UNIVERSITY of GUELPH

Ontario Agricultural College
Department of Horticultural Science
Guelph, Ontario CANADA
N1G 2W1
Tel. (519) 824-4120
Fax. (519) 767-0755

MELiSSA

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Culture Strategies for Higher Plants in Closed Systems

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Cloutier G., Dixon M.A.

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CULTURE STRATEGIES FOR HIGHER PLANTS IN CLOSED SYSTEMS

1 - INTRODUCTION

1.1 - The Role of Higher Plants in Advanced Life Support Systems

Advanced Life Support (ALS) systems are meant to minimize the enormous expenses associated with the resupply of life support elements during long term manned space missions. In the late 1950s and early 1960s, ALS research conducted by the U.S. and U.S.S.R. emphasized the development of continuous production micro-algal systems because of their volume efficiency and ability to produce protein-rich biomass and oxygen. However, such systems were deemed to be inadequate since they were not capable of producing the variety of foods necessary to provide crew with a palatable and nutritious diet. As a result, in the late 1960s and early 1970s research came to embody the idea that higher plants could be coupled with algal systems to more completely address the issue of diet. Furthermore, it was realized that higher plants could also contribute to a number of other ALS issues, including atmosphere, water and waste management and those related to the habitability of a manned outpost (medical, psychological comfort).

The role of higher plants in life support and habitability is summarized by Tamponnet (1993). This summary is reproduced here, with minor modification, for the reader's convenience.

ECLS & HABITATION AREAS	ROLE OF HIGHER PLANTS
Atmospheric Management System	
Total pressure composition and control	
N_2	Leguminous plants transform N_2 to NH_3
O_2	Production of O_2 from H_2O
CO_2	Consumption of CO_2 to produce $(CH_2O)_n$
H_2O	Transpiration (latent heat transfer)
Contamination Control	Plant degradation of contaminants, VOC release by plants
Liquid Management System	
Water Storage	Plant capacitance
Water Recovery	Condensation of H_2O produced during transpiration
Waste Management System	
Recycling of Minerals and N	Some plants may directly absorb nutrients from waste water

ECLS & HABITATION AREAS	ROLE OF HIGHER PLANTS
Food Management System	
Food Production	Primary role of plants
Habitability	
Health	Use of some medicinal plants
Psycho Sociological Aspects	Presence of plants in crew habitat contributes to an Earth-like environment

Table 1: Roles of higher plants in different Environmental Control, Life Support (ECLS) and Habitability areas.

1.2 - The Selection of Plants for Inclusion in an Advanced Life Support System

In January 1994, a workshop entitled **Human Nutrition in Controlled Ecological Life Support Systems** was hosted by F.B. Salisbury at the Johnson Space Centre, Houston, Texas (Salisbury and Clark, 1996). This workshop was organized in response to the seemingly arbitrary nature by which candidate crops were selected for inclusion in the U.S. CELSS program. One of the concerns noted by participants of the workshop was that the choice of candidate crops was based primarily on yield potential and upon the interests and suggestions of individual investigators. The participants, therefore, drafted a preliminary list of candidate crops based on input from vegetarians and nutritionists. The list contains a variety of crops selected for not only their yield potential, but their contribution to a more nutritionally complete menu and psychological value. Candidate crops included wheat, rice, sweet potato, broccoli, kale, lettuce, carrot, rape seed, soybean, peanut, chickpea, lentil, tomato, onion and chilie (Salisbury and Clark, 1996).

Tamponnet (1993) summarizes the selection factors for drafting a list of candidate crops for future ESA research initiatives in life support. These factors include;

- crop nutritional value
- crop harvest index (food productivity)
- crop effectiveness in air and water recycling
- crop range of environmental tolerance (ensure flexibility in multiple cropping scenarios) and,
- other criteria [see Tamponnet (1993)]

From this list of factors, a preliminary set of ESA candidate crops has been drafted. This set includes, potato, wheat, rice, spinach, lettuce, soybean, onion and tomato.

The final list of selected crops will need to address the life support functions listed in Table 1 and, more specifically, meet the criteria outlined by Tamponnet (1993). Given the breadth to the identified roles of higher plant function in ALS systems and the need to provide as nutritionally complete a menu as possible, this resulting list is likely to be extensive. A limited vegan diet consisting of ten crops is expected to represent the minimum size needed to meet crew nutritional requirements alone (Saha and Trumbo, 1996). As such, ALS engineers need to examine various cultural strategies in order to minimize ALS system size while accommodating the wide array of selected crop types.

1.3 - ALS Mass Constraint and its Influence on Cultural Management

An interesting study by Drysdale *et al* (1994) serves to illustrate the impact of multiple crop production on system mass and energy requirements. Using only lettuce, potato, soybean and wheat, and assuming crop production rates equal to the best published data, an array of biomass production units was drafted for an early lunar base meeting the nutritional requirements of a crew of four. In total, eleven separate biomass production areas were required to accommodate differences in cultural management among the four crops and differences in cultural management throughout crop development for each specific crop (ie: each crop and growth stage was assigned a separate biomass production area). These eleven units had a total area of 73 m^2, and a mass equivalency of 39 000 Kg (Drysdale *et al*, 1992; Drysdale *et al*, 1994).

Since it is clear that a production set consisting of only four crops is inadequate, the enormous system size and mass required to accommodate the individual cultural requirements of, say, ten, crops and their various growth stages casts serious doubt on the economic efficiency of multiple crop based life support systems. However, it may be possible to rely on crop specific ranges in environmental tolerance so as to design a food production system having much less equivalent mass. To this end, the prospects of integrating a number of crops with similar cultural requirements in a single production area needs to be investigated. Furthermore, a set of management strategies needs to be devised in order to ensure that the roles identified in Table 1 are adequately met by the integrated food production system.

1.4 - Objectives of TN 40.1

The objectives of this technical note are three-fold. First, the basic physiology underlying crop cultural requirements will be discussed with reference to light, carbon dioxide, temperature, nutrient and humidity conditions. The current state of the art in lighting and nutrient delivery systems will also be discussed with reference to current research practices in ALS analogues. Secondly, specific cultural requirements for each of the eight ESA candidate crops (wheat, soybean, tomato, rice, spinach, potato, lettuce and onion) will be reviewed using literature from both controlled environment and field production research. Finally, a preliminary set of compatible crops within the ESA menu will be drafted and the prospects for integrated food production assessed. These objectives can be conveniently summarized in Table 2;

Section within TN 40.1	Subject of Section	Items Discussed
2.0	Physiology of plant culture	• radiation • carbon dioxide • temperature • humidity • nutrient delivery
	State of the art	• lighting systems • nutrient delivery systems
3.0	Crop specific cultural requirements	• soybean • wheat • rice • potato • spinach • tomato • lettuce • onion
4.0	Integrated crop production	• units of cultural compatibility • techniques of management

Table 2: Information contained in TN 40.1

2 - Basic Physiology of Plant Culture

The purpose of this section is to highlight the physiological basis of plant culture. While this discussion is by no means exhaustive it will provide the basic information necessary to understand the fundamental relationships between environmental conditions and plant growth. The role of radiation, carbon dioxide, temperature, humidity and nutrition will be discussed and, where applicable, the technical aspects of meeting plant demands in growth chambers is addressed.

2.1 - The Role of Radiation

2.11 - Light Reactions and Spectral Sensitivity

Photosynthesis is the primary process by which free energy will enter an ALS. For simplicity, photosynthesis can be regarded as three separate processes: i) the light reactions in which radiant energy is absorbed to generate the high energy compounds ATP and NADPH, ii) the 'dark' reactions whereby CO_2 is reduced to sugars using the energy produced in the light reactions and iii) the supply of CO_2 by the atmosphere to the reducing sites in chloroplasts. Issues relating to CO_2 supply and the dark reactions will be reserved for Section 2.2.

Two chloroplast bound photosystems (photosystems I and II) are responsible for harvesting radiant energy. A number of pigment molecules, including *chlorophylls a* and *b* are present in each photosystem and are sensitive to separate components of the electromagnetic spectrum (Figure 1). Incident photon energy is captured by these pigment molecules and free electrons are generated. Through the process of hydrolysis (charge separation of water), these electrons are returned to the pigments and molecular oxygen is generated. The energy of the free electrons is harnessed through a variety of biophysical reactions (electron transport chain) to produce molecules of ATP and NADH. These molecules then enter the dark reactions and provide the reducing power needed to fix atmospheric carbon dioxide.

It is not surprising that there is a strong correlation between pigment absorption spectra and the photosynthetic action spectra of a number of crop plants (Figure 2). The portion of the electromagnetic spectrum contributing directly to the light reactions is known as Photosynthetically Active Radiation (PAR) and ranges from approximately 400 nm to 700 nm. Most often, the quantity of radiation received by a plant is expressed in terms of Photosynthetic Photon Flux (PPF), having units of μmol m^{-2} s^{-1} PAR. In some cases total incident radiation is expressed in terms of energy (Wm^{-2} PAR). However, a single blue photon has more energy than a single red photon but is just as efficient as the red in driving the light reactions. It is therefore more desirable to express the quantity of incident radiation in terms of PPF. since it is the number of photons absorbed rather than total incident energy that defines the total number of ATP and NADH molecules generated in the light reactions. The spectral composition of any light source plays a major role in its efficiency. This aspect of plant culture is discussed in more detail in Section 2.13.

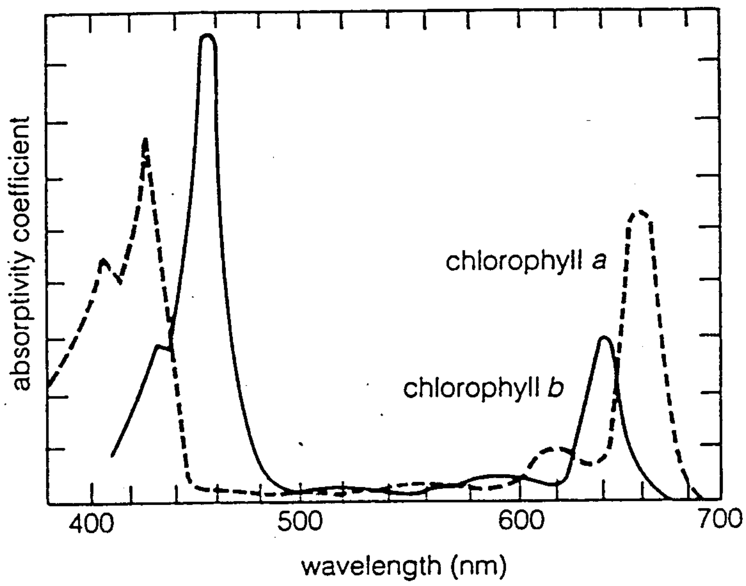

Figure 1. Typical chlorophyll absorption spectra. Taken from Salisbury and Ross (1992).

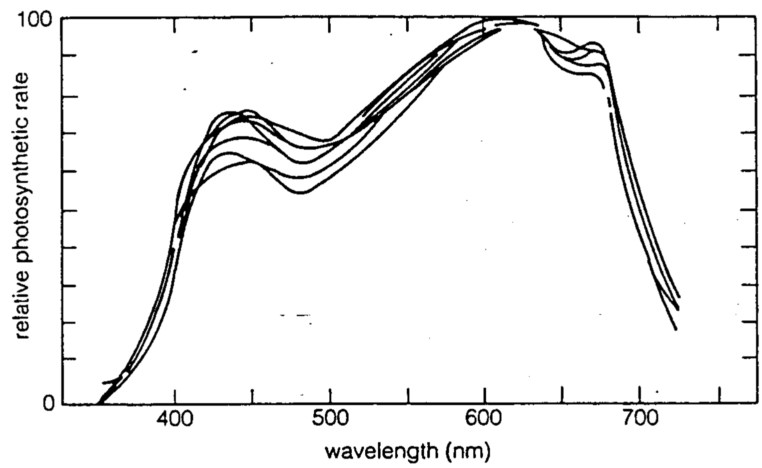

Figure 2. Photosynthesis - irradiance spectral activity of 22 species. Taken from Salisbury and Ross (1992).

2.12 - Light Intensity

Figure 3 presents a typical relationship between light intensity (PPF) and net photosynthesis, expressed as net carbon exchange rate (NCER) for a single plant or leaf.

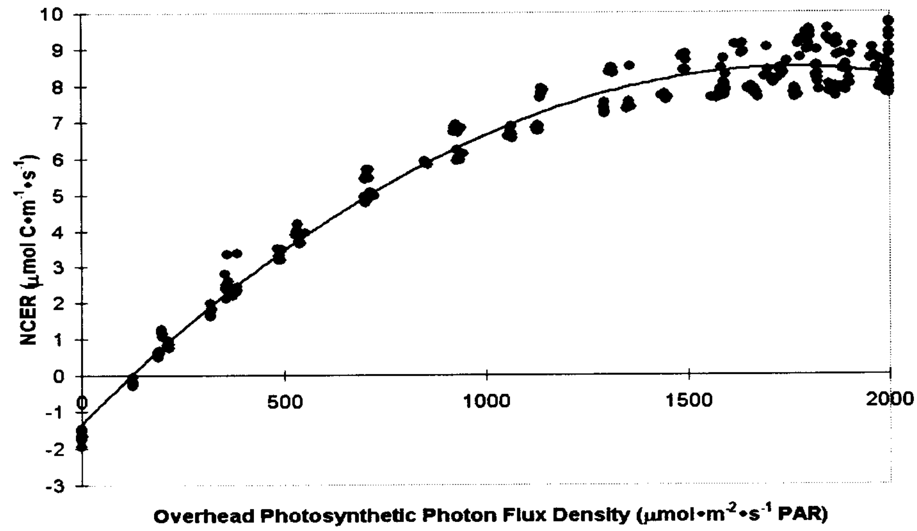

Figure 3. Net carbon exchange rate (NCER) for 40 day old whole soybean plants in small plant growth chambers containing four plants measured over a range of photosynthetic photon fluxes. Carbon dioxide concentration was maintained at 375 μmol/mol (adapted from Stasiak *et al*, 1998).

The x-intercept of this curve is known as the light compensation point. At PPF levels lower than the compensation point, respiratory losses of CO_2 are greater than photosynthetic carbon fixation and no net biomass accumulation is possible. At PPF levels greater than the compensation point, photosynthetic rates are greater than respiration rates and there is a net accumulation of biomass. At high PPF levels there is a saturation of the light harvesting complexes or in the dark reaction regeneration of RuBP (see Section 2.2). Above the point of saturation there is no net return on increased radiation supply.

From an ALS engineering perspective it is desirable to maintain rates of radiation supply near or at the point of saturation. Of course, compensation and saturation points differ between crops and it is therefore unlikely that radiation intensity in integrated production scenarios will coincide exactly with the point of saturation for each crop in the production unit. Models of individual crop responses to radiation intensity will help to quantify concessions made to accommodate crops having different points of light saturation. These models will be more fully addressed in ESA TN 40.3.

The curve in Figure 3 shows how photosynthesis in single leaves or plants changes with irradiance level. This curve is not typical of the response of full canopy systems. Light attenuation in full canopies results in a situation where leaves of the upper canopy are light saturated while those of the lower canopy are not. Because of this attenuation, full canopy systems are saturated at irradiance levels much greater than those of single plants. Further, some C_4 plants show even less tendency to saturation (Baker and Musgrave, 1964). This is the rationale behind the inclusion of an inner-canopy lighting system in one of the University of Guelph ALS chambers (Dixon *et al*, 1996).

2.13 - Selection of Lighting Systems

A number of factors need to be considered when choosing from the wide variety of lighting systems available. These factors include;

- spectral emission
- photosynthetic efficiency (PPF per unit of electrical input)
- rated life
- output loss (decrease in output throughout rated life time)
- absolute PPF

A brief review of the more common lighting systems is presented here. The spectral quality of each of these systems within the range of PAR is presented in Figure 4.

2.131 - Incandescent Lighting Systems

Incandescence is the radiation created by a heated body, the spectrum of which depends primarily on the temperature of the heated element. Most incandescent lamps use a tungsten filament operating between 2430 and 2780° K. Near the upper temperature limit, these systems will produce a spectrum shifted towards shorter (higher energy) wavelengths. However, at high operational temperatures, the life time of incandescent light sources is shortened and so under average operating temperatures (voltage supply) most of the light emitted by these systems is in the infrared range. Incandescent lamps typically show a decrease in radiation output on the order of 15 % by the end of their specified life time. While the life time can be increased by operating at lower temperatures, this is at the expense of spectral quality and photosynthetic efficiency. A more detailed discussion of incandescent lighting systems is presented in Sager and Mc Farlane (1997).

2.132 - Fluorescent Lighting Systems

Fluorescent lamps are usually constructed of long glass tubes containing low pressure mercury vapour with a small amount of inert gas (argon). When the electrodes at either end of the glass tube are supplied with the proper voltage an electric arc is established that excites the mercury ions. When these ions fall to the ground state ultraviolet radiation is released that in turn cases phosphor coatings on the inside of the tube to fluoresce at longer wavelengths. Using a combination of phosphors a variety of spectra, primarily in the PAR range are generated. Broader spectra are generated with the addition of red phosphors (deluxe cool white, warm white bulbs) but there is an associated 30% drop in radiation output as compared to more conventional white bulbs (Sager and

Mc Farlane, 1997). The life time of these lighting systems is largely determined by the phosphor coatings which are evaporated slowly over the course of lamp operation. The frequency of on-off events is also important since system startup results in a greater erosion of the phosphor coatings. These lighting systems are very common in plant growth chambers because of the high PPF output and a spectral quality which very closely matches the requirements of plants.

2.133 - High-Intensity Discharge Lighting Systems

High intensity discharge (HID) lamps are systems which excite elements in an electric arc to produce a characteristic elemental line spectra (ibid). The spectral distribution of these systems is uniform but not necessarily continuous. These lamps produce PPFs greater than fluorescent and incandescent lamps and are recommended when plant lighting requirements exceed 500 μmol $m^{-2}s^{-1}$ PAR. Two more common types of HID lighting systems are metal halide (MH) and high pressure sodium (HPS) lamps.

High pressure sodium lamps are particularly useful in plant growth chambers because of their high photosynthetic efficiency. Radiation from HPS lamps is generated by an electrical arc which excites high concentrations of sodium vapour and some mercury vapour. The emission spectra of these lighting systems is concentrated between 550 and 650 nm, but is low in emission between 400 and 500 nm. Plant morphogenic processes may therefore not be satisfied unless high intensity HPS lights are used or lower intensity lights are used in conjunction with metal halide, blue phosphor or cool white lamps (Tibbitts *et al*, 1983).

Radiation from metal halide lamps is produced by an electrical arc which vapourizes various metal halides (iodides of thorium, thallium, or sodium) to produce characteristic line spectra. This emission spectra spans the range of PAR and with increased mercury vapour pressure the intensity of radiation in this range can be increased. Depending on the power rating of the lamp average life times can range from 20 000 to 1 200 hours but significant drops (as much as 25 %) in output are to be expected during the first half of the lamps rated life time (Sager and Mc Farlane, 1997).

2.134 - Light-Emitting Diodes (LEDs)

Light emitting diodes based on a gallium-aluminum-arsenide substrate (GaAlAs) are available with peak emissions ranging from 630 to 940 nm. The most commonly available GaAlAs LEDs emit radiation in the red region of the spectrum which coincides with the maximum absorption of chlorophyll (Barta *et al*, 1992). An array of light emitting diodes, supplemented with a PPF of 30 μmol m^{-2} s^{-1} in the 400-500 nm range from blue fluorescent lamps was used effectively as a radiation source for growing plants (Bula *et al*, 1991). Growth of lettuce plants maintained under the LED irradiation system at a total PPF of 325 μmol m^{-2} s^{-1} PAR for 21 days was equivalent to that reported in the literature for plants grown under cool white fluorescent and incandescent sources (Bula *et al*, 1991; Hoenecke *et al*, 1992). While LED PPF efficiency is less than that of HID lamps, their electrical energy conversion efficiency may be as much as twice that published for fluorescent systems (Bula *et al*, 1991).

2.135 - Microwave Lighting Systems

Microwave lamps consist of electrodeless bulbs filled with a variety of elemental compounds such as Li, S or Hg. External excitation of these bulbs is achieved using microwaves generated in a magnetron. This source has achieved conversion efficiencies greater than HPS lamps. Further, the lamp's small size, its ability to meet optimal spectral requirements for chlorophyll absorption and its low near infra-red emissions make it an excellent source of radiation in plant growth units. These types of lighting systems are currently employed in the University of Guelph research chambers and those of Kozai *et al*, (1995) with a high degree of success.

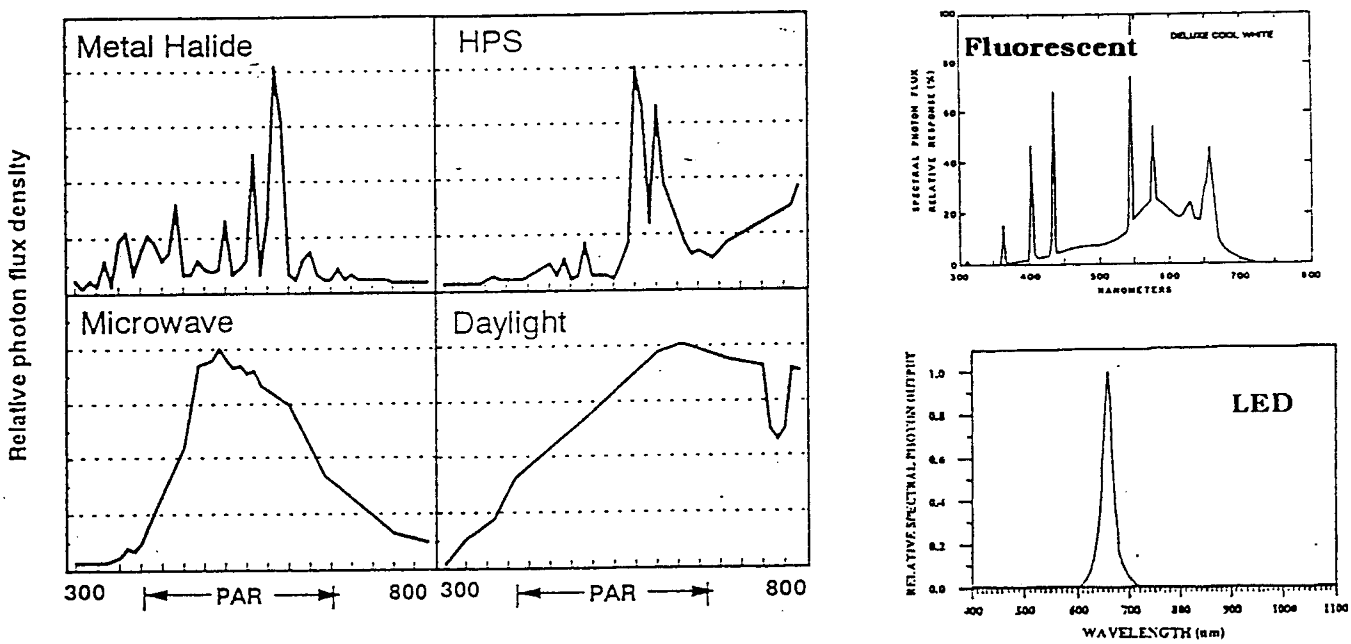

Figure 4. Emission spectra for a number of commonly used lighting systems. Spectral quality of metal halide, high pressure sodium (HPS), microwave and sunlight taken from Dixon *et al*, 1996. Spectral quality of fluorescent and LED systems taken from Sager and Mc Farlane (1997) and Bula *et al*, (1991) respectively.

2.14 - Photomorphogenesis

Photomorphogenesis refers to any process which is affected by the mere presence or absence of light with only minimal dependency on its intensity. Several responses of plants such as germination, flowering and phototaxic movements are not influenced greatly by light intensity providing certain minimum levels are met.

Photoperiodism, a type of plant photomorphogenic response, is dependent upon the relative lengths of day and night periods. Photoperiodism is thought to be mediated by a number of pigment molecules distributed throughout most plant organs. Two of these pigments, referred to as phytochrome, exist in two interchangeable forms with respect to absorption of either red (P_r) or far red (P_{fr}) radiation. During light periods, photoequilibrium is established between these two forms but during dark periods P_{fr} is slowly reverted back to P_r. This phenomena is used in plants as a switch mechanism to detect the relative length of dark periods and to control various processes including flowering, germination and vegetative growth.

Three general classifications of higher plants can be made based in their sensitivity to photoperiod. Long night (short day) plants require a dark period above a critical number of hours, short night (long day) plants require a dark period which is below a critical number of hours and day-neutral plants are indifferent to the relative length of day and night periods. In long night plants, reduced cellular concentrations of P_{fr} promote flowering (P_{fr} inhibition), while in short night plants higher concentrations of P_{fr} (mediation) promote flowering or other phytochrome mediated responses.

In addition to photoperiodism, phytchrome, cryptochrome and a variety of other pigments have been implicated in seed germination, phototropism and vegetative growth. Supply of light levels according to prescribed intensities and photoperiods (Section 3.0) is expected to ensure that the majority of these photomorphogenic responses occur normally.

2.15 - Physiological Abnormalities Resulting from Improper Radiation Supply

Oedema, also referred to as intumescence injury, neoplasm or genetic tumors is a disorder that occurs almost exclusively in controlled environment facilities (Morrow and Wheeler, 1997). This disorder has been observed in tomato and sweetpotato (Lang and Tibbitts, 1983). Oedema appears as a 1-3 mm diameter gall-like protrusion on leaves and callus like growths on stems and petioles which can result in early abscission in severe cases. Oedema is promoted by red radiation and is inhibited by far-red radiation and UV radiation (Lang and Tibbitts, 1983; Morrow and Tibbitts, 1987). An adequate source of UV radiation in the growth chamber is expected to control this disorder (Morrow and Wheeler, 1997).

Because controlled environment chambers give the opportunity to experiment with a number of photoperiods uncommon in nature, some disorders may result. While many plants will not exhibit any obvious effect on plant growth, tomato is particularly sensitive to continuous light injury (Wheeler and Tibbitts, 1986). These plants can become severely chlorotic and stunted (ibid). Potato is also sensitive to continuous radiation supply if a temperature change of 4-6 °C each 12-16 hours is not provided (Tibbitts *et al*, 1990). A dark period on the order of at least 4-6 hours each day will prevent these injuries. Further, unusually rapid photoperiods such as those used to mimic low-earth orbital photoperiods (60 min light/ 30 min dark) can result in reduced tuber production (Morrow *et al*, 1987). Wheat grown in similar conditions showed increased stem length, reduced tillering and increased grain weight (ibid) This effect is expected to be similar to continuous lighting injury.

2.2 - The Role of Carbon Dioxide

2.21 - Dark Reactions and CO_2 Supply

Higher plants are generally classified into three major groups based upon the biochemical pathway by which CO_2 is fixed. The enzyme ribulose bisphosphate carboxylase -oxygenase (RuBP carboxylase or Rubisco) is responsible for the primary fixation of CO_2 in C_3 plants. This initial fixation occurs during daylight hours in the chloroplast and produces a three carbon molecule (hence the term C_3) known as 3-phospho-glyceric acid (PGA). Through a series of subsequent biochemical reactions utilizing the NADH and ATP generated in the light reactions, PGA is further reduced to regenerate RuBP and to generate glucose for use elsewhere in the plant. Despite the fact that most crops utilize the C_3 pathway, Rubisco is an inefficient enzyme and is easily oxygenated in the process of photorespiration. The affinity of Rubisco for oxygen (which is in direct competition with CO_2) is the primary reason why day time respiration is found to occur in chloroplasts at an average rate that is three times higher than the rate of night time respiration. The process of photorespiration is particularly troublesome since it consumes valuable ATP and NADH at low atmospheric CO_2/O_2 ratios.

To counteract the effects of photorespiration some plants have developed the C_4 pathway. In this pathway, the initial carboxylation reaction involves phosphoenolpyruvate carboxylase (PEP carboxylase) instead of Rubisco and produces oxaloacetate (OAA) as the first product of fixation. This four carbon intermediate is transferred to the leaf bundle sheath cells and is then decarboxylated. This initial fixation and subsequent release of CO_2 acts as a concentrating mechanism since PEP has a higher affinity for CO_2 than Rubisco. A third mechanism of CO_2 fixation is known as Crassulacean acid metabolism (CAM). This pathway is similar to the C_4 pathway in that CO_2 is initially fixed into C_4 compounds using PEP carboxylase and is subsequently decarboxylated and fixed by Rubisco. However, the initial carboxylation occurs during the dark period when C_4 acids can accumulate in meosphyll cell vacuoles under reduced evaporative demand. While these alternative carbon fixation pathways are not common in crop plants, their inclusion in an ALS may provide a unique strategy to manage diurnal fluctuations in atmospheric CO_2 concentrations. This subject will be addressed in TN 40.3

The CO_2 that is fixed during the dark reactions must diffuse, in response to a partial pressure gradient, from the ambient air (partial pressure of 34 Pa) through a series of resistances to the carboxylation site. These resistances include the leaf boundary layer, the stomata and the intercellular spaces. Because diffusion of CO_2 is in response to partial pressure gradients, generally, the higher the atmospheric concentration of CO_2, the greater the rate of diffusion and the rate of net photosynthesis. The net photosynthetic response curve for CO_2 is very similar to the light curve presented in Figure 3. At high CO_2 levels, depending on the crop, there is a saturation of Rubisco and hence the net photosynthetic rate saturates. The x-intercept of this type of response curve is known as the CO_2 compensation point. At CO_2 levels below the compensation point, CO_2 is limiting and there can be no net biomass production. This issue will be discussed in greater detail in TN 40.3.

2.3 - The Role of Temperature and Humidity

2.31 - Temperature and DIF

At low temperatures, rates of biochemical reactions are limited but increase as temperatures approach optimality. At high temperatures there is an increasing degree of enzyme inactivity resulting in reduced biochemical reaction rates. While this response is typical of all reactions to some degree, the challenge from a cultural management perspective, is to maintain atmospheric temperatures in the optimal range for yield response. Management protocols have been established for crops included in the MELiSSA menu in order to promote various processes including germination, vegetative growth and floral initiation and development. It is the more common of these protocols that have been included in Section 3.

A critical observation to be made, is the fact that diurnal variations in temperature are often part of the management protocol. In ornamental crops, the difference in day and night temperatures, referred to as temperature DIF, is used as a means to promote stem elongation. While DIF may have the same effect on vegetable and grain crops (Abou-Hadid and Mednay, 1992) its purpose in ALS cultural management is primarily to slow night time respiration rates in addition to satisfying requirements for such other processes as floral initiation and germination. In the absence of a positive DIF, plants may become stunted and spindly due to respiratory losses of carbon. Most photosynthesizing crops will respond positively to a day-night temperature difference.

2.32 - Humidity Control

It is accepted that low atmospheric humidity (high saturation vapour pressure deficits) can result in plant water stress. Due to resistances in the plant hydraulic pathway, this stress can occur even in the presence of adequate root zone water supply. Water stress can manifest itself in stomatal closure, reduced growth rates, wilting and in extreme cases, death. On the other hand, high atmospheric humidity can result in condensation on leaf surfaces (especially under reduced night time temperatures) which can in turn provide an optimal environment for disease causing organisms and reduce the efficacy of leaf evaporative cooling. Generally, atmospheric humidity should be maintained between 60 and 80%.

2.4 - Nutrition and Nutrient Supply

2.41 - Essential Mineral Nutrients

A total of 17 elements are considered essential for higher plants (Jones, 1997). This list of elements is presented in Table 3. The first 8 elements listed are often called trace elements or micro-nutrients since their concentrations in plant parts is typically less than 100 mg kg^{-1} dry matter (ibid). The last 9 are the macronutrients, needed in concentrations of at least 1 000 mg kg^{-1} dry matter (ibid). All of these nutrients are required as constituents in various enzymes, structural molecules and in the direct mediation of physiological processes (osmoregulation), to name only a few. Adequate supply of each of these nutrients can be maintained by matching nutrient uptake and delivery. Given the complexity of this task in soil based culture, it is generally accepted that hydroponic nutrient delivery is the most suitable for ALS systems.

Element	Typical Concentration in Dry Tissue (ppm)
Micronutrient	
Chlorine (Cl^-)	100
Iron (Fe^{3+}, Fe^{2+})	100
Manganese (Mn^{2+})	50
Boron (H_3BO_3)	20
Zinc (Zn^{2+})	20
Copper (Cu^+, Cu^{2+})	6
Molybdenum (MoO_4^{2-})	0.1
Nickel (Ni^{2+})	--
Macronutrient	
Carbon (CO_2)	450 000
Oxygen (O_2, H_2O, CO_2)	450 000
Hydrogen (H_2O)	60 000
Nitrogen (NO_3^-, NH_4^+)	15 000
Potassium (K^+)	10 000
Calcium (Ca^{2+})	5 000
Magnesium (Mg^{2+})	2 000
Sulfur (SO_4^{2-})	1 000
Phosphorus ($H_2PO_4^-$, HPO_4^{2-})	2 000

Table 3. Essential elements for most higher plants and internal concentrations considered adequate. Bracketed ionic forms are those forms available to plants. Adapted from Jones (1997).

2.42 - Nutrient Supply and the NFT System

One of the most effective hydroponic nutrient supply systems is the Nutrient Film Technique (NFT). The NFT system is based on a recirculating stream (film) of nutrient over the roots of plants to provide water, nutrients and oxygen. Although there are many versions of NFT in current use, the basic components of a typical NFT system are as follows;

- parallel troughs in which the plants grown are laid on a slope (1-2%), down which the nutrient solution flows. These troughs can be constructed of a variety of materials including semi-rigid plastic and steel,
- supply tanks for concentrated fertilizer stock solution (usually two solutions to prevent precipitation of concentrated salts), acid solution (typically HNO_3) and base (typically KOH),
- a catchment tank containing a nutrient solution where fertilizers, water and pH stabilizers are added,
- a circulation pump which draws nutrient solution from the catchment tank and delivers it to the upper end of the troughs,
- a catchment pipe into which the troughs discharge their solution which flows back to the catchment tank and,
- monitoring and control equipment to maintain the overall nutrient concentrations (total salts), pH and water level. An electrical conductivity (EC) and pH sensor are used to regulate the feedback operation of pumps controlling the transfer of fertilizers and acid from the supply tanks to the catchment tank. A constant water level can be maintained by using a mechanical floating sensor.

One of the significant limitations of EC/pH based control is the fact that there are differential rates of nutrient uptake which can result in ion imbalances in the recirculating solution through time. EC/pH based feedback control injects fertilizer stock without regard for this differential uptake, and through the effects of competition for ion uptake at the root zone, ion imbalance may ultimately lead to a condition of induced deficiency. As a result, advanced sensor technologies are being explored to balance nutrient uptake and supply at the individual ion level. These sensors are more fully described in Cloutier *et al* (1997).

2.43 - Solution Formulations and the Hoagland's Recipe

One of the most common hydroponic nutrient solution formulations is the Hoagland's solution. While a number of other formulations exist which are appropriate for hydroponic vegetable culture, the Hoagland's solution has been tried and proven in a variety of ALS test systems (Section 3). The composition of the Hoagland's solution (sometimes referred to as a modified Hoagland's since after its initial formulation some nitrogen was included as part of the ammonium ion) is presented in Table 4.

Salt	**mM**	**mg L^{-1} (ppm)**
KNO_3	6.0	235 K 196 N as NO_3^- 14 N as NH_4^+ 160 Ca 31 P 49 Mg 64 S
$Ca(NO_3)_2 \cdot 4H_2O$	4.0	
$NH_4H_2PO_4$	1.0	

Salt	mM	mg L^{-1} (ppm)
$MgSO_4 \cdot 7H_2O$	2.0	
Fe-Chelate		0.5% Fe-Chelate, using 2mL L^- for 1mL L^- final concentration
$MnCl_2 \cdot 4H_2O$	0.009	0.5 Mn, 6.5 Cl
H_3BO_3	0.046	0.5 B
$ZnSO_4 \cdot 7H_2O$	0.0008	0.05 Zn
$CuSO_4 \cdot 5H_2O$	0.0003	0.02 Cu
$H_2MoO_4 \cdot H2O$	0.0001	0.01 Mo

Table 4. Composition of a full strength (1x) modified Hoagland's solution (Adapted from Salisbury and Ross, 1992)

3 - Cultural Management Strategies for ESA-MELiSSA Candidate Crops

3.1 - Purpose and Methodology

The purpose of this section is to provide information relating to cultural management strategies for crops in the ESA-MELiSSA menu. While the information contained in this section is a result of a literature review of current practices in controlled environments, ALS research and commercial greenhouse production, it is by no means exhaustive. The information contained in this section, then, serves to identify where information in closed environments is lacking for specific crops. It must also be pointed out that this information represents common cultural practices, largely in research installations. This technical note does not attempt to quantify the impact of these strategies on yield. These issues will be addressed in more detail in TN 40.3.

The following additional information is provided to assist the reader in interpreting values presented in this section.

Days from planting to harvest:

The number of days from planting to harvest will, of course, depend on environmental conditions. This number represents the average rotation for the cultural management strategies presented for each crop.

PPF Compensation point:

Estimates of PPF compensation point will differ for a single crop depending on the scale at which the estimates are obtained. At the individual leaf scale, reported compensation points are typically lower than those reported from studies at the individual plant or full canopy level. This is a result of light attenuation in full plant and canopy systems. Because of the difficulty in comparing compensation points among crops derived from different scales of measurement, a generic compensation point for C_3 species is given (Larcher, 1996).

Photoperiod requirement:

The photoperiods (number of daylight hours) presented in this section are appropriate for vegetative production. Values cited between 12-20 hrs indicate that plants are relatively insensitive to photoperiod. If lower photoperiods are used than those recommended, PPF should be proportionally higher.

Recommended day night temperatures:

The recommended DIF is presented as the day/night temperature. For example, 23/20 °C, indicates that temperatures should be 23 and 20 °C for day and night periods respectively.

3.2 - LETTUCE CULTURAL REQUIREMENTS

		COMMENTS:
Botanical name:	*Lactuca sativa L.*	
Useable plant part(s):	leaves	
Photosynthesis (C_3, C_4, CAM)	C_3	
Days from planting to harvest:	30	• depends on environmental conditions
Germination requirement	• Rockwool germinate seeds in a chamber at 2 °C for 48-72 hrs under high humidity •Constant illumination in some cultivars until emergence and 48-72 hrs following emergence	• High temperatures can lead to seed dormancy (>25 °C)(Swiader *et al,* 1992) • 'Grand Rapids' has exhibited photodormancy (ibid) • Constant illumination followed by 16 hr photoperiod lead to a 43% increase in yield (Gaudreau *et al,* 1994)
PPF Compensation point (μmol m^{-2} s^{-1}):	20 - 40	
Minimum PPF range (μmolm^{-2} s^{-1}):	250 - 450	• after Hopper *et al* (1997) • High irradiance may result in tip burn
Photoperiod requirement (vegetative production):	12-20	• Gaudreau *et al* (1994) report increased yields as photoperiod approached 24 hrs • Photoperiods of 16 hrs may be more suitable since incidence of tip burn increases with photoperiod (Gaudreau *et al*, 1994; Drysdale *et al*, 1994; Hopper *et al*, 1997; Wheeler *et al*, 1994)
Day Neutral/Short Day/Long Day:	day neutral	
Toleration of continuous lighting	•incidence of tip burn increases	
Flowering/Fruiting requirements:	• temperatures > 25 °C will induce flowering	Swiader *et al* (1992) and Hopper *et al* (1997)
Recommended day night temperatures:	2/2 °C germination 23/20 °C vegetative 30/25 °C flowering	Swiader *et al.* (1992) and Wheeler *et al* (1994)

Hydroponic culture:	• NFT production suitable	OMAF 562; Wheeler *et al* (1994); Giacomelli *et al* (1987)
pH Range:	5.5-6.5	
pH Control:	HNO_3, KOH	
Standard solution used:	½ Modified Hoaglands	Giacomelli *et al* (1987)
Soilless substrate	rockwool	
Spacing/Density:	25-30 plants m^{-2}	OMAF 562, Drysdale *et al* (1994); Martinac and Borosic (1986)
CO_2 enrichment:	• yields can be increased with enrichment	Knight and Mitchell (1988); Knecht and O'Leary (1983)

3.3 - Onion Cultural Requirements

		COMMENTS:
Botanical name:	*Allium cepa L.*	
Useable plant part(s):	bulb	
Photosynthesis (C_3, C_4, CAM)	C_3	
Days from planting to harvest:	more information on complete crop development required for controlled environments	
Germination requirement:	• vernalize seed at temperatures below 10 °C for 50 days • 18/13 °C suitable • photoperiod 11 - 13 hrs • propagation from bulbs is possible	• Dellacecca *et al* (1994); Herison *et al* (1993)
PPF Compensation point (μmol m^{-2} s^{-1}):	20 - 40	
Minimum PPF range (μmolm^{-2} s^{-1}):	no recommendation for controlled environments	
Photoperiod requirement (vegetative production):	• bulb formation for most cultivars best at photoperiods between 12 and 14 hrs	• Peirce (1987)
Day Neutral/Short Day/Long Day:	long day for floral induction	• Brewster and Butler (1989)

Toleration of continuous lighting	unknown	
Flowering requirements:	• 10 °C for floral induction (40 - 50 days) • Photoperiods > 14 hrs	• Brewster (1983)
Recommended day night temperatures:	• no recommendation for controlled environment production	
Hydroponic culture:	• unknown	
pH Range:	• unknown	
pH Control:	• unknown	
Standard solution used:	• unknown	
Soilless substrate	• unknown	
Spacing/Density:	• unknown	
CO_2 enrichment:	• unknown	

3.4 - POTATO CULTURAL REQUIREMENTS

		COMMENTS:
Botanical name:	*Solanum tuberosum* L.	
Useable plant part(s):	tuber	• tubers are enlarged portions of stolons. Tuber initiation usually occurs within a week of emergence of the plant shoot
Photosynthesis (C_3, C_4, CAM)	C_3	
Days from planting to harvest:	90 days	• depends on environmental conditions (Drysdale *et al,* 1994)

Germination requirement:	• Propagation using explant or microtubers in hydroponics • 12/12 photoperiod for first 35-45 days • Air temperatures of 20/16 °C	• Drysdale *et al* (1994); Yorio *et al* (1995)
PPF Compensation point (μmol m^{-2} s^{-1})**:**	20 - 40	
Minimum PPF range (μmolm^{-2} s^{-1})**:**	250 - 450	• Higher PPFs have been utilized (400 - 800 μmolm^{-2} s^{-1}) by Wheeler *et al* (1991); Stutte *et al* (1996)
Photoperiod requirement (vegetative production):	•continuous to promote shoot growth •12/12 for tuber initiation • continuous following tuber initiation	• Some researchers have reported that tuber growth is inhibited by long photoperiods, however work by Wheeler and Tibitts (1986) has shown tuber yields can be increased under continuous lighting. The recommended photoperiod has been employed in a number of growth chamber studies (Yorio *et al*, 1995; Wheeler *et al,* 1990)
Day Neutral/Short Day/Long Day:	day neutral	
Toleration of continuous lighting	•continuous lighting (for 28 days) has been used to stimulate shoot growth, followed by shorter photoperiods for tuber growth (Wheeler et al, 1986) • continuous lighting may reduce net carbon assimilation especially if PPF levels are high (Stutte *et al*, 1996) • Other studies have shown that tuber yields will increase under constant illumination (Wheeler and Tibitts, 1997)	
Flowering/Fruiting requirements:	• age dependent, factors promoting shoot growth	• Propagation from microtubers is preferred since plants generated from seed can be very different from parent
Recommended day night temperatures:	17/17 °C for rapid shoot development 23/18 °C for tuber and initiation 16/16 °C for tuber growth maximization	• Wheeler *et al* (1986); Hopper *et al* (1997)

Hydroponic culture:	• NFT	• Wheeler *et al* (1990)
pH Range:	5.5-6.5	
pH Control:	HNO_3, KOH	
Standard solution used:	½ x modified Hoalgland's	McKeehen *et al* (1996)
Soilless substrate	none	
Spacing/Density:	variable	
CO_2 enrichment:	Enrichment to 1000 μmol mol^{-1} is likely to have a positive effect on tuber yields depending on light intensity and cultivar (Wheeler *et al*, 1991; Wheeler and Tibbitts 1997)	

3.5 - Rice Cultural Requirements

		Comments:
Botanical name:	*Oryza sativa L.*	
Useable plant part(s):	grain	
Photosynthesis (C_3, C_4, CAM)	C_3	
Days from planting to harvest:	85	• Depends on environmental conditions
Germination requirement:	• 30/20 °C suitable • germinate in rockwool	• Hopper *et al* (1997)
PPF Compensation point (μmol m^{-2} s^{-1}):	20 - 40	
Minimum PPF range (μmolm^{-2} s^{-1}):	250 - 450	• Hopper *et al* (1997); Kozai *et al* (1995)
Photoperiod requirement (vegetative production):	10/14	• McKeehen *et al* (1996); • Longer photoperiods may be used (16 hrs) depending on sensitivity of cultivar (Kozai *et al*, 1995)
Day Neutral/Short Day/Long Day:	short day	• cultivar specific; some cultivars are sensitive (Vergara, 1991)

Toleration of continuous lighting	• Likely to increase non-grain biomass only, not suitable in photoperiod sensitive plants	• Volk and Mitchell (1995)
Flowering requirements:	• critical day length varies with cultivar	
Recommended day night temperatures:	• 32/26 following germination	• McKeehen *et al* (1996); Kozai *et al* (1995)
Hydroponic culture:	• Rockwool, deep water NFT production suitable	• McKeehen *et al* (1996)
pH Range:	5.5-6.5	
pH Control:	HNO_3, KOH	
Standard solution used:	• ½ x modified Hoagland's	• McKeehen *et al* (1996)
Soilless substrate	rockwool	
Spacing/Density:	212 plants m^{-2}	• Volk and Mitchell (1995)
CO_2 enrichment:	more information required	

3.6 - Soybean Cultural Requirements

		Comments:
Botanical name:	*Glycine max (L.) Merr.*	
Useable plant part(s):	fruit, oils	
Photosynthesis (C_3, C_4, CAM)	C_3	
Days from planting to harvest:	90	• Depends on environmental conditions
Germination requirement:	• soak seeds in H_2O or an aerated hydroponic solution for 24 hrs • 25 °C day/night • lighting not required	
PPF Compensation point (μmol m^{-2} s^{-1}):	20 - 40	
Minimum PPF range (μmolm^{-2} s^{-1}):	250 - 750	• Stasiak *et al* (1998)

Photoperiod requirement (vegetative production):	12/12	• Wheeler *et al* (1993a)
Day Neutral/Short Day/Long Day:	short day	
Toleration of continuous lighting	no	
Flowering/Fruiting requirements:	• time to flowering is decreased if photoperiod is above 13 hrs and applied during photoperiod sensitive stage	•Acock and Acock (1995)
Recommended day night temperatures:	• 25/25 °C germination • 26/20 °C	
Hydroponic culture:	• Rockwool NFT production suitable	• Harper (1976)
pH Range:	5.5-6.5	
pH Control:	HNO_3, KOH	• Cloutier *et al* (1997)
Standard solution used:	• ½ x modified Hoagland's	• Harper (1976)
Soilless substrate	rockwool, glass beads	• Cloutier *et al* (1997)
Spacing/Density:	16 plants m^{-2}	
CO_2 enrichment:	Enrichment is questionable and seems to be dependent on cultivar	• Wheeler *et al* (1993a); Campbell *et al* (1990)

3.7 - SPINACH CULTURAL REQUIREMENTS

		COMMENTS:
Botanical name:	*Spinacia oleracea* L.	
Useable plant part(s):	leaves	
Photosynthesis (C_3, C_4, CAM)	C_3	
Days from planting to harvest:	27 days	• depends on environmental conditions, Ikeda *et al* (1995) report harvest within 27 days

Germination requirement:	• positively correlated with temperature - occurs within 10 days at 20 °C (Swiader *et al*, 1992)	
PPF Compensation point (μmol m^{-2} s^{-1}):	20 - 40	• Glenn *et al* (1984) report compensation at 1 mol m^{-2} day^{-1} in the greenhouse
Minimum PPF range (μmolm^{-2} s^{-1}):	250 - 450	• after Hopper *et al* (1997) and Iwabuchi *et al* (1995)
Photoperiod requirement (vegetative production):	12/12	• longer photperiods may induce flowering
Day Neutral/Short Day/Long Day:	long day	
Toleration of continuous lighting	likely to induce flowering	
Flowering/Fruiting requirements:	• cool induction period of 4 - 10 °C • post-induction period of 25°C will accelerate seed stalk development • photoperiod >15 hrs	• Cultivar specific • Taken from Peirce (1987), Swiader *et al* (1992) and Hopper *et al* (1997)
Recommended day night temperatures:	25/25 °C germination 20/20 °C vegetative 25/25 °C flowering	
Hydroponic culture:	• NFT and DFT production suitable • Solution temperature control may enhance yield in under high atmospheric temperatures	• Ikeda *et al* (1995)
pH Range:	5.5-6.5	
pH Control:	HNO_3, KOH	
Standard solution used:	Yamazaki Enshi-shoshou Terazoe-Okano	Lee and Takakura (1995) Ikeda *et al* (1995) Terazoe and Okano (1992)
Soilless substrate	rockwool	Ikeda *et al* (1995)
Spacing/Density:	25 plants m^{-2}	Glenn *et al* (1984)
CO_2 enrichment:	more information required	

3.8 - TOMATO CULTURAL REQUIREMENTS

		COMMENTS:
Botanical name:	*Lycopersicon esculentum* L.	
Useable plant part(s):	fruit	
Photosynthesis (C_3, C_4, CAM)	C_3	
Days from planting to harvest:	120 - 150	• Depends on environmental conditions
Germination requirement:	• between 20 - 25 °C day and night • lighting generally not necessary • germinate seed in rockwool cubes with covers to maintain humidity	• Generally, the higher the germination temperature the faster the rate of emergence (Agriculture Canada, 1991; Ontario Ministry of Agriculture, 562)
PPF Compensation point (μmol m^{-2} s^{-1}):	20 - 40	
Minimum PPF range (μmolm^{-2} s^{-1}):	250 - 750	• Ontario Ministry of Agriculture, 562; Hopper *et al* (1997)
Photoperiod requirement (vegetative production):	18/6	• Ontario Ministry of Agriculture, 562
Day Neutral/Short Day/Long Day:	day neutral	
Toleration of continuous lighting	no	
Flowering/Fruiting requirements:	• cool period of 13/10 °C for two weeks following first true leaf emergence will promote later floral set • High light intensities at photoperiods of 9-12 hours will promote floral set • Pruning of stems may be necessary depending on cultivar	• Agriculture Canada (1992); Ontario Ministry of Agriculture, 562
Recommended day night temperatures:	• 25/25 °C germination • 13/10 °C 2 weeks following true leaf emergence to promote floral set • 20/18 °C	• CO_2 enrichment may warrant higher temperatures 26/20 °C

Hydroponic culture:	• NFT production used extensively • structural support of stems needed	
pH Range:	5.5-6.5	
pH Control:	HNO_3, KOH	• Agriculture Canada (1992); Ontario Ministry of Agriculture, 562
Standard solution used:	• ½ x modified Hoagland's	• Agriculture Canada (1992); Ontario Ministry of Agriculture, 562
Soilless substrate	rockwool	
Spacing/Density:	3 plants m^{-2}	• Ontario Ministry of Agriculture 562
CO_2 enrichment:	Enrichment to 1000 μmol mol^{-1}	• Agriculture Canada (1992); Ontario Ministry of Agriculture, 562

3.9 - WHEAT CULTURAL REQUIREMENTS

		COMMENTS:
Botanical name:	*Triticum aestivum L.*	
Useable plant part(s):	grain	
Photosynthesis (C_3, C_4, CAM)	C_3	
Days from planting to harvest:	85	• Depends on environmental conditions
Germination requirement:	• 24 hr soak • sow directly on rockwool cubes • vernalization may be required before germination depending on cultivar (usually 1-2 °C for 42 days)	• Bugbee and Salisbury (1988); Ortiz-Ferrara *et al* (1995)
PPF Compensation point (μmol m^{-2} s^{-1}):	20 - 40	
Minimum PPF range (μmolm^{-2} s^{-1}):	250 - 450	• Hopper *et al* (1997)

Photoperiod requirement (vegetative production):	20/4	• Wheeler *et al* (1993b); Bugbee and Salisbury (1988)
Day Neutral/Short Day/Long Day:	day neutral	
Toleration of continuous lighting	no	
Flowering requirements:	• time to flowering may be increased at higher photoperiods (Ortiz-Ferrara *et al,* 1995) • vernalization may be required (ibid)	
Recommended day night temperatures:	• 24/20 °C germination • 20/16 °C	• Wheeler *et al* (1993b) report higher net photosynthetic rates at 20 °C than 24 °C; Bugbee and Salisbury (1988)
Hydroponic culture:	• Rockwool NFT production suitable	• Wheeler *et al* (1993b)
pH Range:	5.5-6.5	
pH Control:	HNO_3, KOH	
Standard solution used:	• ½ x modified Hoagland's	Wheeler *et al* (1993b)
Soilless substrate	rockwool	
Spacing/Density:	1200 plants m^{-2}	Drysdale *et al* (1994)
CO_2 enrichment:	1000 μmol mol $^{-1}$	Wheeler and Tibbitts (1997)

4.0 - INTEGRATED PRODUCTION SCENARIOS FOR ESA-MELISSA CROPS

4.1 - Biomass Production Units

Based on the cultural requirements presented for each of the MELiSSA crops in Section 3, it is possible to generate a preliminary set of biomass production units (BPUs). In each of these units crops having similar cultural requirements are placed and management strategies for their production are generated. In this amalgamation, onion is excluded since little is known at this stage about its cultural management in controlled environments.

BPUs can be identified based on the two constraints of photoperiod and temperature. These environmental conditions represent those to which crops are expected to be most sensitive. It is further assumed that a separate area for crop germination and establishment will be used. Management strategies for germination and establishment will not be discussed here since a knowledge of ALS planting and harvest schedules is needed. With this in mind, the biomass production units presented here are for vegetative or fruit production stages. It is also assumed that CO_2 concentrations in each BPU will remain at ambient levels unless responses to elevated CO_2 levels have been elucidated for each crop in the BPU.

Based on similarities in photoperiod and temperature requirements for vegetative and fruit production, three BPUs can be suggested. Management strategies for each of these units is presented and compared to those recommendations made for each crop in Section 3. Bracketed values in each of the photoperiod and temperature columns refer to the BPU managament strategy deviation from that recommended in Section 3.0. The impact of these deviations will need to be assessed on a cultivar by cultivar basis.

4.2 - Spinach, Lettuce and Soybean: BPU 1

	Photoperiod (hrs daylight)	**Temperature (°C day/night)**	**CO_2 (ppm)**	**Nutrient Delivery & Formulation**	**PPF (μmol m^{-2} s^{-1})**	**Harvest (days)**
	13 hrs	**23/20 vegetative**	**ambient**	**½ modified Hoaglands**	**250-450**	**30**
Crop	**Recommendations made in Section 3.0**					
Spinach	12 (+1)	20/20 (+3/0)	ambient (350)	Treazoe-Okano	250-450	27
Lettuce	12-20 (0)	23/20 (0/0)	1000	½ Hoagland's	250-450	30
Soybean	<13 (0)	26/20 (-3/0)	1000	½ Hoagland's	250-750	90

4.3 - Potato, Tomato and Wheat: BPU 2

	Photoperiod (hrs daylight)	Temperature (°C day/night)	CO_2 (ppm)	Nutrient Delivery & Formulation	PPF ($\mu mol\ m^{-2}\ s^{-1}$)	Harvest (days)
	18 hrs	**23/18**	**1000**	**½ modified Hoaglands**	**250-450**	**85-120**
Crop	**Recommendations made in Section 3.0**					
Potato	12-20	23/18 (0/0)	1000	½ Hoagland's	250-450	90
Tomato	18	20/18 (+3/0)	1000	½ Hoagland's	250-750	120
Wheat	12-20	20/16 (+3/-2)	1000	½ Hoagland's	250-450	85

4.4 - Rice: BPU 3

	Photoperiod (hrs daylight)	Temperature (°C day/night)	CO_2 (ppm)	Nutrient Delivery & Formulation	PPF ($\mu mol\ m^{-2}\ s^{-1}$)	Harvest (days)
	10 hrs	**32/26**	**1000**	**½ modified Hoaglands**	**250-450**	**85**
Crop	**Recommendations made in Section 3.0**					
Rice	10	32/26 (0/0)	1000	½ Hoagland's	250-450	85

The design and management of these biomass production units represents the first step in the design of more complete ALS systems. Many studies need to be conducted in order to elucidate the effects of common atmospheric and nutrient management on the yield and growth characteristics of each crop. Of course, as more specific information about each crop becomes known, these units will need to be redesigned. While work at the United States, Ames Research Centre has dealt with integrated crop production, at the time of writing this technical note, specific publications could not be sourced. As information becomes available, this technical note will be amended.

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