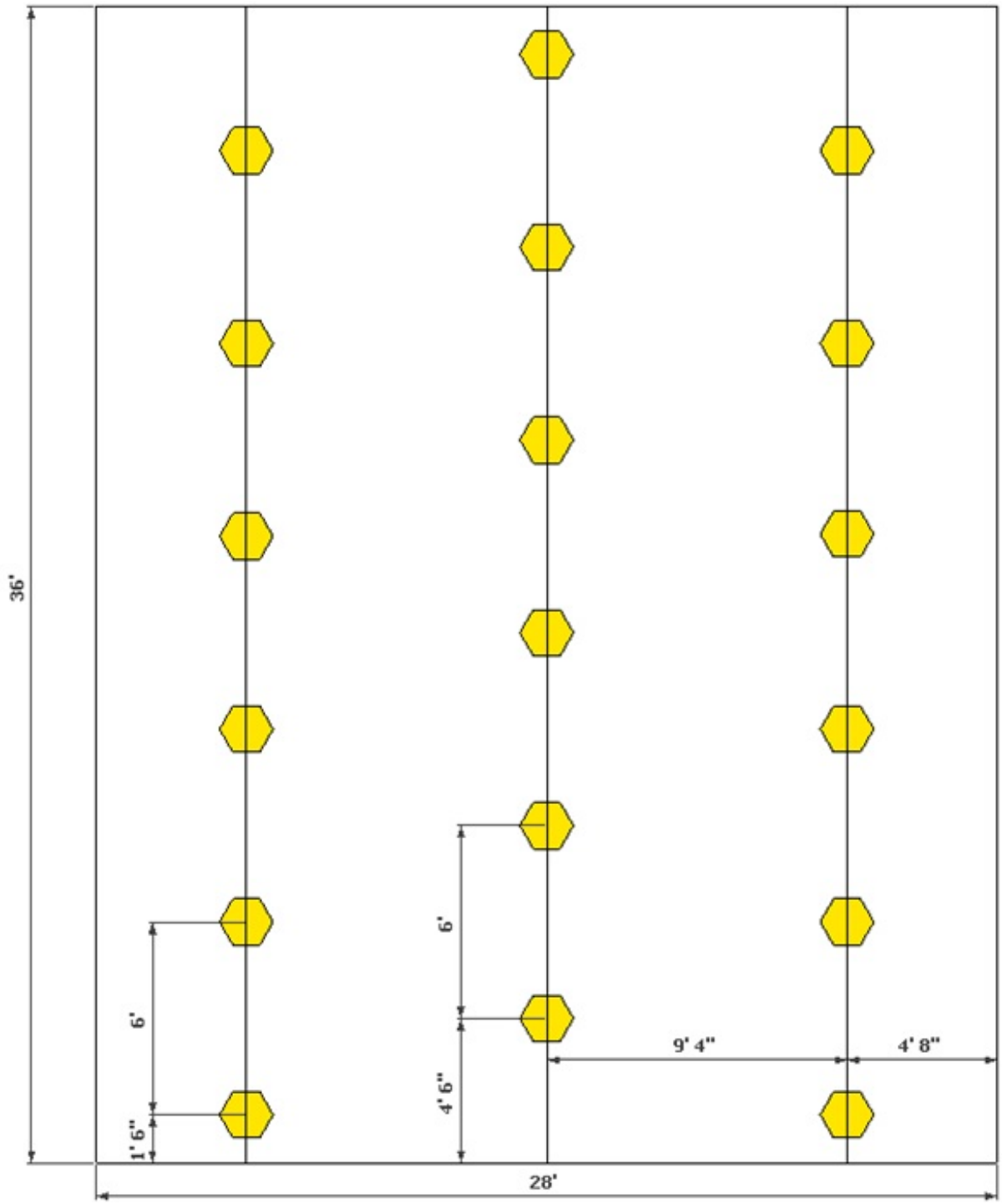

Figure 2.4: Top View of HPS Lamp Placement.
HPS lamp placement with distances in feet for HPS plots.

Figure 2.5: Front view of experimental setup at night.
Floating trays and side cloths.

2.2.3 Light Measurement

Three light maps based on equally spaced grids of treatment areas consisting of six by six sample points were measured with a light sensor to provide photosynthetically active radiation (PAR) measurements. The light maps were completed at the beginning of the first experimental replication, at the beginning of the second replication and at the end of the second replication. These light maps were done after sunset and at canopy level.

The photoperiod was maintained constant with sixteen hours of light and eight hours of darkness per day. Irradiance was measured with pyranometers (Hobo, Bourne, Ma, S-LIB-003) and quantum sensors (Hobo, Bourne, Ma, S-LIA-003) connected to data loggers (Hobo, Bourne, Ma, U30 remote monitoring system) which logged the data for every minute during the entire experimental replication. Data loggers were installed on each sub block with a redundant quantum sensor per data logger. These sensors were placed randomly on the sub block and were mounted at leaf canopy level.

2.2.4 Environmental Measurement

Additional temperature (Hobo, Bourne, Ma, S-TMB-002) and relative humidity (Hobo, Bourne, Ma, S-THB-008) sensors logged the surface temperature, air temperature and relative humidity on all blocks and the water temperature was measured at the control block.

2.2.5 Mass Determination

At the time of the weekly harvest, the aerial and root tissues were separated and fresh mass was determined on site for all of the plants harvested. Plant and root tissues were then individually labelled, transported and dried at Macdonald Campus of McGill University according to the ASABE standard (2007). Drying temperature was between

80 and 95 degrees Celsius and duration of drying was required to be no less than 72 hours to attain stable mass across the oven and establish dry mass.

2.2.6 Energy Measurement

The energy measurements were done using a setup allowing the circuit to be opened and two multimeters to be used simultaneously for current and voltage readings. For voltage readings, a multimeter MTP 2325 (Montreal, CA) at 700V AC scale was used at a 1V resolution. The precision is rated at 1.2% and input impedance is 10MΩ. For current readings, a multimeter Fluke 179 (Calgary, CA) was used. The setting was Amps AC, automatic scale, resolution of 0.001A between 1 and 6 amps and a precision of 1.5% at 37 mV/A.

The multimeters were first connected, and then the lamps were powered on. For HPS lamps, both current and voltage were recorded every five minutes for a maximum of forty minutes to account for the heating-up period. LED lamps were subjected to a similar treatment but because there was little recorded variation in the first recorded measurements, the second LED lamp was measured only once at the forty minute mark.

2.2.7 Experimental Design

The experimental design was a randomized complete block with sub blocks consisting of four light treatment (maximum HPS, maximum LED, Regular greenhouse HPS level, Control with no supplemental artificial light) with two blocks for HPS and LED light treatments. For the sake of simplicity, replications of light treatments are called “near” and “far” to help distinguish between them. This nomenclature was chosen based on relative plot distance from the main walkway at the greenhouse. In general, the “far” replication is slightly more north than the “near” replication. Sub blocks were randomly assigned at the beginning of both experimental replications.

A total of ten plants were randomly harvested from each treatment sub block at four different times during the experiment (day 7, 14, 21, 28). Plants were randomly selected from each treatment and replication but the first three rows of plants on the edge were excluded to remove the edge effect. Sixty plants were harvested during each harvest time across all treatments.

Statistical analysis was performed using SPSS (Somers, NY) to find outliers in plant mass measurements and also to find outliers in light maps across the three readings. These parameters were used to perform UNIANOVA analysis on plant mass: light treatment, replication of treatment, replication of experiment, and weekly dry and wet mass.

The UNIANOVA analysis performed on light map has parameters for light treatment, replication of treatment and replication of map.

2.3 Results

2.3.1 Biomass Yield

The first experimental replication produced higher amounts of plant mass than the second one. Comparing tables A1 through A4 with tables A5 through A8 show that this holds true for all four weeks. As shown in table A4, the high pressure sodium (HPS) light treatment during the first replication produced wet masses of 173.9g (std. dev. 28.8g) for the first treatment replication and 150.2g (std. dev. 24.3g) for the second treatment replication at the end of the fourth week. For the same sample point, dry masses are at 9.0g (std. dev. 1.1g) and 6.3g (std. dev. 1.4g), respectively.

The light emitting diode (LED) light treatment during the first experimental replication produced wet masses of 135.3g (std. dev. 25.2g) for the first treatment replication and 138.4g (std. dev. 18.2g) for the second treatment replication at the end of the fourth week. For the same sample point, dry masses are at 7.6g (std. dev. 2.9g) and 7.6g (std. dev. 1.9g), respectively. The HPS light treatment at regular greenhouse levels, for the first experimental replication and wet masses, produced 127.3g (std. dev. 16.5g) and dry masses of 7.1g (std. dev. 2.0g). Plants subjected to no supplemental artificial lighting (Control) during the first experimental replication at the fourth week produced 118g (std. dev. 10.6g) for wet masses and 6.1g (std. dev. 1.6g) for dry masses. As shown in table A8, the high pressure sodium (HPS) light treatment during the second experimental replication produced wet masses of 66.0g (std. dev. 17.8g) for the first treatment replication and 67.1g (std. dev. 23.4g) for the second treatment replication at the end of the fourth week. For the same sample point, dry masses are at 5.1g (std. dev. 0.8g) and 4.4g (std. dev. 0.8g), respectively.

The light emitting diode (LED) light treatment during the second experimental replication produced wet masses of 51.8g (std. dev. 10.1g) for the first treatment replication and 51.8g (std. dev. 16.2g) for the second treatment replication at the end of the fourth week. For the same sample point, dry masses are at 4.1g (std. dev. 0.5g) and

4.0g (std. dev. 0.7g), respectively. The HPS light treatment at regular greenhouse levels, for the second experimental replication and wet masses, produced 77.7g (std. dev. 9.8g) and dry masses of 4.3g (std. dev. 0.5g). Plants subjected to no supplemental artificial lighting (Control) during the second experimental replication at the fourth week produced 46.5g (std. dev. 11.4g) for wet masses and 3.5g (std. dev. 0.7g) for dry masses.

Table 2.2 indicates that both LED and HPS light treatment achieved similar dry ratios of 0.2 g/mol/m^2 for the first experimental replication and 0.1 g/mol/m^2 for the second experimental replication. This seems to indicate that both light treatments have similar effects on the growth of Boston lettuce.

Table 2.3 is similar to table 2.2 but is dependent on plant instead of area. Therefore, the results are similar with dry ratios of 0.54 g/mol/plant for HPS and 0.59 g/mol/plant for LED for the first experimental replication. Dry ratios are also similar for the second experimental replication with values of 0.35 g/mol/plant for HPS and 0.26 g/mol/plant for LED light treatment.

Table 2.4 shows that the modified dry ratio, which accounts for the mass produced in excess of the control mass, is slightly higher for LED (0.05 g/mol/m^2) than for HPS (0.02 g/mol/m^2) for the first experimental replication while the opposite is true for the second experimental replication with values of 0.01 g/mol/m^2 for LED and 0.02 g/mol/m^2 for HPS light treatment.

Table 2.5 shows similar modified ratios based on plants. The dry ratios for LED (1.17 g/mol/plant) and for HPS (0.51 g/mol/plant) show an advantage during the first experimental replication while the opposite situation holds for the second experimental replication with values of 0.35 g/mol/plant for LED and 0.44 g/mol/plant for HPS light treatment. Regular light treatment yielded the highest ratio for both experimental replications with 1.95 g/mol/plant and 1.56 g/mol/plant, respectively.

2.3.2 Light Map

Figure 2.6, 2.7 and 2.8 and table 2.1 show the various light maps measured before, during and after the experimental replications. Those light maps appear to be fairly consistent from one measurement to the next.

The HPS Near light maps have means of 64.8 µmol s^{-1} m^{-2} (std. dev. 17.5 µmol s^{-1} m^{-2}), 84.9 µmol s^{-1} m^{-2} (std. dev. 12.6 µmol s^{-1} m^{-2}) and 82.2 µmol s^{-1} m^{-2} (std. dev. 10.2 µmol s^{-1} m^{-2}) for the first, second and third light maps, respectively.

The HPS Far light maps have means of 79.4 µmol s^{-1} m^{-2} (std. dev. 15.3 µmol s^{-1} m^{-2}), 86.8 µmol s^{-1} m^{-2} (std. dev. 13.0 µmol s^{-1} m^{-2}) and 83.1 µmol s^{-1} m^{-2} (std. dev. 9.6 µmol s^{-1} m^{-2}) for the first, second and third light maps, respectively.

The HPS Regular light maps have means of 8.6 µmol s^{-1} m^{-2} (std. dev. 4.4 µmol s^{-1} m^{-2}), 8.1 µmol s^{-1} m^{-2} (std. dev. 3.9 µmol s^{-1} m^{-2}) and 13.3 µmol s^{-1} m^{-2} (std. dev. 4.8 µmol s^{-1} m^{-2}) for the first, second and third light maps, respectively.

The LED Near light maps have means of 37.6 µmol s^{-1} m^{-2} (std. dev. 6.8 µmol s^{-1} m^{-2}), 40.4 µmol s^{-1} m^{-2} (std. dev. 4.2 µmol s^{-1} m^{-2}) and 39.8 µmol s^{-1} m^{-2} (std. dev. 3.1 µmol s^{-1} m^{-2}) for the first, second and third light maps, respectively.

The LED Far light maps have means of 39.2 µmol s^{-1} m^{-2} (std. dev. 7.2 µmol s^{-1} m^{-2}), 42.3 µmol s^{-1} m^{-2} (std. dev. 4.2 µmol s^{-1} m^{-2}) and 40.0 µmol s^{-1} m^{-2} (std. dev. 3.5 µmol s^{-1} m^{-2}) for the first, second and third light maps, respectively.

The Control light maps have means of 0.3 µmol s^{-1} m^{-2} (std. dev. 0.4 µmol s^{-1} m^{-2}), 0.5 µmol s^{-1} m^{-2} (std. dev. 0.5 µmol s^{-1} m^{-2}) and 0 µmol s^{-1} m^{-2} (std. dev. 0 µmol s^{-1} m^{-2}) for the first, second and third light maps, respectively.

2.3.3 Energy Results

Table 2.7 shows that a LED lamp consumes about 319.9 watts of electricity while a HPS lamp consumes approximately 648.9 watts. As seen in figure 2.3, there are 24 LED lamps per plot; therefore the energy demand for the LED lamps in the chosen configuration, on an area basis, is 82.0 W/m^2. As seen in figure 2.4, there are 18 HPS lamps per plot; translating into an energy cost of 124.8 w/m^2. The regular HPS light treatment required only 4 lamps for an energy cost of 27.7 W/m^2.

Table 2.8 shows the progressive increase in energy consumption of HPS lamps. On average, at minute 0, the lamps used 78% of their maximum energy draw. By minute 10, the lamps were drawing on average 89% and stabilized at an average peak of 642 watts after 15 minutes of continuous operation. This transient energy draw can be observed through the changing light quality as the lamp heats up to operating condition and glows progressively more orange and less white.

2.4 Data

2.4.1 Light Maps

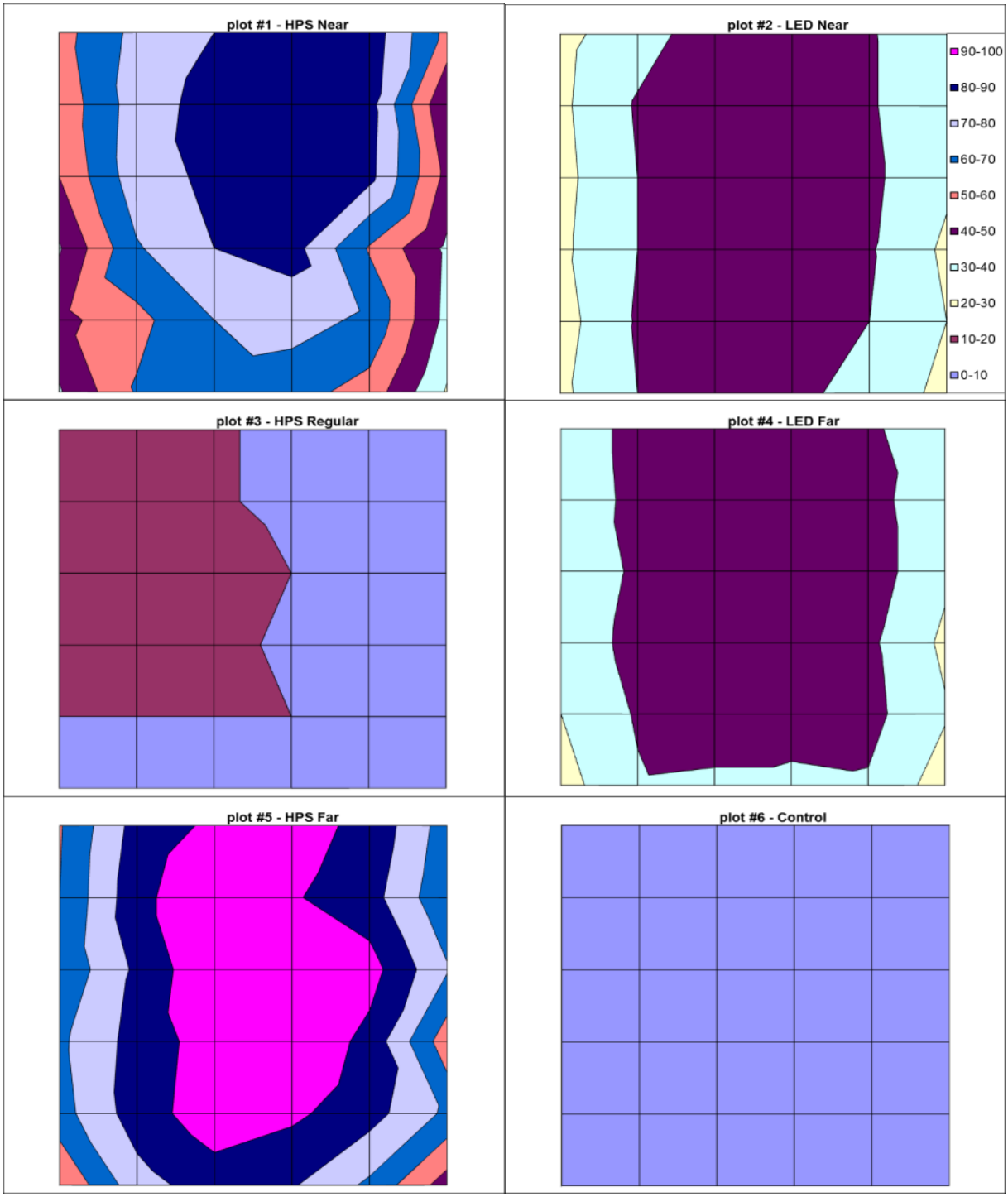

Figure 2.6: Light Map 1. Six test zones at the beginning of the experiment (February 17, 2010).
All data is in µmol s^{-1} m^{-2}. HPS 1 (Plot #1), LED 1 (Plot #2), HPS Regular (Plot #3), LED 2 (Plot #4), HPS 2 (Plot #5) and Control (Plot #6, no supplemental light).

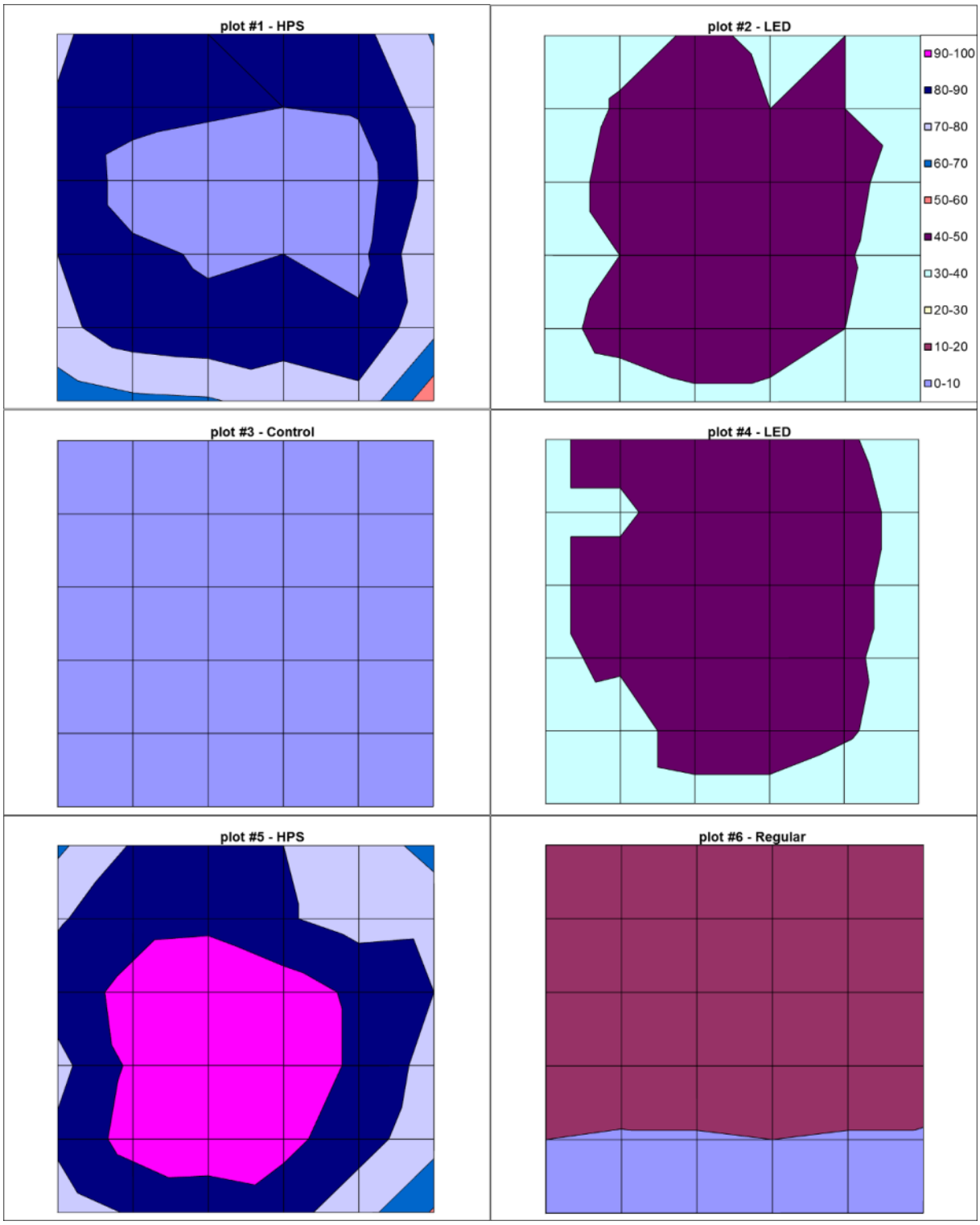

Figure 2.7: Light Map 2. Six test zones in between replications of the experiment (March 25th, 2010). All data is in µmol s^{-1} m^{-2}. HPS 1 (Plot #1), LED 1 (Plot #2), HPS Regular (Plot #3), LED 2 (Plot #4), HPS 2 (Plot #5) and Control (Plot #6, no supplemental light).

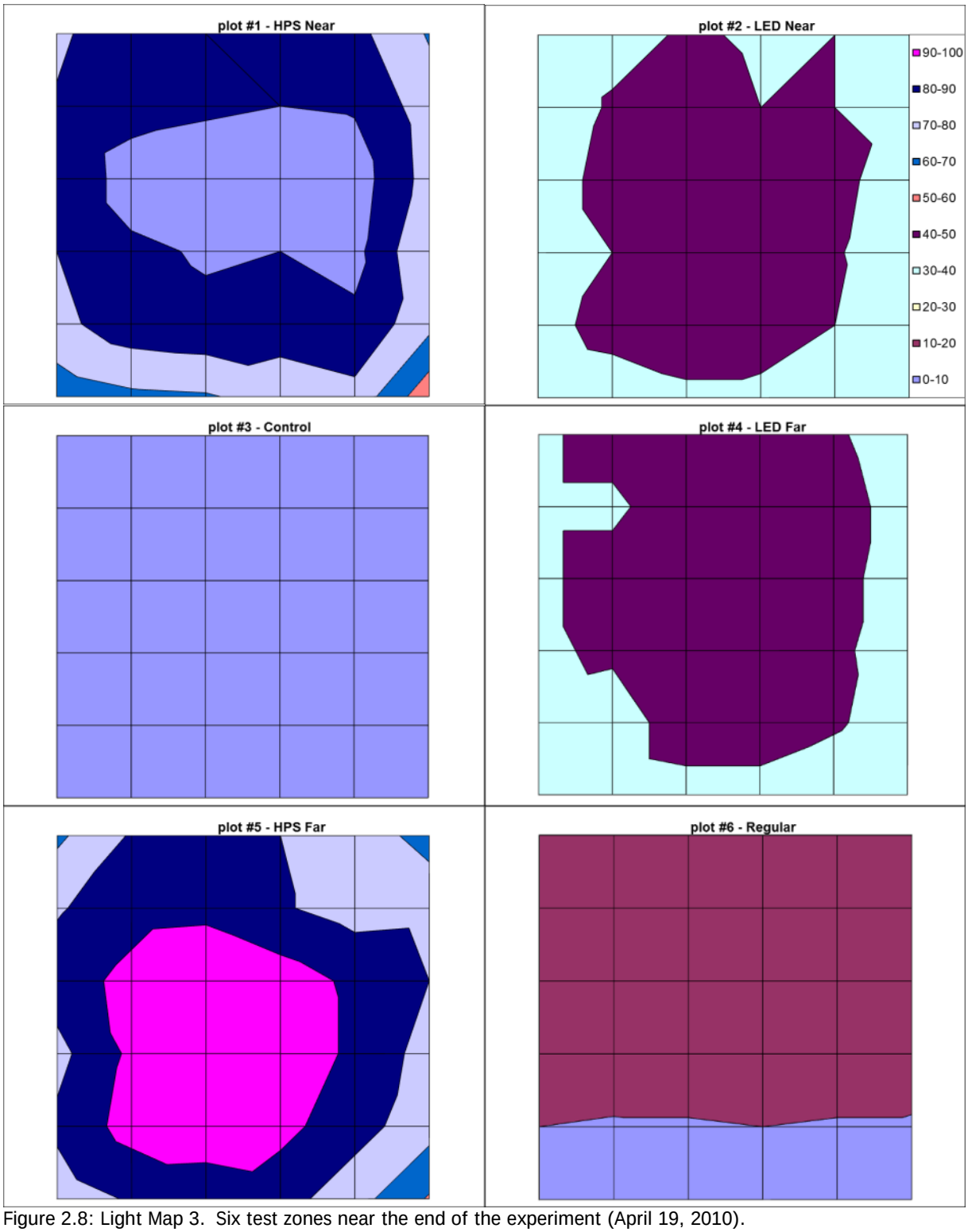

Figure 2.8: Light Map 3. Six test zones near the end of the experiment (April 19, 2010).
All data is in µmol s-1 m-2. HPS 1 (Plot #1), LED 1 (Plot #2), HPS Regular (Plot #6), LED 2 (Plot #4), HPS 2 (Plot #5) and Control (Plot #3, no supplemental light).

Table 2.1: Statistical Summary of Light Maps.
Statistical summary of three light maps for a single sample point after sunset at canopy level. All units are in µmol s^{-1} m^{-2}.

17-Feb-10	mean	std. dev.	maximum	minimum
Plot 1 - HPS Near	64.8	17.5	90.0	29.0
Plot 2 - LED Near	37.6	6.8	46.0	26.0
Plot 3 - Regular	8.6	4.4	17.0	1.0
Plot 4 - LED Far	39.2	7.2	48.0	25.0
Plot 5 - HPS Far	79.4	15.3	103.0	45.0
Plot 6 - Control	0.3	0.4	1.0	0.0
25-Mar-10	mean	std. dev.	maximum	minimum
Plot 1 - HPS Near	84.9	12.6	107.0	60.0
Plot 2 - LED Near	40.4	4.2	47.0	30.0
Plot 3 - Regular	8.1	3.9	16.0	0.0
Plot 4 - LED Far	42.3	4.2	49.0	32.0
Plot 5 - HPS Far	86.8	13	108.0	60.0
Plot 6 - Control	0.5	0.5	1.0	2.0
19-Apr-10	mean	std. dev.	maximum	minimum
Plot 1 - HPS Near	82.2	10.2	98.0	53.0
Plot 2 - LED Near	38.9	3.1	43.0	33.0
Plot 3 - Control	0.0	0	0.0	0.0
Plot 4 - LED Far	40.0	3.5	46.0	32.0
Plot 5 - HPS Far	83.1	9.6	102.0	59.0
Plot 6 - Regular	13.3	4.8	20.0	4.0

2.4.2 Overall Mass Comparisons

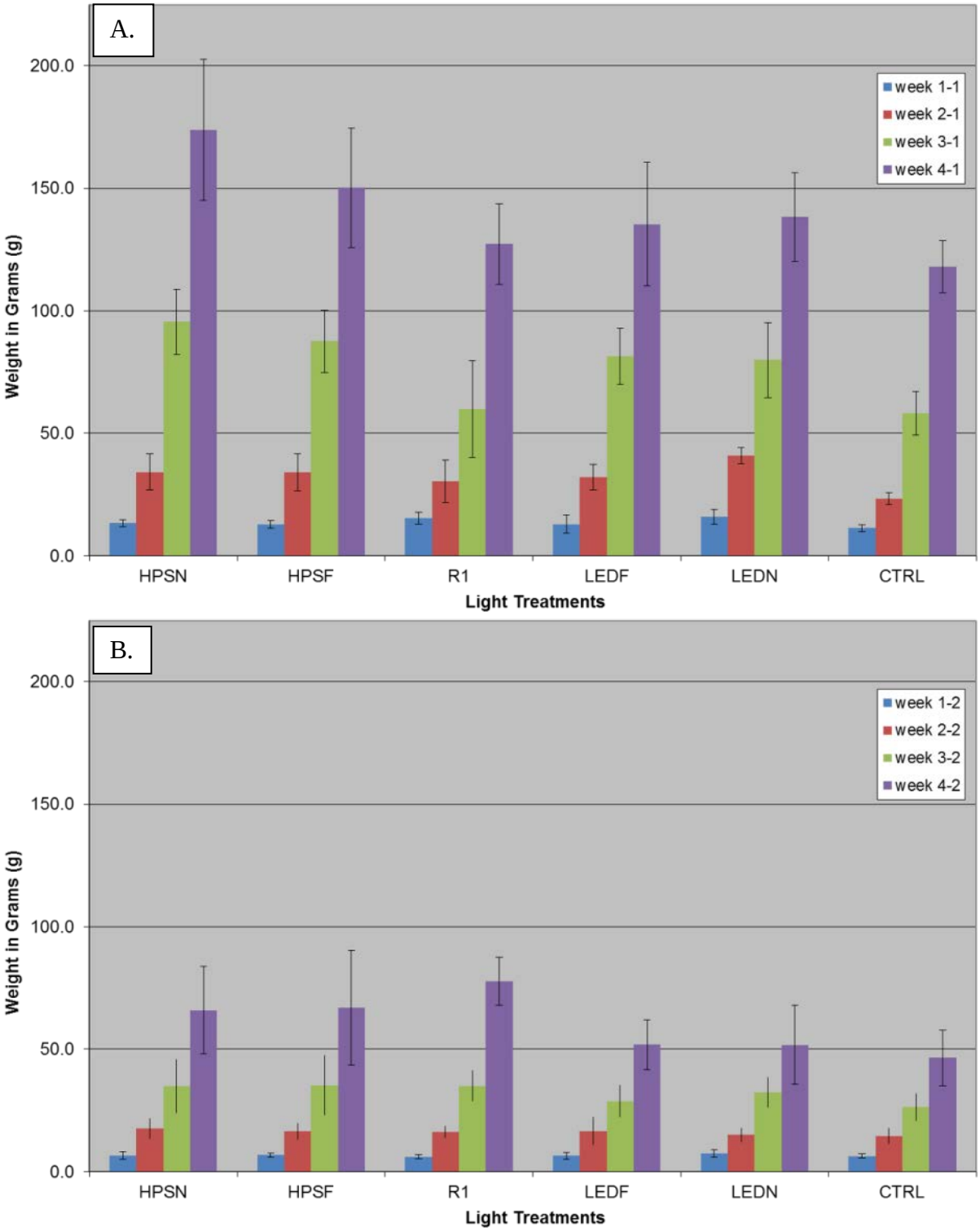

Figure 2.9: Overall Mean Wet Mass Comparison. Mean wet mass with standard deviation for six light treatments over four weeks with two replications (top and bottom figures).
Data tables used to create this graph are available in annex. A. HPS – High pressure sodium; LED – light emitting diode; R1 – regular greenhouse HPS levels; CTRL – control: no supplemental artificial lighting.

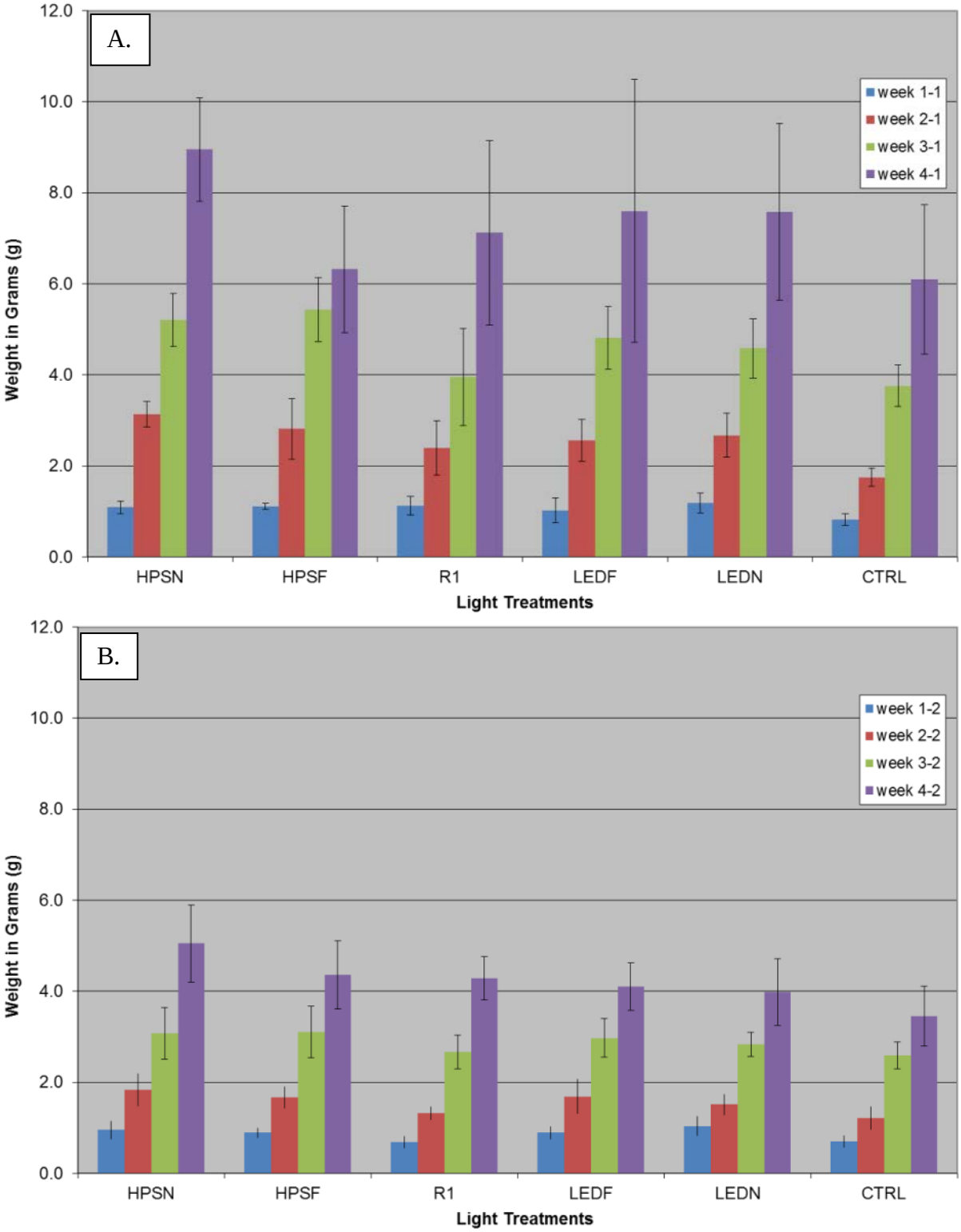

Figure 2.10: Overall Mean Dry Mass Comparison. Mean dry mass with standard deviation for six light treatments over four weeks with two replications (top and bottom figures).
Data tables used to create this graph are available in annex A. HPS – High pressure sodium; LED – light emitting diode; R1 – regular greenhouse HPS levels; CTRL – control: no supplemental artificial lighting.

Table 2.2: Normalized Ratio of Plant Mass versus Artificial Light per meter^2.
Wet and dry plant mass in grams versus artificial light in moles per meter^2; normalized by percentage of supplemental light versus total light.

Supplemental light only	wet ratio per percent	dry ratio per percent	supl light/total light
	(grams/moles of light/m^2)*percent of total light		percentage
HPS near - run 1	0.52	0.03	22.7%
HPS far - run 1	0.42	0.02	19.6%
HPS average - run 1	0.47	0.02	21.1%
HPS near - run 2	0.24	0.02	21.7%
HPS far - run 2	0.17	0.01	20.1%
HPS average - run 2	0.20	0.01	20.9%
LED near - run 1	0.51	0.03	10.9%
LED far - run 1	0.39	0.02	10.7%
LED average - run 1	0.45	0.02	10.8%
LED near - run 2	0.15	0.01	11.6%
LED far - run 2	0.14	0.01	12.0%
LED average - run 2	0.14	0.01	11.8%
Regular - run 1	0.48	0.03	4.8%
Regular - run 2	0.25	0.01	4.2%
Control - run 1	0.36	0.02	0.3%
Control - run 2	0.13	0.01	1.1%

Table 2.3: Normalized Ratio of Plant Mass versus Artificial Light per plant.
Wet and dry plant mass in grams versus artificial light in moles per plant; normalized by percentage of supplemental light versus total light.

Supplemental light only	wet ratio per percent	dry ratio per percent	supl light/total light
	(grams/moles of light/plant)*percent of total light		percentage
HPS near - run 1	12.69	0.65	22.7%
HPS far - run 1	10.18	0.43	19.6%
HPS average - run 1	11.41	0.54	21.1%
HPS near - run 2	5.93	0.45	21.7%
HPS far - run 2	4.02	0.26	20.1%
HPS average - run 2	4.95	0.35	20.9%
LED near - run 1	12.42	0.68	10.9%
LED far - run 1	9.53	0.49	10.7%
LED average - run 1	10.96	0.59	10.8%
LED near - run 2	3.58	0.28	11.6%
LED far - run 2	3.32	0.25	12.0%
LED average - run 2	3.45	0.26	11.8%
Regular - run 1	11.56	0.65	4.8%
Regular - run 2	6.13	0.34	4.2%
Control - run 1	8.74	0.45	0.3%
Control - run 2	3.04	0.23	1.1%

Table 2.4: Ratio of Plant Mass minus Control Plant Mass by Artificial Light per Area.
Wet and dry modified plant mass (average plant mass minus control plant mass, in grams) divided by irradiation per area (in moles/m2).

(Average Plant Mass - Control Mass) / Irradiation Per Area		
Suppl. Light Only	Modified Wet ratio	Modified Dry ratio
	grams/moles/m^2	grams/moles/m^2
Average HPS run 1	0.61	0.02
Average HPS run 2	0.29	0.02
Average LED run 1	0.61	0.05
Average LED run 2	0.13	0.01
Regular run 1	0.74	0.08
Regular run 2	2.41	0.06

Table 2.5: Ratio of Plant Mass minus Control Plant Mass by Artificial Light per Plant.
Wet and dry modified plant mass (average plant mass minus control plant mass, in grams) divided by irradiation per plant (in moles/plant).

(Average Plant Mass - Control Mass) / Irradiation Per Plant		
Suppl. Light Only	Modified Wet ratio	Modified Dry ratio
	grams/moles/plant	grams/moles/plant
Average HPS run 1	14.70	0.51
Average HPS run 2	6.93	0.44
Average LED run 1	14.85	1.17
Average LED run 2	3.14	0.35
Regular run 1	17.82	1.95
Regular run 2	58.48	1.56

Table 2.6: Comparison Between Week 3 – Replication 1 And Week 4 – Replication 2.
Comparison of wet and dry masses between two similar sampling points; typical of the final harvesting day. All masses in grams.

Wet Mass (grams)						
Week 3 - Rep 1	HPS Near	LED Near	Regular	LED Far	HPS Far	Control
Mean	95.5	80.0	59.9	81.4	87.6	58.2
Std. Dev.	13.3	15.3	19.8	11.5	12.7	8.9
Maximum	109.4	104.0	86.3	103.2	116.7	77.2
Minimum	71.9	56.0	27.6	65.9	73.6	46.8
Week 4 - Rep 2	HPS Near	LED Near	Regular	LED Far	HPS Far	Control
Mean	66.0	51.6	77.7	51.8	67.1	46.5
Std. Dev.	17.8	16.2	9.8	10.1	23.4	11.1
Maximum	105.0	84.9	92.5	68.5	104.8	64.8
Minimum	42.8	34.0	66.8	39.2	38.7	32.7

Dry Mass (grams)						
Week 3 - Rep 1	HPS Near	LED Near	Regular	LED Far	HPS Far	Control
Mean	5.1	4.0	4.3	4.1	4.4	3.5
Std. Dev.	0.8	0.7	0.5	0.5	0.8	0.7
Maximum	6.8	5.1	5.4	5.1	5.7	4.3
Minimum	4.0	2.9	3.7	3.3	3.6	2.1
Week 4 - Rep 2	HPS Near	LED Near	Regular	LED Far	HPS Far	Control
Mean	5.2	4.6	4.0	4.8	5.4	3.8
Std. Dev.	0.6	0.6	1.1	0.7	0.7	0.4
Maximum	5.8	5.6	5.6	5.8	6.6	4.7
Minimum	4.1	3.5	2.2	4.1	4.5	3.2

2.4.3 Energy

Table 2.7: Energy Cost Comparison.
Comparison of energy cost between HPS and LED lamps in watts per squared meters (W/m^2).

	energy cost	number of lamps	ernergy cost	plot size	ernergy cost
	per unit	per plot	per plot		per area
unit	Watts (W)	unit	Watts (W)	m^2	W/m^2
LED	319.9	24	7677.6	93.6	82.0
HPS	648.9	18	11680.2	93.6	124.8
HPS - Regular	648.9	4	2595.6	93.6	27.7
Control	0	0	0	93.6	0

Table 2.8: HPS Lamp Warm-Up Table.
HPS lamps energy consumption over time in watts (W).

Time	HPS1	HPS2	HPS3	HPS4	% of maximum
minute	watt	watt	watt	watt	
0	510.7	505.8	510.0	507.8	78%
5		536.8	533.7	558.9	85%
10		577.9	559.8	583.4	89%
15	666.4	646.9	632.1	638.6	100%
20	668.9	648.3	637.0	640.3	100%
25	670.6	648.9	639.0	641.4	100%
30	667.8	641.7	641.1	640.3	100%
35	667.1	645.2	639.7	640.7	100%
40	667.5	645.5	640.0	642.4	100%

2.5 Discussion

This experiment can be interpreted in two ways. Firstly, if the grower wants to maximize production of plant mass with little regards to initial costs, LED light treatment is a good choice for high plant mass production, especially considering the high homogeneity of the crop across the plot. Secondly, if the grower wants to maximize profitability at the expense of maximal levels of production, it is recommended to use limited supplemental light treatments based on transient weather conditions. This choice should be based on economic factors such as initial investment cost, return on investment and market conditions (Carrier, 1999).

The initial hypothesis, which was that lettuces grown under LED light treatment will have equivalent wet and dry masses and visual properties (color, shape, size) compared to lettuces grown under HPS treatment, regular HPS treatment (based on Hydroserre Mirabel's production levels) and control light treatment (no supplemental light) was also found to be correct. Both LED and HPS treatments are relatively similar in wet and dry masses while also being higher on average than the regular HPS treatment and control treatment. LED lamps also did not seem to have any negative visual quality impact when assessed by Hydroserre Mirabel's personnel.

2.5.1 Biomass

Both figures 2.9 and 2.10 show similar results as for the homogeneity of the light treatment replications on the biomass yield. While overall plant mass production differs, both sets of replication show LED treatments to be very similar. HPS light treatment is farther apart during the fourth week of the first trial. This is slightly different from the grouped results seen in the second trial. It is arguable that the second trial seems about ten days late compared to the first trial when looking at the dry mass results, as presented in table 2.6. Comparing the third week of the first trial with the fourth week of the second trial seems to indicate that HPS light treatment replications are also more similar than when compared between both fourth weeks. Further statistical analysis of those two weeks shows no outliers between them. The most likely explanation for this lag is the

lack of proper nutrient solution at the very beginning of the second experimental replication, which persisted for several days before being remedied.

Annex B contain weather data tables extracted from the data loggers over the course of the experiment. These tables were used to create the charts presented in annexes B and C of weather data inside the greenhouse. These were used to quickly and efficiently visually assess if any large scale perturbation happened during the experiment.

Similarly, statistical analysis was completed on all plant mass data to find outliers in masses using p=0.05. The wet masses showed a run by week interaction while the dry masses had a statistically significant change between each week. This basically means that the plants were growing from week to week, therefore indicating no anomalies in the samples. Root masses followed the trends of the leaf masses for all replications and no statistical significance was measured between treatments. While further analysis were performed on subsets of the mass and light maps data to find possible relations and outliers, no statistically significant results were reported and the results can be found in annex E and annex F.

Annex E contains the list of statistically significant interactions for wet and dry masses, separated by light treatments, weekly, experimental replications and light treatment replications. Most of the interactions by individual light treatments are between weeks, which indicate that light treatment replications were statistically similar. Annex F contains plots of plant growth for each light treatments and replications with a quadratic curve fit. This section also contains tables of the parameters of the quadratic equation with the form "constant + B1 * X + B2 * X^2". All of the curve fits have R^2 values between 0.797 and 0.975.

The regular treatment appears to pull slightly ahead in the wet mass comparison but it is similar to both HPS and LED results in the dry mass comparison. One of the possible explanations for this behaviour lies in the sampling process. Multiple samples per plot were harvested in lines parallel to the shading cloth. In fact, a partial shading mechanism

(shade cloth) was employed to reduce the incoming solar radiation during peak hours. This could have affected narrow strips of plants and created a localized effect as demonstrated by Shinohara and Suzuki (1981) in an experiment designed to show the impact of shading on biomass production. This localized effect may have been amplified by the random sampling technique used.

Figure 2.9 shows a larger difference between average dry masses for HPS light treatments than for LED light treatments. This effect is seen in both experimental replications. This seems to indicate that while HPS light treatment has the potential to produce higher amounts of plant mass (Chadjaâ et al., 2001), it can also increase the variability in production. Several factors may come into play. HPS Near, first replication, had slightly more elevated temperatures and less humidity than HPS Far, second replication (data available in annex B). Also, second replication was subjected to freezing air temperatures during at least one sample point.

One of the impacts of HPS light on the plant is a localized hot spot directly under the lamps. This can be potentially harmful to the plants because temperature can rise and heat damage can be caused (Mankin and walker, 1988). Surface temperatures of up to 47 degrees Celsius were reached on the LED plots during the second trial. In fact, the average surface temperatures in LED plots were higher than the average HPS surface temperatures for the second replication during the hours when the LED lamps were not operational. It is important to note that this issue was not as critical during the first experimental replication. It is somewhat difficult to determine if this was due to fan placement, sensor placement, physical location on the test plots or a combination of those factors compounded by the stronger sun impact in the month of March compared to the month of February.

Tables 2.2, 2.3, 2.4, 2.5 and Annex G show the impact of artificial light on plant mass. HPS light treatment gives twice as much light than LED light treatment for equivalent produced mass, which results in a lower ratio as seen in Annex G. When normalized with the ratio of artificial light versus total light, to show the actual impact of artificial

light on plant mass (tables 2.2 and 2.3), LED and HPS light treatments have a similar impact on plant dry matter production. However, it is also shown that the regular light schedule is the highest ratio, indicating that large amounts of supplemental light from both HPS and LED light treatments are not required to obtain the best production of plant mass per light input. It also indicates that Hydroserre Mirabel seems to have found a fairly well optimized HPS light intensity level. The reason for this could be related to the carbon dioxide levels that are maintained slightly higher in the greenhouse. There has been work done by Aikman (1996) showing the positive impact of both supplemental lighting and carbon dioxide enrichment while Both et al. (1997) has shown that combinations of varying levels of PAR and carbon dioxide can attain similar biomass production. This means that when increasing PAR levels is not possible, an increase in carbon dioxide concentration could attain the same results. More recently, work has been done to estimate the optimal levels of PAR and CO_2 for ventilated greenhouses (Ferentinos et al., 2000). In this case, the greenhouse was already optimized for a specific PAR vs CO_2 relationship which was selected for the regular HPS light schedule. It is possible that an increase in carbon dioxide would be more beneficial to HPS/LED light treatments versus the regular light treatment's current "home advantage".

Tables 2.4 and 2.5 are different than tables 2.2 and 2.3 because they take into account only the difference in plant mass between light treatments and control versus the supplemental light. This methodology shows slightly different results, mainly that the average of LED light treatments is slightly ahead on the first run but halved on the second run when compared to the average of HPS light treatments. This analysis is based on the hypothesis that without supplemental light, all plants should be at the control level. It is therefore slightly less rigorous than the previous analyses.

2.5.2 Light Map

The first light map performed on February 17th, 2010, shows differences in the HPS-near compared to later readings. This measure may be slightly off due to electrical problems in the greenhouse. Perhaps the light was at a different point in its power cycle.

Statistical analysis was completed on the light maps (figures 2.6, 2.7 and 2.8) and statistical significance was found between light treatments, light by time and light by time by replication. This indicates that there was in fact a difference between all the light treatments' intensities.

2.5.3 Energy Cost

Table 2.7 shows the energy cost of operating LED and HPS lamps during the test periods. It appears that LED lamps used approximately 66% of the energy of optimal HPS lamps while the regular HPS schedule used approximately 22% of the equivalent optimal HPS plot, or 33.5% of the LED energy use. It is important to note the different number of lamps between both lighting technologies. In fact, a LED lamp is estimated to use about 50% of the energy of a HPS lamp. Concretely, this means that although the lamp density must be higher to maintain acceptable photon flux, LED lamps can produce significant energy savings over time, which may translate into economic incentives that would increase adoption rates amongst producers (Papadopoulos et al., 2007).

2.6 Observation

At the start of the second replication, visible yellow spots occurred on the entire lettuce population and stunted growth ensued for the rest of the experiment. There was a technical issue with the refilling of the water tank that prevented proper nutrient balance from being attained at the start of experimental replication two.

We were also informed that a controller unit closed the lights for the entire experiment area after a certain threshold of solar radiation was reached for three days in the first replication. A similar cut-off also happened during the second replication for four consecutive days. These two periods of no light occurred at roughly the same time and for the same length for both replications and should therefore have limited impact on the overall experiment.

2.7 Conclusion

In conclusion, this experiment has shown that both HPS and LED light treatments have the potential to produce adequate Boston lettuce. While HPS produces more moles of light per time period when compared to LED lights, with 71.3moles/m^2 for HPS and 35.8moles/m^2 for LED over four weeks, the impact on dry plant mass production is very limited, yet still important.

Dry ratios of plant mass (in grams) by artificial irradiation (in moles per plant) normalized by the percentage of supplemental light versus total light were of 0.54 g/mol/plant and 0.35 g/mol/plant for both HPS experimental replication and of 0.59 g/mol/plant and 0.26 g/mol/plant for both LED experimental replication. These ratios indicate the impact of supplemental lighting on dry plant mass and show that in both types of lighting, the results are fairly similar.

Clear gains can be made using some levels of supplemental light to prolong the photoperiod of the plant. It is however important to account for the energy use of the lamps, with 319.9 Watts for a LED lamp and 648.9 Watts for an individual HPS lamp. The average energy requirement of the HPS plots was 124.8 W/m^2 while the LED energy use was 27.7 W/m^2.

Therefore, varying levels of additional light intensity can be explored to provide the best economic scenario with little fluctuation expected in final plant mass productivity. This should be of particular interest to producers subjected to tiered electrical costs based on time of the day or otherwise constrained in their energy use.

Chapter 3. Nutrient Content of Lettuce Leaves

3.1 Introduction

Lettuce plants have been grown under high pressure sodium (HPS) lamps for decades in Quebec, allowing continued profitability during winter time for greenhouse growers (Carrier, 1999). However, HPS lamps have high energy consumption, produce waste heat (from the conversion of electricity to light energy) and are not producing the optimal spectrum of light for photosynthesis. Light emitting diode (LED) lamps are expected to remedy those issues while also lasting longer (Crafford, 2005). Because a LED lamp is built of many individual LED, a typical array can be infinitely modified to produce exactly the desired wavelength spectrum. This should enable a more efficient photosynthesis process, which will translate into increased biomass yield and possibly improved crop quality.

Many studies have been done to quantify the effect of LED lamps on plant growth from a biomass yield perspective (Kim et al., 2004, Yanagi et al., 1996, Yasuhiro et al., 2002, Evans et al., 1965). Fewer have been done regarding nutrient content as a function of supplemental light treatment. Light quality studies have to be tailored for particular subsets of plants, increasing the experimental effort required, if precise relationships between wavelengths (or even groups of wavelengths) and plants is to be determined. For example, it seems that the effect of UV light on carotenoids composition of lettuce is dependent on leaf color: green leaf lettuce had increased compound concentrations while red leaf lettuce had reduced concentrations (Caldwell et al., 2006). Some effects seem to be more widespread to a variety of plants: the effect of red/blue supplemental light has also been shown to be positive on carotenoid concentrations (Ohashi-Kaneko et al., 2007).

Several phytochemicals are present during the photosynthesis process, such as chlorophyll a and b, lutein, β-carotene and xanthophylls (antheraxanthin, zeaxanthin and violaxanthin). The xanthophylls are useful to the plant both for shedding excess energy

and for optimizing low light conditions (Eskling et al., 1997). The importance of the presence of these seven different phytochemicals in lettuce is the expression of their strong antioxidant properties (Khachik et al., 1995).

The following experiment will compare the levels of these seven phytochemicals present in lettuce based on different light treatments from HPS lamps (a regular schedule and an optimized one), a control plot with no supplemental light and LED lamps.

3.1.1-Hypothesis

The initial hypothesis of this experiment is that lettuces grown under LED light treatment will produce the highest phytochemical concentrations, followed by HPS treatment, regular HPS (based on Hydroserre Mirabel's production levels) and control light treatment (no supplemental light).

3.2 Materials and Methods

3.2.1-Plant culture and light treatments

All Boston lettuce plant tissues were provided by Hydroserre Mirabel. A description of the experimental setup, along with harvesting procedures, can be found in chapter 2, section 2.2.

3.2.2- Carotenoid and chlorophyll determination for leaf tissues - extraction

All leaf tissue samples were frozen prior to lyophilization (Martin Christ, Gamma 1-16 LSC, MBI, Kirkland, QC). Pigments were extracted from freeze-dried tissues according to Kopsell et al. (2004) and analyzed according to Kopsell et al. (2007). A 0.1 g tissue subsample was re-hydrated with 0.8 mL of ultra-pure H_2O for 20 min. After incubation, 0.8 mL of the internal standard ethyl-8′-apo-β-caroten-8′-oate (Sigma Chemical Co., St. Louis, MO) was added to determine extraction efficiency. The addition of 2.5 mL of tetrahydrofuran (THF) was performed after sample hydration. The sample was then homogenized in a Potter-Elvehjem (Kontes, Vineland, NJ) tissue grinding tube using a pestle attached to a drill press set at 540 rpm. During homogenization, the tube was immersed in ice to dissipate heat. The tube was then placed into a clinical centrifuge for 3 min at 500 g_n. The supernatant was removed and the sample pellet was re-suspended in 2 mL THF and homogenized again with the same extraction technique. The procedure was repeated for a total of four extractions to obtain a colorless supernatant. The combined supernatants were reduced to 0.5 mL under a stream of nitrogen gas (N-EVAP 111; Organomation Inc., Berlin, MA), and brought up to a final volume of 5 mL with methanol (MeOH). A 2-mL aliquot was filtered through a 0.2-µm polytetrafluoroethylene (PTFE) filter (Model Econofilter PTFE 25/20, Agilent Technologies, Wilmington, DE) prior to high-performance liquid chromatography (HPLC) analysis.

3.2.3- Carotenoid determination for leaf tissues - HPLC pigment analysis

High-performance liquid chromatography separation parameters and pigment quantification followed procedures of Kopsell et al. (2007). An Agilent 1200 series HPLC unit with a photodiode array detector (Agilent Technologies, Palo Alto, CA) was used for pigment separation. The column used was a 250 mm x 4.6 mm inner diameter, 5 μm analytical scale polymeric RP-C_{30}, with a 10 mm x 4.0 mm inner diameter guard cartridge and holder (ProntoSIL, MAC-MOD Analytical Inc., Chadds Ford, PA), which allowed for effective separation of chemically similar carotenoid compounds. The column was maintained at 30 ºC using a thermostatted column compartment. All separations were achieved isocratically using a binary mobile phase of 11% methyl *tert*-butyl ethanol (MTBE), 88.9% MeOH, and 0.1% triethylamine (TEA) (v/v/v). The flow rate was 1.0 mL/min, with a run time of 53 min, followed by a 2 min equilibration prior to the next injection. Eluted compounds from a 10 µL injection loop were detected at 453 nm [carotenoids, chlorophyll b (Chl b), internal standard], and 652 nm [chlorophyll a (Chl a)] and data were collected, recorded, and integrated using ChemStation Software (Agilent Technologies). Peak assignment for individual pigments was performed by comparing retention times and line spectra obtained from photodiode array detection using authentic external standards (ChromaDex Inc., Irvine, CA).

Every effort was made to reduce any effects of light and/or thermal degradation of lettuce leaf tissue pigments during extraction and HPLC analysis. Extractions were carried out under reduced light as the laboratory had no windows and only fluorescent lighting (low light intensity and limited wavelengths below 400 nm). In addition, exposure to all light was reduced during extraction by placing solutions under cover in ice baths. Samples were also filtered into amber HPLC vials that exclude light, and protected when run on the HPLC by a tinted shield covering the autosampler.

3.3 Results

As can be seen in Table 3.1, the first replication of control light treatment (C1) had the highest concentration of antheraxantin (3.44 mg/100gfm), β-carotene (5.77 mg/100gfm), chlorophyll a (16.47 mg/100gfm), second highest concentration of chlorophyll b (12.66 mg/100gfm), highest lutein concentration (6.93 mg/100gfm), 6th highest neoxanthin concentration (1.68 mg/100gfm) and highest violaxanthin concentration (4.50 mg/100gfm). Second replication of control light treatment (C2) had 5th concentration of antheraxantin (3.1 mg/100gfm), 3rd on β-carotene (5.29 mg/100gfm), 3rd on chlorophyll a (15.94 mg/100gfm), 3rd on chlorophyll b (11.92 mg/100gfm), second highest lutein concentration (6.88 mg/100gfm), highest neoxanthin concentration (2.29 mg/100gfm) and second highest violaxanthin concentration (4.28 mg/100gfm).

First replication of regular light treatment (R1) had second highest concentration of antheraxantin (3.33 mg/100gfm), 2nd on β-carotene (5.53 mg/100gfm), 2nd on chlorophyll a (16.03 mg/100gfm), highest concentration of chlorophyll b (12.75 mg/100gfm), 3rd highest lutein concentration (6.83 mg/100gfm), 7th neoxanthin concentration (1.84 mg/100gfm) and 3rd highest violaxanthin concentration (3.77 mg/100gfm). Second replication of regular light treatment (R2) had 8th concentration of antheraxantin (2.43 mg/100gfm), 7th on β-carotene (4.33 mg/100gfm), 8th on chlorophyll a (12.32 mg/100gfm), 8th concentration of chlorophyll b (9.74 mg/100gfm), 8th highest lutein concentration (5.40 mg/100gfm), 4th neoxanthin concentration (1.89 mg/100gfm) and 5th highest violaxanthin concentration (3.56 mg/100gfm).

First replication of HPS Near light treatment (HPSN1) had 10th concentration of antheraxantin (2.03 mg/100gfm), 11th on β-carotene (3.14 mg/100gfm), 9th on chlorophyll a (9.82 mg/100gfm), 9th concentration of chlorophyll b (8.32 mg/100gfm), 10th highest lutein concentration (4.01 mg/100gfm), 11th neoxanthin concentration (1.10 mg/100gfm) and 10th highest violaxanthin concentration (2.15 mg/100gfm). Second replication of HPS Near light treatment (HPSN2) had 3rd concentration of antheraxantin (3.17 mg/100gfm), 4th on β-carotene (4.85 mg/100gfm), 5th on chlorophyll a (14.42

mg/100gfm), 6th concentration of chlorophyll b (11.39 mg/100gfm), 4th highest lutein concentration (6.43 mg/100gfm), 2nd neoxanthin concentration (2.24 mg/100gfm) and 6th highest violaxanthin concentration (3.39 mg/100gfm).

First replication of HPS Far light treatment (HPSF1) had 4th concentration of antheraxantin (3.15 mg/100gfm), 5th on β-carotene (4.74 mg/100gfm), 4th on chlorophyll a (15.08 mg/100gfm), 4th concentration of chlorophyll b (11.88 mg/100gfm), 5th highest lutein concentration (6.33 mg/100gfm), 3rd neoxanthin concentration (1.91 mg/100gfm) and 4th highest violaxanthin concentration (3.76 mg/100gfm). Second replication of HPS Far light treatment (HPSF2) had 11th concentration of antheraxantin (1.78 mg/100gfm), 9th on β-carotene (3.53 mg/100gfm), 10th on chlorophyll a (9.82 mg/100gfm), 10th concentration of chlorophyll b (6.85 mg/100gfm), 11th highest lutein concentration (3.85 mg/100gfm), 10th neoxanthin concentration (1.20 mg/100gfm) and 7th highest violaxanthin concentration (2.94 mg/100gfm).

First replication of LED Near light treatment (LEDN1) had 6th concentration of antheraxantin (2.95 mg/100gfm), 8th on β-carotene (3.90 mg/100gfm), 7th on chlorophyll a (13.62 mg/100gfm), 5th concentration of chlorophyll b (11.72 mg/100gfm), 6th highest lutein concentration (5.80 mg/100gfm), 5th neoxanthin concentration (1.88 mg/100gfm) and 9th highest violaxanthin concentration (2.78mg/100gfm). Second replication of LED Near light treatment (LEDN2) had 12th concentration of antheraxantin (1.11 mg/100gfm), 12th on β-carotene (1.60 mg/100gfm), 12th on chlorophyll a (4.07 mg/100gfm), 12th concentration of chlorophyll b (3.02 mg/100gfm), 12th highest lutein concentration (2.02 mg/100gfm), 12th neoxanthin concentration (0.50 mg/100gfm) and 12th highest violaxanthin concentration (1.19 mg/100gfm).

First replication of LED Far light treatment (LEDF1) had 7th concentration of antheraxantin (2.71 mg/100gfm), 6th on β-carotene (4.69 mg/100gfm), 6th on chlorophyll a (13.95 mg/100gfm), 7th concentration of chlorophyll b (11.00 mg/100gfm), 7th highest lutein concentration (5.58 mg/100gfm), 8th neoxanthin concentration (1.68 mg/100gfm) and 8th highest violaxanthin concentration (2.91 mg/100gfm). Second replication of LED

Far light treatment (LEDF2) had 9th concentration of antheraxantin (2.13 mg/100gfm), 10th on β-carotene (3.15 mg/100gfm), 11th on chlorophyll a (9.31 mg/100gfm), 11th concentration of chlorophyll b (6.75 mg/100gfm), 9th highest lutein concentration (4.07 mg/100gfm), 9th neoxanthin concentration (1.25 mg/100gfm) and 11th highest violaxanthin concentration (2.02 mg/100gfm).

3.4 Data

Table 3.1: Overall Phytochemical Concentrations.
Concentrations of seven phytochemical (antheraxanthin, β-carotene, chlorophyll a and b, lutein, neoxantin and violaxanthin) in mg/100gfm for twelve samples of lettuce grown under HPS, LED and natural light.

mg/100 gfm	antheraxanthin	B-carotene	chlorophyll A	chlorophyll B	lutein	neoxantin	violaxanthin
C	3.27	5.53	16.21	12.29	6.90	2.09	4.39
R	2.88	4.93	14.18	11.24	6.12	1.86	3.67
HPS	2.53	4.06	12.29	9.61	5.16	1.61	3.06
LED	2.22	3.33	10.24	8.12	4.36	1.33	2.22

Table 3.2: Overall Ranking of Light Treatments.
Based on the average of the relative positions per compound (antheraxanthin, β-carotene, chlorophyll a and b, lutein, neoxantin and violaxanthin)

Position									
	antheraxantin	B-carotene	Chloro A	Chloro B	Lutein	neoxanthin	violaxanthin	average	overall position
C	1	1	1	1	1	1	1	1.0	1
R	2	2	2	2	2	2	2	2.0	2
HPS	3	3	3	3	4	3	3	3.1	3
LED	4	4	3	4	3	3	4	3.6	4

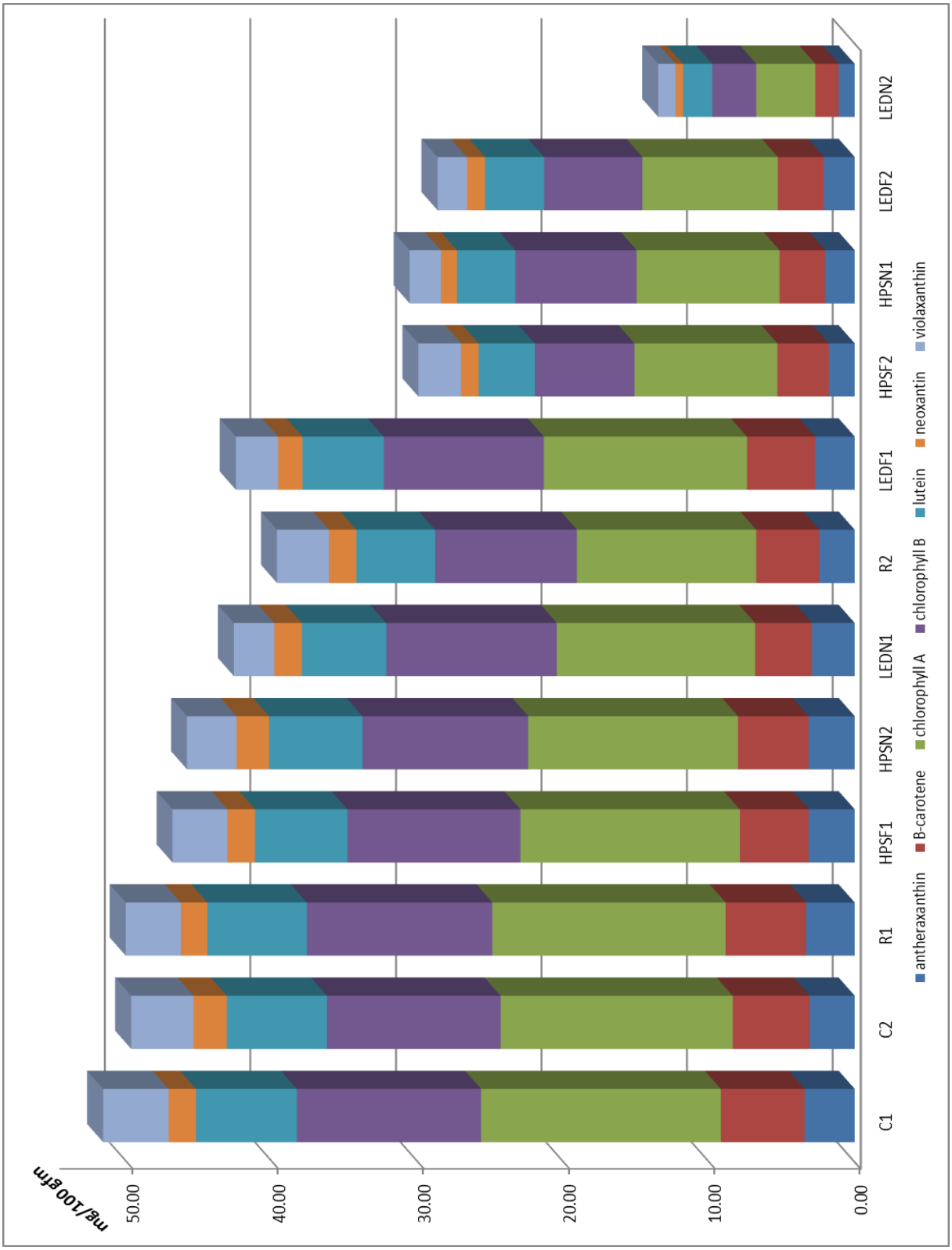

Figure 3.1: Sum of Phytochemicals Sorted by Light Treatments.
Sum of seven phytochemical Concentrations (antheraxanthin, β-carotene, chlorophyll a and b, lutein, neoxantin and violaxanthin) in mg/100gfm for twelve samples of lettuce grown under HPS, LED and natural light.

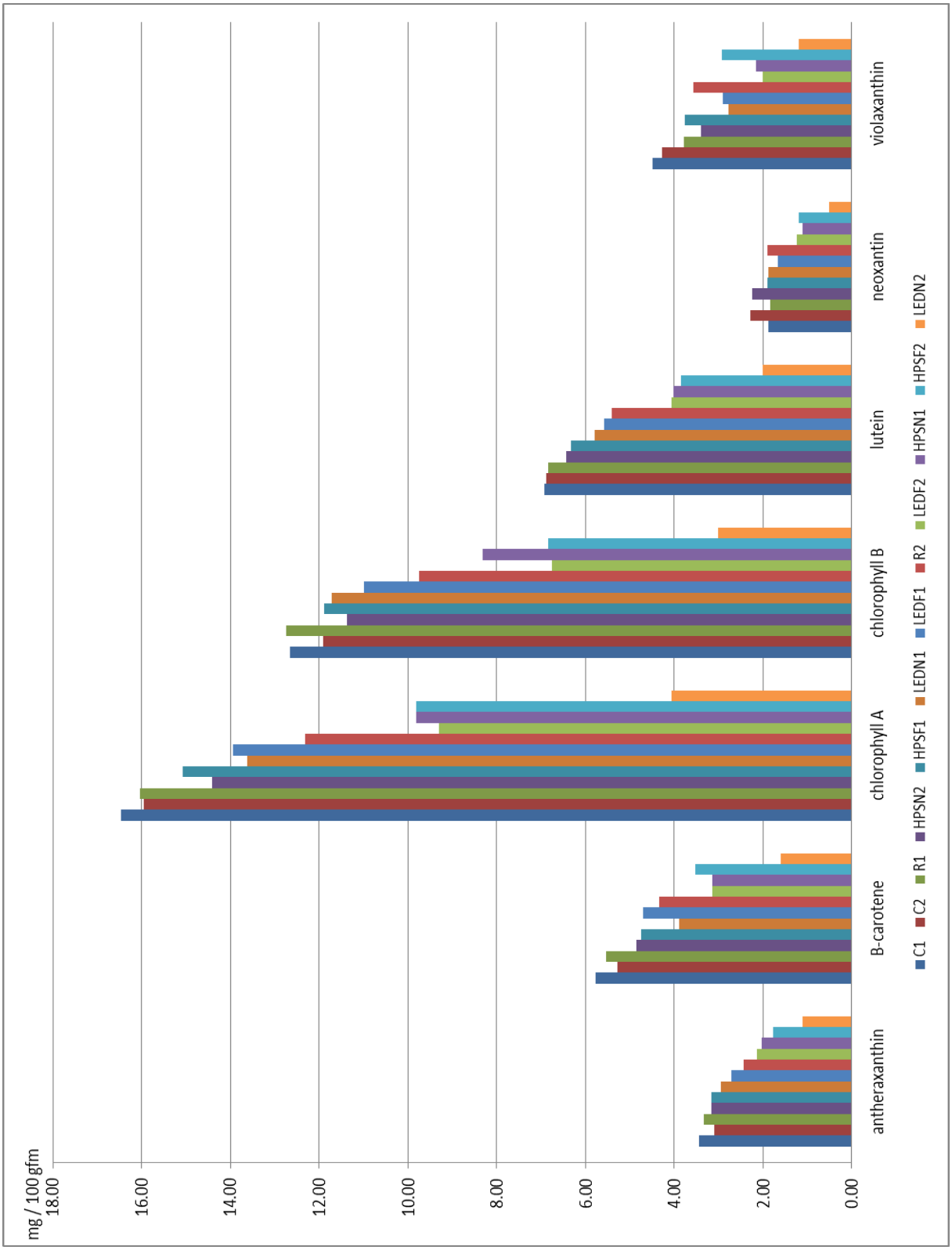

Figure 3.2: Overall Concentrations Sorted by Phytochemicals.
List of concentrations of seven phytochemicals (antheraxanthin, β-carotene, chlorophyll a and b, lutein, neoxantin and violaxanthin) in mg/100gfm for twelve samples of lettuce grown under HPS, LED and natural light.

3.5 Discussion

Tables 3.1 and 3.2 express information regarding the concentration of seven photosynthetically important phytochemicals. The control plots scored best overall while the regular HPS light treatment produced second best results. HPS light treatment had average results in concentrations, placing third, while LED light treatment produced the least amount of phytochemicals overall. Statistical analysis, using univariable ANOVA, showed no outliers ($p = 0.05$) which indicates that even though there is a four-fold difference between the best and the worst concentrations of chlorophyll and a three-fold difference for the xanthophylls, no treatments should be discarded.

While the focus of this experiment was to determine if light quality could influence nutrient content, it has been demonstrated that hydroponic lettuce contains less concentration of lutein, chlorophylls, xanthophylls and carotenes than lettuce grown conventionally (Kimura et al., 2003). Violaxanthin should be a good indicator of low light conditions (Eskling et al., 1997) and table 3.2 indeed shows both control and regular light treatments in the four out of five first positions. However, concentrations of xanthophylls vary daily and are also affected by both cold and hot temperatures, salinity, nutrient and other stresses (Demmig-Adams et al., 1992). It is difficult to determine the exact extent of light quality on xanthophylls concentrations because of all the other possible interactions.

Therefore, the initial hypothesis, which was that lettuces grown under LED light treatment will produce the highest phytochemical concentrations, followed by HPS treatment, regular HPS (based on Hydroserre Mirabel's production levels) and control light treatment (no supplemental light), has not been proven to be correct. In fact, LED light treatment seems to have an adverse effect on phytochemical production in hydroponically grown lettuces. There seems to be an inversely proportional relationship between supplemental light levels and phytochemical levels.

A possible explanation to the low concentrations of phytochemicals in LED treated samples is that the nutrient production cycle is linked to a particular wavelength that wasn't supplemented properly to the plants but that was present in the sunlight. It is also possible that it is not the absolute amount of energy at a distinct wavelength that is crucial to phytochemical production but rather the ratio of energies at different wavelengths. It could also be an interaction between two or more environmental triggers, such as temperature and a wavelength.

Considering that regular HPS treatment produced more phytochemicals than optimized HPS treatment on average, it seems possible that a fraction of that difference can be attributed to the difference in plant mass between both treatments. Perhaps the plants spent energy on increasing their mass instead of improving their phytochemicals content. It is probable that there exists an optimized sequence of lighting cycles that would alternatively stress the plant and take advantage of its hardiness (Yasuhiro et al, 2002). This would potentially increase energy savings while producing higher nutrients content. More research is necessary in this area to verify if optimized wavelength pulses are the next stage of controlled environment biomass production.

Another aspect to consider is the carbon dioxide enrichment program. It has been demonstrated that varying CO_2 levels in function of PAR can increase biomass yield (Both et al., 1998). The relationship present between those two parameters indicates that it is possible that the current CO_2 levels were optimal, from a phytochemical standpoint, for un-supplemented lettuce (control plot) and increasing CO_2 concentrations further could have had a positive impact on the quality of LED and HPS lettuces.

Figure 3.1 shows the sum of all phytochemicals, sorted by light treatments. Figure 3.2 shows a breakdown of the same information. While xanthophylls and carotenoids have associated positive health benefits, the concentrations found in lettuce can stand to be improved across the board. While light quality seems to have a non-negligible impact, genetic modifications could be an alternative way to improve nutrient concentration (Mou, 2005).

Found in the annex are table I1 through I6, containing detailed information regarding the parameters of the samples as they were processed through the HPLC analysis. Xanthophyll compounds are listed by their abundance over all the light treatments. These exhaustive tables are precursors for figures 3.1 and 3.2. Statistical analysis performed on all compounds indicates that the results are coherent and that no outliers are present when using a p-value of 0.05.

3.6 Conclusion

Supplemental lighting has historically been approached from a biomass yield perspective. However, photomorphogenesis of lettuce plants, which improves visual and biochemical quality of the final product (Okamoto et al., 1997), can also be achieved through control of light quality.

Several key carotenoids present in varying quantities in lettuce, such as lutein and β-carotene, are linked with chemopreventive properties and other potential health benefits, when consumed in sufficient amount. However, it seems that those compounds are not only a factor of light intensity and quality but also of temperature, salinity, nutrient intake, water stress, carbon dioxide concentration, growth media and more. If the abundance of carotenoids and xanthophylls could be increased through a particular light treatment, growers could stand to gain important monetary benefits by selling those enhanced crops. Instead of using genetically modified crops for enhanced properties, a practice which currently carries a stigma with the general public, a precise light treatment may be the solution.

LED lamps could be used to achieve those results if specifically designed for a particular plant species, carbon dioxide concentration and management practices. However, in the case of this experiment, it seems that both HPS and LED lamps achieved lower nutrient levels than the control light treatment for all seven compounds. Lettuces grown under LED lamps were the least productive for all compounds on average. The best light treatment in terms of overall nutrient content was the control treatment, followed by the

regular light treatment and then HPS treatment. More specifically, the four HPS treatments placed in the middle of the total twelve treatments, with ranks of 4^{th}, 5^{th}, 9^{th} and 10^{th}, while the four LED treatments had lower concentrations, ranking 6^{th}, 8^{th}, 11^{th} and 12^{th} for all tested xanthophylls, chlorophylls and carotenoids. These results are most likely caused by the light source. For an unknown reason, the LED lamps do not seem to be able to produce as high nutrients concentrations. Perhaps the xanthophyll production is linked to a wavelength not present in LED lamps. It is also possible that the carbon dioxide enrichment treatments and average PAR levels were best suited for no supplemental light or low supplemental light levels at the test location. The relationship between nutrient content and light quality is complex and probably guided by more factors than initially apparent.

Chapter 4. Summary, Conclusions and Suggestions for Future Research

4.1 General Summary

The combined greenhouse industry of Canada exceeds the two billion dollars mark, putting it in the range of canola and wheat, or about 15% of the crop farm business (Papadopoulos et al., 2007). The overwhelming majority of Canadian operations use supplemental lighting under one form or another with a strong trend towards high pressure sodium (HPS) lamps. Recent advances in the light emitting diode (LED) lighting technology, with InGaN and AlInGaP (Kuo et al., 1991) based diodes, more than a thousand times brighter than the earliest LED (Steranka et al., 2002), enable their use as a supplemental light source for greenhouse crops. The most significant advantage of the LED technology is the reduced energy consumption compared to traditional HPS lamps (Crafford, 2005). Many experiments (Zhou, 2008) have demonstrated that changes in both intensities and ratios (Yanagi et al., 1996, Okamoto et al., 1997) of the far-red (Evans et al., 1965), red, blue (Dougher et al., 2001), white and ultra-violet wavelengths (Li et al., 2009) will have an impact on plant physiology. Yellow light has been shown to be an inhibitor of plant growth (Dougher et al., 2001) and green light to be fairly ineffective (Kim et al., 2006). LED lamps based on a combination of those beneficial wavelengths should then be able to increase photosynthesis efficiency, biomass yields and plant quality. Some of the benefits of lutein and carotenoids, present in lettuce, include antioxidant and chemopreventive properties (Khachik et al., 1995).

Photomorphogenesis, was studied from two different perspectives for this thesis. The first experiment, presented in chapter 2, was designed to assess the yield differences between LED and HPS lamps on hydroponics Boston lettuce, in a live production site at a commercial scale. The second experiment, presented in chapter 3, was designed to determine if light treatments could improve xanthophylls, carotenoids and chlorophylls concentrations in the same lettuces.

4.2 Conclusions

In chapter 2, four different types of light treatments were compared on a wet and dry biomass basis for hydroponics lettuce production. There were two replications of an high intensity HPS treatment, two LED replications, one control without additional light and one regular (Hydroserre Mirabel's baseline) HPS treatment, currently used for commercial production. The plants were grown for approximately four weeks and ten samples were taken every week to track biomass change over time, with two experimental replications. Additionally, data loggers collected information on water, air and ground-level temperatures, humidity and radiation in both photosynthetically active radiation range and a wider spectrum. Plants were weighed on-site, dried for 72 hours and weighed again.

It was found that both HPS and LED supplemental light treatments are effective at improving mass yield compared to the control. HPS light treatment produced on average wet masses of 162.0g (std. dev. 26.6g) while LED light treatment produced wet masses of 136.9g (std. dev. 21.7g). The HPS light treatment at regular greenhouse levels produced wet masses averaging 127.3g (std. dev. 16.5g). Plants subjected to no supplemental artificial lighting (Control) produced an average wet mass of 118g (std. dev. 10.6g). While photomorphogenesis accounts for a large portion of biomass fluctuations, other factors such as water stress, temperature (Scaife, 1973), humidity, water pH, salinity (Kim et al., 2008), carbon dioxide concentration and natural PAR levels can all impact yields.

One of the claims of LED technology is reduced energy use (Craford, 2005). The LED lamps consumed about 319.9 Watts of electricity each while the HPS lamps consumed approximately 648.9 Watts each. There were 24 LED lamps per plot; therefore the energy demand for the LED lamps in the chosen configuration, on an area basis, was 82.0 W/m^2. There were 18 HPS lamps per plot; translating into an energy cost of 124.8 W/m^2. The regular HPS light treatment required only 4 lamps for an energy cost of 27.7 W/m^2.

Considering the similar biomass yields between both technologies, it is clear that LED lamps are a credible challenger for greenhouse supplemental lighting.

In chapter 3, leaf tissues samples taken from the final week of each replication of lettuces grown from the previous experiment were freeze dried according to Kopsell et al. (2004) and analyzed for concentrations of chlorophylls, carotenoids and xanthophylls according to Kopsell et al. (2007). The best light treatment in terms of overall nutrient content was the control treatment, followed by the regular light treatment. The four HPS replications placed in the middle of the total twelve treatments replications, with ranks of 4^{th}, 5^{th}, 9^{th} and 10^{th}, while the four LED replications had lowest concentrations, ranking 6^{th}, 8^{th}, 11^{th} and 12^{th} for all tested xanthophylls, chlorophylls and carotenoids.

These results are most likely caused by a lack of a specific wavelength not found in LED lamps and somewhat present in HPS lamps. It seems that supplemental lighting causes a gain in mass but a loss in plant quality, especially as the light quality moves away from that of sunlight. Another likely cause is the carbon dioxide enrichment treatments and average PAR levels being best suited for no supplemental light at the test location, as the relationship between those two parameters is crucial for optimal growth (Both et al., 1997). Concentrations of xanthophylls should vary mostly with PAR because of their role in the plant's heat shedding mechanism (Siefermann-Harms, 1984, 1985). While the HPS treatment produces the most heat and received the most amount of light, it does not seem to be triggering the plants xanthophyll cycle as much. Therefore, if there is a factor driving xanthophyll concentrations and which favours no supplemental light, it has not been discovered here. It is however plausible that the wavelengths emitted by HPS and LED lamps are having a photomorphogenetic impact which increases plant biomass at the cost of plant quality.

4.3 Suggestions for Future Research

In light of the results from the second experiment, it seems that pursuing higher yields may have a cost in nutrient content. Growers do have an interest in both quantity and quality. Therefore, it would be appropriate to study the impact of LED lamps with optimal wavelengths in conjunction with different regimen of carbon dioxide enrichment and hydroponics nutrient solutions. In this case, the greenhouse was already optimized for a specific CO_2 level which was selected based on the average PAR from the sun and regular HPS supplemental light treatment. According to Liebig's Law of the Minimum, it is reasonable to assume that once the plant growth bottleneck from the limited and inefficient supplemental light is removed, other factors will start limiting growth as well.

While the first experiment was unfortunately subject to several days of no supplemental lighting, it did bring up the role of pulsed light treatments as a possible future avenue of research. Current supplemental light treatments do not vary over time but it could be possible to trick the plants into producing higher nutrient contents this way.

Finally, it would be quite interesting to test the synergy of multiple arrays of lamps, built with different wavelengths, positioned on the side, below or through the plant canopy for advantageous combinations. This was not possible with HPS lamps, due to excessive heat generation, but would be potentially hugely advantageous in situations where space is at a premium such as rooftop-based greenhouses in cities.

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Annex A

-Data Tables for plant mass

Table A1: Harvested Plant Mass– Week 1 / Replication 1.
Plant mass harvested on the first week for six light treatments. HPS – High pressure sodium; LED – light emitting diode; R1 – regular greenhouse HPS levels; CTRL – control: no supplemental artificial lighting.

week 1-1

plot 1	plant wet mass	plant dry mass	root wet mass	dry / wet mass
HPSN	grams	grams	grams	grams
1	11.4	0.9	23.8	7.9%
2	11.7	0.9	24.6	7.7%
3	12.2	1.0	25.2	8.2%
4	12.3	1.0	25.6	8.1%
5	13.4	1.1	25.9	8.2%
6	13.9	1.1	26.5	7.9%
7	14.1	1.2	26.5	8.5%
8	14.3	1.2	27.0	8.4%
9	15.0	1.2	29.2	8.0%
10	15.2	1.3	29.2	8.6%
std	1.4	0.1	1.8	10.0%
mean	13.4	1.1	26.4	8.2%
min	11.4	0.9	23.8	7.9%
max	15.2	1.3	29.2	8.6%

plot 4	plant wet mass	plant dry mass	root wet mass	dry / wet mass
LEDF	grams	grams	grams	grams
1	8.2	0.7	19.3	8.5%
2	9.2	0.7	21.8	7.6%
3	9.6	0.8	22.7	8.3%
4	10.7	0.9	23.3	8.4%
5	11.9	1.0	23.4	8.4%
6	13.9	1.1	23.6	7.9%
7	14.6	1.1	25.0	7.5%
8	15.1	1.1	25.2	7.3%
9	16.0	1.2	25.3	7.5%
10	20.1	1.6	26.8	8.0%
std	3.7	0.3	2.1	7.3%
mean	12.9	1.0	23.6	7.9%
min	8.2	0.7	19.3	8.5%
max	20.1	1.6	26.8	8.0%

plot 5	plant wet mass	plant dry mass	root wet mass	dry / wet mass
HPSF	grams	grams	grams	grams
1	10.6	1.0	20.4	9.4%
2	10.6	1.0	22.3	9.4%
3	10.9	1.1	22.7	10.1%
4	12.4	1.1	24.0	8.9%
5	12.8	1.1	24.0	8.6%
6	13.2	1.1	24.2	8.3%
7	14.1	1.1	25.6	7.8%
8	14.3	1.2	25.7	8.4%
9	14.4	1.2	25.8	8.3%
10	14.5	1.2	25.9	8.3%
std	1.6	0.1	1.8	4.6%
mean	12.8	1.1	24.1	8.7%
min	10.6	1.0	20.4	9.4%
max	14.5	1.2	25.9	8.3%

plot 2	plant wet mass	plant dry mass	root wet mass	dry / wet mass
LEDN	grams	grams	grams	grams
1	13.0	0.9	22.3	6.9%
2	13.6	1.0	23.6	7.4%
3	13.7	1.1	24.7	8.0%
4	14.0	1.1	24.8	7.9%
5	14.5	1.1	25.8	7.6%
6	14.7	1.1	26.3	7.5%
7	16.5	1.2	27.2	7.3%
8	18.1	1.3	27.2	7.2%
9	19.6	1.5	27.5	7.7%
10	21.5	1.6	30.0	7.4%
std	2.9	0.2	2.2	7.5%
mean	15.9	1.2	25.9	7.5%
min	13.0	0.9	22.3	6.9%
max	21.5	1.6	30.0	7.4%

plot 3	plant wet mass	plant dry mass	root wet mass	dry / wet mass
R1	grams	grams	grams	grams
1	12.9	0.9	21.9	7.0%
2	13.0	0.9	23.8	6.9%
3	13.0	1.0	24.3	7.7%
4	14.1	1.0	24.6	7.1%
5	14.4	1.1	24.7	7.6%
6	15.3	1.1	25.6	7.2%
7	16.2	1.2	26.5	7.4%
8	16.5	1.2	27.3	7.3%
9	17.8	1.2	27.3	6.7%
10	20.7	1.6	27.6	7.7%
std	2.5	0.2	1.8	8.2%
mean	15.4	1.1	25.4	7.3%
min	12.9	0.9	21.9	7.0%
max	20.7	1.6	27.6	7.7%

plot 6	plant wet mass	plant dry mass	root wet mass	dry / wet mass
CTRL	grams	grams	grams	grams
1	9.6	0.7	22.2	7.3%
2	9.8	0.7	22.3	7.1%
3	10.5	0.7	22.5	6.7%
4	10.9	0.8	22.5	7.3%
5	10.9	0.8	22.7	7.3%
6	11.0	0.8	23.2	7.3%
7	11.5	0.8	23.5	7.0%
8	11.6	0.9	23.8	7.8%
9	12.6	0.9	24.8	7.1%
10	14.7	1.1	25.9	7.5%
std	1.5	0.1	1.2	8.3%
mean	11.3	0.8	23.3	7.3%
min	9.6	0.7	22.2	7.3%
max	14.7	1.1	25.9	7.5%

Table A2: Harvested Plant Mass– Week 2 / Replication 1.
Plant mass harvested on the second week for six light treatments. HPS – High pressure sodium; LED – light emitting diode; R1 – regular greenhouse HPS levels; CTRL – control: no supplemental artificial lighting.

week 2-1

plot 1	plant wet mass	plant dry mass	dry / wet mass
HPSN	grams	grams	grams
1	23.1	3.4	14.7%
2	27.0	2.9	10.7%
3	27.8	3.2	11.5%
4	32.4	2.9	9.0%
5	33.8	2.9	8.6%
6	33.9	3.2	9.4%
7	34.6	3.3	9.5%
8	41.0	3.7	9.0%
9	42.2	2.9	6.9%
10	46.3	2.9	6.3%
std	7.3	0.3	3.8%
mean	34.2	3.1	9.1%
min	23.1	2.9	12.6%
max	46.3	3.7	8.0%

plot 4	plant wet mass	plant dry mass	dry / wet mass
LEDF	grams	grams	grams
1	21.7	1.8	8.3%
2	23.8	3.0	12.6%
3	30.9	2.8	9.1%
4	32.4	3.0	9.3%
5	33.9	2.8	8.3%
6	34.1	1.7	5.0%
7	35.0	2.7	7.7%
8	35.2	2.5	7.1%
9	36.5	2.8	7.7%
10	37.7	2.5	6.6%
std	5.3	0.5	8.6%
mean	32.1	2.6	8.0%
min	21.7	1.7	7.8%
max	37.7	3.0	8.0%

plot 5	plant wet mass	plant dry mass	dry / wet mass
HPSF	grams	grams	grams
1	17.2	2.9	16.9%
2	27.8	2.8	10.1%
3	28.7	2.8	9.8%
4	34.8	2.3	6.6%
5	35.3	3.4	9.6%
6	38.0	3.5	9.2%
7	38.1	2.3	6.0%
8	38.6	1.4	3.6%
9	39.5	3.5	8.9%
10	43.1	3.2	7.4%
std	7.6	0.7	8.8%
mean	34.1	2.8	8.2%
min	17.2	1.4	8.1%
max	43.1	3.5	8.1%

plot 2	plant wet mass	plant dry mass	dry / wet mass
LEDN	grams	grams	grams
1	36.3	2.5	6.9%
2	37.1	3.4	9.2%
3	38.0	2.3	6.1%
4	38.6	2.9	7.5%
5	41.1	2.6	6.3%
6	41.4	3.4	8.2%
7	42.1	2.0	4.8%
8	43.6	2.6	6.0%
9	45.2	2.1	4.6%
10	45.5	2.9	6.4%
std	3.3	0.5	14.7%
mean	40.9	2.7	6.5%
min	36.3	2.0	5.5%
max	45.5	3.4	7.5%

plot 3	plant wet mass	plant dry mass	dry / wet mass
R1	grams	grams	grams
1	19.1	3.4	17.8%
2	21.2	3.3	15.6%
3	24.8	2.2	8.9%
4	26.0	2.6	10.0%
5	28.7	2.2	7.7%
6	29.5	1.5	5.1%
7	32.8	2.4	7.3%
8	33.5	1.8	5.4%
9	43.6	2.1	4.8%
10	45.1	2.4	5.3%
std	8.6	0.6	6.9%
mean	30.4	2.4	7.9%
min	19.1	1.5	7.9%
max	45.1	3.4	7.5%

plot 6	plant wet mass	plant dry mass	dry / wet mass
CTRL	grams	grams	grams
1	20.3	1.8	8.9%
2	20.7	1.9	9.2%
3	21.0	1.9	9.0%
4	22.7	1.9	8.4%
5	22.8	1.5	6.6%
6	23.7	1.7	7.2%
7	23.8	1.6	6.7%
8	25.1	1.5	6.0%
9	25.4	1.6	6.3%
10	27.6	2.1	7.6%
std	2.3	0.2	8.7%
mean	23.3	1.8	7.5%
min	20.3	1.5	7.4%
max	27.6	2.1	7.6%

Table A3: Harvested Plant Mass– Week 3 / Replication 1.
Plant mass harvested on the third week for six light treatments. HPS – High pressure sodium; LED – light emitting diode; R1 – regular greenhouse HPS levels; CTRL – control: no supplemental artificial lighting.

week 3-1

plot 1	plant wet mass	plant dry mass	dry / wet mass
HPSN	grams	grams	grams
1	71.9	4.1	5.7%
2	74.7	4.4	5.9%
3	91.4	5.0	5.5%
4	91.4	5.1	5.6%
5	98.1	5.2	5.3%
6	101.4	5.5	5.4%
7	103.0	5.5	5.3%
8	104.5	5.7	5.5%
9	109.4	5.8	5.3%
10	109.4	5.8	5.3%
std	13.3	0.6	4.4%
mean	95.5	5.2	5.5%
min	71.9	4.1	5.7%
max	109.4	5.8	5.3%

plot 4	plant wet mass	plant dry mass	dry / wet mass
LEDF	grams	grams	grams
1	65.9	4.1	6.2%
2	68.5	4.1	6.0%
3	69.5	4.1	5.9%
4	78.6	4.3	5.5%
5	82.8	4.3	5.2%
6	83.5	5.1	6.1%
7	84.5	5.3	6.3%
8	84.6	5.4	6.4%
9	93.1	5.6	6.0%
10	103.2	5.8	5.6%
std	11.5	0.7	6.0%
mean	81.4	4.8	5.9%
min	65.9	4.1	6.2%
max	103.2	5.8	5.6%

plot 5	plant wet mass	plant dry mass	dry / wet mass
HPSF	grams	grams	grams
1	73.6	4.5	6.1%
2	73.8	4.7	6.4%
3	79.8	4.8	6.0%
4	80.9	5.1	6.3%
5	84.3	5.2	6.2%
6	87.1	5.5	6.3%
7	91.4	5.7	6.2%
8	93.1	5.9	6.3%
9	95.5	6.3	6.6%
10	116.7	6.6	5.7%
std	12.7	0.7	5.5%
mean	87.6	5.4	6.2%
min	73.6	4.5	6.1%
max	116.7	6.6	5.7%

plot 2	plant wet mass	plant dry mass	dry / wet mass
LEDN	grams	grams	grams
1	56.0	3.5	6.3%
2	61.4	3.9	6.4%
3	69.5	4.0	5.8%
4	74.7	4.4	5.9%
5	77.7	4.6	5.9%
6	78.8	4.8	6.1%
7	90.6	4.8	5.3%
8	92.1	4.9	5.3%
9	94.7	5.3	5.6%
10	104.0	5.6	5.4%
std	15.3	0.6	4.2%
mean	80.0	4.6	5.7%
min	56.0	3.5	6.3%
max	104.0	5.6	5.4%

plot 3	plant wet mass	plant dry mass	dry / wet mass
R1	grams	grams	grams
1	27.6	2.2	8.0%
2	35.9	2.7	7.5%
3	48.3	3.5	7.2%
4	51.8	3.5	6.8%
5	53.4	3.8	7.1%
6	67.1	3.8	5.7%
7	67.4	4.6	6.8%
8	78.9	4.7	6.0%
9	82.1	5.1	6.2%
10	86.3	5.6	6.5%
std	19.8	1.1	5.4%
mean	59.9	4.0	6.6%
min	27.6	2.2	8.0%
max	86.3	5.6	6.5%

plot 6	plant wet mass	plant dry mass	dry / wet mass
CTRL	grams	grams	grams
1	46.8	3.2	6.8%
2	51.5	3.4	6.6%
3	51.6	3.5	6.8%
4	51.6	3.5	6.8%
5	54.6	3.6	6.6%
6	59.9	3.7	6.2%
7	62.5	3.8	6.1%
8	62.9	3.9	6.2%
9	63.7	4.3	6.8%
10	77.2	4.7	6.1%
std	8.9	0.4	5.0%
mean	58.2	3.8	6.5%
min	46.8	3.2	6.8%
max	77.2	4.7	6.1%

Table A4: Harvested Plant Mass– Week 4 / Replication 1.
Plant mass harvested on the fourth week for six light treatments. HPS – High pressure sodium; LED – light emitting diode; R1 – regular greenhouse HPS levels; CTRL – control: no supplemental artificial lighting.

week 4-1

plot 1	plant wet mass	plant dry mass	dry / wet mass
HPSN	grams	grams	grams
1	129.6	7.3	5.6%
2	133.6	7.3	5.5%
3	153.9	7.9	5.1%
4	156.2	8.3	5.3%
5	180.9	9.5	5.3%
6	183.8	9.5	5.2%
7	189.9	9.6	5.1%
8	196.0	9.8	5.0%
9	207.3	10.0	4.8%
10	207.6	10.3	5.0%
std	28.8	1.1	4.0%
mean	173.9	9.0	5.1%
min	129.6	7.3	5.6%
max	207.6	10.3	5.0%

plot 4	plant wet mass	plant dry mass	dry / wet mass
LEDF	grams	grams	grams
1	76.8	4.5	5.9%
2	119.7	5.5	4.6%
3	131.3	6.2	4.7%
4	133.1	6.2	4.7%
5	133.4	6.9	5.2%
6	137.4	7.0	5.1%
7	146.4	7.2	4.9%
8	148.3	7.9	5.3%
9	154.7	9.9	6.4%
10	172.3	14.7	8.5%
std	25.2	2.9	11.4%
mean	135.3	7.6	5.6%
min	76.8	4.5	5.9%
max	172.3	14.7	8.5%

plot 5	plant wet mass	plant dry mass	dry / wet mass
HPSF	grams	grams	grams
1	116.8	4.7	4.0%
2	128.1	4.9	3.8%
3	131.9	5.0	3.8%
4	134.1	6.0	4.5%
5	134.8	6.1	4.5%
6	152.7	6.2	4.1%
7	164.9	6.7	4.1%
8	175.6	6.9	3.9%
9	177.5	7.3	4.1%
10	185.7	9.4	5.1%
std	24.3	1.4	5.7%
mean	150.2	6.3	4.2%
min	116.8	4.7	4.0%
max	185.7	9.4	5.1%

plot 2	plant wet mass	plant dry mass	dry / wet mass
LEDN	grams	grams	grams
1	103.2	5.7	5.5%
2	118.7	6.1	5.1%
3	126.2	6.2	4.9%
4	137.4	6.6	4.8%
5	137.8	6.8	4.9%
6	142.8	7.3	5.1%
7	147.6	8.2	5.6%
8	150.8	8.2	5.4%
9	155.7	8.3	5.3%
10	163.6	12.4	7.6%
std	18.2	1.9	10.7%
mean	138.4	7.6	5.5%
min	103.2	5.7	5.5%
max	163.6	12.4	7.6%

plot 3	plant wet mass	plant dry mass	dry / wet mass
R1	grams	grams	grams
1	96.6	5.1	5.3%
2	112.5	5.7	5.1%
3	114.7	6.0	5.2%
4	121.8	6.3	5.2%
5	128.1	6.4	5.0%
6	130.3	6.8	5.2%
7	133.7	6.8	5.1%
8	138.2	7.8	5.6%
9	146.6	8.0	5.5%
10	150.7	12.3	8.2%
std	16.5	2.0	12.3%
mean	127.3	7.1	5.6%
min	96.6	5.1	5.3%
max	150.7	12.3	8.2%

plot 6	plant wet mass	plant dry mass	dry / wet mass
CTRL	grams	grams	grams
1	102.6	4.5	4.4%
2	102.9	4.8	4.7%
3	111.6	5.0	4.5%
4	115.0	5.4	4.7%
5	115.5	5.6	4.8%
6	117.9	6.1	5.2%
7	125.6	6.3	5.0%
8	126.5	6.3	5.0%
9	129.2	6.7	5.2%
10	133.2	10.3	7.7%
std	10.6	1.6	15.5%
mean	118.0	6.1	5.2%
min	102.6	4.5	4.4%
max	133.2	10.3	7.7%

Table A5: Harvested Plant Mass– Week 1 / Replication 2.
Plant mass harvested on the fifth week for six light treatments. HPS – High pressure sodium; LED – light emitting diode; R1 – regular greenhouse HPS levels; CTRL – control: no supplemental artificial lighting.

week 1-2

plot 1	plant wet mass	plant dry mass	dry / wet mass
HPSN	grams	grams	grams
1	5.1	0.8	15.7%
2	5.2	0.8	15.4%
3	5.3	0.8	15.1%
4	5.6	0.8	14.3%
5	6.3	0.9	14.3%
6	6.5	0.9	13.8%
7	6.7	0.9	13.4%
8	7.4	1.0	13.5%
9	8.7	1.2	13.8%
10	9.3	1.4	15.1%
std	1.5	0.2	13.7%
mean	6.6	1.0	14.4%
min	5.1	0.8	15.7%
max	9.3	1.4	15.1%

plot 4	plant wet mass	plant dry mass	dry / wet mass
LEDF	grams	grams	grams
1	4.5	0.7	15.6%
2	4.9	0.7	14.3%
3	5.4	0.8	14.8%
4	5.4	0.8	14.8%
5	6.4	0.9	14.1%
6	6.8	0.9	13.2%
7	7.3	1.0	13.7%
8	7.8	1.0	12.8%
9	7.8	1.0	12.8%
10	8.6	1.1	12.8%
std	1.4	0.1	9.8%
mean	6.5	0.9	13.7%
min	4.5	0.7	15.6%
max	8.6	1.1	12.8%

plot 5	plant wet mass	plant dry mass	dry / wet mass
HPSF	grams	grams	grams
1	5.6	0.8	14.3%
2	5.8	0.8	13.8%
3	6.4	0.8	12.5%
4	6.7	0.8	11.9%
5	6.7	0.9	13.4%
6	6.8	0.9	13.2%
7	7.0	0.9	12.9%
8	7.3	0.9	12.3%
9	7.7	1.0	13.0%
10	8.6	1.1	12.8%
std	0.9	0.1	11.3%
mean	6.9	0.9	13.0%
min	5.6	0.8	14.3%
max	8.6	1.1	12.8%

plot 2	plant wet mass	plant dry mass	dry / wet mass
LEDN	grams	grams	grams
1	5.8	0.8	13.8%
2	6.1	0.8	13.1%
3	6.6	0.8	12.1%
4	6.9	1.0	14.5%
5	7.1	1.0	14.1%
6	7.5	1.1	14.7%
7	7.7	1.1	14.3%
8	7.8	1.1	14.1%
9	8.8	1.2	13.6%
10	11.2	1.5	13.4%
std	1.6	0.2	14.0%
mean	7.6	1.0	13.8%
min	5.8	0.8	13.8%
max	11.2	1.5	13.4%

plot 3	plant wet mass	plant dry mass	dry / wet mass
R1	grams	grams	grams
1	4.9	0.5	10.2%
2	5.2	0.6	11.5%
3	5.5	0.6	10.9%
4	5.7	0.6	10.5%
5	5.7	0.6	10.5%
6	6.4	0.7	10.9%
7	6.6	0.8	12.1%
8	7.0	0.8	11.4%
9	7.3	0.8	11.0%
10	7.5	0.9	12.0%
std	0.9	0.1	14.2%
mean	6.2	0.7	11.2%
min	4.9	0.5	10.2%
max	7.5	0.9	12.0%

plot 6	plant wet mass	plant dry mass	dry / wet mass
CTRL	grams	grams	grams
1	5.4	0.5	9.3%
2	5.5	0.6	10.9%
3	5.6	0.6	10.7%
4	5.9	0.6	10.2%
5	6.1	0.7	11.5%
6	6.2	0.7	11.3%
7	6.7	0.7	10.4%
8	7.1	0.8	11.3%
9	7.7	0.9	11.7%
10	7.7	0.9	11.7%
std	0.9	0.1	15.4%
mean	6.4	0.7	11.0%
min	5.4	0.5	9.3%
max	7.7	0.9	11.7%

Table A6: Harvested Plant Mass– Week 2 / Replication 2.
Plant mass harvested on the sixth week for six light treatments. HPS – High pressure sodium; LED – light emitting diode; R1 – regular greenhouse HPS levels; CTRL – control: no supplemental artificial lighting.

week 2-2

plot 1	plant wet mass	plant dry mass	dry / wet mass
HPSN	grams	grams	grams
1	12.6	1.3	10.3%
2	12.8	1.5	11.7%
3	14.9	1.6	10.7%
4	15.6	1.6	10.3%
5	16.3	1.7	10.4%
6	16.5	1.8	10.9%
7	20.1	2.1	10.4%
8	21.3	2.1	9.9%
9	22.0	2.2	10.0%
10	24.8	2.4	9.7%
std	4.1	0.4	8.6%
mean	17.7	1.8	10.3%
min	12.6	1.3	10.3%
max	24.8	2.4	9.7%

plot 4	plant wet mass	plant dry mass	dry / wet mass
LEDF	grams	grams	grams
1	11.6	1.4	12.1%
2	13.7	1.4	10.2%
3	14.2	1.5	10.6%
4	14.2	1.6	11.3%
5	15.0	1.6	10.7%
6	15.1	1.6	10.6%
7	15.2	1.6	10.5%
8	15.8	1.6	10.1%
9	18.9	1.9	10.1%
10	31.9	2.7	8.5%
std	5.7	0.4	6.7%
mean	16.6	1.7	10.2%
min	11.6	1.4	12.1%
max	31.9	2.7	8.5%

plot 5	plant wet mass	plant dry mass	dry / wet mass
HPSF	grams	grams	grams
1	13.5	1.4	10.4%
2	13.8	1.5	10.9%
3	14.2	1.5	10.6%
4	14.9	1.5	10.1%
5	15.0	1.6	10.7%
6	16.3	1.7	10.4%
7	17.0	1.7	10.0%
8	18.0	1.7	9.4%
9	19.1	1.9	9.9%
10	24.0	2.2	9.2%
std	3.2	0.2	7.4%
mean	16.6	1.7	10.1%
min	13.5	1.4	10.4%
max	24.0	2.2	9.2%

plot 2	plant wet mass	plant dry mass	dry / wet mass
LEDN	grams	grams	grams
1	9.6	1.0	10.4%
2	12.2	1.4	11.5%
3	13.8	1.5	10.9%
4	14.0	1.5	10.7%
5	14.1	1.5	10.6%
6	15.9	1.5	9.4%
7	15.9	1.5	9.4%
8	17.0	1.6	9.4%
9	17.3	1.7	9.8%
10	20.2	1.9	9.4%
std	2.9	0.2	7.7%
mean	15.0	1.5	10.1%
min	9.6	1.0	10.4%
max	20.2	1.9	9.4%

plot 3	plant wet mass	plant dry mass	dry / wet mass
R1	grams	grams	grams
1	13.2	1.1	8.3%
2	14.0	1.1	7.9%
3	14.6	1.2	8.2%
4	15.0	1.3	8.7%
5	15.5	1.3	8.4%
6	15.6	1.4	9.0%
7	16.7	1.4	8.4%
8	18.7	1.4	7.5%
9	19.8	1.5	7.6%
10	19.9	1.5	7.5%
std	2.4	0.1	6.2%
mean	16.3	1.3	8.1%
min	13.2	1.1	8.3%
max	19.9	1.5	7.5%

plot 6	plant wet mass	plant dry mass	dry / wet mass
CTRL	grams	grams	grams
1	12.9	1.1	8.5%
2	13.0	1.1	8.5%
3	13.2	1.1	8.3%
4	13.2	1.1	8.3%
5	13.5	1.1	8.1%
6	13.6	1.1	8.1%
7	13.6	1.2	8.8%
8	14.2	1.2	8.5%
9	15.7	1.3	8.3%
10	23.3	1.9	8.2%
std	3.2	0.2	7.9%
mean	14.6	1.2	8.3%
min	12.9	1.1	8.5%
max	23.3	1.9	8.2%

Table A7: Harvested Plant Mass– Week 3 / Replication 2.
Plant mass harvested on the seventh week for six light treatments. HPS – High pressure sodium; LED – light emitting diode; R1 – regular greenhouse HPS levels; CTRL – control: no supplemental artificial lighting.

week 3-2

plot 1	plant wet mass	plant dry mass	dry / wet mass
HPSN	grams	grams	grams
1	22.5	2.3	10.2%
2	24.6	2.5	10.2%
3	26.3	2.7	10.3%
4	29.4	2.9	9.9%
5	31.8	3.0	9.4%
6	32.4	3.0	9.3%
7	37.0	3.1	8.4%
8	38.8	3.2	8.2%
9	48.8	3.8	7.8%
10	56.8	4.2	7.4%
std	10.9	0.6	5.2%
mean	34.8	3.1	8.8%
min	22.5	2.3	10.2%
max	56.8	4.2	7.4%

plot 4	plant wet mass	plant dry mass	dry / wet mass
LEDF	grams	grams	grams
1	20.6	2.3	11.2%
2	22.4	2.6	11.6%
3	24.3	2.7	11.1%
4	25.7	2.7	10.5%
5	27.2	2.9	10.7%
6	28.7	3.1	10.8%
7	30.4	3.2	10.5%
8	33.2	3.2	9.6%
9	33.4	3.2	9.6%
10	42.6	3.8	8.9%
std	6.4	0.4	6.5%
mean	28.9	3.0	10.3%
min	20.6	2.3	11.2%
max	42.6	3.8	8.9%

plot 5	plant wet mass	plant dry mass	dry / wet mass
HPSF	grams	grams	grams
1	19.1	2.5	13.1%
2	21.2	2.5	11.8%
3	25.6	2.7	10.5%
4	27.1	2.9	10.7%
5	35.3	3.0	8.5%
6	39.2	3.0	7.7%
7	39.6	3.1	7.8%
8	39.6	3.3	8.3%
9	49.9	3.6	7.2%
10	56.6	4.4	7.8%
std	12.2	0.6	4.7%
mean	35.3	3.1	8.8%
min	19.1	2.5	13.1%
max	56.6	4.4	7.8%

plot 2	plant wet mass	plant dry mass	dry / wet mass
LEDN	grams	grams	grams
1	24.5	2.6	10.6%
2	25.6	2.6	10.2%
3	29.5	2.6	8.8%
4	29.5	2.6	8.8%
5	30.8	2.7	8.8%
6	32.1	2.9	9.0%
7	33.5	2.9	8.7%
8	34.1	2.9	8.5%
9	41.3	3.1	7.5%
10	43.7	3.4	7.8%
std	6.1	0.3	4.3%
mean	32.5	2.8	8.7%
min	24.5	2.6	10.6%
max	43.7	3.4	7.8%

plot 3	plant wet mass	plant dry mass	dry / wet mass
R1	grams	grams	grams
1	27.8	2.2	7.9%
2	28.4	2.3	8.1%
3	28.6	2.4	8.4%
4	30.9	2.5	8.1%
5	33.8	2.5	7.4%
6	35.7	2.7	7.6%
7	37.4	2.8	7.5%
8	40.6	2.8	6.9%
9	41.2	3.1	7.5%
10	45.7	3.4	7.4%
std	6.2	0.4	6.0%
mean	35.0	2.7	7.6%
min	27.8	2.2	7.9%
max	45.7	3.4	7.4%

plot 6	plant wet mass	plant dry mass	dry / wet mass
CTRL	grams	grams	grams
1	19.5	2.1	10.8%
2	19.8	2.1	10.6%
3	20.2	2.5	12.4%
4	24.0	2.5	10.4%
5	26.8	2.7	10.1%
6	28.0	2.7	9.6%
7	28.4	2.8	9.9%
8	30.1	2.8	9.3%
9	32.3	2.8	8.7%
10	35.4	2.9	8.2%
std	5.5	0.3	5.3%
mean	26.5	2.6	9.8%
min	19.5	2.1	10.8%
max	35.4	2.9	8.2%

Table A8: Harvested Plant Mass– Week 4 / Replication 2.
Plant mass harvested on the eighth week for six light treatments. HPS – High pressure sodium; LED – light emitting diode; R1 – regular greenhouse HPS levels; CTRL – control: no supplemental artificial lighting.

week 4-2

plot 1	plant wet mass	plant dry mass	dry / wet mass
HPSN	grams	grams	grams
1	42.8	4.0	9.3%
2	51.4	4.1	8.0%
3	52.0	4.3	8.3%
4	54.6	4.6	8.4%
5	65.0	5.2	8.0%
6	68.1	5.2	7.6%
7	69.0	5.3	7.7%
8	71.7	5.3	7.4%
9	80.1	5.7	7.1%
10	105.0	6.8	6.5%
std	17.8	0.8	4.8%
mean	66.0	5.1	7.7%
min	42.8	4.0	9.3%
max	105.0	6.8	6.5%

plot 4	plant wet mass	plant dry mass	dry / wet mass
LEDF	grams	grams	grams
1	39.2	3.3	8.4%
2	41.7	3.7	8.9%
3	46.6	3.8	8.2%
4	47.8	3.8	7.9%
5	48.0	3.9	8.1%
6	48.5	4.1	8.5%
7	50.9	4.2	8.3%
8	59.4	4.5	7.6%
9	67.8	4.6	6.8%
10	68.5	5.1	7.4%
std	10.1	0.5	5.1%
mean	51.8	4.1	7.9%
min	39.2	3.3	8.4%
max	68.5	5.1	7.4%

plot 5	plant wet mass	plant dry mass	dry / wet mass
HPSF	grams	grams	grams
1	38.7	3.6	9.3%
2	42.0	3.6	8.6%
3	49.6	3.7	7.5%
4	52.3	3.8	7.3%
5	55.7	4.0	7.2%
6	68.5	4.4	6.4%
7	76.6	4.5	5.9%
8	82.8	5.1	6.2%
9	99.6	5.2	5.2%
10	104.8	5.7	5.4%
std	23.4	0.8	3.2%
mean	67.1	4.4	6.5%
min	38.7	3.6	9.3%
max	104.8	5.7	5.4%

plot 2	plant wet mass	plant dry mass	dry / wet mass
LEDN	grams	grams	grams
1	34.0	2.9	8.5%
2	36.4	3.0	8.2%
3	38.0	3.3	8.7%
4	43.4	3.7	8.5%
5	45.4	4.1	9.0%
6	50.1	4.2	8.4%
7	54.9	4.3	7.8%
8	62.0	4.5	7.3%
9	69.0	4.7	6.8%
10	84.9	5.1	6.0%
std	16.2	0.7	4.5%
mean	51.8	4.0	7.7%
min	34.0	2.9	8.5%
max	84.9	5.1	6.0%

plot 3	plant wet mass	plant dry mass	dry / wet mass
R1	grams	grams	grams
1	66.8	3.7	5.5%
2	69.0	3.9	5.7%
3	70.7	4.0	5.7%
4	71.2	4.1	5.8%
5	73.0	4.1	5.6%
6	75.8	4.2	5.5%
7	76.7	4.3	5.6%
8	89.1	4.4	4.9%
9	92.1	4.7	5.1%
10	92.5	5.4	5.8%
std	9.8	0.5	4.9%
mean	77.7	4.3	5.5%
min	66.8	3.7	5.5%
max	92.5	5.4	5.8%

plot 6	plant wet mass	plant dry mass	dry / wet mass
CTRL	grams	grams	grams
1	32.7	2.1	6.4%
2	33.9	3.1	9.1%
3	34.9	3.1	8.9%
4	35.4	3.1	8.8%
5	50.2	3.3	6.6%
6	52.0	3.7	7.1%
7	52.0	3.7	7.1%
8	52.6	3.8	7.2%
9	56.9	4.3	7.6%
10	64.8	4.3	6.6%
std	11.4	0.7	5.8%
mean	46.5	3.5	7.4%
min	32.7	2.1	6.4%
max	64.8	4.3	6.6%

Annex B

-Weather Data Tables – 1st replication

Table B1: HPS Near - Condensed Weather Data – 1st replication.
Weather data accumulated and summed for the first high-pressure sodium light treatment replication during the first experiment replication.

[Herbie - plot 1] - HPS near						
total	mean	std. dev.	max	min	sum	Fraction
Surface Temp, °C	13.87	5.45	35.58	5.26		
Solar Radiation, W/m²	78.88	106.56	614.40	0.60	3167626.10	100.0%
PAR #1, umol/m2/sec	137.28	143.07	1436.20	1.20		
moles of light / m2					330.78	100.0%
PAR #2, umol/m2/sec	138.09	147.69	1318.70	1.20		
moles of light / m2					332.73	100.0%
Air Temp, °C	11.92	4.97	29.34	1.15		
RH, %	80.70	14.71	98.40	22.00		
sunlight only	mean	std. dev.	max	min	sum	
Surface Temp, °C	14.61	6.28	35.58	5.26		
Solar Radiation, W/m²	96.85	122.35	614.40	0.60	2747577.50	86.7%
PAR #1, umol/m2/sec	150.17	168.13	1436.20	1.20		
moles of light / m2					255.61	77.3%
PAR #2, umol/m2/sec	151.11	173.87	1318.70	1.20		
moles of light / m2					257.21	77.3%
Air Temp, °C	12.82	5.57	29.34	1.15		
RH, %	79.02	16.98	98.40	22.00		
HPS only	mean	std. dev.	max	min	sum	
Surface Temp, °C	12.11	1.43	18.06	7.59		
Solar Radiation, W/m²	35.64	2.87	48.10	9.40	420184.20	13.3%
PAR #1, umol/m2/sec	106.25	18.36	146.20	8.70		
moles of light / m2					75.16	22.7%
PAR #2, umol/m2/sec	106.86	16.61	141.20	6.20		
moles of light / m2					75.60	22.7%
Air Temp, °C	9.76	1.74	16.92	5.08		
RH, %	84.74	4.54	93.50	69.70		

Table B2: LED Near - Condensed Weather Data – 1st replication.
Weather data accumulated and summed for the first light emitting diode light treatment replication during the first experiment replication.

[Ella - plot 2] - LED near						
total	mean	std. dev.	max	min	sum	Fraction
Surface Temp, °C	12.58	5.69	33.03	4.01		
Solar Radiation, W/m²	58.78	93.82	550.60	0.60	1574369.30	100.0%
PAR #1, umol/m2/sec	111.91	147.83	841.20	1.20		
moles of light / m2					269.76	100.0%
PAR #2, umol/m2/sec	111.40	142.60	761.20	1.20		
moles of light / m2					268.52	100.0%
Air Temp, °C	11.44	4.84	28.87	0.85		
RH, %	83.15	14.48	99.30	24.80		
sunlight only	mean	std. dev.	max	min	sum	
Surface Temp, °C	13.88	6.27	33.03	4.01		
Solar Radiation, W/m²	80.62	104.50	550.60	0.60	1517344.20	96.4%
PAR #1, umol/m2/sec	142.15	167.08	841.20	1.20		
moles of light / m2					240.78	89.3%
PAR #2, umol/m2/sec	140.86	160.94	761.20	1.20		
moles of light / m2					238.60	88.9%
Air Temp, °C	12.47	5.32	28.87	0.85		
RH, %	81.05	16.52	99.30	24.80		
LED only	mean	std. dev.	max	min	sum	
Surface Temp, °C	9.49	1.57	16.61	4.97		
Solar Radiation, W/m²	7.16	2.75	20.60	0.60	57025.10	3.6%
PAR #1, umol/m2/sec	40.44	15.88	73.70	1.20		
moles of light / m2					28.97	10.7%
PAR #2, umol/m2/sec	41.75	16.41	68.70	1.20		
moles of light / m2					29.92	11.1%
Air Temp, °C	9.00	1.82	16.51	2.58		
RH, %	88.11	4.97	97.20	64.00		

Table B3: Regular - Condensed Weather Data – 1st replication.
Weather data accumulated and summed for the regular high-pressure sodium light treatment during the first experiment replication.

[Ray - plot 3] - Regular						
total	mean	std. dev.	max	min	sum	Fraction
Surface Temp, °C	12.95	6.21	34.57	2.85		
Solar Radiation, W/m²	71.15	114.71	650.60	0.60	2858601.10	100.0%
PAR #1, umol/m2/sec	106.32	159.30	818.70	1.20		
moles of light / m2					256.31	100.1%
PAR #2, umol/m2/sec	115.73	172.91	891.20	1.20		
moles of light / m2					278.99	100.1%
Air Temp, °C	14.36	4.88	32.28	3.25		
RH, %	83.03	14.71	99.70	23.10		
sunlight only	mean	std. dev.	max	min	sum	
Surface Temp, °C	14.19	6.90	34.57	2.85		
Solar Radiation, W/m²	96.39	126.94	650.60	0.60	2774549.30	97.1%
PAR #1, umol/m2/sec	141.56	176.75	2553.70	1.20		
moles of light / m2					244.48	95.4%
PAR #2, umol/m2/sec	153.89	191.80	2553.70	1.20		
moles of light / m2					265.78	95.3%
Air Temp, °C	15.27	5.40	32.28	3.25		
RH, %	80.85	16.65	99.70	23.10		
HPS only	mean	std. dev.	max	min	sum	
Surface Temp, °C	9.83	1.58	16.80	6.81		
Solar Radiation, W/m²	7.39	3.59	26.90	0.60	84222.40	2.9%
PAR #1, umol/m2/sec	17.53	8.64	53.70	1.20		
moles of light / m2					11.98	4.7%
PAR #2, umol/m2/sec	19.55	9.48	58.70	1.20		
moles of light / m2					13.37	4.8%
Air Temp, °C	12.07	1.74	19.67	7.82		
RH, %	88.55	4.57	97.30	64.70		

Table B4: LED Far - Condensed Weather Data – 1st replication.
Weather data accumulated and summed for the second light emitting diode light treatment replication during the first experiment replication.

[Duke - plot 4] - LED far						
total	mean	std. dev.	max	min	sum	Fraction
Surface Temp, °C	12.62	5.60	31.92	2.96		
Solar Radiation, W/m²	59.02	93.28	559.40	0.60	2371654.40	100.0%
PAR #1, umol/m2/sec	129.10	162.97	851.20	1.20		
moles of light / m2					311.26	100.0%
PAR #2, umol/m2/sec	119.94	159.14	1516.20	1.20		
moles of light / m2					289.18	100.0%
Air Temp, °C	11.44	5.03	28.20	0.05		
RH, %	83.01	14.77	99.60	24.30		
sunlight only	mean	std. dev.	max	min	sum	
Surface Temp, °C	13.72	6.20	31.92	2.96		
Solar Radiation, W/m²	79.43	103.31	559.40	0.60	2286705.30	96.4%
PAR #1, umol/m2/sec	160.35	183.04	851.20	1.20		
moles of light / m2					276.97	89.0%
PAR #2, umol/m2/sec	150.09	179.03	1516.20	1.20		
moles of light / m2					259.24	89.6%
Air Temp, °C	12.38	5.55	28.20	0.05		
RH, %	80.81	16.69	99.60	24.30		
LED only	mean	std. dev.	max	min	sum	
Surface Temp, °C	9.84	1.60	16.75	6.51		
Solar Radiation, W/m²	7.45	2.66	24.40	0.60	84949.10	3.6%
PAR #1, umol/m2/sec	50.15	17.72	81.20	1.20		
moles of light / m2					34.29	11.0%
PAR #2, umol/m2/sec	43.78	15.45	68.70	1.20		
moles of light / m2					29.93	10.4%
Air Temp, °C	9.07	1.88	16.61	5.00		
RH, %	88.57	4.82	97.00	63.90		

Table B5: HPS Far - Condensed Weather Data – 1st replication.
Weather data accumulated and summed for the second high-pressure sodium light treatment replication during the first experiment replication.

[Aretha - plot 5] - HPS far						
total	mean	std. dev.	max	min	sum	Fraction
Surface Temp, °C	13.49	5.35	32.07	3.70		
Solar Radiation, W/m²	66.63	85.88	498.10	0.60	2677940.90	100.0%
PAR #1, umol/m2/sec	156.50	164.25	853.70	1.20		
moles of light / m2					377.38	100.0%
PAR #2, umol/m2/sec	139.99	148.04	821.20	1.20		
moles of light / m2					337.57	100.0%
Air Temp, °C	11.65	5.03	28.67	-0.28		
RH, %	82.89	14.43	100.00	23.90		
sunlight only	mean	std. dev.	max	min	sum	
Surface Temp, °C	14.21	6.08	32.07	3.70		
Solar Radiation, W/m²	81.67	97.20	498.10	0.60	2351617.30	87.8%
PAR #1, umol/m2/sec	175.70	188.99	853.70	1.20		
moles of light / m2					303.53	80.4%
PAR #2, umol/m2/sec	157.22	170.15	821.20	1.20		
moles of light / m2					271.60	80.5%
Air Temp, °C	12.47	5.61	28.67	-0.28		
RH, %	81.23	16.49	100.00	23.90		
HPS only	mean	std. dev.	max	min	sum	
Surface Temp, °C	11.69	1.76	18.63	6.94		
Solar Radiation, W/m²	28.63	11.01	49.40	0.60	326323.60	12.2%
PAR #1, umol/m2/sec	108.01	40.12	158.70	1.20		
moles of light / m2					73.85	19.6%
PAR #2, umol/m2/sec	96.48	38.67	153.70	1.20		
moles of light / m2					65.97	19.5%
Air Temp, °C	9.56	1.93	17.51	5.05		
RH, %	87.09	4.74	96.90	63.70		

Table B6: Control - Condensed Weather Data – 1st replication.
Weather data accumulated and summed for the control (no additional artificial light) treatment during the first experiment replication.

[John - plot 6] - Control						
total	mean	std. dev.	max	min	sum	Fraction
Water Temp, °C	15.90	0.57	23.59	14.41		
Solar Radiation, W/m²	61.88	102.14	520.60	0.60	2446191.30	100.0%
PAR #1, umol/m2/sec	131.11	215.27	1808.70	1.20		
moles of light / m2					310.99	100.0%
Air Temp, °C	11.47	5.05	28.35	-0.54		
RH, %	84.98	14.24	100.00	26.10		
sunlight only	mean	std. dev.	max	min	sum	
Water Temp, °C	15.85	0.56	23.59	14.41		
Solar Radiation, W/m²	86.14	111.81	520.60	0.60	2437724.80	99.7%
PAR #1, umol/m2/sec	182.57	235.40	1808.70	1.20		
moles of light / m2					310.01	99.7%
Air Temp, °C	12.43	5.53	28.35	-0.54		
RH, %	82.78	16.00	100.00	26.10		
HPS only	mean	std. dev.	max	min	sum	
Water Temp, °C	16.05	0.54	17.03	14.84		
Solar Radiation, W/m²	0.75	1.14	18.10	0.60	8466.50	0.3%
PAR #1, umol/m2/sec	1.46	1.97	31.20	1.20		
moles of light / m2					0.98	0.3%
Air Temp, °C	9.05	2.14	17.27	3.70		
RH, %	90.50	5.14	99.80	65.40		

-Weather Data Tables – 2nd replication

Table B7: HPS Near - Condensed Weather Data – 2nd replication.
Weather data accumulated and summed for the first high-pressure sodium light treatment replication during the second experiment replication.

[Duke - plot 1] - HPS Near						
total	mean	min	max	std. dev.	sum	Fraction
Surface Temp, °C	14.60	2.98	37.70	6.43		
Solar Radiation, W/m²	79.09	0.60	721.90	91.97	2365937.60	100.0%
PAR #1, uE	151.46	1.20	1366.20	142.29		
moles of light / m2					271.85	100.0%
PAR #2, uE	149.00	1.20	1393.70	144.12		
moles of light / m2					267.44	100.0%
Air Temp, °C	12.85	0.83	32.74	5.73		
RH, %	73.44	15.30	97.90	21.64		
sunlight only	mean	min	max	std. dev.	sum	
Surface Temp, °C	15.99	2.98	37.70	7.18		
Solar Radiation, W/m²	106.72	0.60	721.90	103.59	2074094.80	87.7%
PAR #1, uE	182.34	1.20	1366.20	164.87		
moles of light / m2					212.63	78.2%
PAR #2, uE	179.70	1.20	1393.70	167.48		
moles of light / m2					209.55	78.4%
Air Temp, °C	14.08	0.83	32.74	6.25		
RH, %	69.29	15.30	97.90	23.87		
HPS only	mean	min	max	std. dev.	sum	
Surface Temp, °C	12.00	3.54	25.19	3.48		
Solar Radiation, W/m²	27.85	0.60	79.40	14.27	291842.80	12.3%
PAR #1, uE	94.18	1.20	201.20	48.32		
moles of light / m2					59.22	21.8%
PAR #2, uE	92.07	1.20	208.70	47.78		
moles of light / m2					57.89	21.6%
Air Temp, °C	10.57	1.45	25.14	3.65		
RH, %	81.45	19.70	96.80	13.27		

Table B8: LED Near - Condensed Weather Data – 2nd replication.
Weather data accumulated and summed for the first light emitting diode light treatment replication during the second experiment replication.

[Ray - plot 2] - LED Near						
Total	mean	min	max	std. dev.	sum	Fraction
Surface Temp, °C	15.04	1.94	46.32	8.24		
Solar Radiation, W/m²	77.60	0.60	908.10	122.10	3094310.50	100.0%
PAR #1, uE	136.41	1.20	1288.70	151.91		
moles of light / m2					326.37	100.0%
PAR #2, uE	158.57	1.20	1751.20	210.26		
moles of light / m2					379.39	100.0%
Air Temp, °C	15.61	3.09	36.20	5.42		
RH, %	76.78	16.20	99.70	22.01		
Sunlight only	mean	min	max	std. dev.	sum	
Surface Temp, °C	17.31	1.94	46.32	9.21		
Solar Radiation, W/m²	114.92	0.60	908.10	137.82	2972612.50	96.1%
PAR #1, uE	183.94	1.20	1288.70	169.99		
moles of light / m2					285.47	87.5%
PAR #2, uE	218.47	1.20	1751.20	240.21		
moles of light / m2					339.07	89.4%
Air Temp, °C	16.84	3.09	36.20	5.94		
RH, %	71.95	16.20	99.70	24.32		
LED only	mean	min	max	std. dev.	sum	
Surface Temp, °C	10.87	2.64	24.22	3.10		
Solar Radiation, W/m²	8.74	0.60	69.40	6.95	122458.20	4.0%
PAR #1, uE	48.74	1.20	153.70	21.49		
moles of light / m2					40.97	12.6%
PAR #2, uE	48.05	1.20	143.70	20.96		
moles of light / m2					40.39	10.6%
Air Temp, °C	13.35	4.04	27.75	3.24		
RH, %	85.66	21.30	97.80	12.84		

Table B9: Control - Condensed Weather Data – 2nd replication.
Weather data accumulated and summed for the control (no additional artificial light) treatment during the second experiment replication.

[John - plot 3] - Control						
total	mean	min	max	std. dev.	sum	Fraction
Water Temp, °C	14.73	11.20	16.01	0.50		
Solar Radiation, W/m²	69.53	0.60	715.60	101.66	2727804.10	100.0%
PAR #1, uE	159.67	1.20	1698.70	238.54		
moles of light / m2					300.13	100.0%
Air Temp, °C	12.75	0.25	32.12	5.54		
RH, %	76.98	19.10	99.40	21.53		
sunlight only	mean	min	max	std. dev.	sum	
Water Temp, °C	14.66	13.88	15.96	0.48		
Solar Radiation, W/m²	105.81	0.60	715.60	110.27	2692804.90	98.7%
PAR #1, uE	243.48	1.20	1698.70	260.06		
moles of light / m2					296.05	98.6%
Air Temp, °C	14.02	0.25	32.12	6.06		
RH, %	72.38	19.10	99.40	23.73		
HPS only	mean	min	max	std. dev.	sum	
Water Temp, °C	14.87	11.20	16.01	0.49		
Solar Radiation, W/m²	2.54	0.60	65.60	6.98	34999.20	1.3%
PAR #1, uE	4.93	1.20	116.20	13.25		
moles of light / m2					4.08	1.4%
Air Temp, °C	10.41	1.07	24.58	3.32		
RH, %	85.49	22.60	97.70	12.95		

Table B10: LED Far - Condensed Weather Data – 2nd replication.
Weather data accumulated and summed for the second light emitting diode light treatment replication during the second experiment replication.

[Herbie - plot 4] - LED far						
total	mean	min	max	std. dev.	sum	Fraction
Surface Temp, °C	13.74	2.53	41.07	6.09		
Solar Radiation, W/m²	70.42	0.60	698.10	92.10	2809364.80	100.0%
PAR #1, uE	134.74	1.20	1121.20	159.55		
moles of light / m2					322.50	100.0%
PAR #2, uE	149.99	1.20	1316.20	189.21		
moles of light / m2					359.01	100.0%
Air Temp, °C	12.74	-0.03	32.38	5.54		
RH, %	76.35	18.30	99.60	21.66		
sunlight only	mean	min	max	std. dev.	sum	
Surface Temp, °C	15.26	2.53	41.07	6.76		
Solar Radiation, W/m²	103.45	0.60	698.10	99.72	2677103.90	95.3%
PAR #1, uE	181.63	1.20	1121.20	180.92		
moles of light / m2					282.02	87.4%
PAR #2, uE	204.74	1.20	1316.20	215.43		
moles of light / m2					317.91	88.6%
Air Temp, °C	13.99	-0.03	32.38	6.07		
RH, %	71.77	18.30	99.60	23.90		
LED only	mean	min	max	std. dev.	sum	
Surface Temp, °C	10.94	3.56	24.22	3.04		
Solar Radiation, W/m²	9.44	0.60	74.40	7.25	132260.90	4.7%
PAR #1, uE	48.15	1.20	158.70	21.33		
moles of light / m2					40.48	12.6%
PAR #2, uE	48.88	1.20	146.20	21.16		
moles of light / m2					41.10	11.4%
Air Temp, °C	10.44	0.69	24.56	3.34		
RH, %	84.80	20.30	97.80	13.06		

Table B11: HPS Far - Condensed Weather Data – 2nd replication.
Weather data accumulated and summed for the second high-pressure sodium light treatment replication during the second experiment replication.

[Aretha - plot 5] - HPS far						
total	mean	min	max	std. dev.	sum	Fraction
Surface Temp, °C	15.33	2.34	37.43	6.49		
Solar Radiation, W/m²	79.77	0.60	668.10	94.76	3182621.60	100.0%
PAR #1, uE	172.27	1.20	1881.20	195.51		
moles of light / m2					412.37	100.0%
PAR #2, uE	165.43	1.20	1268.70	159.54		
moles of light / m2					396.01	100.0%
Air Temp, °C	13.06	0.16	32.72	5.55		
RH, %	76.11	17.30	99.60	21.41		
sunlight only	mean	min	max	std. dev.	sum	
Surface Temp, °C	16.67	2.34	37.43	7.36		
Solar Radiation, W/m²	105.98	0.60	668.10	108.53	2743169.80	86.2%
PAR #1, uE	214.52	1.20	1881.20	230.08		
moles of light / m2					333.14	80.8%
PAR #2, uE	201.48	1.20	1268.70	186.05		
moles of light / m2					312.89	79.0%
Air Temp, °C	14.21	0.16	32.72	6.14		
RH, %	72.00	17.30	99.60	23.84		
HPS only	mean	min	max	std. dev.	sum	
Surface Temp, °C	12.86	3.04	25.65	3.25		
Solar Radiation, W/m²	31.36	0.60	101.90	14.14	439451.80	13.8%
PAR #1, uE	94.23	1.20	213.70	40.76		
moles of light / m2					79.23	19.2%
PAR #2, uE	98.86	1.20	243.70	41.25		
moles of light / m2					83.12	21.0%
Air Temp, °C	10.94	0.93	25.48	3.35		
RH, %	83.69	19.80	97.90	12.91		

Table B12: Regular - Condensed Weather Data – 2nd replication.
Weather data accumulated and summed for the regular high-pressure sodium light treatment during the second experiment replication.

[Ella + Louis - plot 6] - Regular						
total	mean	min	max	standard	sum	
Surface Temp, °C	13.97	4.66	32.59	5.52		
Solar Radiation, W/m²	67.87	0.60	683.10	90.59	2708262.40	100.0%
PAR #1, umol/m2/sec	131.46	1.20	1233.70	187.74		
moles of light	0.01	0.00	0.07	0.01	314.72	100.0%
PAR #2, umol/m2/sec	125.48	1.20	1118.70	178.16		
moles of light	0.01	0.00	0.07	0.01	300.42	100.0%
Air Temp, °C	12.81	3.27	26.11	4.62		
RH, %	77.00	19.10	99.80	19.15		
sunlight only	mean	min	max	standard	sum	
Surface Temp, °C	15.60	4.66	32.59	6.11		
Solar Radiation, W/m²	101.13	0.60	683.10	97.29	2618144.50	96.7%
PAR #1, umol/m2/sec	195.04	1.20	1233.70	206.71		
moles of light	0.01	0.00	0.07	0.01	302.95	96.3%
PAR #2, umol/m2/sec	184.36	1.20	1118.70	197.36		
moles of light	0.01	0.00	0.07	0.01	286.37	95.3%
Air Temp, °C	14.00	3.27	26.11	5.14		
RH, %	72.94	19.10	99.80	21.12		
HPS only	mean	min	max	standard	sum	
Surface Temp, °C	10.98	6.10	17.63	2.01		
Solar Radiation, W/m²	6.43	0.60	74.40	7.78	90117.90	3.3%
PAR #1, umol/m2/sec	14.00	3.70	121.20	12.64		
moles of light	0.00	0.00	0.01	0.00	11.77	3.7%
PAR #2, umol/m2/sec	16.71	3.70	138.70	13.70		
moles of light	0.00	0.00	0.01	0.00	14.05	4.7%
Air Temp, °C	10.60	5.41	17.89	2.11		
RH, %	84.49	33.90	97.30	11.59		

Annex C

-Weather data charts - Replication #1 – temperature charts

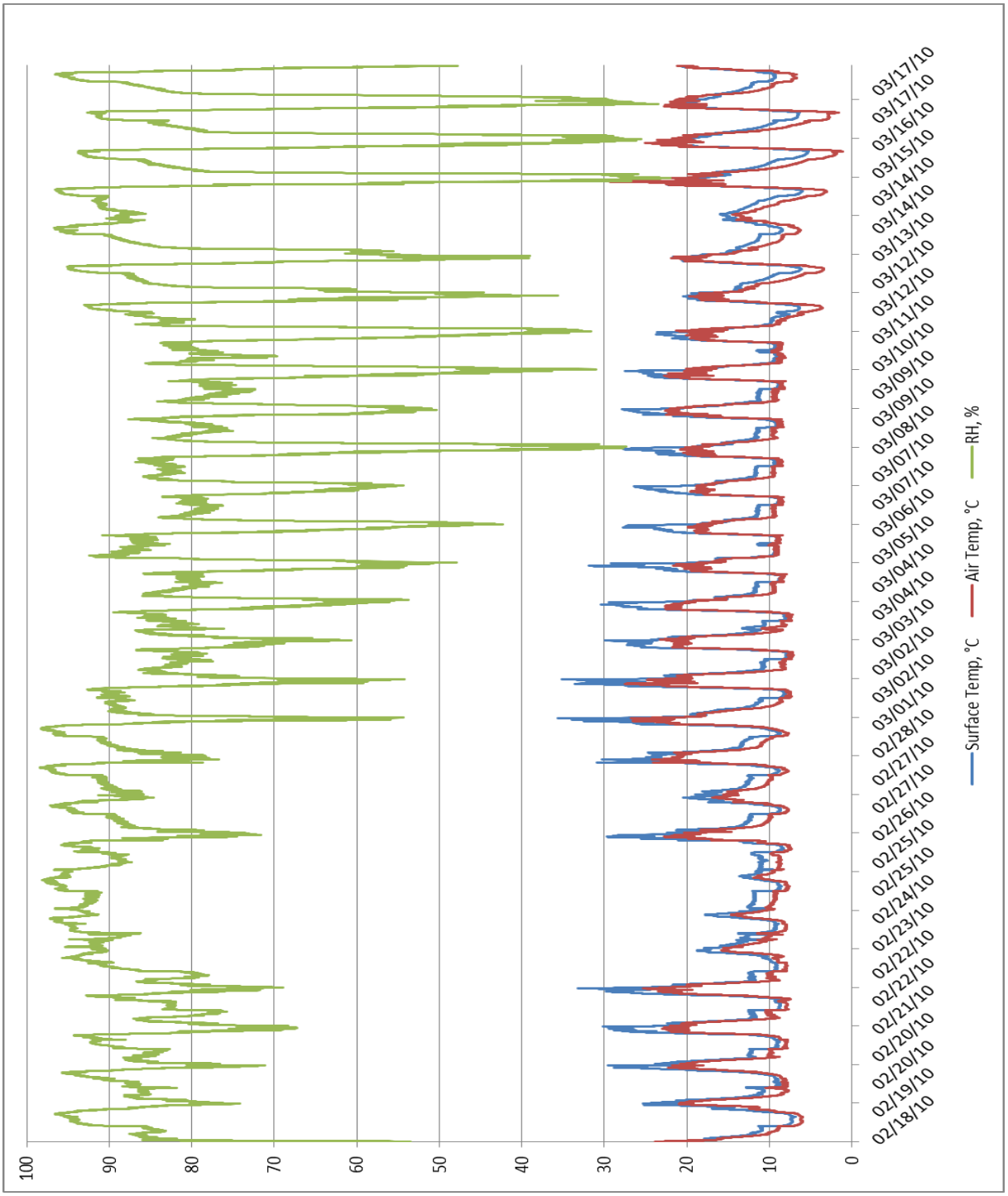


Figure C1: [Herbie - plot 1] - HPS Near Historical Weather Data.
Weather data over four weeks for first high pressure sodium light treatment replication during the first experiment replication. Surface and air temperatures in degree celcius; relative humidity in percentage.

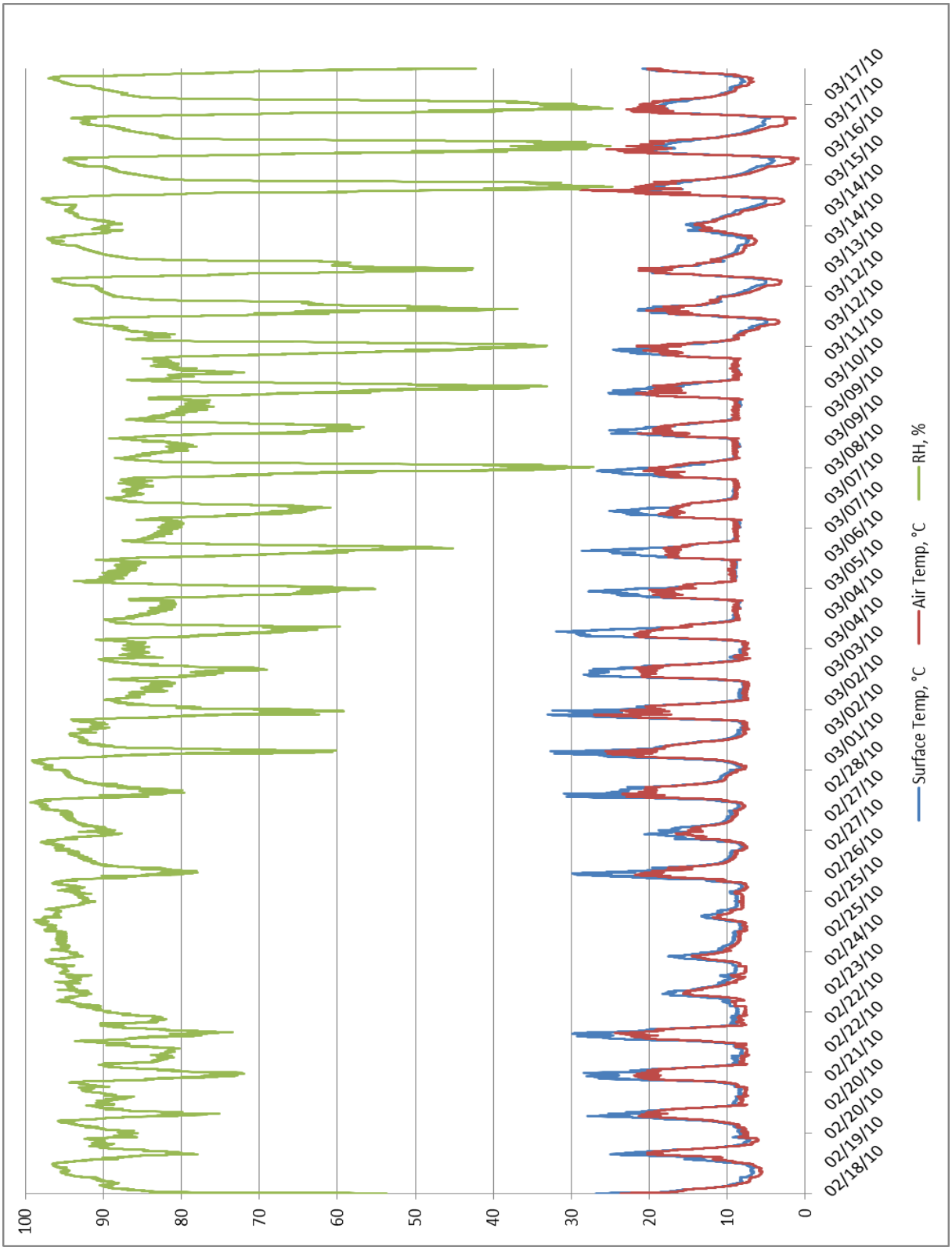


Figure C2: [Ella - plot 2] - LED near Historical Weather Data.
Weather data over four weeks for first light emitting diode light treatment replication during the first experiment replication. Surface and air temperatures in degree celcius; relative humidity in percentage.

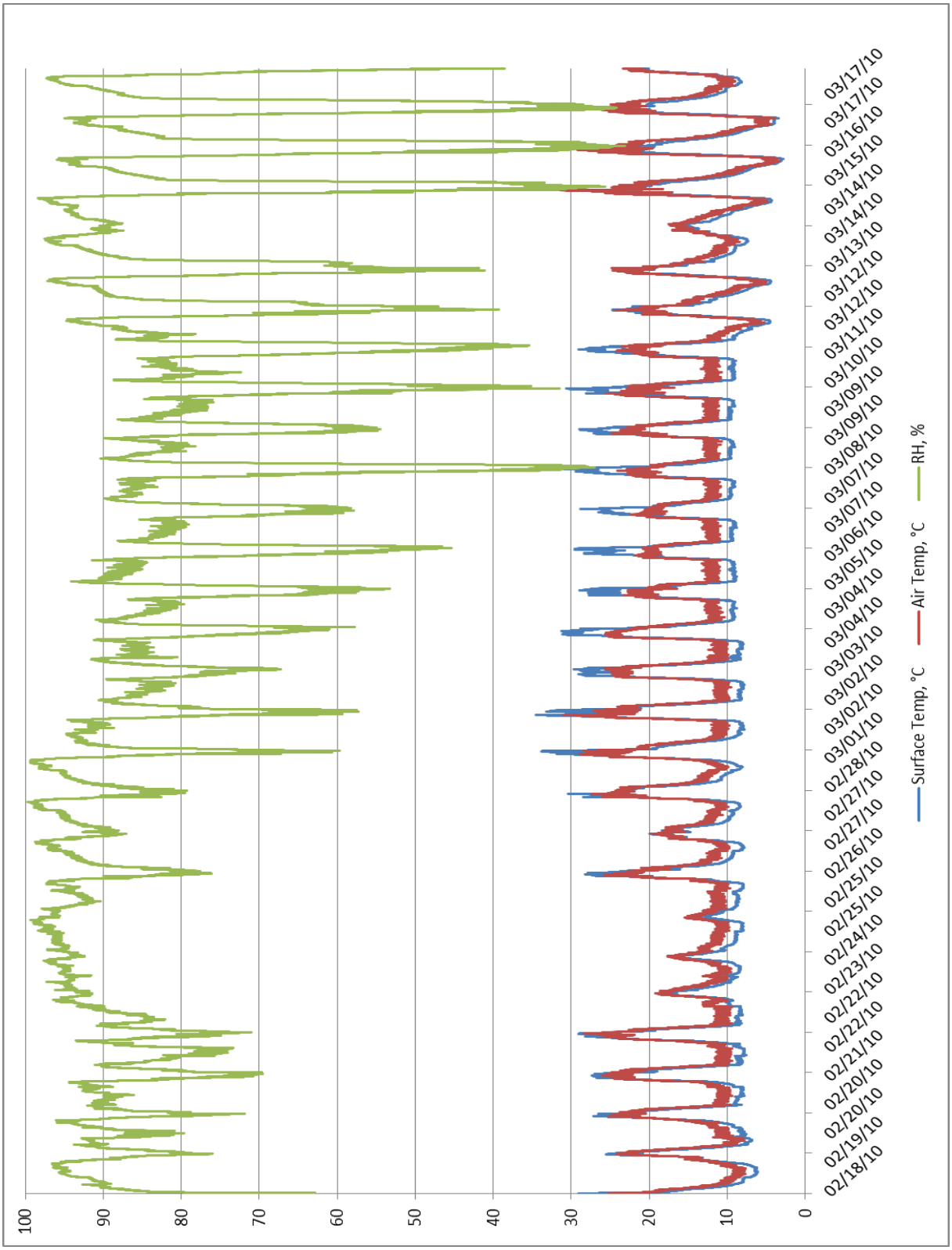


Figure C3: [Ray - plot 3] – Regular Historical Weather Data.
Weather data over four weeks for the regular high pressure sodium light treatment during the first experiment replication. Surface and air temperatures in degree celcius; relative humidity in percentage.

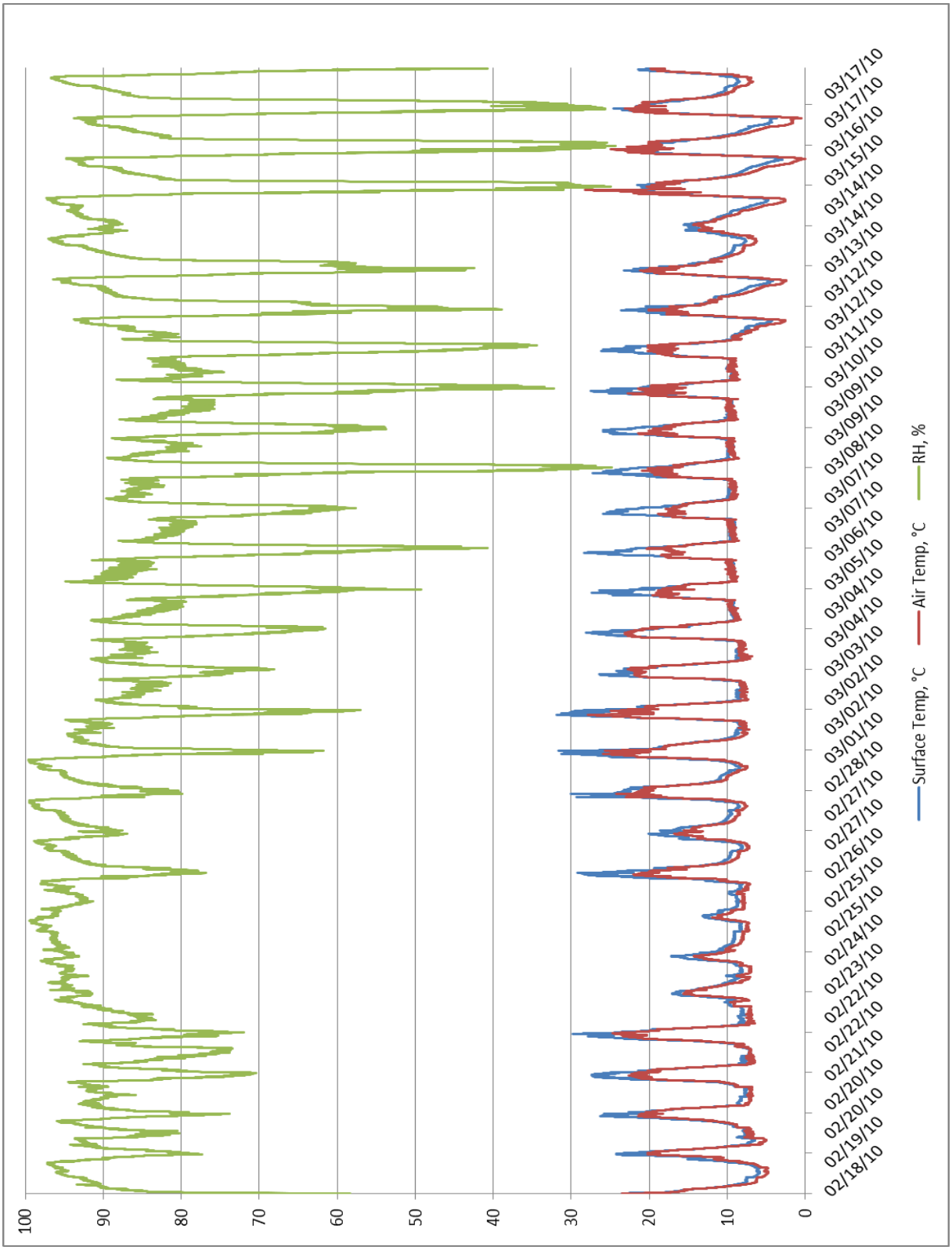


Figure C4: [Duke - plot 4] - LED far Historical Weather Data.
Weather data over four weeks for second light emitting diode light treatment replication during the first experiment replication. Surface and air temperatures in degree celcius; relative humidity in percentage.

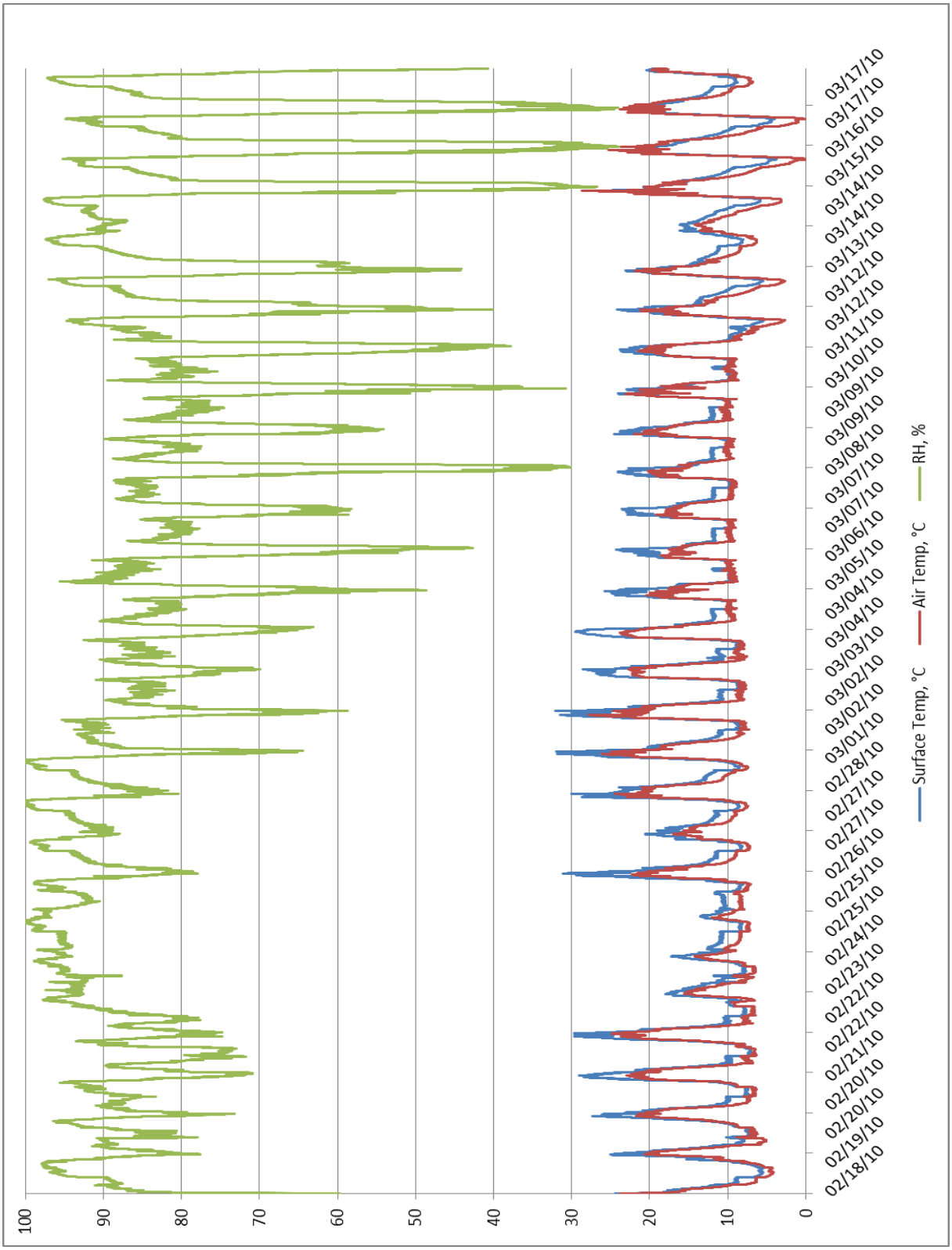


Figure C5: [Aretha - plot 5] - HPS far Historical Weather Data.
Weather data over four weeks for second high pressure sodium light treatment replication during the first experiment replication. Surface and air temperatures in degree celcius; relative humidity in percentage.

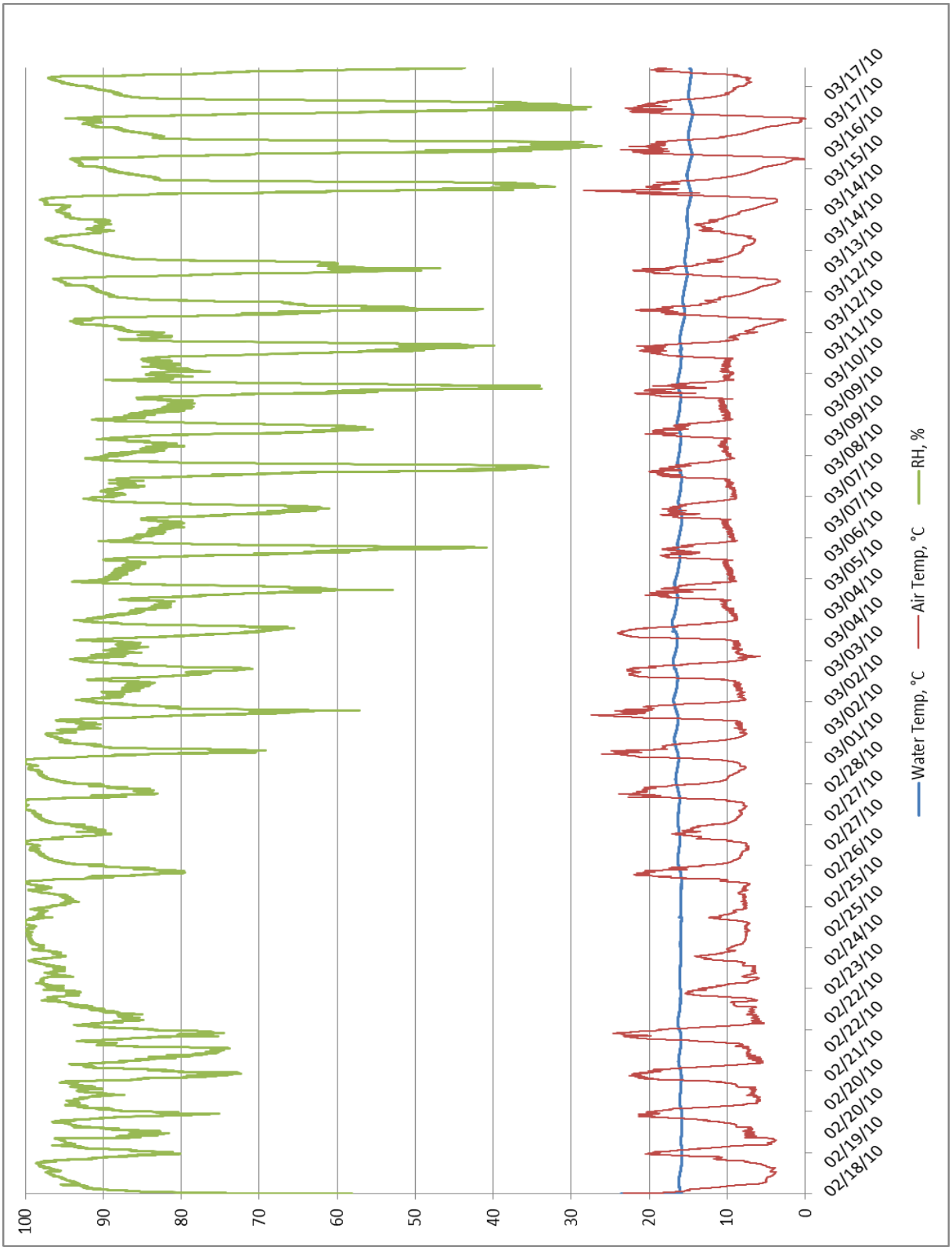


Figure C6: [John - plot 6] – Control Historical Weather Data.
Weather data over four weeks for the control (no additional artificial light) treatment during the first experiment replication. Water and air temperatures in degree celcius; relative humidity in percentage.

-Weather data charts - Replication #2 – temperature charts

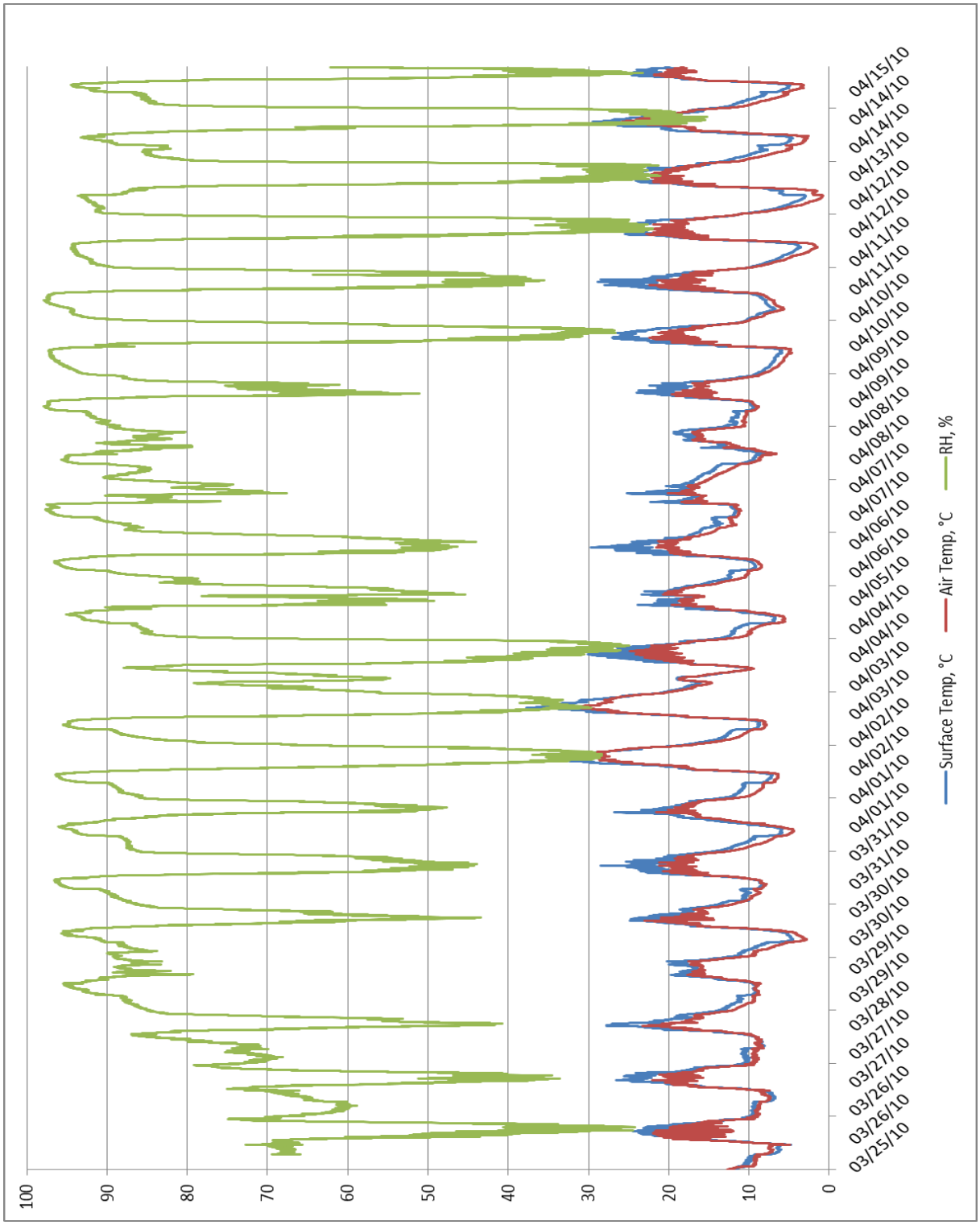


Figure C7: [Duke - plot 1] - HPS Near Historical Weather Data.
Weather data over four weeks for first high pressure sodium light treatment replication during the second experiment replication. Surface and air temperatures in degree celcius; relative humidity in percentage.

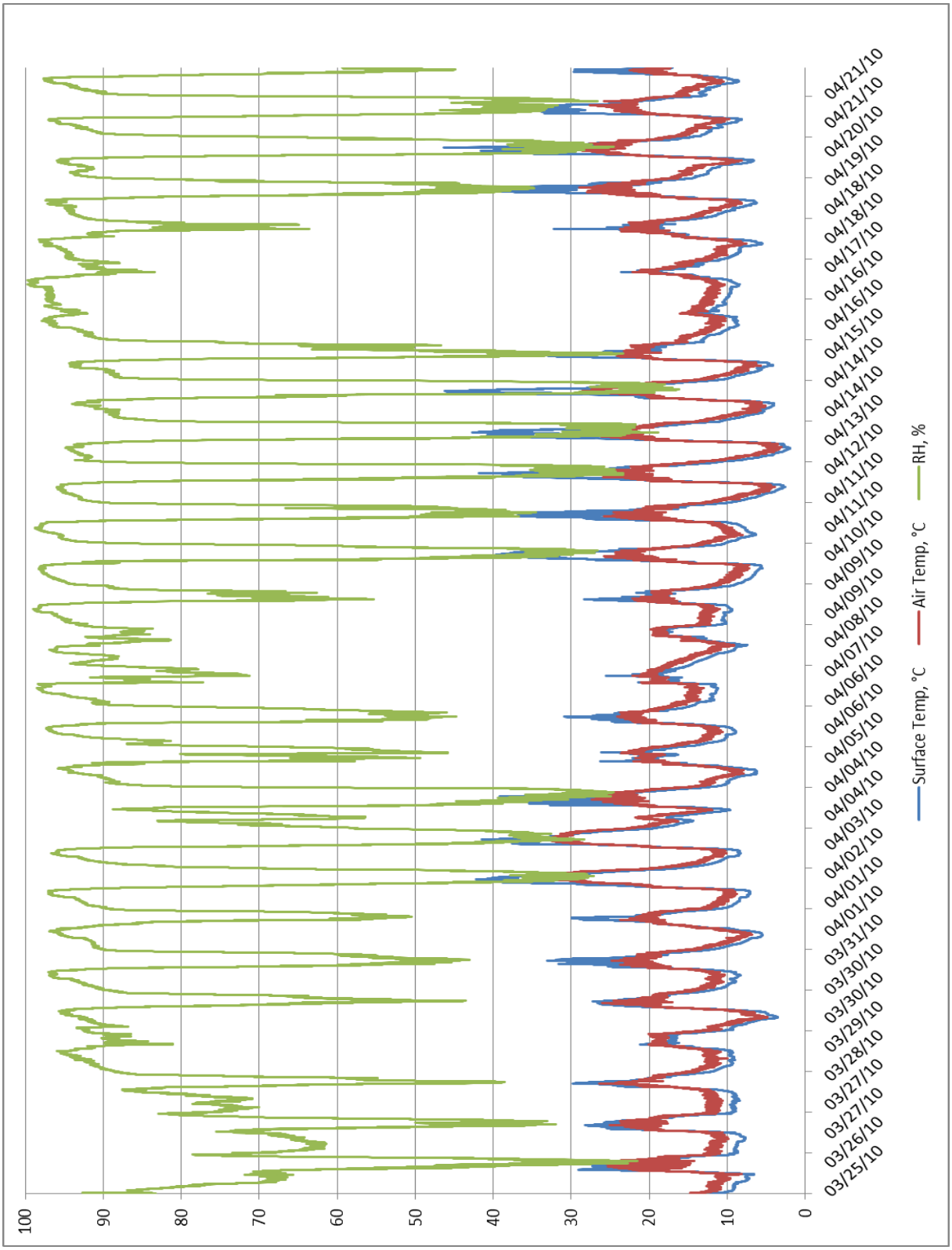


Figure C8: [Ray - plot 2] - LED near Historical Weather Data.
Weather data over four weeks for first light emitting diode light treatment replication during the second experiment replication. Surface and air temperatures in degree celcius; relative humidity in percentage.

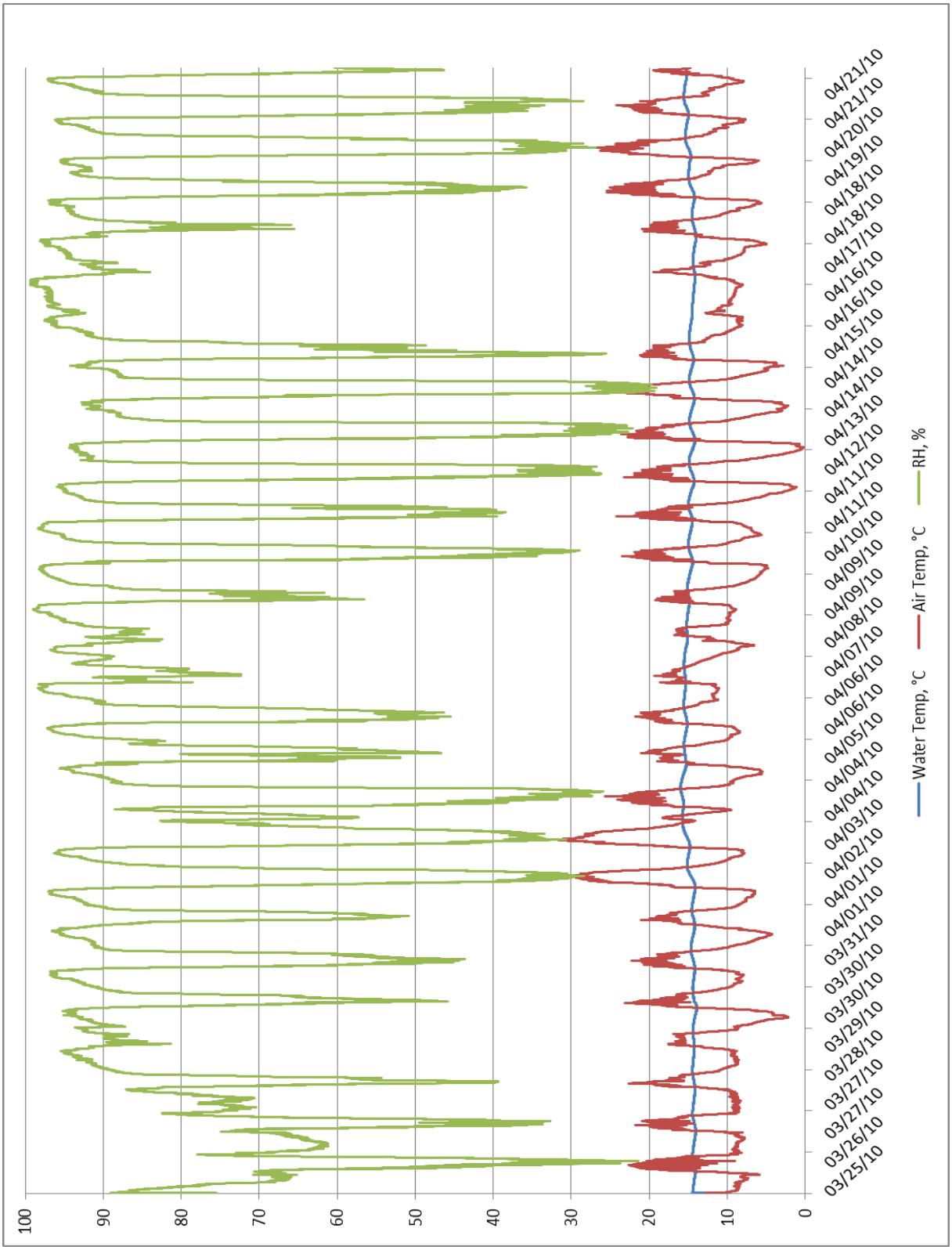


Figure C9: [John - plot 3] - Control Historical Weather Data.
Weather data over four weeks for the control (no additional artificial light) treatment during the second experiment replication. Surface and air temperatures in degree celcius; relative humidity in percentage.

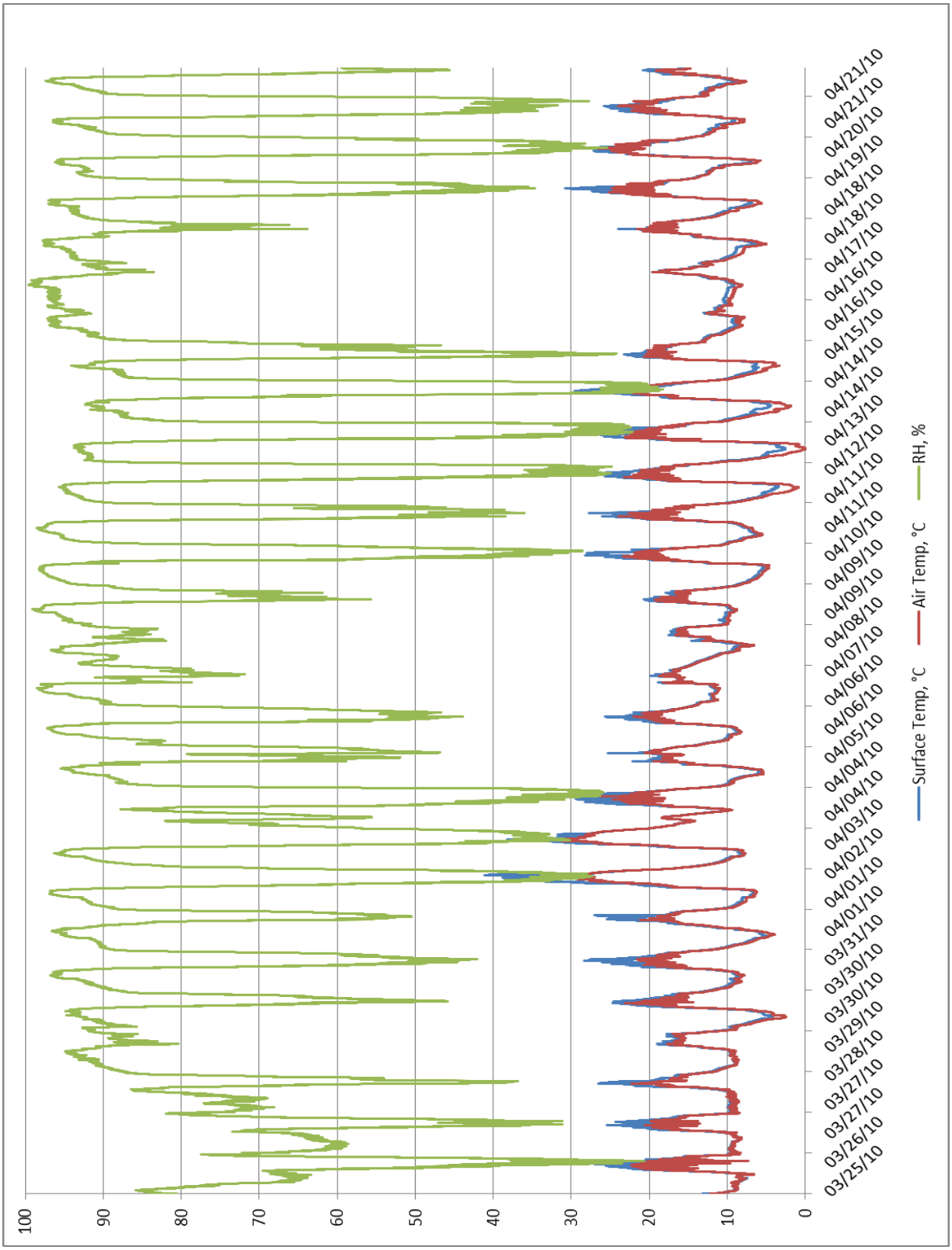


Figure C10: [Herbie - plot 4] - LED far Historical Weather Data.
Weather data over four weeks for second light emitting diode light treatment replication during the second experiment replication. Surface and air temperatures in degree celcius; relative humidity in percentage.

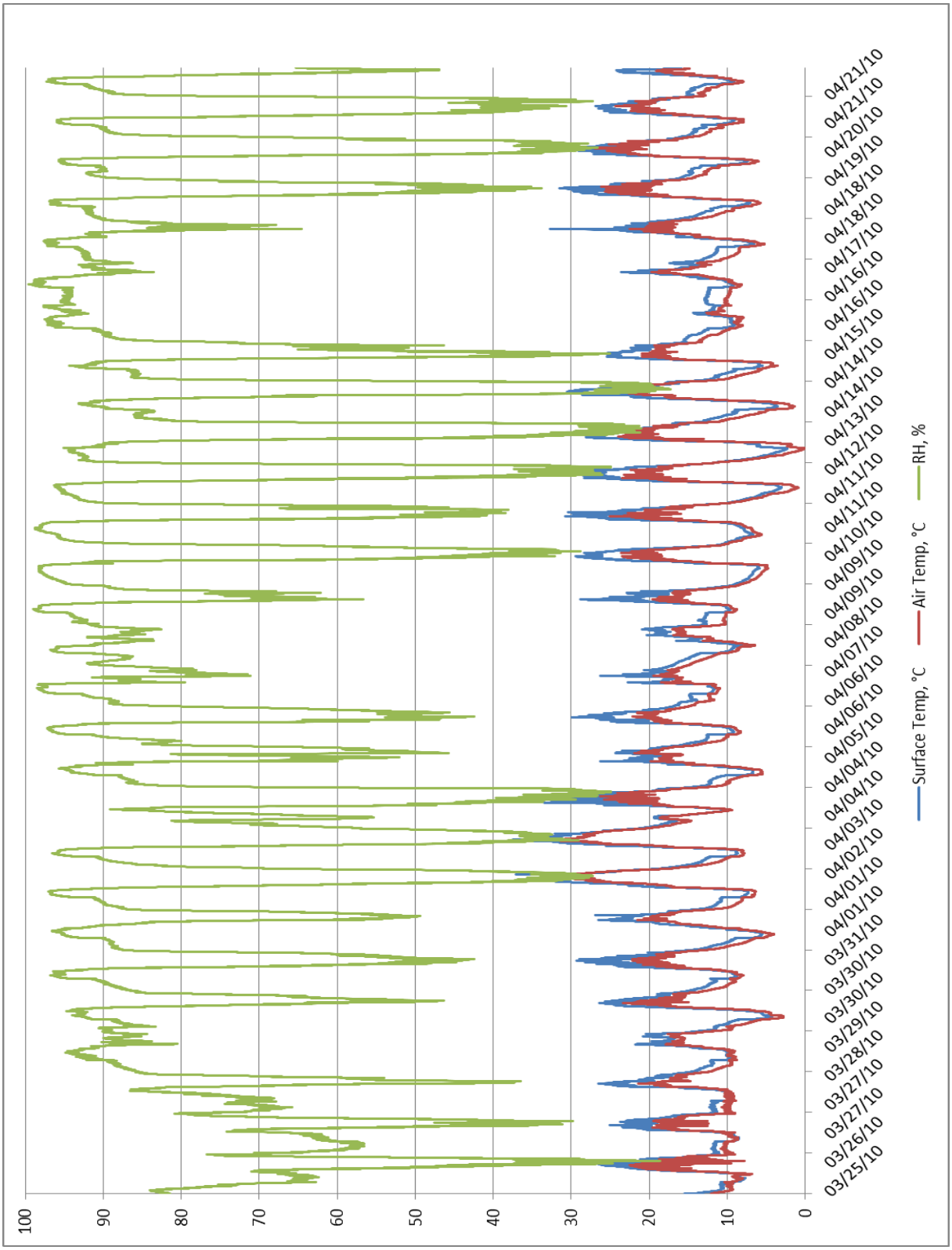


Figure C11: [Aretha - plot 5] - HPS far Historical Weather Data.
Weather data over four weeks for second high pressure sodium light treatment replication during the second experiment replication. Surface and air temperatures in degree celcius; relative humidity in percentage.

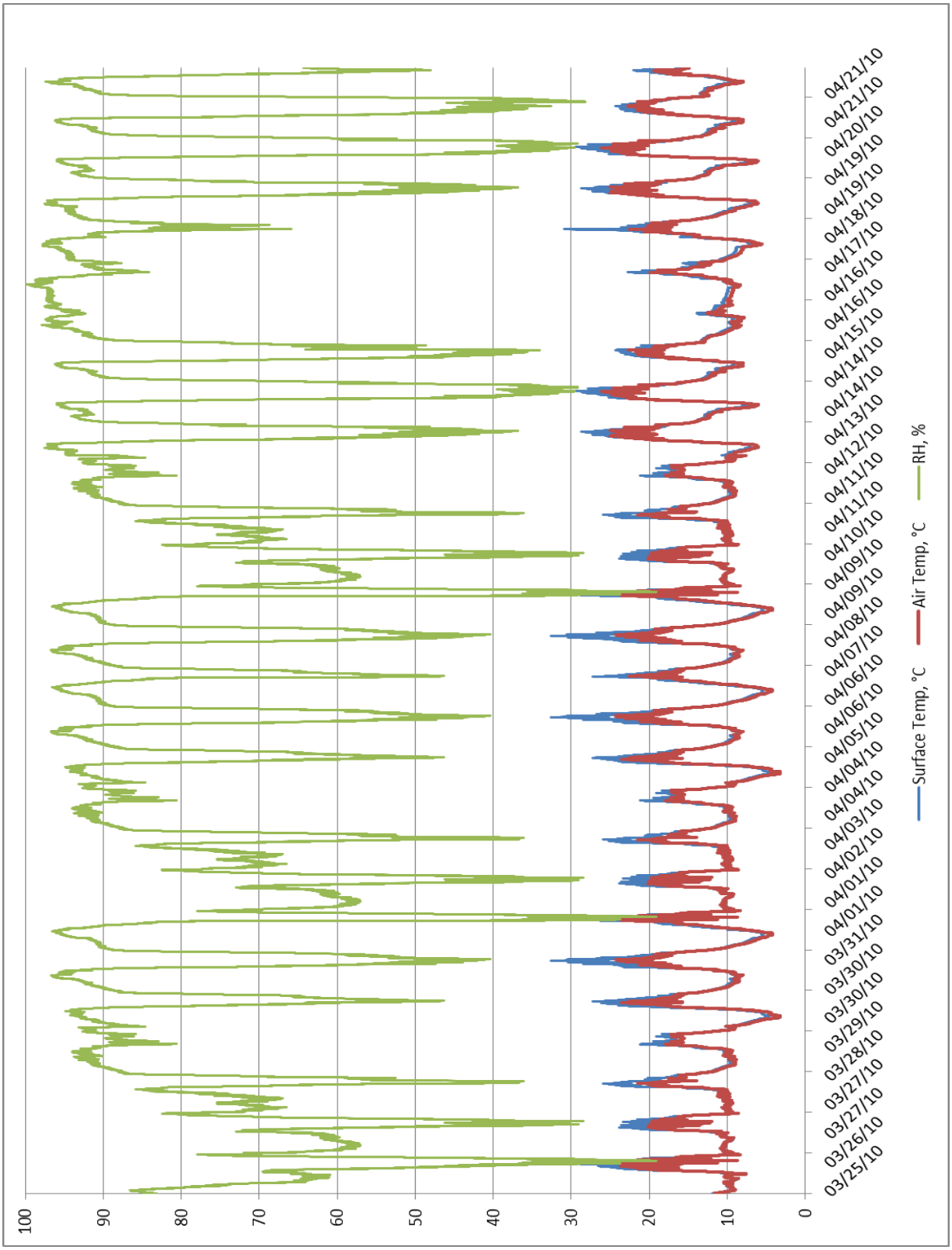


Figure C12: [Ella+Louis - plot 6] - Regular Historical Weather Data.
Weather data over four weeks for the regular high pressure sodium light treatment during the second experiment replication. Surface and air temperatures in degree celcius; relative humidity in percentage.

Annex D

-Weather data charts - Replication #1 – radiation charts

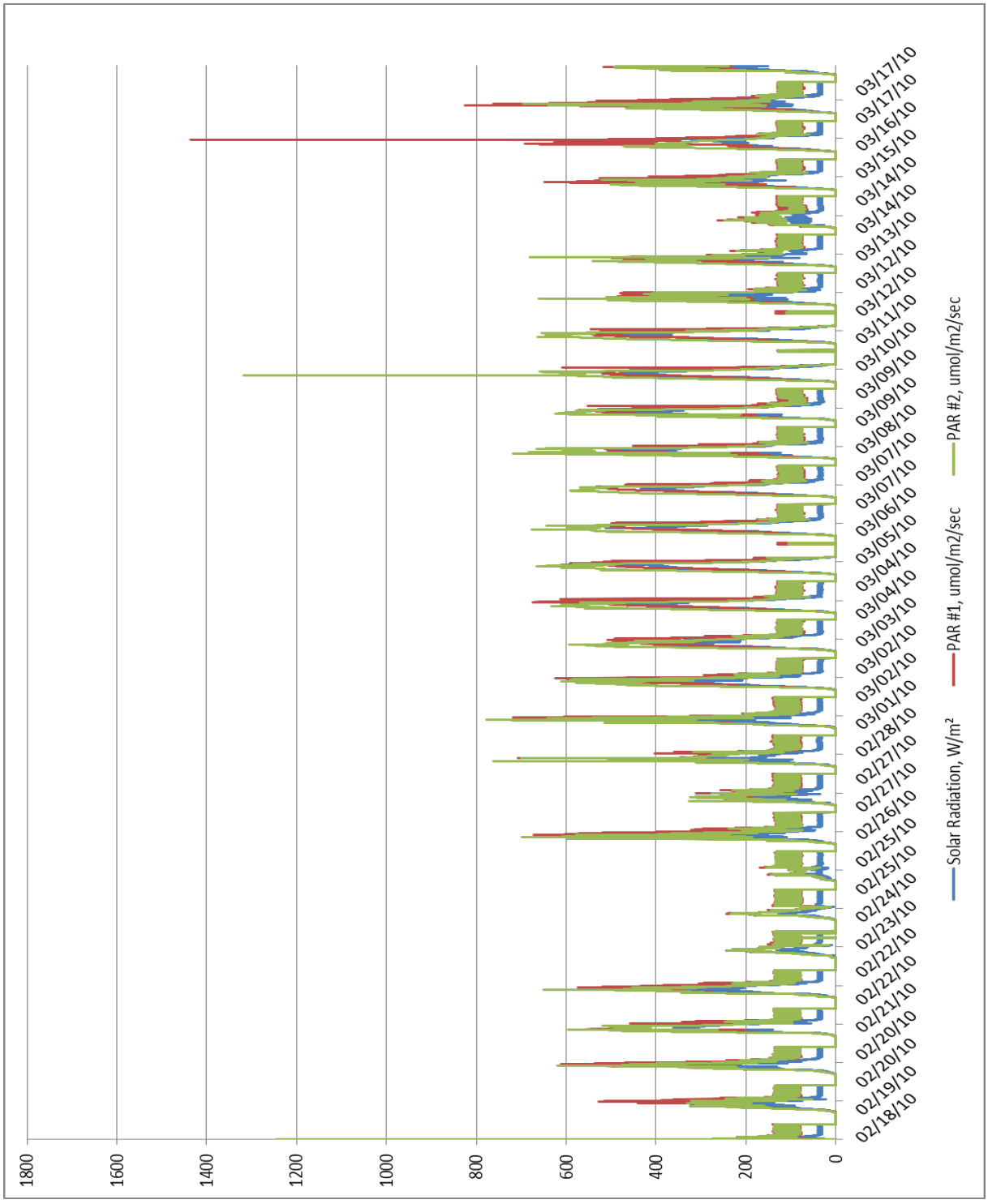


Figure D1: [Herbie - plot 1] - HPS Near Historical Radiation Data.
Radiation data over four weeks for first high pressure sodium light treatment replication during the first experiment replication. Solar radiation in watts per squared meters; Photosynthetically Active Radiation in micro-moles per meter^{2}per second.

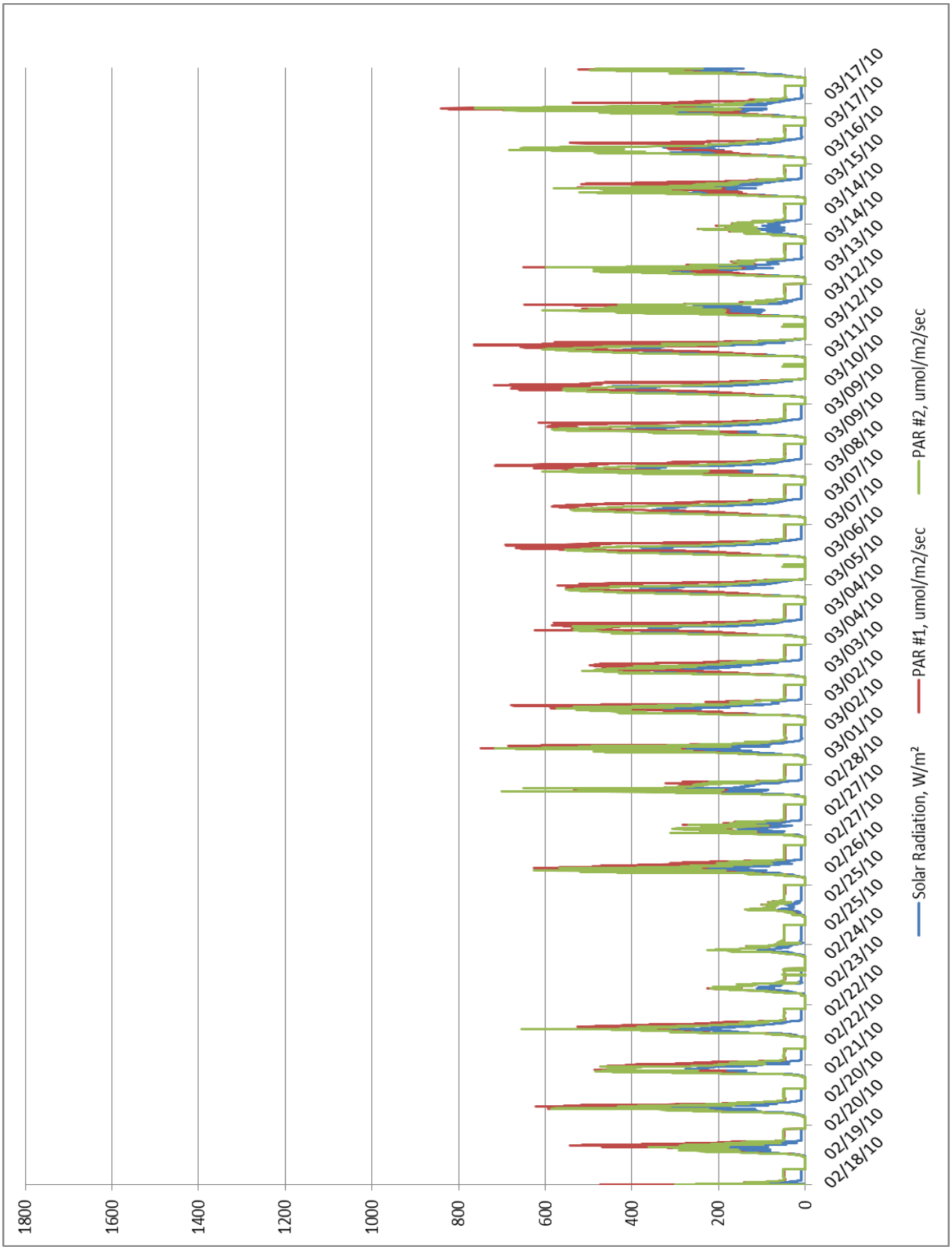


Figure D2: [Ella - plot 2] - LED near Historical Radiation Data.
Radiation data over four weeks for first light emitting diode light treatment replication during the first experiment replication. Solar radiation in watts per squared meters; Photosynthetically Active Radiation in micro-moles per meter^{2}per second.

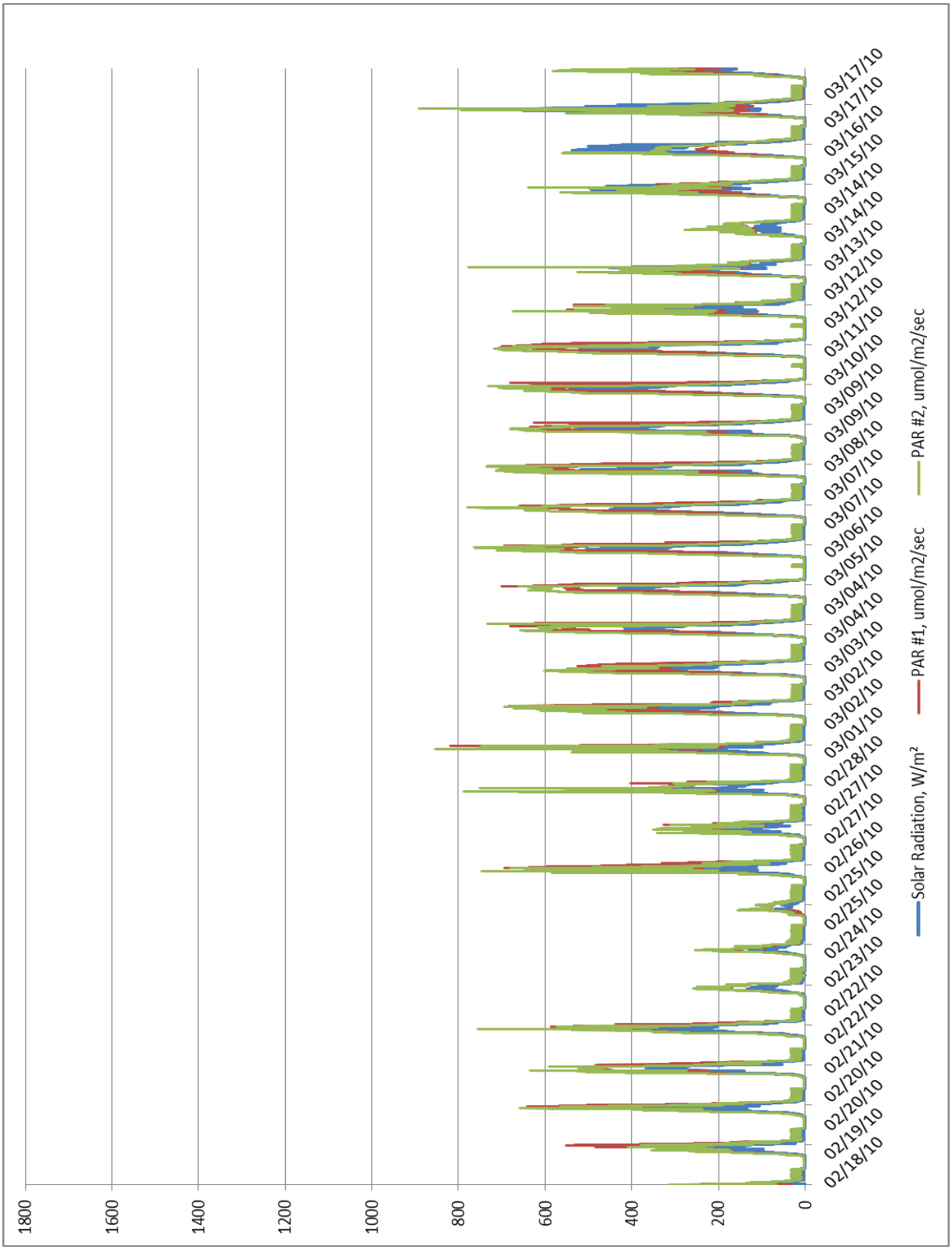


Figure D3: [Ray - plot 3] – Regular Historical Radiation Data.
Radiation data over four weeks for the regular high pressure sodium light treatment during the first experiment replication. Solar radiation in watts per squared meters; Photosynthetically Active Radiation in micro-moles per meter^{2}per second.

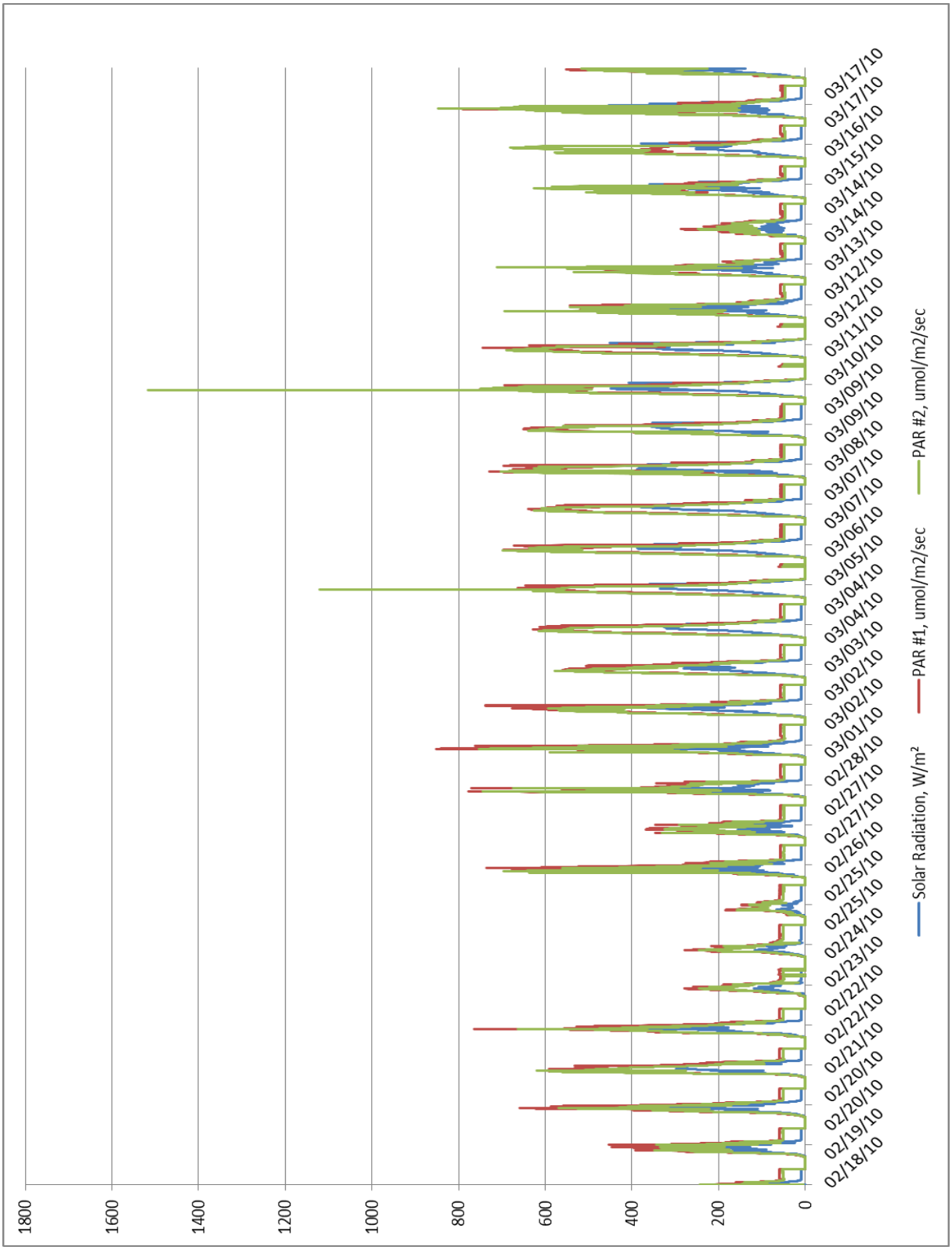


Figure D4: [Duke - plot 4] - LED far Historical Radiation Data.
Radiation data over four weeks for second light emitting diode light treatment replication during the first experiment replication. Solar radiation in watts per squared meters; Photosynthetically Active Radiation in micro-moles per meter^{2}per second.

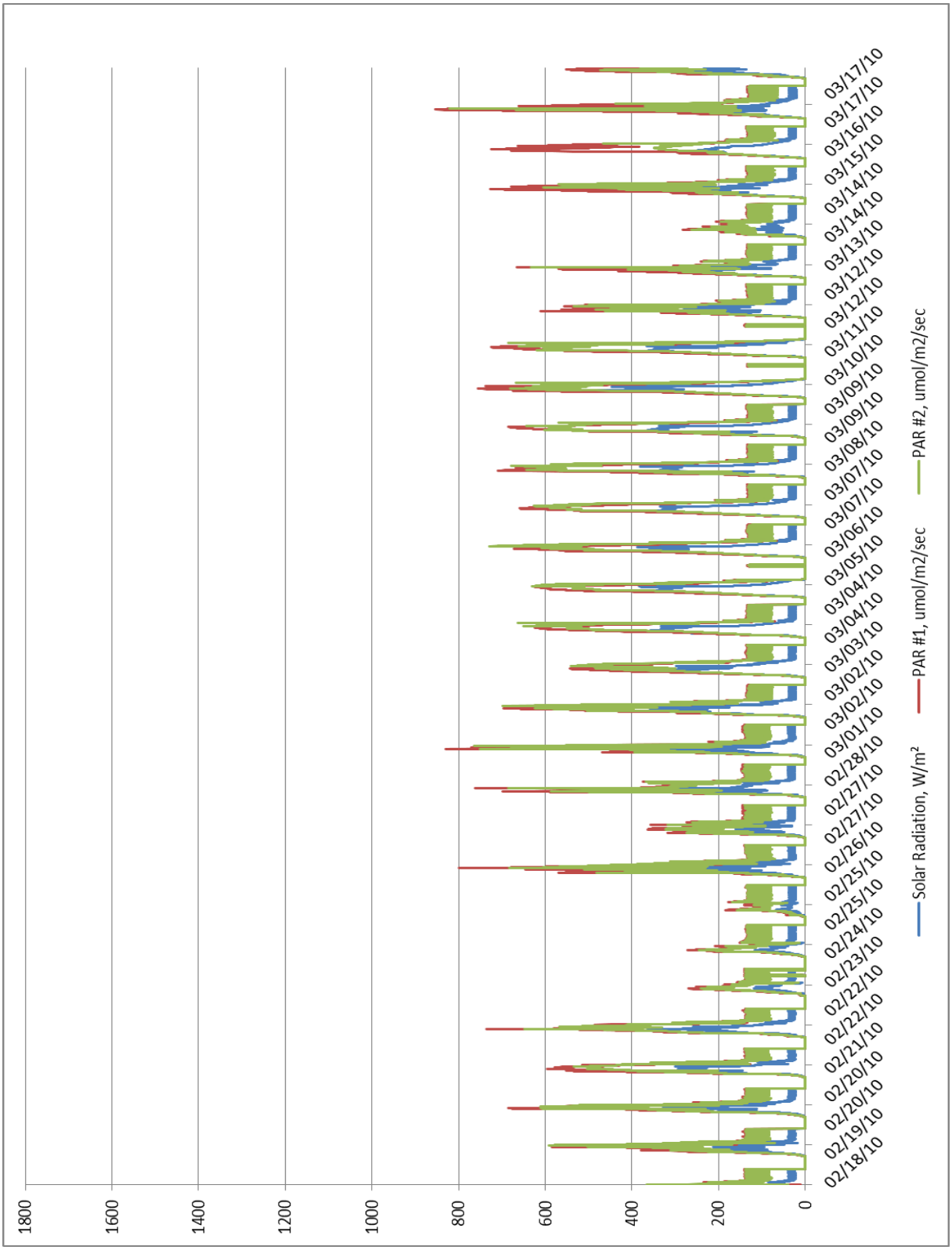


Figure D5: [Aretha - plot 5] - HPS far Historical Radiation Data.
Radiation data over four weeks for second high pressure sodium light treatment replication during the first experiment replication. Solar radiation in watts per squared meters; Photosynthetically Active Radiation in micro-moles per meter^{2}per second.

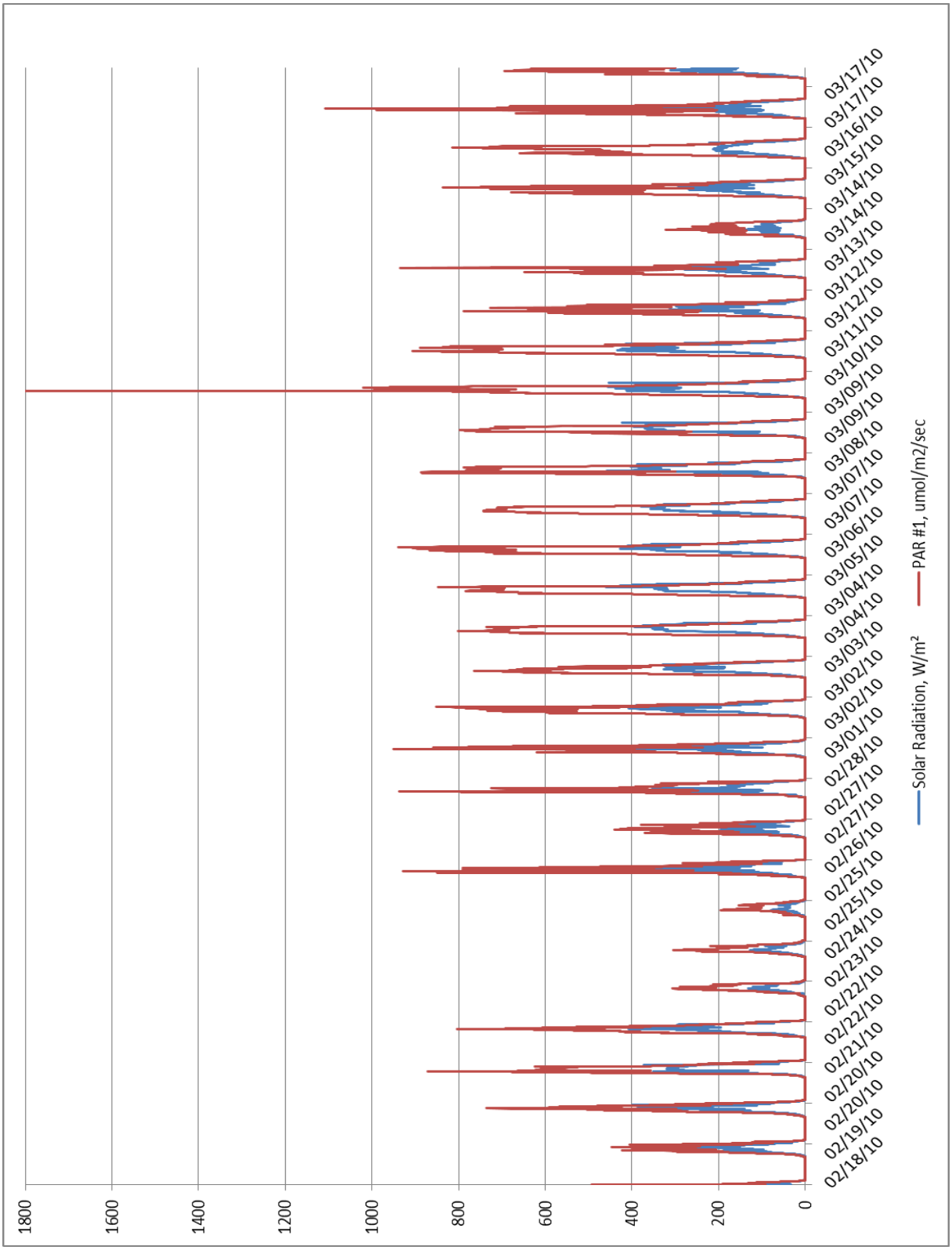


Figure D6: [John - plot 6] – Control Historical Radiation Data.
Radiation data over four weeks for the control (no additional artificial light) treatment during the first experiment replication. Solar radiation in watts per squared meters; Photosynthetically Active Radiation in micro-moles per meter^{2}per second.

-Weather data charts - Replication #2 – radiation charts

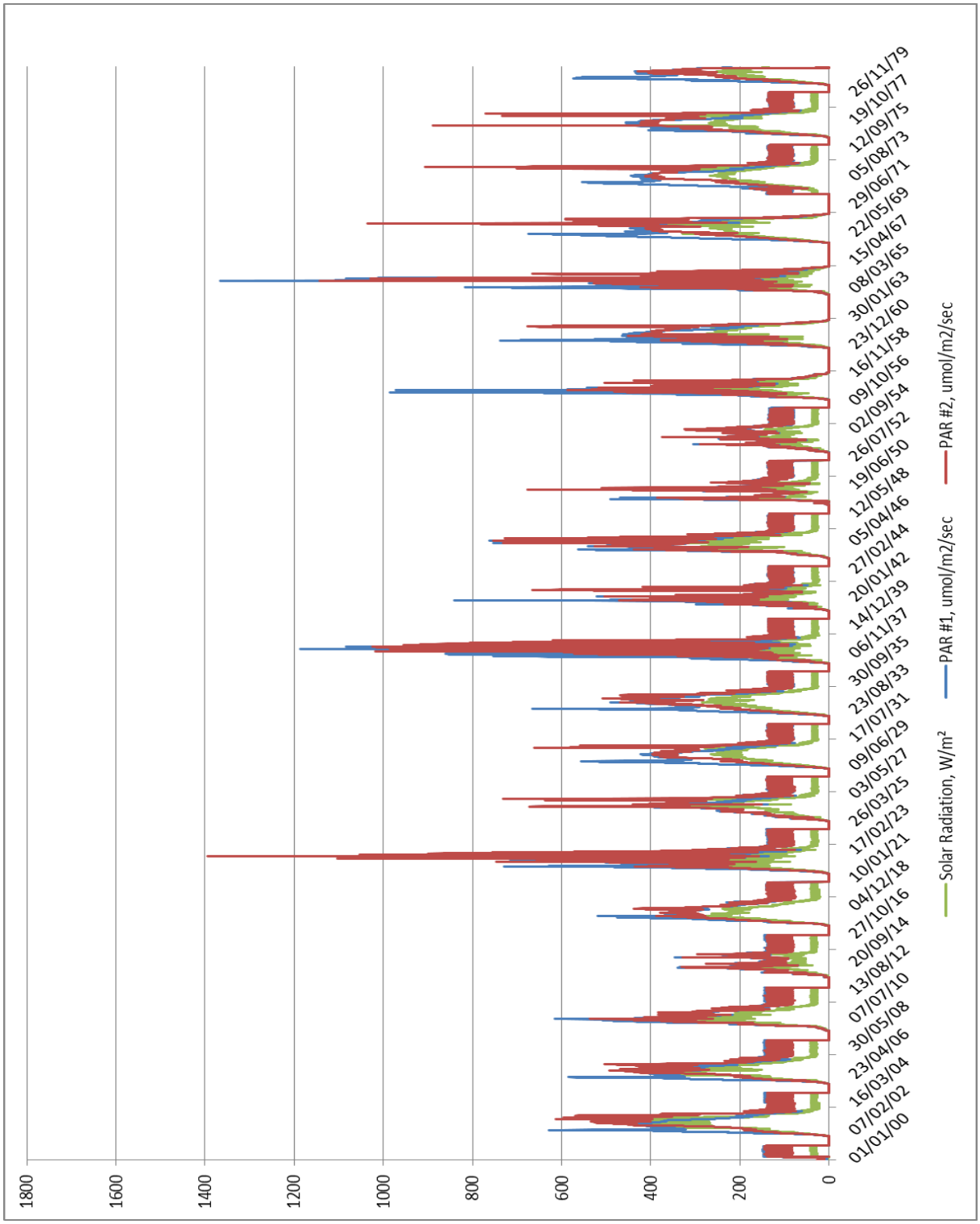


Figure D7: [Duke - plot 1] - HPS Near Historical Radiation Data.
Radiation data over four weeks for first high pressure sodium light treatment replication during the second experiment replication. Solar radiation in watts per squared meters; Photosynthetically Active Radiation in micro-moles per meter^{2}per second.

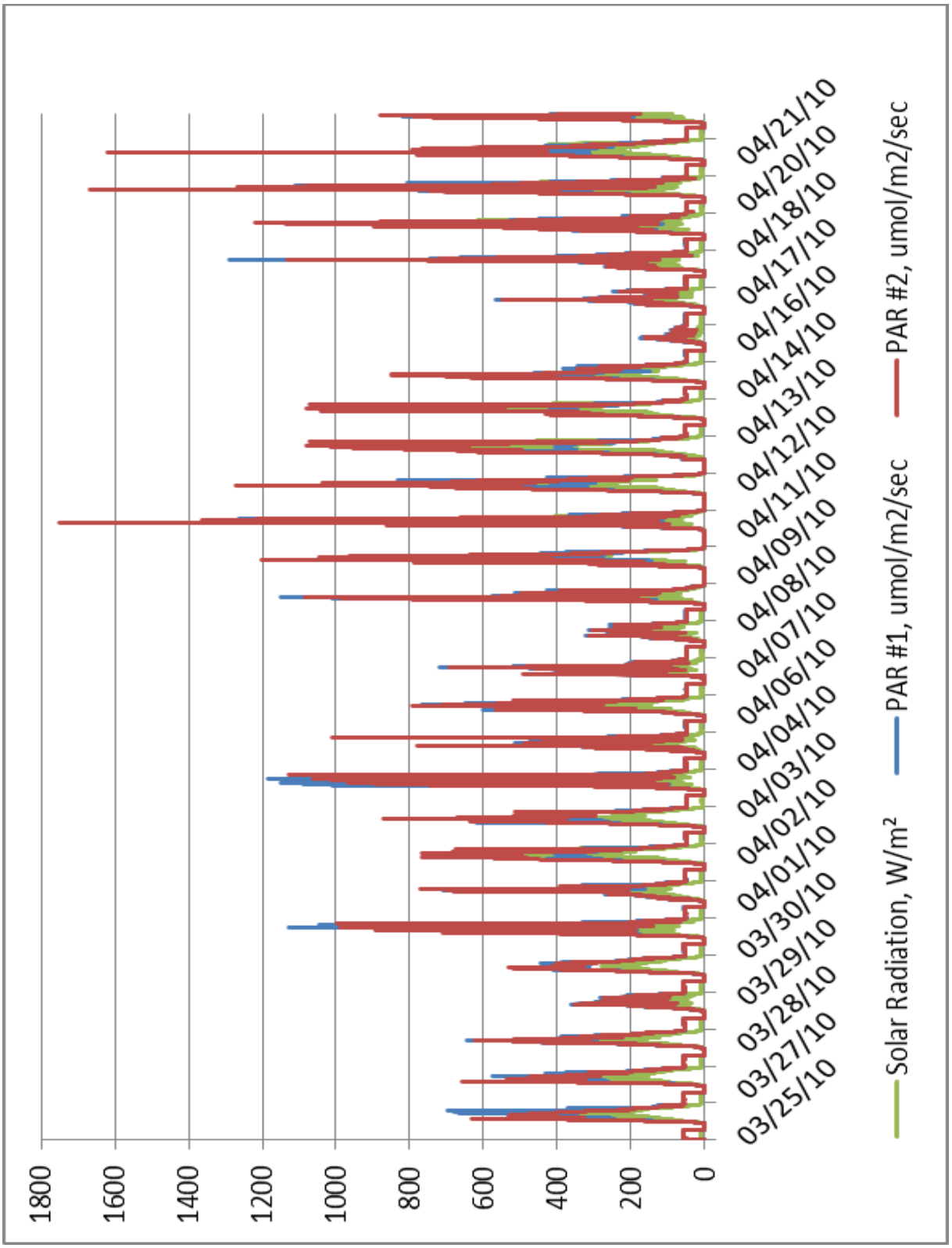


Figure D8: [Ray - plot 2] - LED near Historical Radiation Data.
Radiation data over four weeks for first light emitting diode light treatment replication during the second experiment replication. Solar radiation in watts per squared meters; Photosynthetically Active Radiation in micro-moles per meter^{2}per second.

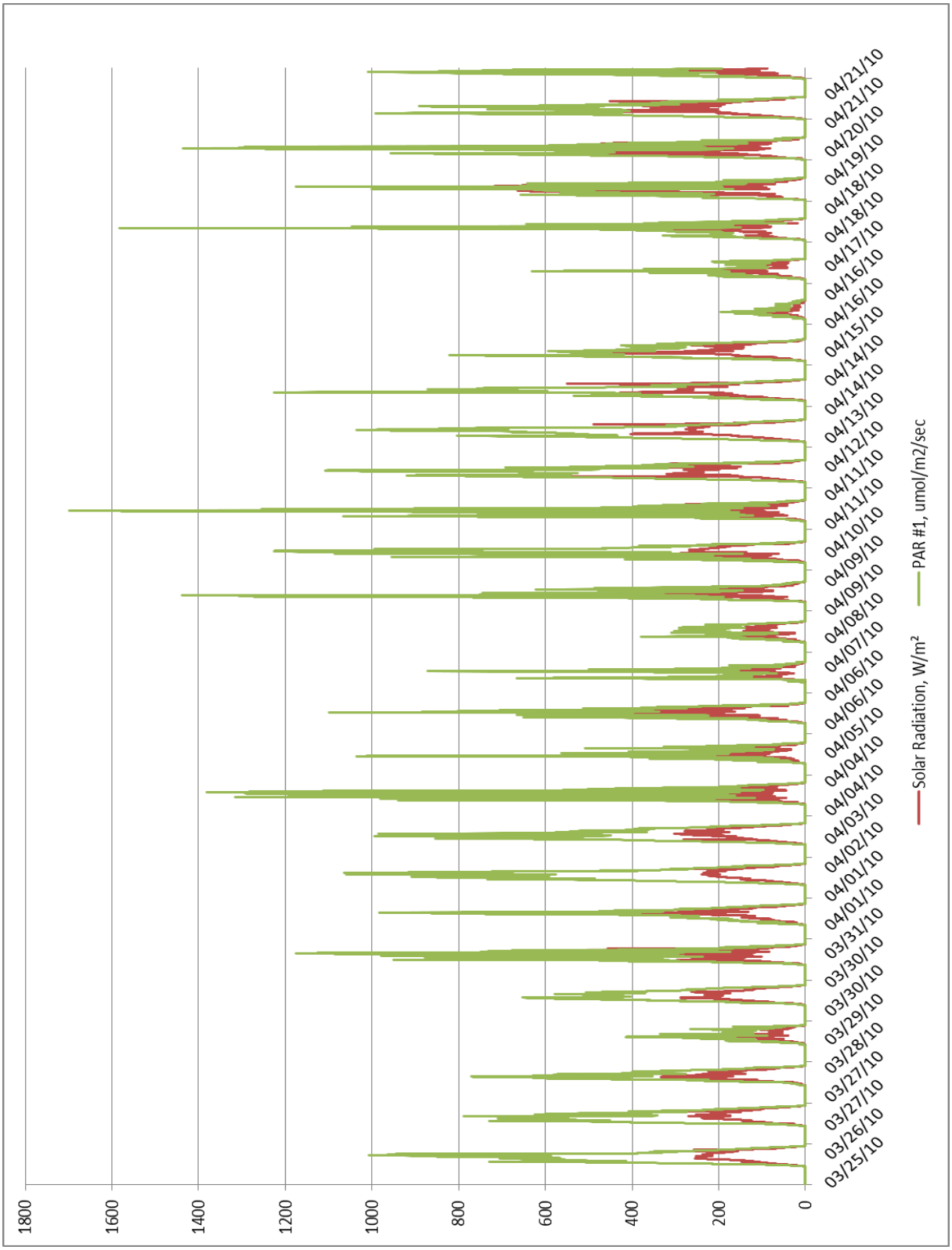


Figure D9: [John - plot 3] - Control Historical Radiation Data.
Radiation data over four weeks for the control (no additional artificial light) treatment during the second experiment replication. Solar radiation in watts per squared meters; Photosynthetically Active Radiation in micro-moles per meter^{2}per second.

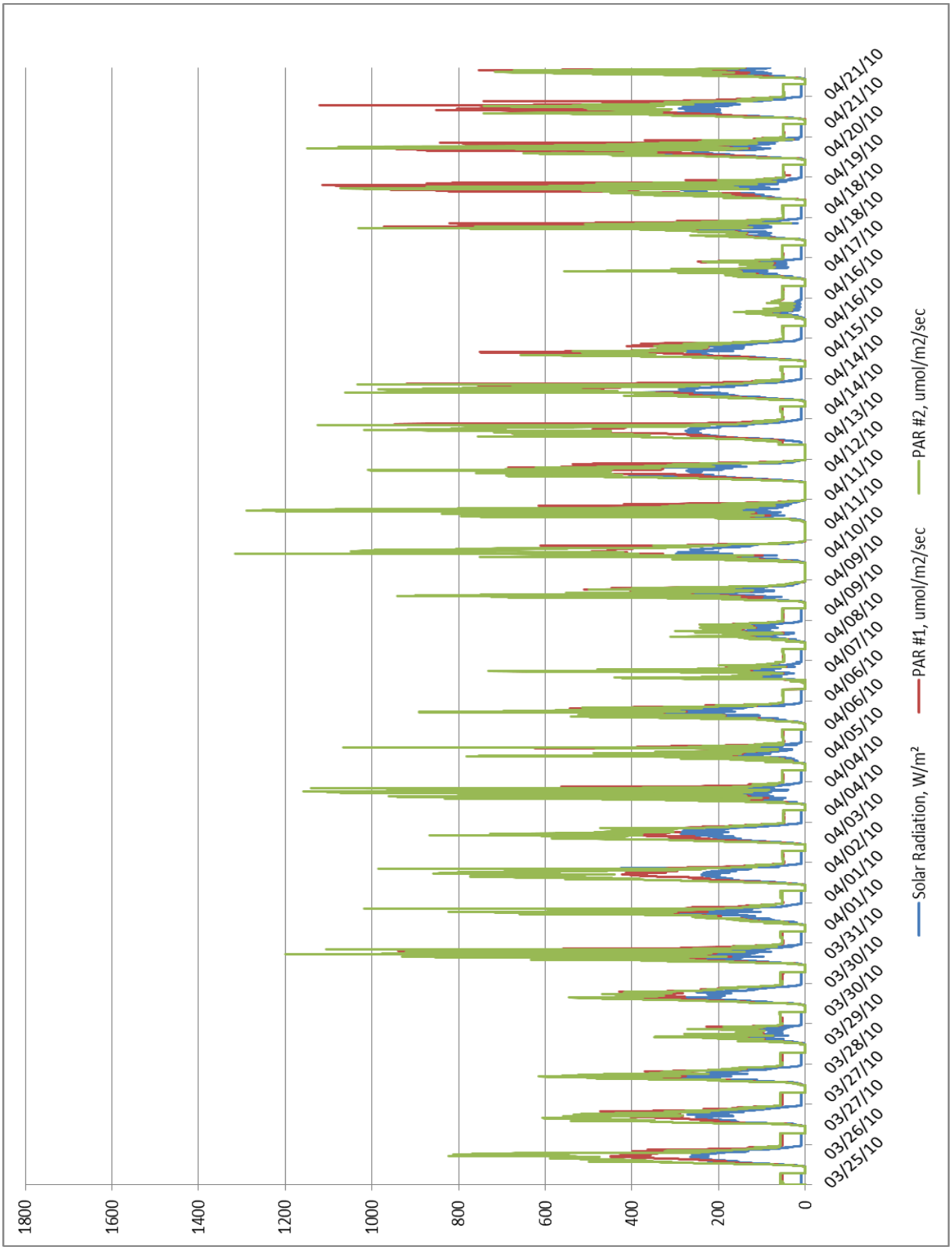


Figure D10: [Herbie - plot 4] - LED far Historical Radiation Data.
Radiation data over four weeks for second light emitting diode light treatment replication during the second experiment replication. Solar radiation in watts per squared meters; Photosynthetically Active Radiation in micro-moles per meter^{2}per second.

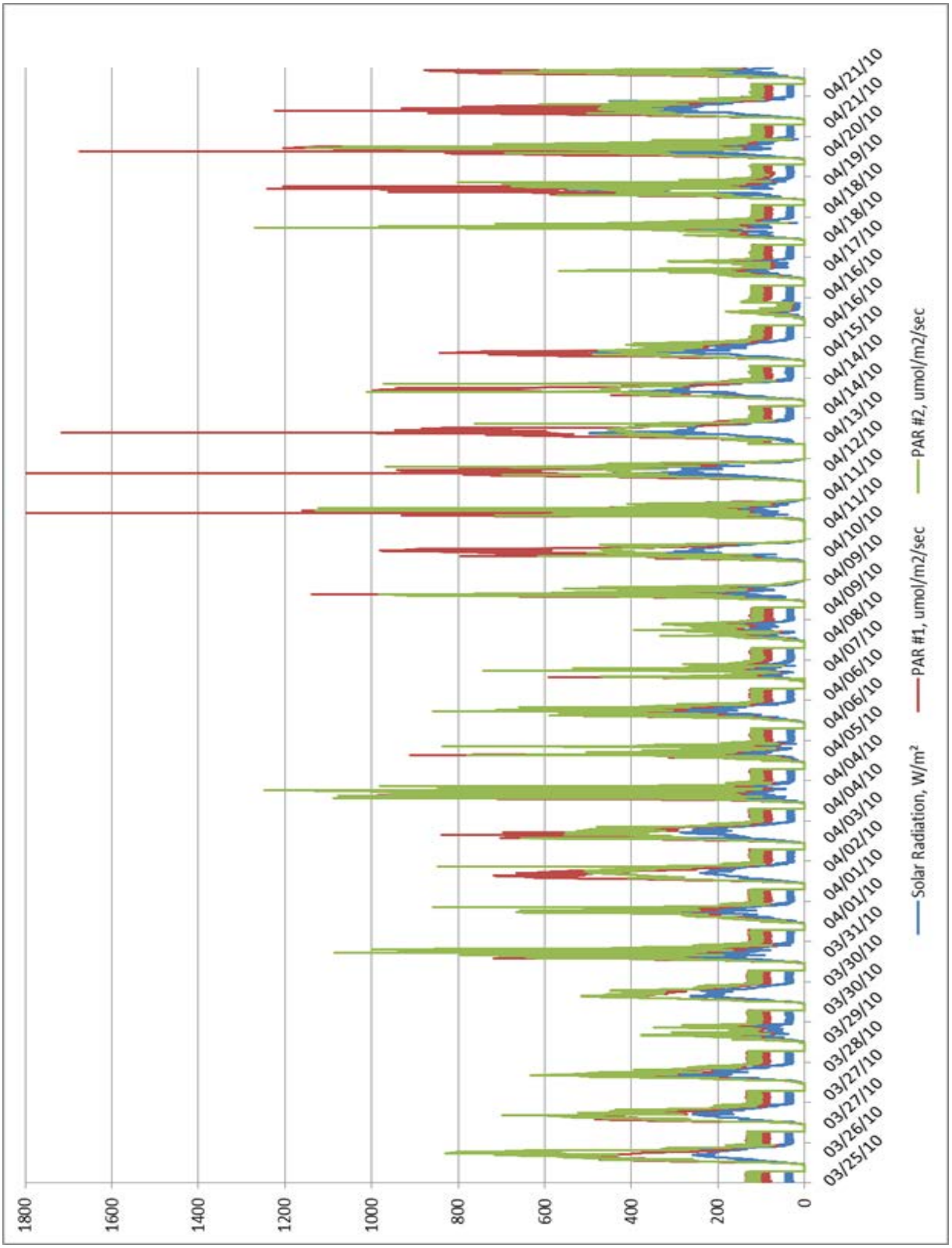


Figure D11: [Aretha - plot 5] - HPS far Historical Radiation Data.
Radiation data over four weeks for second high pressure sodium light treatment replication during the second experiment replication. Solar radiation in watts per squared meters; Photosynthetically Active Radiation in micro-moles per meter^{2}per second.

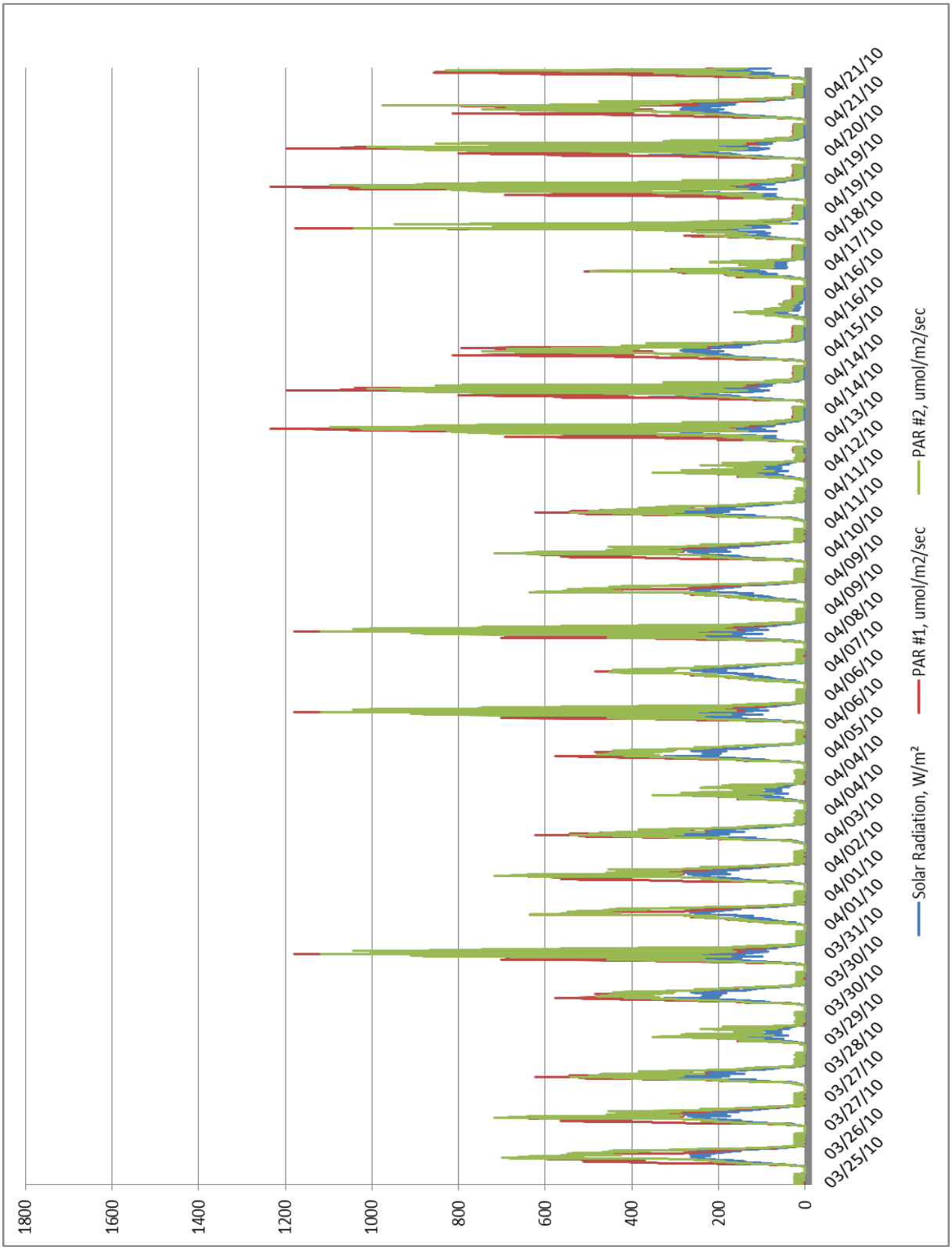


Figure D12: [Ella+Louis - plot 6] - Regular Historical Radiation Data.
Radiation data over four weeks for the regular high pressure sodium light treatment during the second experiment replication. Solar radiation in watts per squared meters; Photosynthetically Active Radiation in micro-moles per meter^{2}per second.

-Annex E

Statistically significant (p=0.05) aspects and interactions

-Overall dataset for plant masses:
Overall masses - wet: run * week
Overall masses - dry: week

-Separated by runs:
1st run only – wet: week
1st run only – dry: light * replication * week

2nd run only – wet: week, week*light
2nd run only – dry: week

-Separated by runs, then light treatments:
1st run – LED only – wet: week
1st run – LED only – dry: week

1st run – HPS only – wet: week
1st run – HPS only – dry: week, week*replication

1st run – Control only – wet: week
1st run – Control only – dry: week

1st run – Regular only – wet: week
1st run – Regular only – dry: week

2nd run – LED only – wet: week
2nd run – LED only – dry: week

2nd run – HPS only – wet: week
2nd run – HPS only – dry: week

2nd run – Control only – wet: week
2nd run – Control only – dry: week

2nd run – Regular only – wet: week
2nd run – Regular only – dry: week

-Separated by weeks
1st week only – wet: run
1st week only – dry: none

2nd week only – wet: run*light*replication

2nd week only – dry: run

3rd week only – wet: run
3rd week only – dry: run

4th week only – wet: run
4th week only – dry: no interactions

-LED versus HPS light treatment over both runs and both replication:
Wet: no interactions
Dry: week

LED versus HPS light treatment over 1st run and both replication:
Wet: week
Dry: week*light*replication

LED versus HPS light treatment over 2nd run and both replication:
Wet: week, week*light
Dry: week

-Overall dataset for light maps:
Total: light, light*time, light*time*replication

-Separated by runs only:
1st run only: light*replication

2nd run only: light, replication

3rd run only: light

-Separated by light treatments over all runs

LED only: time, replication

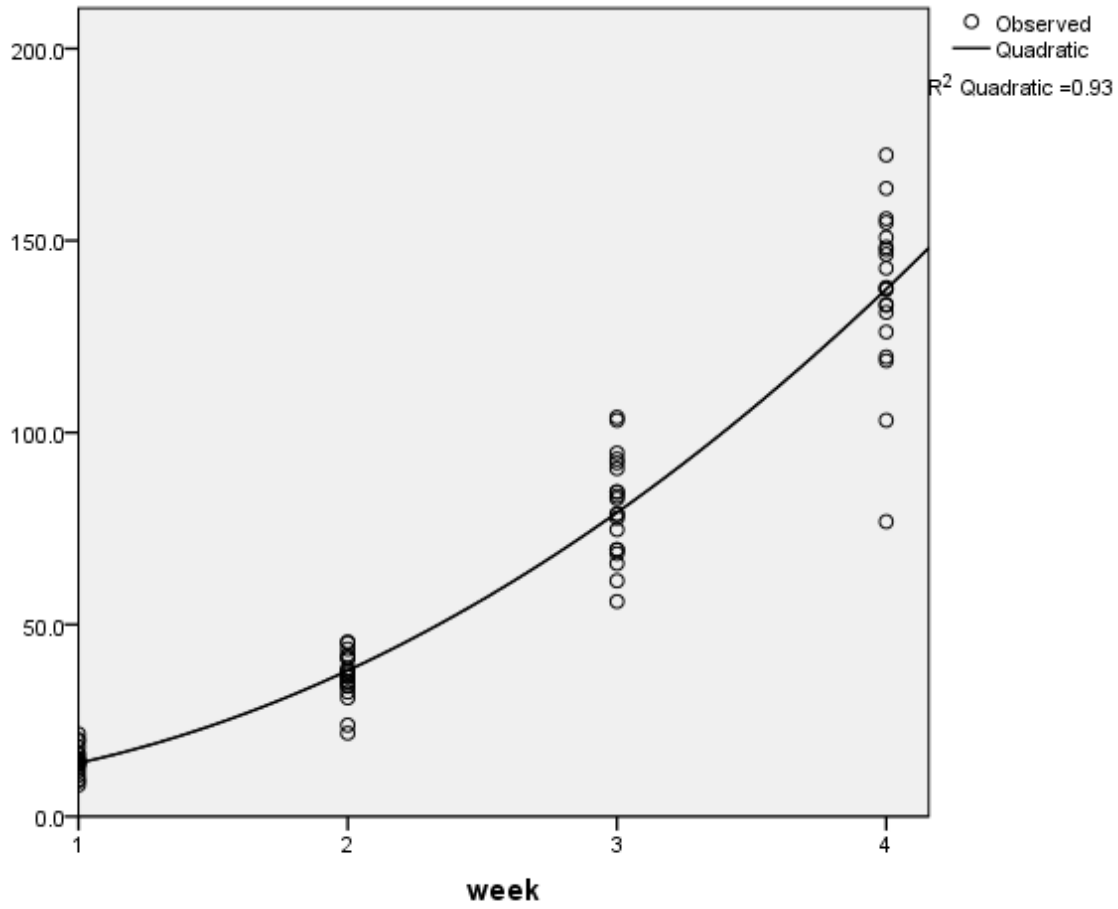
HPS only: time*replication

Control only: time

Regular only: time

-Annex F

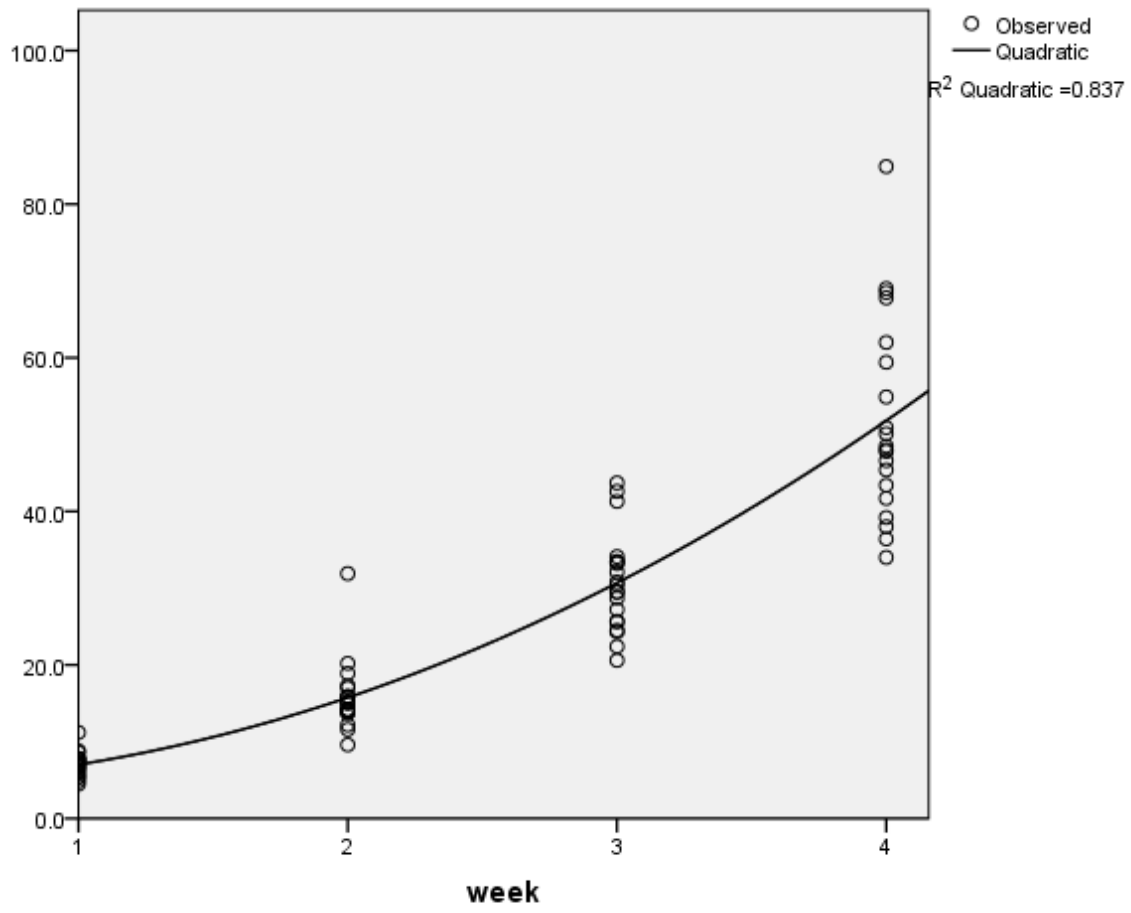
Curve fits for wet plant growth cycle



Model Summary and Parameter Estimates								
Equation			Model Summary				Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1	b2
Quadratic	0.93	512.622	2	77	0	6.866	-1.47	8.524

Figure F1: Quadratic Curve Fit Of Wet Masses Versus Sampling Weeks For LED Light Treatment – 1st Replication.

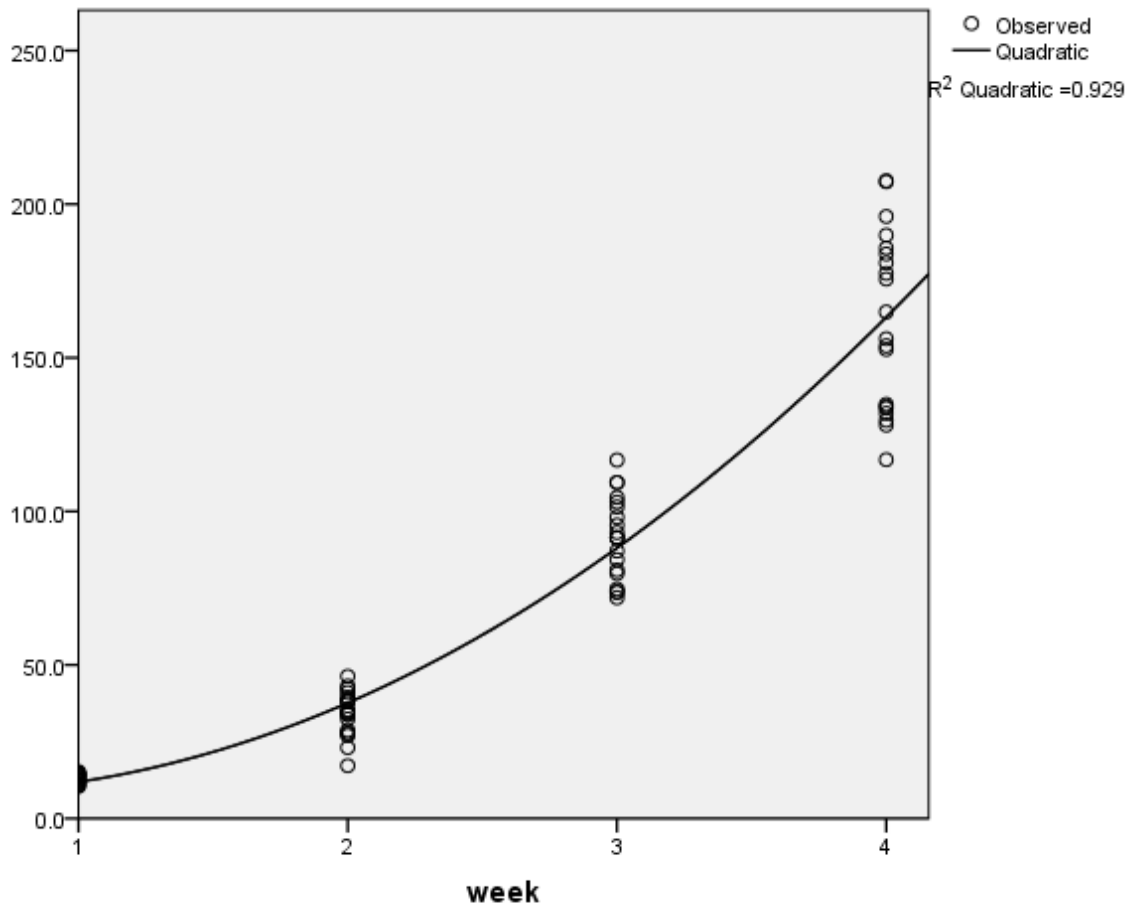
Quadratic curve fit for wet masses under LED light treatment with table describing the parameters of the quadratic equation.



Model Summary and Parameter Estimates								
Equation			Model Summary				Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1	b2
Quadratic	0.837	197.63	2	77	0	4.51	-0.584	3.103

Figure F2: Quadratic Curve Fit Of Wet Masses Versus Sampling Weeks For LED Light Treatment – 2nd Replication.

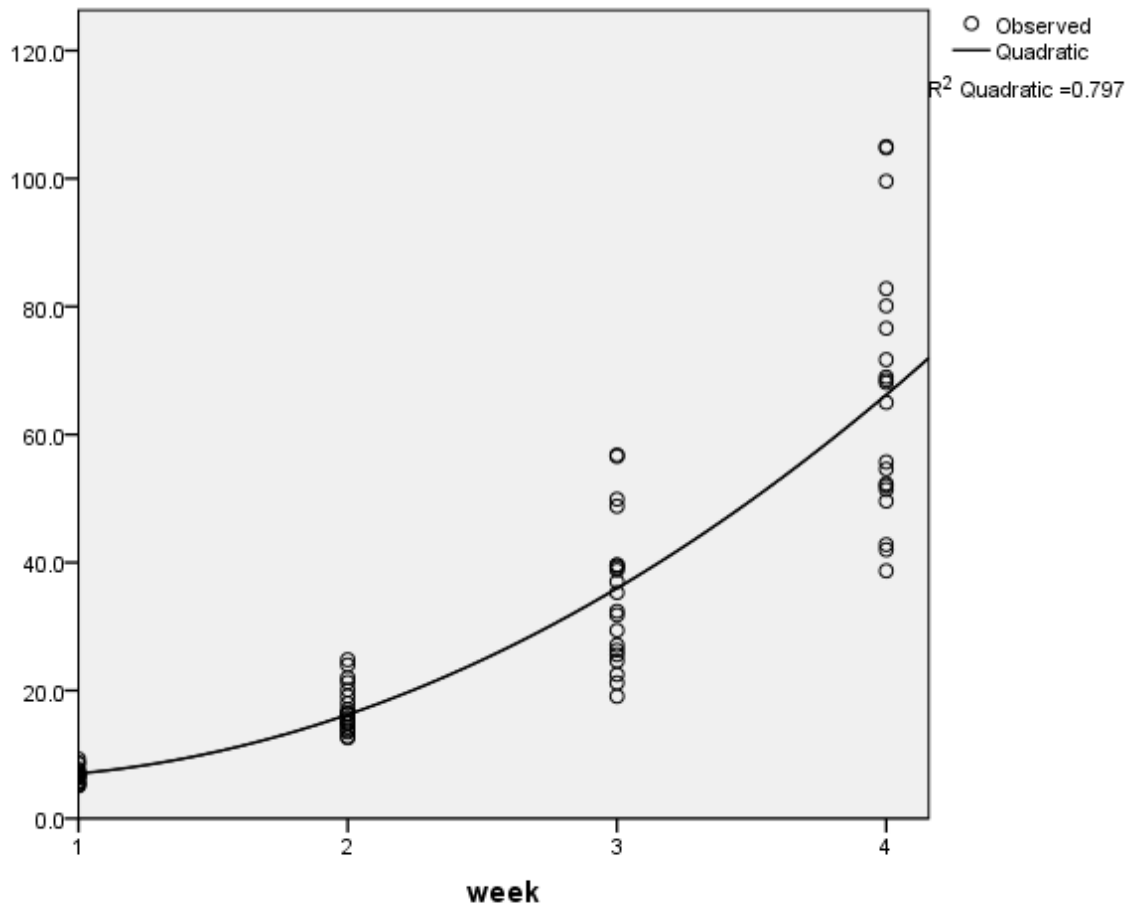
Quadratic curve fit for wet masses under LED light treatment with table describing the parameters of the quadratic equation.



Model Summary and Parameter Estimates								
Equation			Model Summary				Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1	b2
Quadratic	0.929	500.949	2	77	0	10.847	-11.29	12.35

Figure F3: Quadratic Curve Fit Of Wet Masses Versus Sampling Weeks For HPS Light Treatment – 1st Replication.

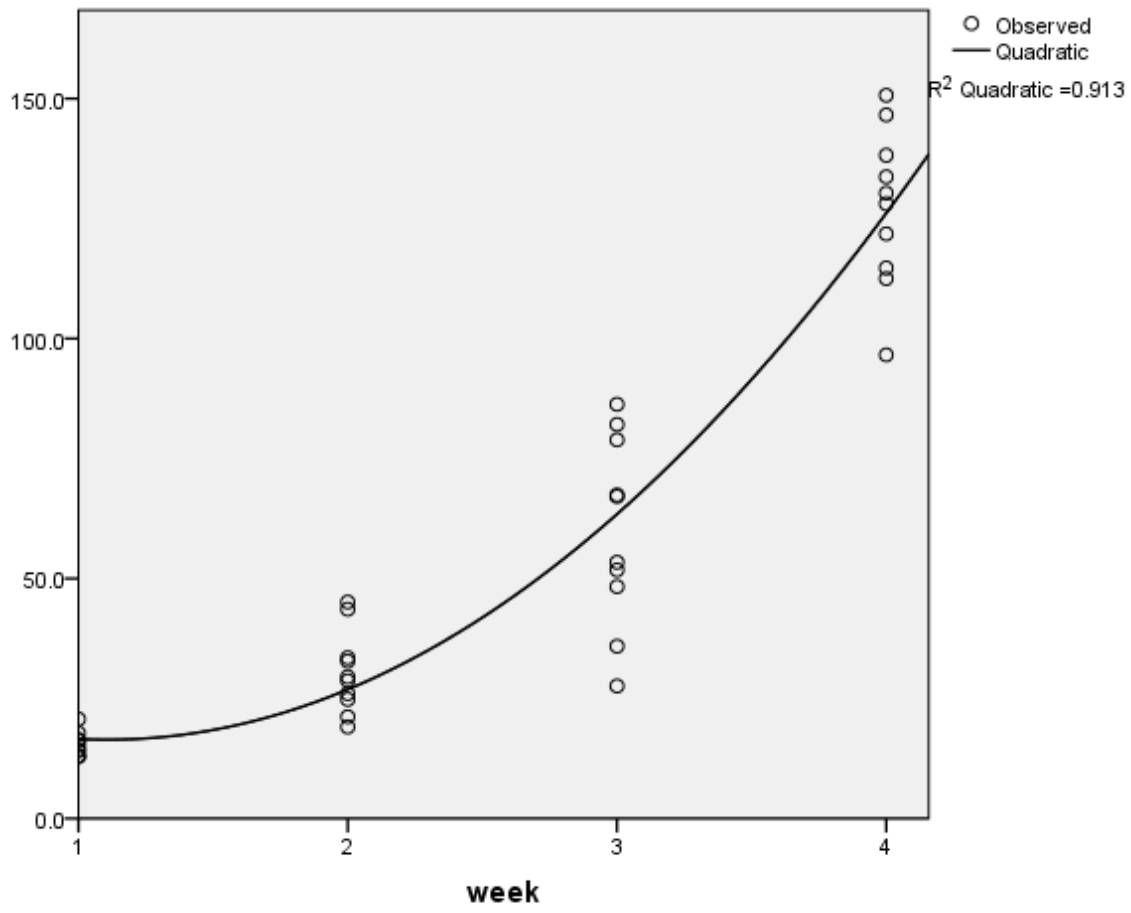
Quadratic curve fit for wet masses under HPS light treatment with table describing the parameters of the quadratic equation.



Model Summary and Parameter Estimates								
Equation			Model Summary				Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1	b2
Quadratic	0.797	151.019	2	77	0	8.339	-6.565	5.259

Figure F4: Quadratic Curve Fit Of Wet Masses Versus Sampling Weeks For HPS Light Treatment – 2nd Replication.

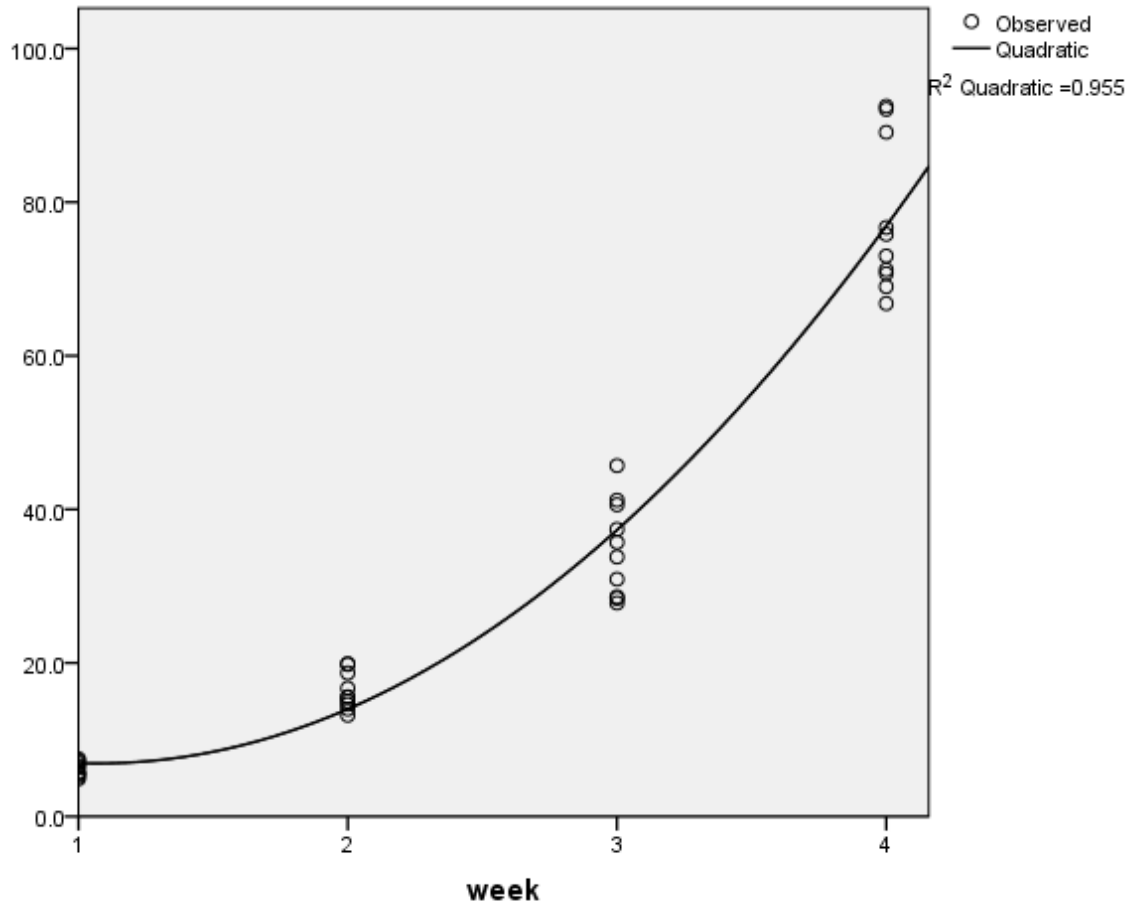
Quadratic curve fit for wet masses under HPS light treatment with table describing the parameters of the quadratic equation.



Model Summary and Parameter Estimates								
Equation			Model Summary				Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1	b2
Quadratic	0.913	195.336	2	37	0	32.445	-28.976	13.1

Figure F5: Quadratic Curve Fit Of Wet Masses Versus Sampling Weeks For Regular HPS Light Treatment – 1st Replication.

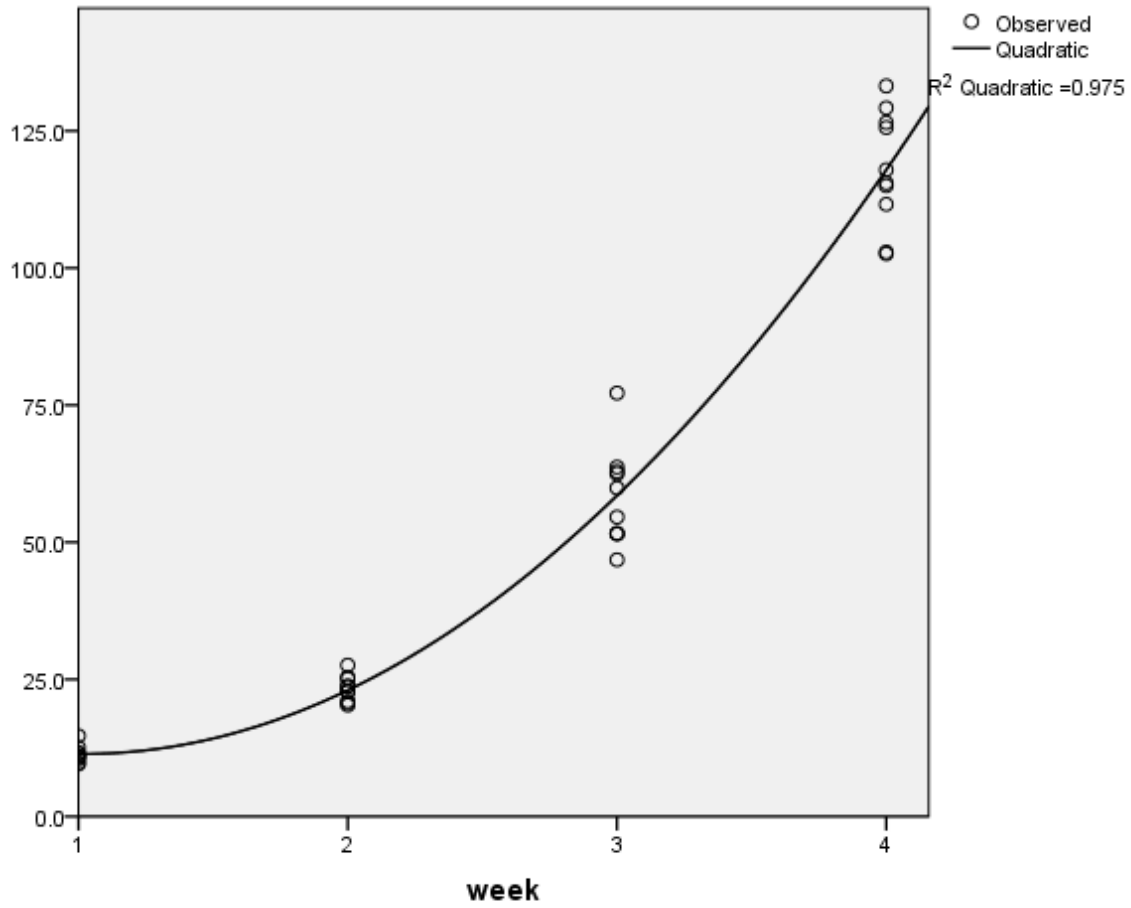
Quadratic curve fit for wet masses under regular HPS light treatment with table describing the parameters of the quadratic equation.



Model Summary and Parameter Estimates								
Equation			Model Summary				Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1	b2
Quadratic	0.955	396.899	2	37	0	16.185	-17.376	8.14

Figure F6: Quadratic Curve Fit Of Wet Masses Versus Sampling Weeks For Regular HPS Light Treatment – 2nd Replication.

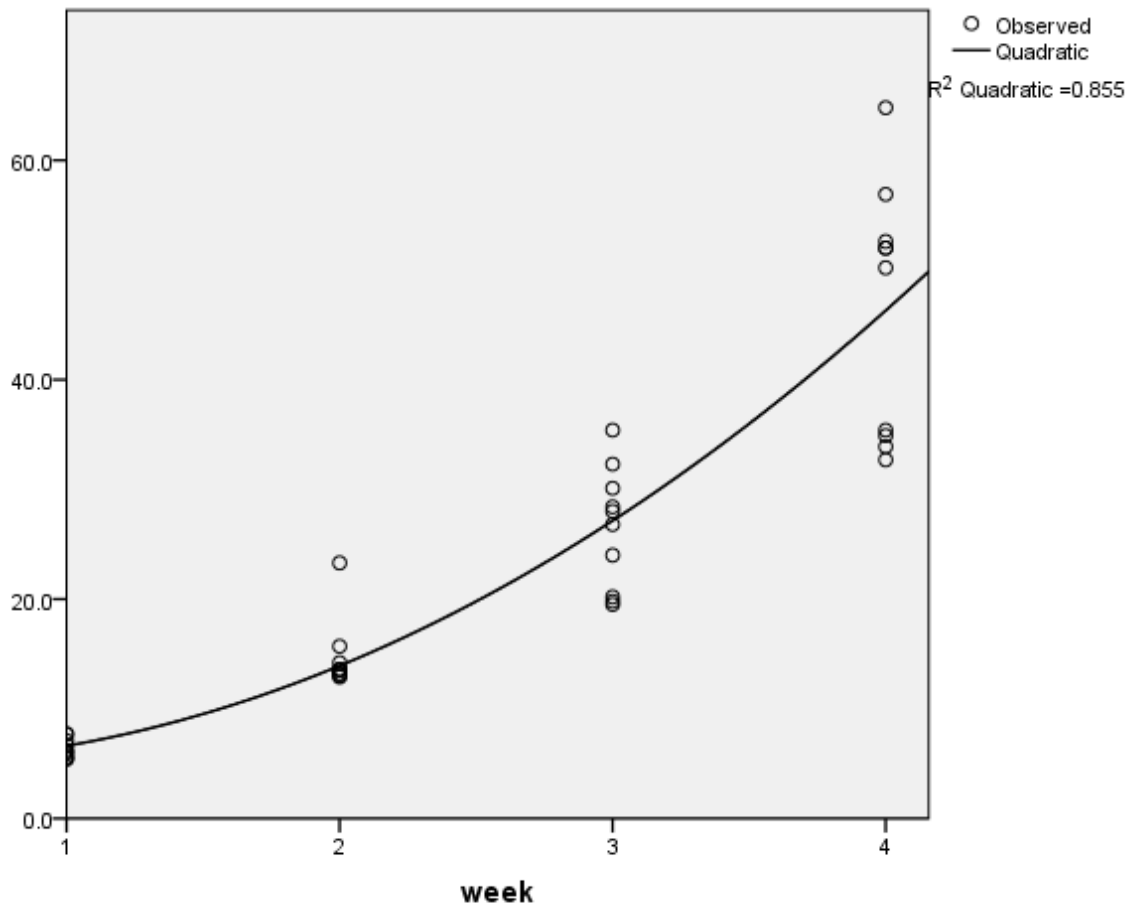
Quadratic curve fit for wet masses under regular HPS light treatment with table describing the parameters of the quadratic equation.



Model Summary and Parameter Estimates								
Equation			Model Summary				Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1	b2
Quadratic	0.975	711.299	2	37	0	23.677	-24.213	11.94

Figure F7: Quadratic Curve Fit Of Wet Masses Versus Sampling Weeks For Control Light Treatment – 1st Replication.

Quadratic curve fit for wet masses under control light treatment with table describing the parameters of the quadratic equation.



Model Summary and Parameter Estimates								
Equation			Model Summary				Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1	b2
Quadratic	0.855	109.308	2	37	0	5.255	-1.597	2.965

Figure F8: Quadratic Curve Fit Of Wet Masses Versus Sampling Weeks For Control Light Treatment – 2nd Replication.

Quadratic curve fit for wet masses under control light treatment with table describing the parameters of the quadratic equation.

-Annex G

Tables of wet and dry ratio of plant mass versus irradiation

Table G1: Ratio of Plant Mass versus Artificial Light per meter^2.
Wet and dry plant mass in grams versus artificial light in moles per meter2.

Supplemental light only	wet ratio	dry ratio	supl light/total light
	grams/moles of light/m2		percentage
HPS near - run 1	2.31	0.12	22.7%
HPS far - run 1	2.15	0.09	19.6%
HPS average - run 1	2.23	0.10	21.1%
HPS near - run 2	1.13	0.09	21.7%
HPS far - run 2	0.83	0.05	20.1%
HPS average - run 2	0.98	0.07	20.9%
LED near - run 1	4.70	0.26	10.9%
LED far - run 1	3.67	0.19	10.7%
LED average - run 1	4.19	0.22	10.8%
LED near - run 2	1.27	0.10	11.6%
LED far - run 2	1.14	0.08	12.0%
LED average - run 2	1.21	0.09	11.8%
Regular - run 1	10.04	0.56	4.8%
Regular - run 2	6.02	0.33	4.2%
Control - run 1	120.23	6.22	0.3%
Control - run 2	11.41	0.85	1.1%

Table G2: Ratio of Plant Mass versus Artificial Light per plant.
Wet and dry plant mass in grams versus artificial light in moles per plant.

Supplemental light only	wet ratio	dry ratio	supl light/total light
	grams/moles of light/plant		percentage
HPS near - run 1	55.91	2.88	22.7%
HPS far - run 1	52.08	2.19	19.6%
HPS average - run 1	53.99	2.53	21.1%
HPS near - run 2	27.30	2.09	21.7%
HPS far - run 2	20.02	1.30	20.1%
HPS average - run 2	23.66	1.70	20.9%
LED near - run 1	113.90	6.24	10.9%
LED far - run 1	89.07	4.60	10.7%
LED average - run 1	101.48	5.42	10.8%
LED near - run 2	30.87	2.37	11.6%
LED far - run 2	27.66	2.05	12.0%
LED average - run 2	29.26	2.21	11.8%
Regular - run 1	243.46	13.61	4.8%
Regular - run 2	145.86	8.04	4.2%
Control - run 1	2914.15	150.65	0.3%
Control - run 2	276.62	20.51	1.1%

-Annex H

Energy Data Tables

Table H1: Energy Measurements Table.
Current (amps, A), voltage (volts, V) and power (watts, W) readings over forty minutes for HPS and LED lamps.

HPS 1			
Time	Current	Voltage	Power
minute	amp	volt	watt
0	1.5	343	510.7
5		343	
10		343	
15	1.9	343	666.4
20	2.0	343	668.9
25	2.0	343	670.6
30	1.9	343	667.8
35	1.9	343	667.1
40	1.9	343	667.5

LED 1			
Time	Current	Voltage	Power
minute	amp	volt	watt
0	1.7	189	318.4
5	1.7	190	317.9
10	1.7	190	317.5
15	1.7	190	317.9
20	1.7	190	317.5
25	1.7	190	317.8
30	1.7	190	317.5
35	1.7	190	317.7
40	1.7	190	317.5

HPS 2			
Time	Current	Voltage	Power
minute	amp	volt	watt
0	1.5	345	505.8
5	1.6	345	536.8
10	1.7	345	577.9
15	1.9	345	646.9
20	1.9	345	648.3
25	1.9	345	648.9
30	1.9	345	641.7
35	1.9	345	645.2
40	1.9	345	645.5

LED 2			
Time	Current	Voltage	Power
minute	amp	volt	watt
0			
5			
10			
15			
20			
25			
30			
35			
40	1.7	190	322.2

HPS 3			
Time	Current	Voltage	Power
minute	amp	volt	watt
0	1.5	343	510.0
5	1.6	343	533.7
10	1.6	343	559.8
15	1.8	343	632.1
20	1.9	343	637.0
25	1.9	343	639.0
30	1.9	343	641.1
35	1.9	343	639.7
40	1.9	343	640.0

HPS 4			
Time	Current	Voltage	Power
minute	amp	volt	watt
0	1.5	345	507.8
5	1.6	345	558.9
10	1.7	345	583.4
15	1.9	345	638.6
20	1.9	345	640.3
25	1.9	345	641.4
30	1.9	345	640.3
35	1.9	345	640.7
40	1.9	345	642.4

-Annex I

Phytochemicals Tables

Table I1: Regular Light Treatment Phytochemicals Data Table
Concentrations of phytochemicals for both replications of regular light treatment on plot 3 and 6.

		Actual Recovered	Freeze dry				% dry freeze	Recovery
Treatment	Rep	mg/100 gfw	fresh mass	dry mass	% moisture	Factor		Factor
R1	antheraxanthin	3.33	22.1	1.4	71.43	1.24	6.33	0.59
R2	antheraxanthin	2.43	23.8	1.4	71.43	1.24	5.88	0.75
R1	B-carotene	5.53	22.1	1.4	71.43	1.24	6.33	0.59
R2	B-carotene	4.33	23.8	1.4	71.43	1.24	5.88	0.75
R1	chlorophyll A	16.03	22.1	1.4	71.43	1.24	6.33	0.59
R2	chlorophyll A	12.32	23.8	1.4	71.43	1.24	5.88	0.75
R1	chlorophyll B	12.74	22.1	1.4	71.43	1.24	6.33	0.59
R2	chlorophyll B	9.74	23.8	1.4	71.43	1.24	5.88	0.75
R1	lutein	6.83	22.1	1.4	71.43	1.24	6.33	0.59
R2	lutein	5.40	23.8	1.4	71.43	1.24	5.88	0.75
R1	neoxantin	1.84	22.1	1.4	71.43	1.24	6.33	0.59
R2	neoxantin	1.89	23.8	1.4	71.43	1.24	5.88	0.75
R1	violaxanthin	3.77	22.1	1.4	71.43	1.24	6.33	0.59
R2	violaxanthin	3.56	23.8	1.4	71.43	1.24	5.88	0.75

Table I2: LED Near Light Treatment Phytochemicals Data Table
Concentrations of phytochemicals for both replications of light emitting diode light treatment on plot 2.

		Actual Recovered	Freeze dry				% dry freeze	Recovery
Treatment	Rep	mg/100 gfw	fresh mass	dry mass	% moisture	Factor		Factor
LEDN1	antheraxanthin	2.95	20.4	1.1	90.91	1.05	5.39	0.77
LEDN2	antheraxanthin	1.10	24.5	1.9	52.63	1.43	7.76	0.95
LEDN1	B-carotene	3.90	20.4	1.1	90.91	1.05	5.39	0.77
LEDN2	B-carotene	1.59	24.5	1.9	52.63	1.43	7.76	0.95
LEDN1	chlorophyll A	13.62	20.4	1.1	90.91	1.05	5.39	0.77
LEDN2	chlorophyll A	4.07	24.5	1.9	52.63	1.43	7.76	0.95
LEDN1	chlorophyll B	11.72	20.4	1.1	90.91	1.05	5.39	0.77
LEDN2	chlorophyll B	3.02	24.5	1.9	52.63	1.43	7.76	0.95
LEDN1	lutein	5.80	20.4	1.1	90.91	1.05	5.39	0.77
LEDN2	lutein	2.01	24.5	1.9	52.63	1.43	7.76	0.95
LEDN1	neoxantin	1.88	20.4	1.1	90.91	1.05	5.39	0.77
LEDN2	neoxantin	0.50	24.5	1.9	52.63	1.43	7.76	0.95
LEDN1	violaxanthin	2.78	20.4	1.1	90.91	1.05	5.39	0.77
LEDN2	violaxanthin	1.19	24.5	1.9	52.63	1.43	7.76	0.95

Table I3: LED Far Light Treatment Phytochemicals Data Table
Concentrations of phytochemicals for both replications of light emitting diode light treatment on plot 4.

		Actual Recovered	Freeze dry				% dry freeze	Recovery
Treatment	Rep	mg/100 gfw	fresh mass	dry mass	% moisture	Factor		Factor
LEDF1	antheraxanthin	2.71	22.4	1.3	76.92	1.19	5.80	0.76
LEDF2	antheraxanthin	2.13	23.8	1.8	55.56	1.40	7.56	0.91
LEDF1	B-carotene	4.69	22.4	1.3	76.92	1.19	5.80	0.76
LEDF2	B-carotene	3.15	23.8	1.8	55.56	1.40	7.56	0.91
LEDF1	chlorophyll A	13.95	22.4	1.3	76.92	1.19	5.80	0.76
LEDF2	chlorophyll A	9.31	23.8	1.8	55.56	1.40	7.56	0.91
LEDF1	chlorophyll B	11.00	22.4	1.3	76.92	1.19	5.80	0.76
LEDF2	chlorophyll B	6.75	23.8	1.8	55.56	1.40	7.56	0.91
LEDF1	lutein	5.58	22.4	1.3	76.92	1.19	5.80	0.76
LEDF2	lutein	4.06	23.8	1.8	55.56	1.40	7.56	0.91
LEDF1	neoxantin	1.67	22.4	1.3	76.92	1.19	5.80	0.76
LEDF2	neoxantin	1.25	23.8	1.8	55.56	1.40	7.56	0.91
LEDF1	violaxanthin	2.91	22.4	1.3	76.92	1.19	5.80	0.76
LEDF2	violaxanthin	2.02	23.8	1.8	55.56	1.40	7.56	0.91

Table I4: HPS Near Light Treatment Phytochemicals Data Table
Concentrations of phytochemicals for both replications of high pressure sodium light treatment on plot 1.

		Actual Recovered	Freeze dry				% dry freeze	Recovery
Treatment	Rep	mg/100 gfw	fresh mass	dry mass	% moisture	Factor		Factor
HPSN1	antheraxanthin	2.03	21.5	1.1	90.91	1.05	5.12	0.71
HPSN2	antheraxanthin	3.17	24.2	1.6	62.50	1.33	6.61	0.81
HPSN1	B-carotene	3.13	21.5	1.1	90.91	1.05	5.12	0.71
HPSN2	B-carotene	4.85	24.2	1.6	62.50	1.33	6.61	0.81
HPSN1	chlorophyll A	9.82	21.5	1.1	90.91	1.05	5.12	0.71
HPSN2	chlorophyll A	14.42	24.2	1.6	62.50	1.33	6.61	0.81
HPSN1	chlorophyll B	8.32	21.5	1.1	90.91	1.05	5.12	0.71
HPSN2	chlorophyll B	11.38	24.2	1.6	62.50	1.33	6.61	0.81
HPSN1	lutein	4.01	21.5	1.1	90.91	1.05	5.12	0.71
HPSN2	lutein	6.43	24.2	1.6	62.50	1.33	6.61	0.81
HPSN1	neoxantin	1.10	21.5	1.1	90.91	1.05	5.12	0.71
HPSN2	neoxantin	2.23	24.2	1.6	62.50	1.33	6.61	0.81
HPSN1	violaxanthin	2.15	21.5	1.1	90.91	1.05	5.12	0.71
HPSN2	violaxanthin	3.39	24.2	1.6	62.50	1.33	6.61	0.81

Table I5: HPS Far Light Treatment Phytochemicals Data Table
Concentrations of phytochemicals for both replications of high pressure sodium light treatment on plot 5.

		Actual Recovered	Freeze dry				% dry freeze	Recovery
Treatment	Rep	mg/100 gfw	fresh mass	dry mass	% moisture	Factor		Factor
HPSF1	antheraxanthin	3.15	22.2	1.2	83.33	1.12	5.41	0.74
HPSF2	antheraxanthin	1.78	24.8	1.9	52.63	1.43	7.66	0.79
HPSF1	B-carotene	4.74	22.2	1.2	83.33	1.12	5.41	0.74
HPSF2	B-carotene	3.53	24.8	1.9	52.63	1.43	7.66	0.79
HPSF1	chlorophyll A	15.08	22.2	1.2	83.33	1.12	5.41	0.74
HPSF2	chlorophyll A	9.82	24.8	1.9	52.63	1.43	7.66	0.79
HPSF1	chlorophyll B	11.88	22.2	1.2	83.33	1.12	5.41	0.74
HPSF2	chlorophyll B	6.85	24.8	1.9	52.63	1.43	7.66	0.79
HPSF1	lutein	6.33	22.2	1.2	83.33	1.12	5.41	0.74
HPSF2	lutein	3.85	24.8	1.9	52.63	1.43	7.66	0.79
HPSF1	neoxantin	1.91	22.2	1.2	83.33	1.12	5.41	0.74
HPSF2	neoxantin	1.20	24.8	1.9	52.63	1.43	7.66	0.79
HPSF1	violaxanthin	3.76	22.2	1.2	83.33	1.12	5.41	0.74
HPSF2	violaxanthin	2.94	24.8	1.9	52.63	1.43	7.66	0.79

Table I6: Control Light Treatment Phytochemicals Data Table
Concentrations of phytochemicals for both replications of control light treatment on plot 3 and 6.

		Actual Recovered	Freeze dry				% dry freeze	Recovery
Treatment	Rep	mg/100 gfw	fresh mass	dry mass	% moisture	Factor		Factor
C1	antheraxanthin	3.44	21.4	1.7	58.82	1.37	7.94	0.71
C2	antheraxanthin	3.10	24.1	1.7	58.82	1.37	7.05	0.78
C1	B-carotene	5.77	21.4	1.7	58.82	1.37	7.94	0.71
C2	B-carotene	5.29	24.1	1.7	58.82	1.37	7.05	0.78
C1	chlorophyll A	16.47	21.4	1.7	58.82	1.37	7.94	0.71
C2	chlorophyll A	15.94	24.1	1.7	58.82	1.37	7.05	0.78
C1	chlorophyll B	12.66	21.4	1.7	58.82	1.37	7.94	0.71
C2	chlorophyll B	11.92	24.1	1.7	58.82	1.37	7.05	0.78
C1	lutein	6.92	21.4	1.7	58.82	1.37	7.94	0.71
C2	lutein	6.88	24.1	1.7	58.82	1.37	7.05	0.78
C1	neoxantin	1.88	21.4	1.7	58.82	1.37	7.94	0.71
C2	neoxantin	2.29	24.1	1.7	58.82	1.37	7.05	0.78
C1	violaxanthin	4.50	21.4	1.7	58.82	1.37	7.94	0.71
C2	violaxanthin	4.28	24.1	1.7	58.82	1.37	7.05	0.78