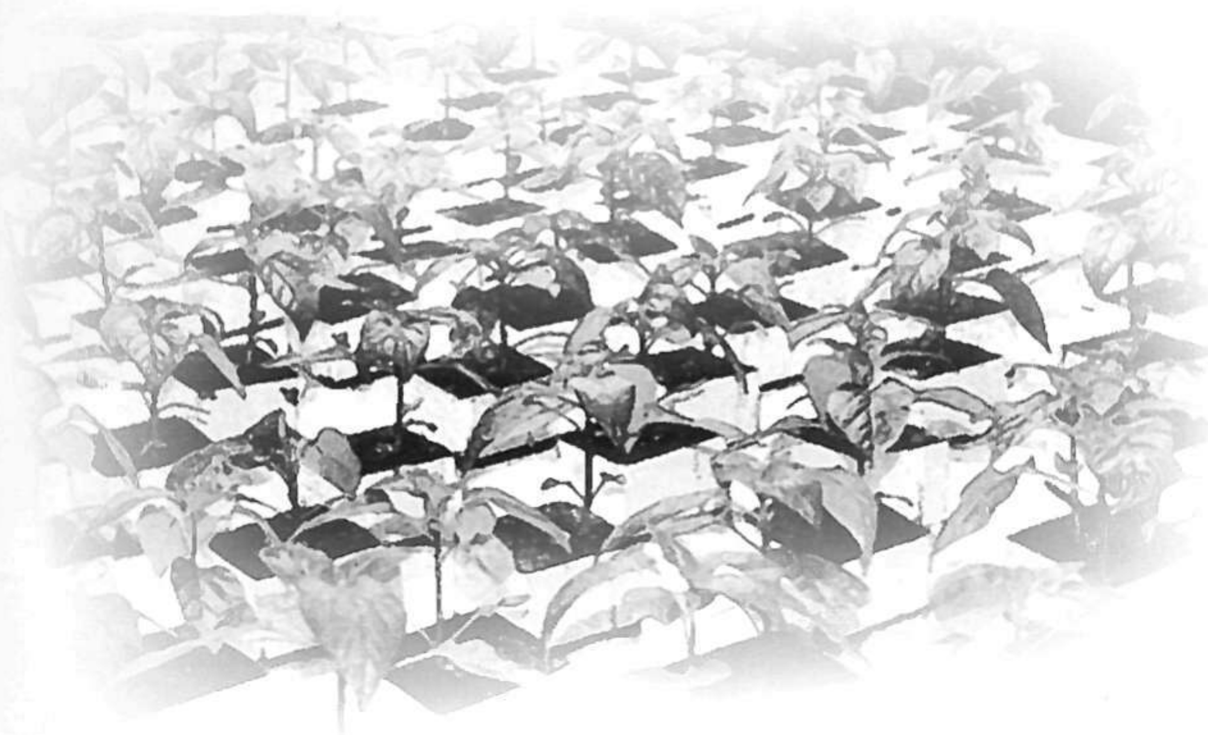

Commercial Greenhouse Production

in Alberta

Alberta
AGRICULTURE, FOOD AND
RURAL DEVELOPMENT

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NOTE:

The depiction of certain brands or products in the images in this publication does not constitute an endorsement of any brand or manufacturer. The images were chosen to illustrate certain aspects of commercial greenhouse production only, and the author does not wish to suggest that the brands or products shown are in any way superior to others. Growers should note that there are many products on the market, and buyers should research these products carefully before purchasing them.

Introduction

A greenhouse is a controllable, dynamic system managed for intensive production of high quality, fresh market produce. Greenhouse production allows for crop production under very diverse conditions. However, greenhouse growers have to manage a number of variables to obtain maximum sustainable production from their crops. These variables include the following:

- air temperature
- root zone temperature
- vapour pressure deficit
- fertilizer feed
- carbon dioxide enrichment
- growing media
- plant maintenance

The task of managing these related variables simultaneously can appear overwhelming; however, growers do have successful strategies to manage them. The main approach is to try to optimize these variables to get the best performance from the crop over the production season.

Optimization is the driver used to determine how to control these variables in the greenhouse for maximum yield and profit, taking into account the costs of operation and increased value of the product grown in the modified environment. The greenhouse system is complex; to simplify the decision-making process, growers use indicators. An indicator can be thought of as a small window to a bigger world; you don't get the entire picture, when you see an indicator, but you do gain an understanding of what is happening. Another way to look at it is to understand the basic rules of thumb, which can be used to get insights on the direction and dynamics of the crop-environment interaction.

Indicators provide information concerning complex systems, information that makes the systems more easily understandable. Indicators quickly reveal changes in the greenhouse, which may cause growers to alter the management strategies. Indicators also help identify the specific changes in crop management that need to be made.

The purpose of this publication is to provide information regarding greenhouse management. It presents basic indicators to help growers evaluate the plant-environment interaction as they move towards optimizing the environment and crop performance. Over time and with experience, growers will be able to build on their understanding of these basic indicators to improve their ability to respond to changes in the crop and to anticipate crop needs.

Optimizing the Greenhouse Environment for Crop Production

Greenhouse vegetable crop production is based on controlling the environment to provide the conditions most favorable for maximum yield. A plant's ability to grow and develop depends on the photosynthetic process. In the presence of light, the plant combines carbon dioxide and water to form sugars, which are then utilized for growth and fruit production. Optimizing the greenhouse environment is directed at optimizing the photosynthetic process in the plants, enhancing the plant's ability to utilize light at maximum efficiency.

Photosynthesis

$6\ CO_2 + 12\ H_2O$ - Light energy - $> C_6H_{12}O_6 + 6\ O_2 + 6\ H_20$

Photosynthesis is one of the most significant life processes; all the organic matter in living things comes about through photosynthesis.

The above formula is not quite complete as photosynthesis will only take place in the presence of chlorophyll, certain enzymes and cofactors. Without discussing all these requirements in detail, let it be enough to say that these cofactors, enzymes, and chlorophyll will be present if the plant receives adequate nutrition. One other point to clarify is that it takes 673,000 calories of light energy to drive the equation.

Photosynthesis requires certain inputs to get the desired outputs. Carbon dioxide and water are combined and modified to produce sugar. The sugars are further used to form more complex carbohydrates, oils and so on. Along with the photosynthetic process are many more processes in the plant that help ensure the plant can grow and develop using the energy from the light energy. From the grower's point of view, the result of photosynthesis is the production of fruit. This outcome serves to remind that the management decisions made in growing crops affect the outcome of how well the plant is able to run its photosynthetic engines to manufacture those products that are shipped to market.

Growers provide the nutrition and environment that direct the plant to optimize photosynthesis and fruit development. Crop management decisions require a knowledge of how to keep the plants in balance so that yield and the productive life of the crop are maximized.

Transpiration

Closely associated with the photosynthetic process is the process of transpiration. Transpiration can be defined as the evaporation of water from plants, and it occurs through pores in the leaf surface called stomata (Figure 1).

As water is lost from the leaf, a pressure is built up that drives the roots to find additional water to compensate for the loss. The evaporation of the water from the leaf serves to cool the leaf, ensuring that optimum leaf temperatures are maintained. As the roots bring additional water into the plant, they also bring in nutrients that are sent throughout the plant along with the water.

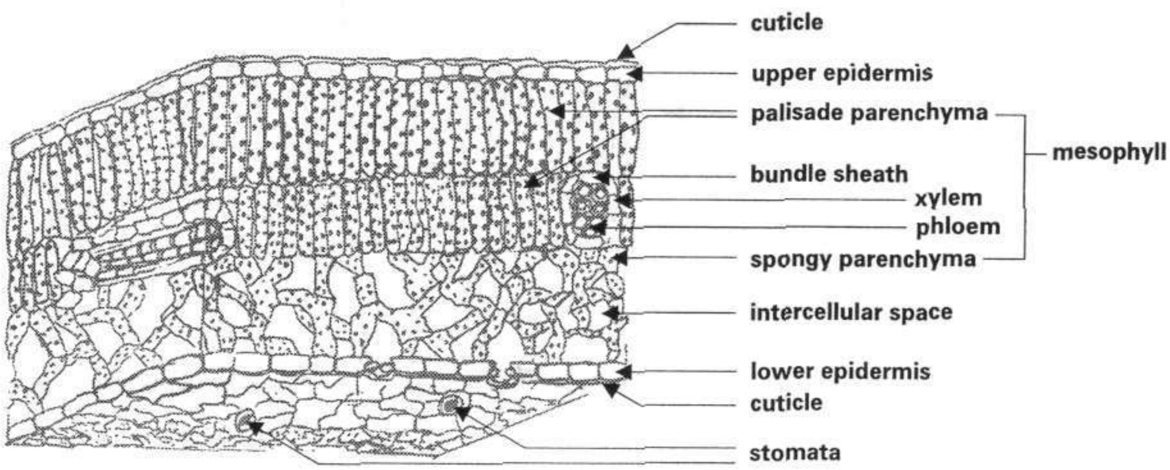

Figure 1. Cross section of leaf showing stomata

Water is a key component of photosynthesis, as is carbon dioxide (CO_2), which is often the limiting component of the process. The plant's source of carbon dioxide is the atmosphere, as carbon dioxide exists as a gas at temperatures in the growing environment. Carbon dioxide enters the plant through the stomata in the leaves. This is the stage where it can be seen why transpiration represents a compromise to photosynthesis for the plant.

Plants have control over whether the stomata are open or closed. They are closed at night and then open in response to the increasing light intensity that comes with the morning sun. The plant begins to photosynthesize, and the stomata open to allow more carbon dioxide into the leaf. As light intensity increases, so does leaf temperature, and water vapour is lost from the leaf, which serves to cool the leaf.

The compromise with photosynthesis occurs when the heat stress in the environment causes such a loss of water vapour through the stomata that the movement of carbon dioxide into the leaf is reduced. The other factor involved with this process is the relative humidity in the environment. The transpiration stress on a leaf and the plant at any given temperature is greater at a lower relative humidity than at a higher relative humidity. There also comes a point where the transpiration stress on the plant is so great that the stomata close and photosynthesis stops completely.

Respiration

Respiration is another process tied closely to photosynthesis. All living cells respire continuously, and the overall process involves the breakdown of sugars within the cells, resulting in the release of energy that is then used for growth. Through photosynthesis, plants utilize light energy to form sugars, which are then broken down by the respiration process, releasing the energy required by plant cells for growth and development.

Strategies

Photosynthesis responds instantaneously to changes in light, as light energy is the driving force behind the process. Light is generally a given, with greenhouse growers relying on natural light to grow their crops. Optimum photosynthesis can occur through providing supplemental lighting when natural light is limiting. This strategy is not common in Alberta greenhouses, with the economics involved in supplemental lighting being the determining factor.

The common strategy for optimizing photosynthesis comes about through optimizing transpiration. If, under any given level of light, transpiration is optimized such that the maximum amount of carbon dioxide is able to enter the stomata, then photosynthesis is also optimized. The benefit of optimizing photosynthesis through controlling transpiration is that the optimization can occur over both low and high light levels, even though photosynthesis proceeds at a lower rate under lower light levels. Supplemental lighting is only useful in optimizing photosynthesis when light levels are low.

Inherent to high yielding greenhouse crop production are the concepts of plant balance and directed growth. A plant growing in the optimum environment for maximum photosynthetic efficiency may not be allocating the resulting production of sugars for maximum fruit production. Greenhouse vegetable plants respond to a number of environmental triggers, or cues, and can alter their growth habits as a result.

The simplest example is to consider whether the plants have a vegetative focus or a generative focus. A plant with a vegetative focus is primarily growing roots, stems and leaves, while a plant with a generative focus is concentrating on flowers and fruit production. Vegetative and generative plant growth can be thought of as two opposite ends of a continuum; the point where maximum sustained fruit production takes place is where vegetative growth is balanced with generative growth. Complete optimization of the growing environment for crop production also includes providing the correct environmental cues to direct plant growth to maintain a plant balance for profitable production.

The critical environmental parameters affecting plant growth that growers can control in the greenhouse are as follows:

- temperature
- relative humidity
- carbon dioxide
- nutrition
- availability of water
- growing media

The way the environment affects plant growth is not necessarily straightforward, and the effect of one parameter is mediated by the others. The presence of the crop canopy also exerts considerable influence on the greenhouse environment. The ability of growers to provide the optimal environment for their crops improves over time, with experience. There is a conviction that environmental control of greenhouses is an art that expert growers practice to perfection. That being said, there are basic rules and environmental setpoints that beginning growers can follow as a blueprint to grow a successful crop.

As the plants develop from the seedling phase to maturity, the conditions that determine the optimum environment for the crop also change. Even when the crop is into full production, modifications of the environment may be necessary to ensure maximum production is maintained. For example, the plants may start to move out-of-balance to become too vegetative or too generative. Through all stages of the crop cycle, growers must train themselves to recognize the indicators displayed by the crop to determine what adjustments in the environment are necessary, if any.

Environmental Control of the Greenhouse

Greenhouse production is a year-round proposition. In Alberta, this concept means providing an optimal indoor growing environment when the outside environment can be warmer, or colder and drier, than what the crop plants require. Winter temperatures in Alberta can drop to - 30 to - 40°C, so the temperature differential between the greenhouse environment and the outdoors can range from 50 to 60°C. By contrast, during the summers, the outdoor temperatures can rise to +35°C under the intense Alberta sun; this situation is especially true in southern Alberta.

Greenhouse temperatures rise under intense sunlight. This rise in temperature is referred to as "solar gain." To enter the greenhouse, light has to travel through the greenhouse covering. In doing so, the light loses some of its energy, which is converted to heat. Without a cooling system, the temperature within the greenhouse can rise to over + 45°C. To successfully optimize the environment within the greenhouse means countering the adverse effects of the external environment as it varies over the seasons of the year.

The effectiveness of greenhouses to allow for environmental control depends on the component parts. This section of the publication describes the component parts of a typical Alberta vegetable production greenhouse, recognizing that specific systems for environmental control can vary and change from one greenhouse to the next. Over time, as new technology is developed and commercialized, the environmental control systems will change with the technology.

There are basic requirements for environmental control that all greenhouses must meet to be able to produce a successful crop. The simplest example of these requirements is that a structure is required.

Beyond this fundamental requirement, a number of options can be included. The most precise control of an environment invariably comes with the inclusion of more technology and equipment, with the associated higher cost. The driving forces for inclusion of newer or more complex systems are the effect on the financial bottom line and the availability of capital.

The Greenhouse Structure

The greenhouse structure represents both the barrier to direct contact with the external environment and the containment of the internal environment to be controlled. By design, the covering material allows for maximum light penetration for growing crops. A number of commercial greenhouse manufacturers and greenhouse designs are suitable for greenhouse vegetable crop production. The basic greenhouse design used for vegetable production, is a gutter connect greenhouse.

By design, a gutter connect greenhouse allows for relatively easy expansion of the greenhouse when additions are planned. Gutter connect greenhouses are composed of a number of "bays" or compartments running side by side along the length of the greenhouse (Figure 2).

Typically, these compartments are approximately 37 meters (120 feet) long by 6.5 to 7.5 meters (21 to 25 feet) wide. The production area is completely open between the bays inside the greenhouse. The roof of the entire structure consists of a number of arches, with each arch covering one bay, and the arches are connected at the gutters where one bay meets the next. The design of a gutter connect greenhouse allows for a single bay greenhouse of 240 m^2 (2,500 feet) to easily expand by the addition of more bays to cover an area of 1 hectare (2.5 acres) or more.

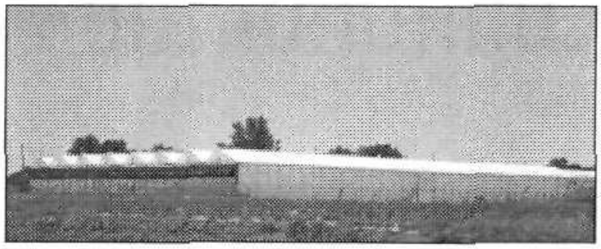

Figure 2. Typical gutter connect, double poly, vegetable production greenhouse

With a gutter connect greenhouse, the lowest parts of the roof are the gutters, the points where the adjacent arches begin and end. The trend for gutter heights in modern greenhouses is to increase, with greenhouses getting taller.

The reasons for this change are two-fold: firstly, newer vegetable crops like peppers require a higher growing environment. Peppers will often reach 3.5 meters (12 feet) in height during the course of the production cycle, so taller greenhouses allow for more options in crop handling and training.

Secondly, taller greenhouses allow for a larger air mass to be contained within the structure. The advantage is that a larger air mass is easier to control, with respect to maintaining an optimum environment, than a smaller air mass. Once a grower has established an environment in the larger air mass, it is easier to maintain the environment.

Typical gutter heights for modern greenhouse structures are 4 to 4.25 meters (13 to 14 feet) and are quite suitable for greenhouse pepper production. The trend for future gutter height is to increase further, with new construction designs moving to 4.9 to 5.5 meters (16 to 18 feet) (Figure 3).

There are a number of options for greenhouse covering materials: glass panels, polycarbonate panels and polyethylene skins. Each of the coverings has advantages and disadvantages, the main determining factors usually being the trade-off between cost and length of service. Glass is more expensive, but will generally have a longer service life than either polycarbonate or polyethylene.

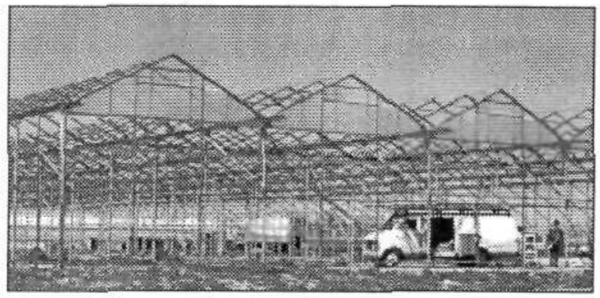

Figure 3. New greenhouse under construction

Typical Alberta vegetable production greenhouses are constructed with double polyethylene skins. Two layers of polyethylene are used, with pressurized air filling the space between the two layers to provide rigidity to the covering. The life expectancy of a polyethylene greenhouse covering is about four years.

Energy conservation is also an important factor. The covering must allow light into the greenhouse and yet reduce the heat loss from the greenhouse to the environment during the winter.

New coverings are being developed that selectively exclude certain wavelengths of light and, as a result, can help in reducing insect and disease problems.

Header house

The header house is an important component of the greenhouse design. The header house serves as a loading dock where produce is shipped and supplies are received. It also serves to house the nerve center of the environmental control system, as well as housing boilers and the irrigation and fertilizer tanks. The header house is kept separate from the main greenhouse, with access gained through doors.

Lunchroom and washroom facilities are also located in the header house. These facilities should be placed so that they satisfy all food safety requirements with respect to the handling of produce.

Plant nursery

The greenhouse design can also include a plant nursery for those vegetable growers interested in starting their own plants from seed. The alternative is to contract another greenhouse to grow and deliver young plants ready to go into the main production area. For example, pepper plants are transplanted into the main greenhouse at about six weeks of age.

Growers starting their plants from seed must have a nursery area in which to do this. It is important to have a nursery of adequate size to supply enough transplants for the entire area of the production greenhouse. Generally speaking, the nursery area is built so that growers can achieve a higher degree of specific environmental control than the main production area of the greenhouse since young plants are more sensitive to the environment. The nursery area can be used for production once the seedlings have been moved out. Heated benches or floors are a must, as is supplemental lighting. The specific requirements for pepper seedling production are discussed in detail in Alberta Agriculture's *Commercial Greenhouse Bell Pepper Production in Alberta* manual.

Heating the Greenhouse

An adequately-sized heating system is a must for greenhouse production in Alberta. The output of the system must be able to maintain optimal temperatures on the coldest days of the year. Beyond the actual size of the system, and deciding what form of heating to use, i.e. forced air, boiler heat, or both; there are special factors to consider as to where the heat is applied.

Heat applied to the air is directed at influencing the plant canopy; heat is applied to the floor to influence the root system. The basic premise behind this concept of directing heat to both the air and the floor is that it is difficult to provide optimum root zone temperatures during the cold period of the year by heating the air only.

Beside the difficulty in driving warm air down to the greenhouse floor, there is also the associated problem of having to provide too much heat to the canopy as growers try to optimize root zone temperature. Conversely, although floor heat (usually hot water systems) can easily maintain root zone temperature, floor heat systems cannot be used to optimize air temperatures without causing excessive root zone temperatures.

It is also important to note that heating systems can also be employed in combination with controlled venting to dehumidify the greenhouse.

Heating the air and plant canopy

Forced air systems are common in Alberta greenhouses. Overhead natural gas burning furnaces are normally located at one end of the greenhouse. These systems move the heated air down the length of the greenhouse to the far end. There are a number of types of forced air systems, and all try to ensure the heat is adequately distributed throughout the greenhouse to maintain the air temperature set points.

Boilers and pipe and fin systems can also be used to provide heat to the air. The main consideration for heating the air is uniform distribution of the heat throughout the entire greenhouse so that the entire plant canopy is affected equally.

Heating the root zone

The most common system to provide heat to the floor or root zone is the "pipe and rail" system. A 5 centimeter (2 inch) diameter steel pipe is placed on the floor between the rows of the crop so that the pipe runs down and returns along the same row approximately 45 centimeters (18 inches) apart. Boilers deliver hot water through this heating pipe.

The delivery and return pipe run parallel to one another, forming a "rail" that can be used by carts to run up and down the rows (Figure 4). The carts are useful when working with the plants during pruning and harvest. With this application, the heating pipes serve a dual purpose.

Heating the plant heads

The term "plant head" is not likely to be found in any botany textbook. Greenhouse vegetable growers use the term to refer to the tops of the plant where the growing points are actively developing new shoots, leaves, flowers and young fruit. Some growers run hot water fin pipe 15 centimeters (6 inches) above the plant heads to obtain a more precise temperature control. This approach optimizes pollination of the flowers as well as enhancing the early stages of fruit and leaf development. This pipe is then raised as the crop grows. Currently, this system is not commonly employed by Alberta greenhouse vegetable growers.

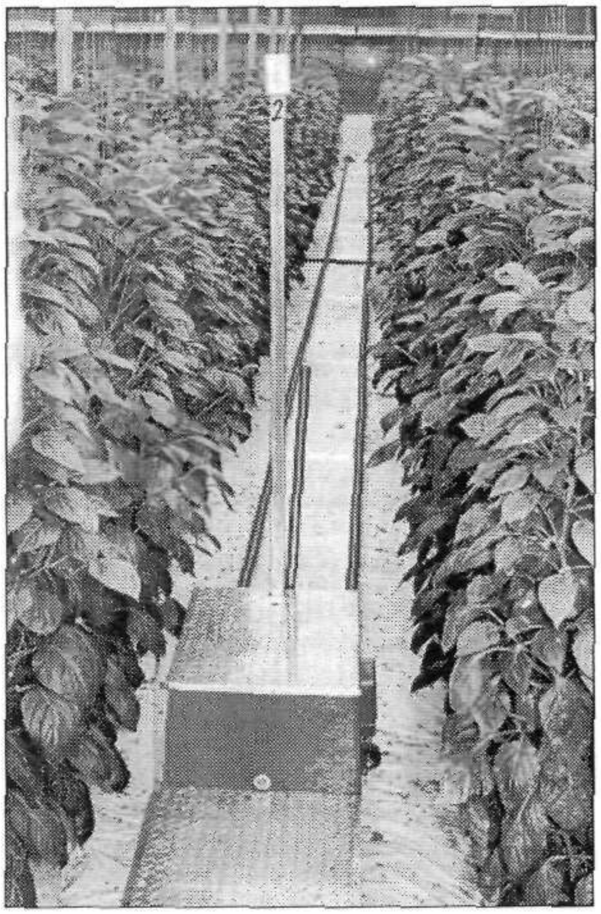

Figure 4. Pipe and rail floor heat and electric cart

Ventilation and Air Circulation

Ventilation systems

The ventilation system provides the means by which the greenhouse air is circulated, mixed and exchanged. The system allows for a more uniform climate and helps to distribute heat from the heating system as well as to remove heat from the greenhouse when cooling is required. In combination with the heating system, ventilation also provides a means for dehumidifying the greenhouse environment.

Ventilation is required throughout the year; however, the ventilation required varies depending on the outside environment. During the winter months, ventilation is required primarily for dehumidification as warm, humid air is exhausted and cool, dry air is brought in.

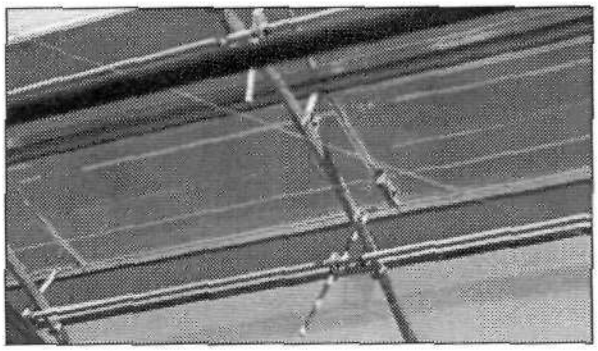

Figure 5. Ridge vent

The important consideration when bringing cold air in is proper mixing with the main mass of greenhouse air to minimize the negative effects of the cold air contacting the plants. Maximum winter ventilation rates in Alberta usually do not exceed fifteen air changes per hour.

Under Alberta conditions, summer ventilation serves primarily to help cool the crop; venting for dehumidification is not usually the goal. In fact in southern Alberta, maintaining humid air is often the concern. Summer ventilation is triggered primarily by temperature set points, and as air is moved through the greenhouse to remove heat, humidity is also lost. So much so that it is difficult to maintain optimum relative humidity levels without also having mist systems or other cooling systems in place. Maximum summer air exchange rates are in the range of one complete air exchange every 45 to 60 seconds.

Ventilation systems can be primarily mechanical, relying on exhaust fans, or natural, relying on the natural upward movement of hot air to exit the greenhouse through ridge or gutter vents (Figure 5). The mechanical or forced air ventilation equipment can be costly both to purchase and to operate. However, forced ventilation is required for some evaporative cooling systems to function.

Air circulation, horizontal air flow (HAF) fans

Additional air circulation within the greenhouse can provide for more uniform distribution of carbon dioxide, humidity and temperature, especially during the winter. Used in combination with the ventilation system, recirculating fan systems ensure the cold air brought in by the ventilation system mixes uniformly with the warm inside air. The fans are relatively inexpensive to operate and are located in such a way so as to move air along the length of the greenhouse, with the direction of movement alternating between adjacent bays.

The fans must be of adequate size to ensure that proper mixing of the air occurs without the fans being over-sized, which can cause excessive air movement and a reduction in yield. The general recommendation for sizing is a fan capacity of 0.9 to 1.1 cubic meters per minute per square meter of floor area, with a velocity no greater that 1 meter per second across the plants.

Cooling and Humidification

During periods of high light intensity, air temperatures rise inside the greenhouse, and cooling is required. Increasing ventilation rates serves to bring cooler outside air into the greenhouse. But during the typical Alberta summer months, ventilation alone is often not enough to maintain optimum greenhouse air temperatures.

Alberta growers depend on cooling systems to ensure optimum growing temperatures are maintained. These cooling systems also serve to humidify the greenhouse. Requirements for cooling and humidification vary depending on location within the province. Southern Alberta growers generally contend with harsher summer growing conditions, higher outside temperatures and lower outside relative humidity than growers in central Alberta. In areas of the province where cooling is required, evaporative cooling systems are used. Evaporative cooling is most effective in areas where the outside relative humidity is less than 60 per cent.

Pad and fan evaporative cooling

As the name implies, evaporative cooling pads are used in conjunction with mechanical ventilation systems to reduce the temperatures inside the greenhouse. The principle of the system is that outside air is cooled by drawing it through continually wetted pads (Figure 6). Pad systems work best in tightly-built greenhouses because these systems require that the air entering the greenhouse must first pass through the pad rather than holes or gaps in the walls. If the greenhouse is not tightly built, the incoming air will bypass the evaporative pads as the pads provide more resistance to air movement than do holes or gaps. Exhaust fans at the opposite end of the greenhouse provide the necessary energy to draw the outside air through the pads. As the air passes through the pad and is cooled, the air also takes up water vapour and adds humidity to the greenhouse.

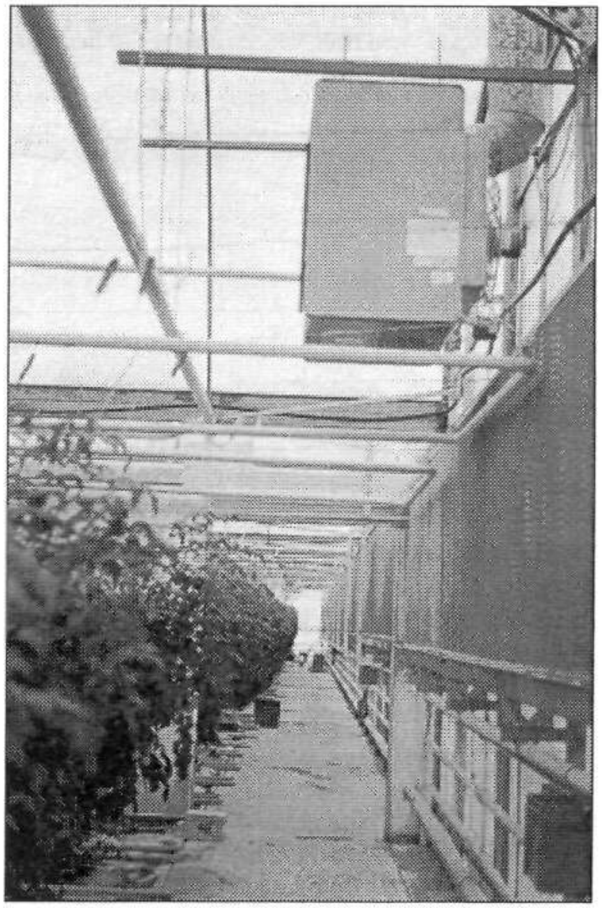

Figure 6. Evaporative pad

Mist systems

Both high and low-pressure mist systems are used for cooling and adding humidity to the greenhouse. Mist systems can be employed in both mechanically and naturally ventilated greenhouses. Mist systems work by forcing water through nozzles that break up the water into fine droplets. This process allows the droplets to evaporate fairly quickly into the air. Because the evaporation of water requires heat from the environment, the air is cooled (Figure 7).

Misting systems must be carefully controlled for two reasons: to provide the required cooling without increasing the relative humidity beyond optimum levels for plant performance and to prevent free water from forming on the plants, which can encourage the development of disease.

If the quality of the water used for misting is poor, there is the possibility of mineral salts being deposited on the leaves and fruit, which could result in reduced fruit quality and yield loss.

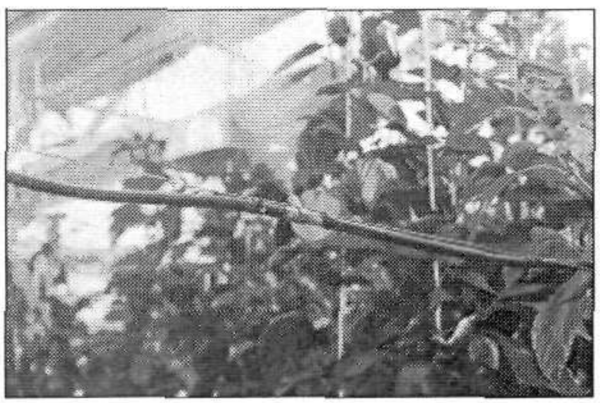

Figure 7. High pressure mist nozzle

Greenhouse Floors

Preparation of the greenhouse floor for greenhouse vegetable production is important to the overall operation of the greenhouse. The floor is contoured so that low spots, which would allow for the pooling of water, are eliminated. Small channels are placed in alignment with the crop rows, with one channel running the length of the single or double row. These channels allow for any drainage from irrigation to the plants to be carried to one end of the greenhouse to the holding tanks for recirculation.

These channels are approximately 15 centimeters wide by 15 centimeters deep (6 inches by 6 inches). The depth varies slightly from one end of the channel to the other, so the water drains towards a common end of the greenhouse. Another channel then carries the water towards a reservoir in the floor located in one corner of the greenhouse.

The floor is covered with white plastic film to seal off the soil from the greenhouse environment, reducing the problems associated with soil borne plant diseases and weed problems. The plants are rooted in bags or slabs of growing media placed on top of the plastic floor. The white plastic also serves to reflect any light reaching the floor back up into the plant canopy. Estimates place the amount of light reflected back into the crop by white plastic floors to be about 13 per cent of the light reaching the floor. This reflected light can increase crop yield.

Due to the large area under production, concrete floors are generally too expensive for greenhouses. A concrete walkway is a practical necessity, usually running the width of the greenhouse along one end wall. This walkway allows for the efficient, high traffic movement of staff within the greenhouse and the subsequent movement of produce out of the greenhouse.

Carbon Dioxide Supplementation

Carbon dioxide (CO_2) plays an important role in increasing crop productivity. An actively photosynthesizing crop will quickly deplete the CO_2 from the greenhouse environment. In summer, even with maximum ventilation, CO_2 levels within the typical Alberta vegetable production greenhouse typically fall below ambient levels of CO_2 [below 350 parts per million (350 ppm)]. It has been estimated that if the amount of CO_2 in the atmosphere doubled to 700 ppm, the yield of field crops should increase by 33 per cent. Optimum CO_2 targets in the greenhouse atmosphere are generally accepted to be approximately 700 to 800 ppm.

CO2 supplementation via combustion

As carbon dioxide is one of the products of combustion, this process can be used to introduce CO_2 into the greenhouse. The major concern with using combustion is that CO_2 is only one of the products of combustion. Other gases that can be produced by the combustion process are detrimental to crop production (see the section on "Air Pollution in the Greenhouse" later in this publication). The production of pollutant gases from combustion depends on the type and quality of the fuel used for combustion and whether complete combustion occurs. Faulty burners could result in incomplete combustion.

Natural gas CO_2 generators

One method of CO_2 supplementation in Alberta greenhouses is the use of natural gas burning CO_2 generators placed throughout the greenhouse above the crop canopy (Figures 8 and 9). Under lower light, low ventilation conditions, these generators can effectively maintain optimum CO_2 levels. However, during periods of intense summer sunlight, it is still difficult to maintain ambient CO_2 levels in the crop. Also, since the combustion process takes place in the greenhouse, the heat of combustion contributes to driving the greenhouse temperatures higher, increasing the need for cooling. Even distribution of the CO_2 throughout the crop is also difficult to obtain because the CO_2 originates from point sources above the canopy. A fresh air intake should be provided when using these generators to ensure adequate combustion air.

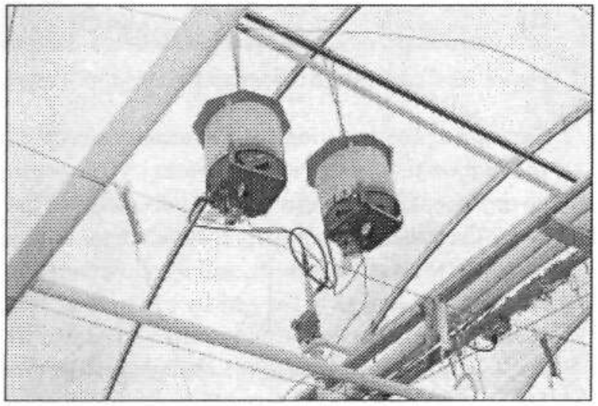

Figure 8. Natural gas CO_2 generators

Boiler stack recovery systems

Stack recovery systems are receiving more attention by Alberta growers. These systems require a clean burning, high output boiler and a system to recover the CO_2 from the exhaust stack for distribution to the crop. The CO_2 is directed through pipes placed within the crop rows. With this method, the CO_2 distribution is improved by introducing the CO_2 right to the plant canopy. Carbon monoxide can also be present in the exhaust gas, and sensors are used to regulate the delivery of exhaust gas into the greenhouse and ensure that carbon monoxide levels do not rise to unsafe levels.

Liquid CO_2 supplementation

Liquid CO_2 is another alternative for supplementation. The advantage with liquid CO_2 is that it is a clean source of CO_2 for the greenhouse because the other by-products of combustion are not present. As a result, liquid CO_2 is especially advantageous for use on sensitive seedling plants early in the crop season. Distribution to the crop can be achieved through a system of delivery pipes to the crop canopy, similar to the stack recovery systems.

The drawback with the use of liquid CO_2 has been the cost. Historically, it has been less expensive to obtain CO_2 through the combustion of natural gas than by buying liquid carbon dioxide. Recent work at the Crop Diversification Centre South in Brooks has developed a cost effective method for liquid CO_2 supplementation under Alberta greenhouse growing conditions.

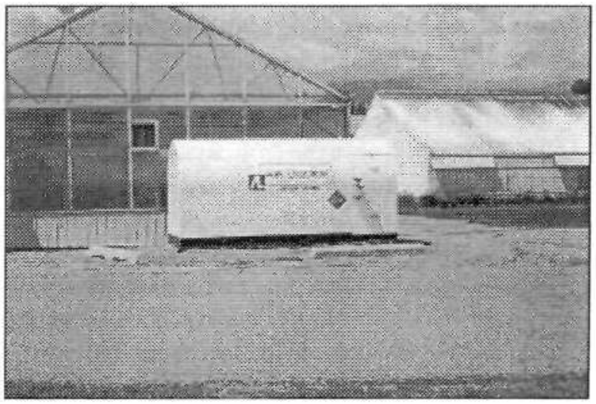

Figure 9. Liquid CO_2 tank

Irrigation and Fertilizer Feed Systems

The fertilizer and irrigation systems provide control of the delivery of water and nutrients to the plants. The two systems complement each other to deliver precise amounts of water and fertilizer to the plants as frequently as required. The systems can be configured a number of ways; however, the basic requirements are that incoming water is injected or amended with precise amounts of fertilizer before being delivered to the plants. The key point to keep in mind is that every time a plant is watered, it also receives fertilizer.

Pumps deliver the fertilizer and water through hoses running the length of each of row. Small diameter tubing, spaghetti tubes, come off the main hoses with one tube generally feeding one plant.

The systems are designed so the amount of fertilizer and water delivered to the plants is equal throughout the greenhouse. Larger greenhouses are often partitioned into a number of zones for watering, with each zone watered sequentially in turn. The watering is modified independently in each zone as required.

Recirculating systems add another level of complexity to the process. In most modern vegetable greenhouses, a certain percentage of the water delivered to the plants on a daily basis is allowed to flow past the root system. The water that flows past the plant roots is referred to as the "leachate." The principles of leaching, as well as how to fertilize and water the crop, are explained in more detail in the section on "Fertilizer and Water Application."

Recirculating systems are designed to collect the leachate for reuse in the crop. Reusing the leachate minimizes the loss of fertilizer and water from the greenhouse to the environment. Before the leachate can be reused, it must first be treated to kill any disease organisms that may have accumulated in the system. A number of treatment methods are available and include UV light, ozone treatment, heat pasteurization and biofiltration.

Computerized Environmental Control Systems

Computerized environmental control systems allow growers to integrate the control of all systems involved in manipulating the greenhouse environment. The effect is to turn the entire greenhouse and its component systems into a single instrument for control, where optimum environmental parameters are defined, and control is the result of the on-going input of the component systems acting in concert (Figure 10).

Virtually all computer programs for controlling the greenhouse environment provide for optimal plant growth. A wide variety of computerized control systems are on the market. Generally, the higher the degree of integration of control of the various component systems, i.e. heating, cooling, ventilation and irrigation systems, the higher the cost of the computer system.

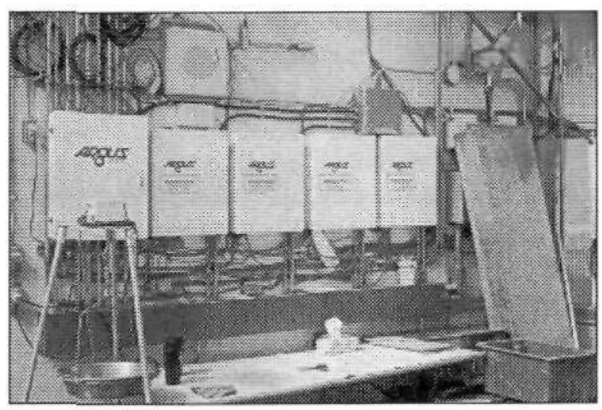

Figure 10. Computerized environmental control system

Optimizing the environment for maximum crop production requires timely responses to changes in the environment and the changing requirements of the crop. The greenhouse environment changes as the crop responds to its environment, and the environment changes in response to the activity of the crop. Fast crop processes such as photosynthesis are considered to respond instantaneously to the changing environment. Due to the dynamics of the greenhouse and the inertia of the environment, it takes longer to implement changes to the environment, upwards of 15 minutes.

Much of the disturbance to the greenhouse environment is due to the following factors: the normal cycle of the day/night periods, the outside temperature and the effects of scattered clouds on an otherwise sunny day. The environmental control system has to continually work to modify the environment to optimize crop performance in response to ongoing change of the dynamic environment.

The computer system's ability to control the environment is only as good as the information it receives from the environment. The computer's contact with the environment occurs through various sensors recording temperature, relative humidity, light levels and CO_2 levels. It is important that quality sensors be used and routinely maintained to ensure they are operating properly (Figure 11).

Sensor placement is also important to ensure accurate readings of the crop environment. For example, a temperature sensor placed in direct sunlight is going to give a different set of readings than a temperature sensor placed within the crop canopy.

Figure 11. Environmental sensor box

Managing the Greenhouse Environment

This section looks at how the environmental control tools that growers have at their disposal are manipulated, with respect to the important environmental influences on plant growth and development, to optimize the greenhouse environment. As noted earlier in this publication, the primary goal of optimizing the greenhouse environment is to maximize the photosynthetic process in the crop. The strategy used to maximize photosynthesis is to manage transpiration. Therefore, ongoing modifications are made to the greenhouse environment to manage the transpiration of the crop to match the maximum rate of photosynthesis.

Growth can be defined as an increase in biomass or the increase in size of a plant or other organism. Plant growth is associated with changes in the numbers of plant organs occurring through the initiation of new leaves, stems and fruit, abortion of leaves and fruit and the physiological development of plant organs from one age class to the next.

Managing the growth and development of an entire crop for maximum production involves the manipulation of temperature and humidity to obtain both the maximum rate of photosynthesis under the given light conditions and the optimum balance of vegetative and generative plant growth for sustained production and high yields. This statement implies that growers can direct the results of photosynthesis (the production of assimilates, sugars and starches) towards both vegetative and generative growth, in a balance.

Generative growth is the growth associated with fruit production. For maximum fruit production to occur, the plant has to be provided with both the appropriate cues to trigger the setting of fruit and the cues to maintain adequate levels of stem and leaf development (vegetative growth). The balance is achieved when the assimilates from photosynthesis are directed towards maintaining the production of the new leaves and stems required to support the continued production of fruit. The appropriate cues are provided through the manipulation of the environment and are subject to change depending on the behavior of the crop.

Careful attention must be paid to the signals given by the plant, the indicators of which direction the plant is primarily headed, vegetative or generative, and how corrective action is applied through further manipulation of the environment.

Light

Light limits the photosynthetic productivity of all crops and is the most important variable affecting productivity in the greenhouse. The transpiration rate of any greenhouse crop is the function of three variables: ambient temperature, humidity and light. Of these three variables, light is the given, the natural light received from the sun.

Supplementary lighting does offer the opportunity to increase yield during low light periods, but it is generally considered commercially unprofitable. The other means for manipulating light are limited to screening or shading, and these approaches are employed when light intensities are too high. However, general strategies help to maximize the crop's access to the available light in the greenhouse.

Properties and measurement of light

To understand how to control the environment to make the maximum use of the available light in the greenhouse, it is important to know about the properties of light and how light is measured. Considerable confusion has existed regarding the measurement of light; however, it is worthwhile for growers to approach the subject.

Light has both wave properties and properties of particles or photons. Depending on how light is considered, the measurement of light can reflect either its wave or particle properties. Different companies provide a number of different types of light sensors for use with computerized environmental control systems. It is important that the sensors measure the amount of light available to the plants. For practical purposes, it is not as important how the light is measured as it is for growers to understand how these measurements relate to crop performance.

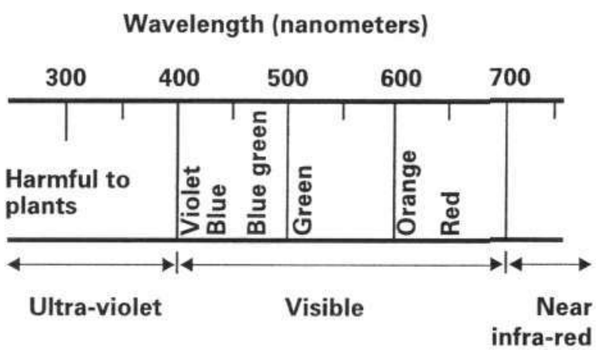

Figure 12. The visible spectrum

Light is a form of radiation produced by the sun, electromagnetic radiation. A narrow range of this electromagnetic radiation falls within the range of 400 to 700 nanometers (nm) of wavelength, one nanometer being equal to 0.000000001 meters. The portion of the electromagnetic spectrum that falls between 400 to 700 nm is referred to as the spectrum of visible light, which is essentially the range of the electromagnetic spectrum that can be seen. Plants respond to light in the visible spectrum, and they use this light to drive photosynthesis (Figure 12).

Photosynthetically Active Radiation (PAR) is defined as radiation in the 400 to 700 nm waveband. PAR is the general term that covers both photon terms and energy terms. The rate of flow of radiant (light) energy in the form of an electromagnetic wave is called the radiant flux, and the unit used to measure this rate is the Watt (W). The units of Watts per square meter (W/m^2) are used by some light meters and represent an example of an "instantaneous" measurement of PAR. Other meters commonly seen in greenhouses take "integrated" measurements, reporting in units of joules per square centimeter (j/cm^2). Although the units seem fairly similar, there is no direct conversion between the two.

Photosynthetic Photon Flux Density (PPFD) is another term associated with PAR, but refers to the measurement of light in terms of photons or particles. PPFD is also sometimes referred to as Quantum Flux Density. Photosynthetic Photon Flux Density is defined as the number of photons in the 400 - 700 nm waveband reaching a unit surface per unit of time. The units of PPFD are micromoles per second per square meter ($\mu mol/s\ m^2$).

As the scientific community begins to agree on how best to measure light, there may be more standardization in light sensors and the units used to describe the light radiation reaching a unit area. Greenhouse growers will still be left with the task of making day-to-day meaning of the light readings with respect to control of the overall environment. Generally speaking, the more intense the light, the higher the rate of photosynthesis and transpiration (increased humidity), as well as solar heat gain in the greenhouse. Of these factors, it is heat gain that usually calls for modification of the environment as temperatures rise on the high end of the optimum range for photosynthesis, and ventilation and cooling begins. Plants also require more water under increasing light levels.

Plant light use

Plants use the light in the 400 to 700 nm range for photosynthesis, but they make better use of some wavelengths than others. Figure 13 presents the photosynthetic action spectrum of plants, the relative rate of photosynthesis of plants over the range of PAR,

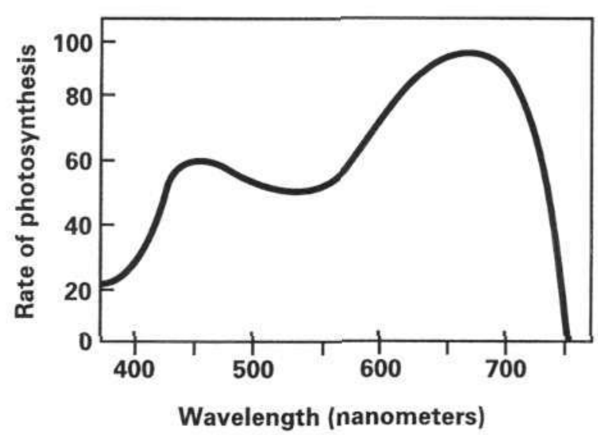

Figure 13. The photosynthetic action spectrum

photosynthetically available light. All plants show a peak of light use in the red region, approximately 650 nm and a smaller peak in the blue region at approximately 450 nm.

Plants are relatively inefficient at using light and are only able to use about a maximum of 22 per cent of the light absorbed in the 400 to 700 nm region. Light use efficiency by plants depends not only on the photosynthetic efficiency of plants, but also on the efficiency of the interception of light.

Accessing available light

The high cost of greenhouse production requires growers to maximize the use of light falling on the greenhouse area. Before the crops are able to use the light, it first has to pass through the greenhouse covering, which does not transmit light perfectly. The greenhouse intercepts a percentage of light falling on it, allowing a maximum of 80 per cent of the light to reach the crop at around noon, with an overall average of 68 per cent over the day. However, the greenhouse covering also partially diffuses or scatters the light coming into the greenhouse so that the light is not all moving in one direction. The implication of this outcome is that scattered light tends to reach more leaves in the canopy rather than directional light, which throws more shadows.

The crop should be oriented in such a way that the light transmitted through the structure is optimized to allow for efficient distribution to the canopy. Greenhouse vegetable crops have a vertical structure in the greenhouse, so light filters down through "layers" of leaves before a smaller percentage actually reaches the floor.

Leaf area index (LAI) is widely used to indicate the ratio of the area of leaves over the area of ground the leaves cover. The optimum leaf area index varies with the amount of sunlight reaching the crop. Under full sun, the optimum LAI is 7, at 60 per cent full sun, the optimum is 5, at 23 per cent full sunlight, the optimum is only 1.5. Leaf area indexes of up to 8 are common for many mature crop communities, depending on species and planting density. Mature canopies of greenhouse sweet peppers have a relatively high leaf area index of approximately 6.3 when compared to greenhouse cucumbers and tomatoes at 3.4 to 2.3 respectively.

In Alberta, vegetable crops are seeded in November to December, the low light period of the year. Young crops have lower leaf area indexes, which increase as the crop ages. Under this crop cycle, the plants are growing and increasing their LAI as the light conditions improve. Crop productivity increases with LAI up to a certain point because of more efficient light interception. As LAI increases beyond this point, no further efficiency increases are realized, and in some cases, decreases occur.

There is also a suggestion that an efficient crop canopy must allow some penetration of PAR below the upper-most leaves, and the sharing of light by many leaves is a prerequisite for high productivity. Leaves can be divided into two groups: sun leaves that intercept direct radiation and shade leaves that receive scattered radiation. The structures of these leaves are distinctly different.

The major greenhouse vegetable crops (tomatoes, cucumbers and peppers) are arranged in either single or double rows. These arrangements of the plants, and subsequent leaf canopy, represent an effective compromise between accessibility to work the crop and light interception by the crop. For a greenhouse pepper crop, this canopy provides for light interception exceeding 90 per cent under overcast skies and 94 per cent for much of the day under clear skies.

There is a dramatic decrease in interception that occurs around noon, and lasts for about an hour, when the sun aligns along the axis of north-south aligned crop rows. Interception falls to 50 per cent at the gap centers where the remaining light reaches the ground, and the overall interception of the canopy drops to 80 per cent.

A strategy to reduce this light loss would be to align the rows east-west, instead of north-south. The reduced light interception would then occur when the sun aligns with the rows early and late in the day when the light intensities are already quite low. The use of white plastic ground cover can reflect back light that has penetrated the canopy and can result in an overall light increase of 13 per cent over crops without white plastic ground cover.

The effect of row orientation varies with time of the day, season, latitude and canopy geometry. It has been demonstrated that at 34° latitude, north-south oriented rows of tall crops, such as tomatoes, cucumbers and peppers, intercepted more radiation over the growing season than those oriented east-west. This finding was completely the opposite for crops grown at 51.3° latitude. The majority of greenhouse vegetable crop production in Alberta occurs between 50° (Redcliff) and 53° (Edmonton) North.

This situation would suggest that the optimum row alignment of tall crops for maximum light interception over the entire season in Alberta would be east-west. However, in Alberta, high yielding greenhouse vegetable crops are grown in greenhouses with north-south aligned rows as well as in greenhouses with east-west aligned rows.

Alberta is known for its sunshine, and the sun is not usually limiting during the summer. In fact, many vegetable growers apply whitewash shading to the greenhouses during the high light period of the year because the light intensity and associated solar heat gain can be too high for optimal crop performance.

The strategies for increasing light interception by the canopy should focus specifically on the times in year when light is limiting. For Alberta, this period occurs in early spring and late fall. When light is limiting, a linear function exists between light reduction and decreased growth, with a 1 per cent increase in growth occurring with a 1 per cent increase in light, at light levels below 200 W/m^2.

Supplementary Lighting

When light levels are limiting, supplementary lighting will increase plant growth and yield. However, the use of supplemental lighting has its limits as well. For example, using supplemental lighting to increase the photoperiod to 16 and 20 hours increased the yield of pepper plants while continuous light decreased yields compared to the 20-hour photoperiod.

The economics of artificial light supplementation generally do not warrant the use of supplementary light on a greenhouse vegetable crop in full production. However, supplementary lighting of seedling vegetable plants before transplanting into the production greenhouse is recommended for those growers growing their own plants from seed.

Light is generally limiting in Alberta when greenhouse vegetable seedlings are started in November to December. Using supplemental lighting for seedling transplant production when natural light is limiting has been shown to result in increased weight of tomato and pepper transplants grown under supplemental light compared to control transplants grown under natural light. Also, young plants exposed to supplemental light were ready for transplanting one to two weeks earlier than plants grown under natural light.

When supplemental lighting was combined with carbon dioxide supplementation at 900 ppm, not only did the weight of the transplants increase, but total yield of the tomato crop was also higher by 10 per cent over the control plants.

It is recommended that supplementary lighting be used for the production of vegetable transplant production in Alberta during the low light period of the year. This translates to about four to seven weeks of lighting, depending on the crop. Greenhouse sweet peppers are transplanted into the production greenhouse at six to seven weeks of age.

The amount of light required varies with the crop but ranges between approximately 120 - 180 W/m^2, coming from 400 W lights (Figure 14). A typical arrangement of lights for the seedling/transplant nursery would include lights in rows 1.8 m (6 ft) off the floor, spaced at 2.7 m (9 ft.) along a row, with 3.6 m (12 ft) between rows.

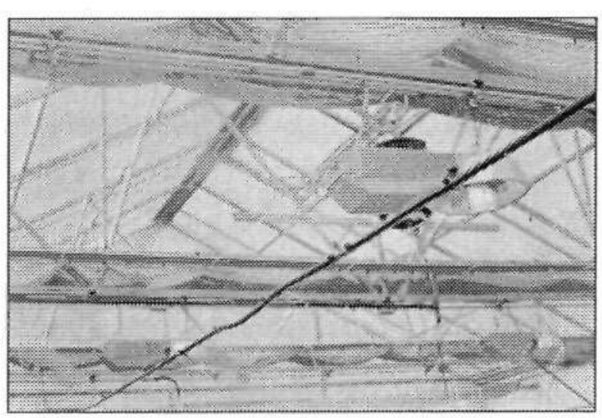

Figure 14. High pressure 400 W sodium light

Natural light levels vary throughout the province, with areas in southern Alberta at 50° latitude receiving 13 per cent more light annually than areas around Edmonton at 53° latitude.

Strategies to optimize the use of available light for commercial greenhouse production involve a number of crop management variables. Row orientation, plant density, plant training and pruning, maintaining optimum growing temperatures and relative humidity levels, CO_2 supplementation and even light supplementation all play a role. All the variables must be optimized for a given light level for a given crop, and none of these variables are independent of one another. If a grower manipulates one variable, then the others will be affected.

Temperature Management

The development and flowering of the plants relates to both root zone and air temperature, and temperature control is an important tool for the control of crop growth.

Managing air temperatures

The optimum temperature is determined by the processes involved in the utilization of assimilate products of photosynthesis, i.e. distribution of dry matter to shoots, leaves, roots and fruit. For the control of crop growth, the average temperature over one or several days is more important than the day/night temperature differences. This average temperature is also referred to as the 24-hour average temperature or 24-hour mean temperature. Various greenhouse crops show a very close relationship between growth, yield and the 24-hour mean temperature.

With the goal of directing growth and maintaining optimum plant balance for sustained high yield production, the 24-hour mean temperature can be manipulated to direct the plant to be more generative in growth or more vegetative in growth. Optimum photosynthesis occurs between 21° to 22°C. This temperature serves as the target for managing temperatures during the day when photosynthesis occurs.

Optimum temperatures for vegetative growth for greenhouse peppers is between 21° to 23°C, with the optimum temperature for yield about 21°C. Fruit set, however, is determined by the 24-hour mean temperature and the difference in day/night temperatures, with the optimum night temperature for flowering and fruit setting at 16° to 18 °C. Target 24-hour mean temperatures for the main greenhouse vegetable crops (cucumbers, tomatoes, peppers) can vary from crop to crop with differences even between cultivars of the same crop.

The 24-hour mean temperature optimums for vegetable crops generally range between 21° to 23°C, depending on light intensity. The general management strategy for directing the growth of the crop is to raise the 24-hour average temperature to push the plants in a generative direction and to lower the 24-hour average temperature to encourage vegetative growth. Adjustments to the 24-hour mean temperature are made usually within only 1° to 1.5°C, with careful attention paid to the crop response.

One assumption made when using air temperature as the guide to directing plant growth is to assume that it represents the actual plant temperature. The role of temperature in the optimization of plant performance and yield is ultimately based on the temperature of the plants.

Plant temperatures are usually within a degree of air temperature; however, during the high light periods of the year, plant tissues exposed to high light can reach 10 ° to 12 °C higher than air temperatures. It is important to be aware of this fact and to use strategies such as shading and evaporative cooling to reduce overheating of the plant tissues. Infra-red thermometers are useful for determining actual leaf temperature.

Precision heat in the canopy

Precision heating of specific areas within the crop canopy adds another dimension of air temperature control beyond maintaining optimum temperatures of the entire greenhouse air mass. Using heating pipes that can be raised and lowered, heat can be applied close to flowers and developing fruit to provide optimum temperatures for maximum development in spite of the day-night temperature fluctuations required to signal the plant to produce more flowers. The rate of fruit development can be enhanced with little effect on overall plant balance and flower set.

The precise application of heat in this manner can avoid the problem of low temperatures to the flowers and fruit, a situation known to disturb flowering and fruit set. The functioning of pepper flowers is affected below 14°C; the number of pollen grains per flower are reduced, and fruit set under low night temperatures are generally deformed.

Problems with low night temperatures can be sporadic in the greenhouse during the cold winter months and can occur even if the environmental control system is apparently meeting and maintaining the set optimum temperature targets. There can be a number of reasons for this situation, but the primary reasons include:

- lags in response time between the system's detection of the heating setpoint temperature and when the operation of the system is able to provide the required heat throughout the greenhouse
- specific temperature variations in the greenhouse due to drafts and "cold pockets"

Managing root zone temperatures

Root zone temperatures are managed primarily to remain in a narrow range to ensure proper root functioning. Target temperatures for the root zone are 18° to 21°C. Control of the root zone temperature is primarily a concern for Alberta growers in winter, and this control is obtained through the use of bottom heat systems such as pipe and rail systems. Control is maintained by monitoring the temperature at the roots and then subsequently maintaining the pipe at a temperature that ensures optimum root zone temperature.

The use of tempered irrigation water is also a strategy employed by some growers. Maintaining warm irrigation water (20°C is optimum) minimizes the shock to the root system associated with the delivery of cold irrigation water. In some cases during the winter months, in the absence of a pipe and rail system, root zone temperatures can drop to 15°C or lower. The performance of most greenhouse vegetable crops is less than optimum at this low root zone temperature.

Using tempered irrigation water alone is not usually successful in raising and maintaining root zone temperatures to optimum levels. The reasons for this are twofold. Firstly, the volume of water required for irrigation over the course of the day during the winter months is too small to allow for the adequate, sustained warming of the root zone. Secondly, the temperature of the irrigation water would have to be almost hot to effect any immediate change in root zone temperature. Root injury can begin to occur at water temperatures in excess of 23°C in direct contact with the roots. The recommendation for irrigation water temperature is not to exceed 24° to 25°C.

The purpose of the irrigation system is to optimize the delivery of water and nutrients to the root systems of the plants. Using the system for any other purpose generally compromises the main function of the irrigation system.

Systems for controlling root zone temperatures are confined primarily to providing heat during the winter months. During the hot summer months, temperatures in the root zone can climb to over 25°C if the plants are grown in sawdust bags or rockwool slabs and if the bags are exposed to prolonged direct sunlight. Avoiding high root zone temperatures is accomplished primarily by ensuring an adequate crop canopy to shade the root system. Also, since larger volumes of water are applied to the plants during the summer, ensuring that the irrigation water is relatively cool, approximately 18°C (if possible), will help in preventing excessive root zone temperatures.

One important point to keep in mind with respect to irrigation water temperatures during the summer months is that irrigation pipe exposed to the direct sun can cause the standing water in the pipe to reach very high temperatures, over 35°C! Irrigation pipe is often black to prevent light penetration into the line, which can result in the development of algae and the associated problems with clogged drippers. It is important to monitor irrigation water temperatures at the plant, especially during the first part of the irrigation cycle, to ensure the temperatures are not too high. All exposed irrigation pipe should be shaded with white plastic or moved out of the direct sunlight if a problem is detected.

Managing Relative Humidity Using Vapour Pressure Deficits

Plants exchange energy with the environment primarily through the evaporation of water, the process of transpiration. Transpiration is the only type of transfer process in the greenhouse that has both a physical basis as well as a biological one. This plant process is almost exclusively responsible for the subtropical climate in the greenhouse. Seventy per cent of the light energy falling on a greenhouse crop goes towards transpiration, the changing of liquid water to water vapour, and most of the irrigation water applied to the crop is lost through transpiration.

Relative humidity (RH) is a measure of the water vapour content of the air. The use of relative humidity to measure the amount of water in the air is based on the fact that the ability of the air to hold water vapour depends on the air temperature. Relative humidity is defined as the amount of water vapour in the air compared to the maximum amount of water vapour the air is able to hold at that temperature. The implication of this concept is that a given reading of relative humidity reflects different amounts of water vapour in the air at different temperatures. For example, air at a temperature of 24°C at a RH of 80 per cent is actually holding more water vapour than air at a temperature of 20°C at a RH of 80 per cent.

Using relative humidity to control water content of the greenhouse air mass has commonly been approached by maintaining the relative humidity below threshold values, one for the day and one for the night. This type of humidity control was directed at preserving minimum humidity levels, and avoiding humidity levels high enough to favour the development of disease. There are better approaches to control the humidity levels in the greenhouse environment than relying exclusively on relative humidity.

The sole use of relative humidity as the basis of controlling the water content of greenhouse air does not allow for optimization of the growing environment, as it does not provide a firm basis for dealing with plant processes, such as transpiration, in a direct manner. The common purpose of humidity control is to sustain a minimal rate of transpiration.

The transpiration rate of a given greenhouse crop is a function of three in-house variables:

- temperature
- humidity
- light

Light is the one variable usually outside the control of most greenhouse growers. If the existing natural light levels are accepted, then crop transpiration is primarily determined by the temperature and humidity in the greenhouse. Achievement of the optimum "transpiration set point" depends on the management of temperature and humidity within the greenhouse. More specifically, at each level of natural light received into the greenhouse, a transpiration set point should allow for the determination of optimal temperature and humidity set points.

The relationship between transpiration and humidity is awkward to describe because it is largely related to the reaction of the stomata to the difference in vapour pressure between the leaves and the air. The most certain piece of knowledge about how stomata behave under an increasing vapour pressure difference depends on the plant species in question. However, even with the current uncertainties with understanding the relationships and determining mechanisms involved, the main point to remember about environmental control of transpiration is that it is possible.

The concept of vapour pressure difference or vapour pressure deficit (VPD) can be used to establish set points for temperature and relative humidity in combination to optimize transpiration under any given light level. VPD is one of the important environmental factors influencing the growth and development of greenhouse crops and offers a more accurate characteristic for describing water saturation of the air than relative humidity because VPD is not temperature dependent.

Vapour pressure can be thought of as the concentration or level of saturation of water existing as a gas in the air. Since warm air can hold more water vapour than cool air, the vapour pressures of water in warm air can reach higher values than in cool air. There is a natural movement from areas of high concentration to areas of low concentration. Just as heat naturally flows from warm areas to cool areas, so does water vapour move from areas of high vapour pressure, or high concentration, to areas of low vapour pressure, or low concentration. This situation is true for any given air temperature.

The vapour pressure deficit is used to describe the difference in water vapour concentration between two areas. The size of the difference also indicates the natural "draw" or force driving the water vapour to move from the area of high concentration to low concentration. The rate of transpiration or water vapour loss from a leaf into the air around the leaf can be thought of and managed using the concept of vapour pressure deficit (VPD). Plants maintained under low VPD have lower transpiration rates while plants under high VPD can experience higher transpiration rates and greater water stress.

A key point when considering the concept of VPD as it applies to controlling plant transpiration is that the vapour pressure of water vapour is always higher inside the leaf than outside the leaf. That means the concentration of water vapour is always greater within the leaf than in the greenhouse environment, with the possible exception of having a very undesirable 100 per cent relative humidity in the greenhouse environment. Thus, the natural tendency of movement of water vapour is from within the leaf into the greenhouse environment.

The rate of movement of water from within the leaf into the greenhouse air, or transpiration, is governed largely by the difference in the vapour pressure of water in the greenhouse air and the vapour pressure within the leaf. The relative humidity of the air within the leaf can be considered to always be 100 per cent, so by optimizing the temperature and relative humidity of the greenhouse air, growers can establish and maintain a certain rate of water loss from the leaf, a certain transpiration rate. The ultimate goal is to establish and maintain the optimum transpiration rate for maximum yield. Crop yield is linked to the relative increase or decrease in transpiration. A simplified relationship relates increase in yield to increase in VPD.

Transpiration is a key plant process for cooling the plant, bringing nutrients in from the root system and for allocating resources within the plant. Transpiration rate can determine the maximum efficiency by which photosynthesis occurs, how efficiently nutrients are brought into the plant and combined with the products of photosynthesis, and how these resources for growth are distributed throughout the plant. Since the principles of VPD can be used to control the transpiration rate, there is a range of optimum VPDs corresponding to optimum transpiration rates for maximum sustained yield.

The measurement of VPD is done in terms of pressure, using units such as millibars (mb) or kilopascals (kPa) or units of concentration, grams per cubic meter (g/m^3). The units of measurement can vary from sensor to sensor or between the various systems used to control VPD. The optimum range of VPD is between 3 to 7 g/m^3, and regardless of how VPD is measured, maintaining VPD in the optimum range can be obtained by meeting specific corresponding relative humidity and temperature targets. Table 1 presents the temperature-relative humidity combinations required to maintain the range of optimal VPD in the greenhouse environment. It is important to remember that this table only displays the temperature and humidity targets to obtain the range of optimum VPDs; it does not consider the temperature targets that are optimal for specific crops. There is a range of optimal growing temperatures for each crop that will determine a narrower band of temperature-humidity targets for optimizing VPD.

The plants themselves exert tremendous influence on the greenhouse climate. Transpiration not only serves to add moisture to the environment, but it is also the mechanism by which plants cool themselves and add heat to the environment.

Optimization of transpiration rates through the management of air temperature and relative humidity can change over the course of the season. Early in the season, when plants are young and the outside

Table 1. Relative humidity and temperature targets to obtain optimal vapour pressure deficits – g/m³* and millibars (mb)

Temp °C	Relative Humidity: 95 per cent		90 per cent		85 per cent		80 per cent		75 per cent		70 per cent		65 per cent		60 per cent		55 per cent		50 per cent	
	gm/m³	mb	gm/m³	mb	gm/m³	mb	gm/m³	mb	gm/m³	mb	gm/m³	mb	gm/m³	mb	gm/m³	mb	gm/m³	mb	gm/m³	mb
15	0.5	0.6	1.1	1.4	1.7	2.2	2.2	2.9	2.8	3.7	3.3	4.3	3.9	5.1	4.4	5.8	5.0	6.6	5.5	7.2
16	0.6	0.8	1.2	1.6	1.8	2.4	2.3	3.0	2.9	3.8	3.5	4.6	4.1	5.4	4.7	6.2	5.3	7.0	5.8	7.6
17	0.6	0.8	1.3	1.7	1.9	2.5	2.5	3.3	3.1	4.1	3.7	4.9	4.3	5.6	5.0	6.6	5.6	7.4	6.2	8.1
18	.07	0.9	1.3	1.7	2.0	2.6	2.7	3.6	3.3	4.3	4.0	5.3	4.6	6.1	5.3	7.0	5.9	7.8	6.6	8.7
19	.07	0.9	1.4	1.8	2.1	2.8	2.9	3.8	3.6	4.7	4.3	5.6	5.0	6.6	5.7	7.5	6.4	8.4	7.1	9.3
20	.08	1.0	1.5	2.0	2.2	2.9	3.0	3.9	3.8	5.0	4.5	5.9	5.3	7.0	6.1	8.0	6.8	8.9	7.5	9.9
21	.08	1.0	1.6	2.1	2.4	3.2	3.3	4.3	4.1	5.4	4.9	6.4	5.7	7.5	6.5	8.6	7.3	9.6	8.1	10.7
22	.09	1.2	1.7	2.2	2.6	3.4	3.5	4.6	4.3	5.7	5.2	6.8	6.0	7.9	6.8	8.9	7.7	10.1	8.6	14.8
23	.09	1.2	1.8	2.4	2.7	3.6	3.7	4.9	4.6	6.1	5.5	7.2	6.4	8.4	7.4	9.7	8.3	10.9	9.2	12.1
24	1.0	1.3	2.0	2.6	3.0	3.9	3.9	5.1	4.9	6.4	5.8	7.6	6.8	8.9	7.8	10.3	8.8	11.6	9.7	12.7
25	1.0	1.3	2.0	2.6	3.0	3.9	4.1	5.4	5.2	6.8	6.2	8.1	7.2	9.5	8.2	10.7	9.2	12.1	10.3	13.6
26	1.1	1.4	2.2	2.9	3.3	4.3	4.4	5.8	5.5	7.2	6.6	8.7	7.7	10.1	8.8	11.6	9.9	13.0	11.0	14.5
27	1.2	1.6	2.4	3.2	3.6	4.7	4.7	6.2	5.9	7.8	7.1	9.3	8.3	10.9	9.4	12.3	10.6	13.9	11.7	15.4
28	1.3	1.7	2.5	3.3	3.7	4.9	5.0	6.6	6.3	8.3	7.5	9.9	8.7	11.4	9.9	13.0	11.2	14.7	12.4	16.3
29	1.4	1.8	2.7	3.6	4.1	5.4	5.3	7.0	6.7	8.8	8.0	10.1	9.3	12.2	10.8	14.2	11.9	15.6	13.2	17.4
30	1.4	1.8	2.8	3.7	4.2	5.5	5.7	7.5	7.1	9.3	8.5	11.2	9.9	13.0	11.3	14.8	12.7	16.7	14.0	18.4

** Optimum range 3 to 7 g/m³ or 3.9 to 9.2 mb* temperatures are cold, both heat and humidity (from mist systems) can be applied to maintain temperature and humidity targets. As the season progresses and the crop matures, increasing light intensity increases the transpiration rate and the moisture content of the air.

To maintain optimum rates of transpiration, venting is employed to reduce the relative humidity in the air. However under typical summer conditions in Alberta, particularly in the south, ventilation is almost exclusively triggered by high temperature set points calling for cooling. Under these conditions, ventilation can occur continuously throughout the daylight period and will result in very low relative humidity in the greenhouse. As the hot, moist air is vented, it is replaced by warm, dry air.

Southern Alberta is a dry environment with the relative humidity of the air in summer regularly falling below 30 per cent. Under these conditions, some form of additional cooling (mist systems or pad and fan evaporative cooling) is required to both reduce the amount of ventilation for cooling as well as to add moisture to the air.

Carbon Dioxide Supplementation

Carbon dioxide (CO_2) is one of the inputs of photosynthesis, and as such, CO_2 plays an important role in increasing crop productivity. Optimal CO_2 concentrations for the greenhouse atmosphere fall within the range of 700 to 900 ppm (parts per million). Carbon dioxide enrichment to 1,200 ppm increases the maximum conversion efficiency of light to chemical energy in photosynthesis by a substantial amount (between 28 to 59 per cent). Crop productivity depends not only on efficiency of interception of light but also on the efficiency with which light is converted to chemical energy in photosynthesis.

Photosynthetic efficiencies appear to never exceed about 22 per cent of the absorbed light energy in the 400 to 700 nm range. The maximum efficiency is obtained at relatively low light intensities, not in brightest sunlight. Considering the supply of light to available land area on which a crop is growing, the overall yield efficiencies are always well below 22 per cent.

The use of CO_2 in greenhouses can give light use efficiencies exceeding those of field crops. Greenhouse crops with CO_2 enrichment achieve maximum efficiency of light energy utilization between 12 to 13 per cent. The ability of plants to utilize CO_2 depends on the presence of light. For this reason, it is only useful to supplement CO_2 during the daylight hours.

The key enzyme for CO_2 fixation is rubisco. The activity of rubisco depends on the ratio of the O_2 and CO_2 concentration in the atmosphere. The major effect of CO_2 enrichment is the shift in balance in the O_2 and CO_2 ratio, which improves the rubisco activity. The effect is just as important at low light levels as at high ones since the percentage effect on relative growth rate is about the same over a range of light levels.

Transpiration rates are reduced under CO_2 enrichment conditions by 34 per cent. Increased net leaf photosynthesis rate and decreased transpiration rate under CO_2 enrichment is well documented. One of the most important effects of CO_2 enrichment is the increased water use efficiency.

The technique of enriching the greenhouse atmosphere with CO_2 to maximize yield is standard practice. The largest increase in growth rate achieved with CO_2 enrichment is obtained with high light intensities. A high CO_2 concentration may partially compensate for low light levels. There is obviously a potential for synergism between CO_2 and light; however, the relationship between CO_2 and light conditions may be relatively loose.

When greenhouse ventilation rates are high, the cost of CO_2 supplementation can rise steeply. This situation is particularly true with a ventilation regime where ventilation is triggered at temperatures between 19 to 21°C.

Investigations into delaying ventilation to increase the cost effectiveness of CO_2 supplementation have shown that the amounts of CO_2 supplied to the greenhouse could be reduced by 23 to 35 per cent while still maintaining the CO_2 content of the greenhouse atmosphere above ambient CO_2 concentrations. Delaying ventilation to conserve CO_2 resulted in higher greenhouse temperatures with fruit temperatures exceeding 30°C. Total marketable yield fell by 11 per cent, and the proportion of fruit graded as Class 1 was reduced by 20 per cent on average.

The best advice for CO_2 supplementation under high ventilation rates is to maintain the CO_2 concentration at or just above the normal ambient level of approximately 350 ppm. This is a highly efficient way of using CO_2 supplementation. Maintaining the CO_2 concentration at the same level as ambient means there can be no net exchange of CO_2 with the outside air through leakage or ventilation. For practical purposes, the input of CO_2 is therefore equal to that being assimilated by the crop during photosynthesis, i.e. the utilization of supplementary CO_2 is totally efficient. The main point being that ventilation and economical CO_2 enrichment may be applied simultaneously.

At higher temperatures, such as 25 °C, net photosynthesis begins to decline and the supplementation of CO_2 above this temperature is not considered cost effective in some areas. During longer periods of elevated CO_2 (800 to 1,000 ppm), the stomata remain partially closed, and the reduction of transpiration may cause insufficient cooling, hence, heat damage to the leaves under intense light conditions. However, the increased VPD associated with the higher temperatures has been shown to counteract the effect of stomatal closure due to high CO_2 supplementation. This situation is true in Alberta where high CO_2 levels with higher temperatures and light intensities do not result in heat damage to the leaves.

Since young plants grow nearly exponentially, they can benefit more from optimal growing conditions than mature plants. Carbon dioxide enrichment results in heavier transplants and can be used to accelerate the growth as well as improve the quality of the transplants. Carbon dioxide may increase sugar translocation in the roots as well as facilitate the movement of nitrogen and carbon compounds directed towards the development of new roots. In short, CO_2 supplementation shortens the nursery period and results in sturdier, higher quality plants.

Air Pollution in the Greenhouse

Air pollutants can be a concern for greenhouse production. The incidence of air pollutant injury to plants is increasing as more growers use double plastic greenhouses or other forms of greenhouse sealing to reduce energy loss. Air pollutants can cause both visible injury to the leaves, and reduced growth rates. Tomatoes and cucumbers are particularly sensitive to air pollutant injury. When considering the effects of greenhouse air pollutants, it is also important to remember that these pollutants pose significant health risks for people working the crops.

Common pollutants are often the by-products of combustion. Although sources of pollutants can be outside the greenhouse, a number of pollutant sources can also be found within the greenhouse. Pollutants can be produced by direct-fired heating units, gas supply lines or carbon dioxide generators that burn hydrocarbon fuels such as natural gas. Significant sources of pollutants outside the greenhouse can include industrial plants or vehicle exhaust (Table 2).

Table 2. Maximum acceptable concentration (ppm)* of some noxious gases for humans and plants.

Gas	Humans	Plants
Carbon dioxide (CO_2)	5,000	4,500
Carbon monoxide (CO)	47	100
Sulfur dioxide (SO_2)	3.5	0.1
Hydrogen Sulfide (H_2S)	10.5	0.01
Ethylene (C_2H_4)	5.0	0.01
Nitrous oxide (NO)	5.0	0.01 to 0.1
Nitrogen dioxide (NO_2)	5.0	0.2 to 2.0

(Adapted from Portree 1996) *ppm = parts per million

Air pollution from sources within the greenhouse commonly occurs through cracked heat exchangers on furnaces or incomplete combustion in the furnace or CO_2 generators. Heaters and generators should be checked at the beginning of the cropping season to ensure they are operating properly and that complete combustion is occurring. The most common air pollutants resulting from incomplete combustion include nitrogen oxides, nitric oxide (NO) and nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ethylene (C_2H_4), propylene (C_3H_6), ozone (O_3), carbon monoxide (CO) and hydrogen sulfide (H_2S).

Symptoms of air pollutant injury vary with the specific gases involved. The common symptoms of sulfur dioxide injury are characterized by severe leaf burn appearing withing 24 to 36 hours of exposure to high levels of the gas. There is a distinct line between the affected and unaffected areas on the leaves, and young leaves are more susceptible to injury than mature leaves. Symptoms of NO_2 injury include darker than normal green leaves, with downward curling leaf margins and dead areas on the leaves in severe cases.

Ethylene functions as a plant growth regulator, involved in seed germination, root development, flower development and leaf abscission. Ethylene injury can include a reduction in growth, shortening and thickening of stems and twisting of stems, as well as premature leaf and flower drop. Propylene injury is similar to ethylene, but usually occurs at concentrations 100 times higher than those for ethylene. Ozone injury is characterized by mottling, necrotic flecking or bronzing necrosis of leaves, premature leaf drop and decreased growth.

Growing Media

Most commercial vegetable production greenhouses in Alberta use some form of "hydroponic culture." The term hydroponics essentially translates as "water culture." It is an advanced form of crop culture that allows for specific control of the delivery of nutrients to the plants. The term hydroponics can bring to mind a number of variations on the same theme. Hydroponic growing systems can include:

- substrate culture where the roots are allowed to grow in an inert or semi-inert media
- solution culture where the roots are immersed in ponds of nutrient solution
- NFT culture (nutrient film technique) where the roots are contained such that a thin film of nutrient solution constantly runs by the roots
- aeroponics where the root systems are suspended within an enclosed area and are misted with nutrient solution

A general working definition of hydroponic culture that would include all the above systems would be a plant culture where the plants receive fertilizer nutrients every time they receive water.

Using this working definition of hydroponics also leaves room for the inclusion of soil as a growing medium. However, soil culture is not widely practiced in commercial vegetable greenhouses in Alberta. The main reason for moving out of soil into soilless culture is to escape problems due to soil borne diseases that can build up in the soil that is used year after year. Soilless media such as rockwool and sawdust offer an initially disease-free growing medium. There are other advantages to moving the root system out of the soil and into confined spaces such as sawdust bags or rockwool slabs. The main advantages are realized in the improved management of watering and nutrition, topics discussed in more detail in following sections.

Media for seeding and propagation

Rockwool plugs are the most common media used for seeding. Rockwool is manufactured by subjecting rock mineral materials to very high temperatures and then spinning the materials into a fibre. The plugs can be square (2 cm x 2 cm by 4 cm deep) and can come joined together as a rockwool "flat" that fits into standard 28 cm x 54 cm plastic seeding flats. As the seed germinates and the seedlings are ready for their first transplanting, the plugs easily separate from each other when the seedlings are transplanted into rockwool blocks.

Rockwool blocks are typically around 10 cm x 10 cm by 8 cm deep, with a depression cut into the upper surface to receive the rockwool plug at the first transplanting. As the seedling continues to grow, the root system develops from the rockwool plug into the confines of the block. When the seedling is ready for transplanting into the main production greenhouse at "house set," the bottom of the rockwool block is placed in direct contact with the larger volume of growing media used in the production house.

Growing media for the production greenhouse

The majority of Alberta's commercial greenhouse vegetable production is based on substrate culture where the plants are grown in sawdust or rockwool. These substrates contain practically nothing in the way of plant nutrients and serve as a medium for the root system to anchor the plant. The growing media plays a significant role in defining the environment of the root system and allows for the transfer of water and nutrients to the plant.

Typically for sawdust culture, two or three plants are grown in 20 to 25 litre white plastic bags (white reflects more light) filled with spruce and/or pine sawdust. Rockwool culture uses approximately 16 litres of rockwool substrate for every two to three plants. The sawdust bags or rockwool slabs are placed directly on the white plastic floor of the greenhouse.

Sawdust is less expensive than rockwool in initial cost; however, standard density rockwool slabs can be pasteurized and reused for up to three years. Sawdust is a waste product of the lumber milling process, which is usually burned, so the use of sawdust as a growing media is an environmentally sound practice.

For sawdust culture, it is important to use a moderately fine sawdust. Lumber mills in Alberta understand the sawdust requirements for plant production and will supply "horticultural grade" sawdust if they are made aware the sawdust is to be used for plant culture. Sawdust that is too fine will break down over the production season, with a resulting loss of airspace around the roots that can lead to root death.

There is always some sawdust decomposition during the growing season, which makes the product useful for further composting or adding to mineral soils to improve soil quality. Through the continued action of soil microbes, the sawdust residue is returned to the environment in an ecologically sound manner at the end of the cropping season. The waste from sawdust culture is confined to the plastic bags themselves, which are recovered when the sawdust bags are dumped. These bags can be recycled where facilities exist.

Managing Irrigation and Fertilizer

In hydroponic crop production systems, water application is integrated with fertilizer feed application. The management of fertilizer application to the plants is therefore integrated with the management of watering. The management of watering and nutrition is focused on the optimal delivery of water and nutrients over the various growth stages of the plant to maximize yield through the changing growing environment over the production year.

Water

Water quality

Plants are comprised of 80 to 90 per cent water, and the availability of adequate quality water is very important to successful crop production. Water quality is determined by what is contained in the water at the source (well, dugout, town or city water supply) and the acidity or alkalinity of the water.

Water is a solvent, and as such, it can contain or hold a certain quantity of soluble salts in solution. Fertilizers, by their nature, are soluble salts, and growers dissolve fertilizers in water to obtain nutrient solutions to provide the plants with adequate nutrition.

Before using any source of water for crop production, it is important to have the water quality tested. Water quality tests determine the amount of various salts commonly associated with water quality concerns. The maximum desirable concentrations, in parts per million (ppm), for specific salt ions in water for greenhouse crop production are presented in Table 3.

Parts per million are one unit of measurement of the amount of dissolved ions, or salt in water, and are also used to measure the level of dissolved fertilizer salts in nutrient solutions. The level of nutrients as dissolved ions in water can also be reported in milligrams/Litre of solution. There is a direct relationship between milligrams/Litre (mg/L) and ppm, where 1 mg/L = 1 ppm. Another common unit of measure for dissolved fertilizer salts is the millimole (mM). The concept of millimoles and the relationship between millimoles and ppm is explained in the "Feed Targets and Plant Balance" section. Water quality tests will also report the pH, the acidity or alkalinity of the water.

Table 3. The maximum desirable concentrations, in parts per million (ppm), for specific salt ions in water for greenhouse crop production.

Element	Maximum Desirable (ppm)
Nitrogen (NO_3 - N)	5
Phosphorus (H_2PO_4 - P)	5
Potassium (K^+)	5
Calcium (Ca^{++})	120
Magnesium (Mg^{++})	25
Chloride (Cl^-)	100
Sulphate (SO_4^-)	200
Bicarbonate (HCO_3^-)	60
Sodium (Na^{++})	30
Iron (Fe^{+++})	5
Boron (B)	0.5
Zinc (Zn^{++})	0.5
Manganese (Mn^{++})	1.0
Copper (Cu^{++})	0.2
Molybdenum (Mo)	0.02
Fluoride (F-)	1
pH	7.5
E.C.	1.0 mmho

Once the water source has been determined to be suitable for greenhouse crop production, it is also important to have the water tested routinely to ensure any fluctuations in quality that may occur do not compromise crop production.

Electrical Conductivity of Water

Water quality analyses also report the electrical conductivity or E.C. of the water. The ability of water to conduct an electrical current depends on the amount of ions or salts dissolved in the water. The greater the amount of dissolved salts in the water, the more readily the water will conduct electricity.

Electrical conductivity is an indirect measure of the level of salts in the water and can be a useful tool for both determining the general suitability of water for crop production and for the ongoing monitoring of the fertilizer feed solution. Using electrical conductivity as a measure to maintain E.C. targets in the nutrient solution and the root zone can be a management tool for making decisions regarding the delivery of fertilizer solution to the plants.

Electrical conductivity is measured and reported using a number of measurement units including millimhos per centimeter (mmho/cm), millisiemens per centimeter (mS/cm) or microsiemens per centimeter (μS/cm). Water suitable for greenhouse crop production should not have a E.C. of more than 1.0 mmho/cm.

1 mmho/cm = 1mS/cm = 1000 μs/cm

pH

The relative acidity and alkalinity of the water is expressed as pH, and is measured on a scale from 0 to 14. The lower the number, the more acidic the water or solution; the higher the number, the more alkaline. The pH scale is a logarithmic scale, meaning that every increase of one number, i.e. 4 to 5, represents a tenfold increase in alkalinity. Conversely, every single number decrease, i.e. 5 to 4, represents a tenfold increase in acidity.

Most water supplies in Alberta are alkaline, with typical pH levels of 7.0 to 7.5. Alkalinity of the water increases with increasing levels of bicarbonate. The pH measurement reflects the chemistry of the water and nutrient solution. The pH of a fertilizer solution has a dramatic determining effect on the solubility of nutrients and how available nutrients are to the plant.

The optimum pH of a feed solution, with respect to the availability of nutrients to plants, falls within the range of 5.5 to 6.0. The pH of a solution can be adjusted through the use of acids, such as phosphoric or nitric acid, or potassium bicarbonate, depending on which direction the feed solution needs to be adjusted. When acids or bases are used to adjust the pH of the feed solution, the nutrients added by the acid (nitrogen, phosphorus) must be accounted for when the feed solution is calculated. Most water supplies in Alberta are basic in pH and require the use of acid for pH correction.

The amount of acid required to adjust the pH usually depends on the bicarbonate (HCO_3^-) level in the water. The amount of bicarbonate in the water supply can be determined by a water analysis and is reported in parts per million (ppm). A good target pH for nutrient feed solutions is 5.8, and as a general rule, this pH corresponds to a bicarbonate level of about 60 ppm. If the incoming water has, for example, a pH of 8.1 and a bicarbonate level reported at 207 ppm, then 207 ppm - 60 ppm = 147 ppm of bicarbonate, which needs to be neutralized by acid to reduce the pH from 8.1 to 5.8.

To neutralize 61 ppm or 1 milliequivalent of bicarbonate, it takes about 70 ml of 85 per cent phosphoric acid, or about 76 ml of 67 per cent nitric acid per 1,000 litres of water. To neutralize 147 ppm of bicarbonate, the following approach could be used:

Using 85% phosphoric acid:

140 ÷ 61 = 2.3 milliequivalents of bicarbonate to be neutralized.

2.3 milliequivalents x 70 ml of 85% phosphoric acid for each milliequivalent = 2.3 x 70 ml = **161 mls** of 85% phosphoric acid for every 1,000 litres of water.

Using 67% nitric acid:

2.3 milliequivalents of bicarbonate to be neutralized.

2.3 milliequivalents x 76 ml per milliequivalent = 2.3 x 76 ml = **175 mls** of 67% nitric acid for every 1,000 litres of water.

These calculations have to be made for each water sample based on the results of a water analysis reporting the level of bicarbonates. In addition to phosphoric and nitric acid, sulfuric and hydrochloric acids can also be used to adjust the pH of the water down.

Acids are corrosive. Special care and attention must be used when handling them for pH correction. The common acids used to lower the pH are phosphoric acid (85 per cent) and nitric acid (67 per cent). Of these two, nitric acid is the most corrosive and must be handled very carefully. Acid resistant safety glasses, rubber gloves and a rubber apron should be the minimum safety equipment used when handling acids.

Mineral Nutrition of Plants

To support optimum growth, development and crop yield, the fertilizer feed solution has to continually meet the nutritional requirements of the plants. Although the mineral nutrition of plants is complex, experience in crop culture has determined basic requirements for the successful hydroponic culture of plants.

There are 12 mineral elements considered essential for plant growth. Water (H_2O) and carbon dioxide (CO_2) are also necessary for plant growth and supply hydrogen, carbon and oxygen to the plants, bringing the total to 15 essential elements.

A criterion to determine whether an element is essential to plants is to determine if the plant cannot complete its life cycle in the complete absence of the element.

Other elements, although not necessarily considered universally essential, can affect the growth of plants. Sodium (Na), chloride (Cl) and silicon (Si) are in this category. All three of these nutrients either enhance the growth of plants or are considered essential nutrients for some plant species.

The essential nutrients can be grouped into two categories that reflect the quantities of the nutrients required by plants. Macronutrients, or major elements, are required by plants in larger quantities than the amounts of micronutrients, or trace elements, required for growth (Table 4).

Another useful grouping of the mineral nutrients is based on the relative ability of the plant to translocate the nutrients from older leaves to younger leaves. Mobile nutrients are those that can be moved readily by the plant from older leaves to younger leaves. Nitrogen is an example of a mobile nutrient. Calcium is an example of an immobile nutrient, one which the plant is not able to move after it has initially been translocated to a specific location.

The discussion of plant nutrients only as elements does not allow for a more complete discussion of how plants access the elements from the root environment and how hydroponic growers ensure their crop plants are adequately supplied with nutrients. The term "element" can be defined as a substance that cannot be broken down into simpler substances by chemical means; the basic unit of an element is the atom. With the simplest or purest form of plant nutrients being the atom, nutrients are often not available to plants in their purest form. Pure nitrogen is an example of a nutrient element represented by its atom.

Table 4. Essential mineral elements for plants.				
Element	**Symbol**	**Type**	**Mobility in Plant**	**Symptoms of Deficiency**
Nitrogen	N	macronutrient	mobile	Plant light green, lower (older) leaves yellow.
Phosphorus	P	macronutrient	mobile	Plant dark green turning to purple.
Potassium	K	macronutrient	mobile	Yellowish green margins on older leaves.
Magnesium	Mg	macronutrient	mobile	Chlorosis between the veins on older leaves first, turning to necrotic spots, flecked appearance at first.
Calcium	Ca	macronutrient	immobile	Young leaves of terminal bud dying back at tips and margins. Blossom end rot of fruit (tomato and pepper).
Sulfur	S	macronutrient	immobile	Leaves appear light green.
Iron	Fe	micronutrient	immobile	Yellowing between veins on young leaves (interveinal chlorosis), netted pattern.
Manganese	Mn	micronutrient	immobile	Interveinal chlorosis, netted pattern.
Boron	B	micronutrient	immobile	Leaves of terminal bud becoming light green at bases, eventually dying. Plants "brittle."
Copper	Cu	micronutrient	immobile	Young leaves dropping, wilted appearance.
Zinc	Zn	micronutrient	mobile	Interveinal chlorosis of older leaves.
Molybdenum	Mo	micronutrient	immobile	Lower leaves pale, developing a scorched appearance.

When the atoms of different elements combine, they can form other substances that are based on a particular combination of atoms, substances based on molecules. Nitrate (NO_3-), is a molecule based on nitrogen and oxygen atoms; nitrate is absorbed by plant roots as a source of nitrogen. Nitrate is an "available" form of nitrogen (Table 5). The nitrate molecule has an overall negative charge, which causes the molecule to be fairly reactive chemically and therefore more available.

The availability of nutrient elements to plants is generally based on the existence of the nutrient element as a charged particle, either a charged atom or charged molecule. An atom or molecule that carries an electric charge is called an ion. Positively charged ions are called cations, while negatively charged ions are called anions. The nitrate molecule (NO_3^-) is an anion, while the iron atom can exist as the Fe^{+2} (ferrous) or Fe^{+3} (ferric) cations. Plants are able to acquire the essential mineral elements via the root system utilizing the chemical properties of ions. In particular, to acquire negatively charged anions, the plant roots have sites that are positively charged. The plant is also able to attract positively charged cations to negatively charged sites on the root.

Water is a very important component in the plants acquisition of nutrient elements because the nutrient ions exist only when they are in solution, when they are dissolved in water. As solids, the ions generally exist as salts; a salt can be defined as any compound of anions and cations. In the absence of water, the nutrient ions form compounds with ions of the opposite charge. Anions combine with cations to form a stable solid compound.

For example, the nitrate anion (NO_3^-) commonly combines with the calcium (Ca^{+2}) or potassium (K^+) cations forming the larger calcium nitrate $Ca(NO_3)_2$ or potassium nitrate (KNO_3) salt molecules. As salts are added to water, they dissolve, or dissociate, into their respective anion and cation components. Once in solution, these components become available to plants.

Table 5. Forms of nutrient elements commonly available to plants.			
Element	**Symbol**	**Available as**	**Symbol**
Macronutrients:			
Nitrogen	N	Nitrate ion	NO_3^-
		Ammonium ion	NH_4^+
Phosphorus	P	Monovalent phosphate ion	$H_2PO_4^-$
		Divalent phosphate ion	HPO_4^{-2}
Potassium	K	Potassium ion	K^+
Calcium	Ca	Calcium ion	Ca^{+2}
Magnesium	Mg	Magnesium ion	Mg^{+2}
Sulfur	S	Divalent sulfate ion	SO_4^{-2}
Chlorine	Cl	Chloride ion	Cl^-
Micronutrients:			
Iron	Fe	Ferrous ion	Fe^{+2}
		Ferric ion	Fe^{+3}
Manganese	Mn	Manganous ion	Mn^{+2}
Boron	B	Boric acid	H_3BO_4
Copper	Cu	Cupric ion chelate	Cu^{+2}
		Cuprous ion chelate	Cu^+
Zinc	Zn	Zinc ion	Zn^{+2}
Molybdenum	Mo	Molybdate ion	MoO_4^-

An important point to remember is that different salts have different solubilities; that is, some salts dissolve readily in water (highly soluble), and some salts do not. Calcium sulfate ($CaSO_4$) is a relatively insoluble salt and would be a poor choice as a fertilizer because very little of the calcium would go into solution as the calcium cation (Ca^{++}) and be available to plants. Fertilizer salts, by their very nature, are useful because they go into solution readily. In hydroponic culture, greenhouse growers formulate and make a water-based nutrient solution by dissolving fertilizer salts.

In addition to existing as salts, some of the micronutrients (iron, zinc, manganese and copper) exist in chelates. A chelate is a soluble product formed when certain atoms combine with certain organic molecules. The sulphate salts of iron, zinc, manganese and copper are relatively insoluble, and chelates function to make these mineral nutrients more readily available in quantity to the plants.

Fertilizer Feed Programs

Fertilizer nutrient solutions are formulated to meet the needs of the plants using a combination of component fertilizer salts. The amounts of the various fertilizers used depend on target levels that have been determined to be optimal for the crop in question.

Although there is considerable similarity between fertilizer programs for the various vegetable crops, there can be some differences reflecting the different crop requirements. In any event, when mixing fertilizer solutions, only high quality, water-soluble fertilizers should be used.

The required nutrient levels, or target nutrient levels, of the various essential elements are often expressed as the desired parts per million (ppm) in the final nutrient solution. The recommended nutrient fertilizer feed targets for greenhouse peppers are listed in Table 6.

Table 6. Nutrient feed targets (ppm) for greenhouse sweet peppers grown in sawdust.	
Nutrient	**Target (ppm)**
Nitrogen	200
Phosphorus	55
Potassium	318
Calcium	200
Magnesium	55
Iron	3.00
Manganese	0.50
Copper	0.12
Molybdenum	0.12
Zinc	0.20
Boron	0.90

Even though all 12 mineral elements are essential for plant growth and development, nutrient targets for sulfur and chlorine (not considered universally essential) are not listed. The reason for this omission is that adequate amounts of sulfur are obtained from the use of sulfate fertilizers, potassium sulfate or magnesium sulfate. Chloride is assumed to be present in adequate amounts as a contaminant in a number of fertilizers.

As the purity of fertilizers has improved, growers will have to pay more attention to ensuring these other elements, particularly chloride, are present in adequate amounts. Once the recommended nutrient targets are known, calculations are made to determine how much of each fertilizer is needed to meet these targets.

To make these calculations, some other basic information is required:

- the volume of water that will be used to make the feed solution.
- the types of fertilizers available and the relative amounts of each nutrient present in the fertilizer.

When considering what volume of water to use for the nutrient solution, it is first important to understand the delivery of the nutrient solution to the plants as discussed earlier in the "Irrigation and Fertilizer Feed" section.

Every greenhouse must be able to supply water and nutrients to the plants on an ongoing basis. During hot, dry Alberta summers, mature pepper plants can use approximately 3.5 to 4.0 litres of water per plant per day, while cucumbers can require over 6 litres and tomatoes up to 3 litres. This water always contains fertilizer, which is added as the water comes into the greenhouse, before it is pumped to the plants. Greenhouses may vary in their delivery systems, but some form of fertilizer injection system is used in all commercial scale greenhouses.

Feed targets and plant balance

The first approach to altering the feed solution in response to a crop that is overly vegetative is to increase the feed electrical conductivity (E.C.) to direct the plants to become more generative and set and fill more fruit. The feed E.C. can be increased from 2.5 mmhos to approximately 3.0 mmhos over the course of a few days.

Dialing up the feed E.C. increases the absolute amounts of fertilizer nutrients in the feed, but does not affect the ratio of the nutrient levels with respect to one another. Increasing the feed E.C. increases the level of fertilizer salts in the root zone, increasing the stress on the plant as it becomes more difficult for the plant to take up water. The plant responds to the stress by putting more emphasis on fruit production, a stressed plant begins preparations for the end by trying to ensure that the next generation will carry forward. The fruit holds the seed, and in plant terms, developing fruit means that the next generation will survive and carry on. Plants don't think these things out, but stressing the plant does direct the plant to set more fruit. There is a limit to how far growers can go with this technique because a successful crop requires having enough vegetative growth to continually fill a high volume of fruit consistently throughout the season.

Another option is available for affecting the vegetative/generative balance of the plants through manipulating the nutrient ratios, particularly the nitrogen-potassium ratio (Table 7).

Table 7. Typical absolute value and relative ration targets for N*, K*, and Ca* in vegetable feed programs (E.C. of 2.5 mmhos) for Southern Alberta production conditions.

	Nutrient Targets Crop			Nutrient Ratio (ppm)		
	N	K	Ca	N	K	Ca
cucumber	200	302	173	1.00	1.51	0.86
pepper	214	318	200	1.00	1.48	0.93

* N = Nitrogen, K = Potassium, Ca = Calcium

The N:K ratios presented in the table are all about 1:1.5. Increasing the level of potassium, with respect to nitrogen, and increasing the ratio to 1:1.7 will direct the plant to be more generative. The reason for this change is that nitrogen promotes vegetative growth while potassium promotes mature growth, generative growth. Calcium is also important for promoting strong tissues, fruit and mature growth. Shifting the feed program to favor potassium over nitrogen will direct the plant to be generative. Calcium is important in the equation in that it should always be approximately equal to the amount of nitrogen. A N:Ca ration of 1:1 works for both tomatoes and peppers, while a N:Ca ratio of 1:0.85 has shown to work well for cucumbers.

Changes to the N:K ratio should be made carefully. The above ratios come from the feed programs of successful Alberta growers and can serve as a guide. *The place to start is to determine the ratios in the* current feed program and examine the performance of the crop. If it is determined that there is room for improving the balance of the plants, alterations in the nutrient ratios can be undertaken.

Always be aware that many factors influence plant balance: day/night temperature split, 24-hour average temperature, relative humidity and watering. These factors should be optimized before feed ratios are changed. You have to know where the crop is in order for you to make sound decisions on where it should be and how to get there.

Due to the large volumes of fertilizer feed solution that can be required daily, it is impractical to make the fertilizer feed on a day-to-day basis. Instead, the required fertilizers can be mixed in a concentrated form, usually 100 to 200 times the strength delivered to the plants. Injectors or ratio feeders are then used to "meter-out" the correct amount of fertilizer into the water that make up the nutrient solution going to the plants.

By using concentrated volumes of the fertilizer feed held in "stock tanks," growers are able to reduce the number of fertilizer batches they have to make. Depending on the number of plants in the crop, the size of the stock tanks and the strength of the concentrate, growers may only have to mix fertilizer once every two to four weeks.

Designing a fertilizer feed program

The design of a fertilizer feed program is a relatively straightforward process once the nutrient target levels are decided and basic information about the water quality, feed delivery system and component fertilizers is known. Fertilizer targets and the component fertilizers used to make the fertilizer solution can change over the course of the year, depending on the crop and the knowledge of the grower. The changes are often slight adjustments in the relative proportion of the macronutrients from one to another, particularly the nitrogen/phosphorus/potassium (N:P:K) ratio.

Changes can also include the addition of alternate forms of a nutrient in question. A common example is the use of ammonium nitrogen (NH_4^-N) in addition to nitrate nitrogen (NO_3^-N) during the summer months. Ammonium nitrate is the common source of ammonium nitrogen, which is a more readily available form of nitrogen that works to promote vegetative growth. During the summer months, a target of approximately 17 ppm of ammonium nitrogen is recommended to help optimize plant balance and crop production.

Moles and millimoles in the greenhouse

Some greenhouse vegetable growers have been concerned about millimoles and moles. Not to worry, these growers are not referring to four-legged moles. Rather, they are using another unit of measure to discuss fertilizer feed targets and root zone targets.

A millimole is one thousandth of a mole, and a mole, is defined as the amount of a substance of a system that contains as many elementary entities as there are atoms in exactly 12 grams of Carbon 12. The concept of the mole has come out of stoichiometry, a branch of chemistry that studies the quantities of reactants and products in chemical reactions.

Chemists and physicists have argued for a long time over how to measure the masses of individual elements (some of those same elements that growers feed their crops in fertilizer feed solutions), and in 1961, they settled on using the mole.

A good way to understand what a mole is and why to use it is to relate it to the concept of a dozen. We understand that a dozen is twelve of something, be it cucumbers, eggs or whatever. A mole is 6.02×10^{23} of some entity, and chemists usually refer to actual molecules of a substance when they talk about moles, although you could have a mole of eggs or a mole of cucumbers.

You would be quite the grower to grow a mole of cucumbers, tomatoes or peppers. The number 6.02×10^{23}, which in longhand is 602 000 000 000 000 000 000 000, is called Avogadro's number after the nineteenth century chemist who did some pioneering work on gases and was largely ignored for his trouble.

Moles do relate to parts per million (ppm). Both concepts are ways to measure how much of a given nutrient we are dealing with in a fertilizer feed sample, leachate or tissue sample. The difference is that ppm is a measure of mass (e.g. 1 ppm = 1 milligram/litre) while moles measure amounts. One mole of any substance contains Avogadro's number of entities or basic units. Those entities, as mentioned earlier, can be atoms or molecules or whatever you want.

When we talk about one mole of nitrate nitrogen, NO_3, we are referring to 6.02×10^{23} molecules of NO_3, because the basic NO_3 entity is made up of one atom of nitrogen (N) and three atoms of oxygen (O). If we are talking about a mole of iron, Fe, we are talking about atoms, because the basic entity of iron is the iron atom.

All atoms and molecules have different basic weights, some being heavier than others. If we talk about 1 ppm of NO_3 versus 1 ppm of Fe, we are talking about the same mass of each, i.e., 1 milligram/litre. However, there will be a different number of basic entities or moles of NO_3 and Fe in a solution that contains 1 ppm each of NO_3 and Fe.

The atomic weights of all the elements can be found on the periodic table. The atomic weights of the elements are given in grams per mole. The molecular weight of oxygen is 16 grams/mole. This means that 6.02×10^{23} atoms of oxygen weights 16 grams. One mole of nitrogen weighs 14 grams. By combining all the atoms that make up molecules we can arrive at the molecular weights. Therefore, the molecular weight of NO_3 would equal 14 + 3(16) grams/mole or
62 grams/mole. One last thing to remember is that moles are related to millimoles in the same way that grams are related to milligrams. So if moles are related in the range of grams, millimoles are in the range of milligrams.

We know that 1 ppm is equal to 1 milligram/litre, so to convert ppm to millimoles, divide ppm by the molecular weight of the element you are working with. For example:

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1 ppm of NO_3 = 1 mg/litre

1 mg/ litre of NO_3 ÷ 62 mg/mole = 0.016 millimoles of NO_3 in one litre.

1 ppm of Fe = 1 mg/litre

1 mg/litre of Fe ÷ 56 mg/millimole = 0.018 millimoles of Fe in one litre.

1 ppm of magnesium (Mg) = 1 mg/litre

1 mg/litre of Mg ÷ 24 mg/millimole = 0.041 millimoles of Mg in one litre.

As these examples show, a solution containing 1 ppm of various elements or molecules will contain different mole or millimole amounts of these same elements.

To convert millimoles to ppm:

ppm = millimoles/litre x molecular weight (mg/millimole)

Example:

ppm NO_3 = 0.016 millimoles of NO_3 in one litre x 62 mg/millimole

= 1 ppm NO_3

Once you can work back and forth between ppms and millimoles, you might be asking if there is any benefit to working in millimoles rather than ppm. If you are comfortable working with ppms and you are comfortable with designing and managing your fertilizer feed programs in ppms, stick to what you know. However, if you want to be working with actual amounts of atoms and molecules of the nutrients you are feeding, then you may want to work with millimoles. Whatever the case, with a little practice you can work with either unit.

Water volumes

Calculating the required amounts of the various fertilizers depends on the volume of water to be used. This figure is determined by the volume of the stock tank (e.g. 200 litres) multiplied by the injection ratio (e.g. 100:1 or 200:1). For example, using a 200 litre fertilizer concentrate stock tank and a 200:1 injection ratio, the volume of water that will be used to calculate the amount of fertilizer to add will be:

200 litres (stock tank volume) x 200 (injector ratio) = 40,000 litres

Calculations in the following sections on fertilizer and water will be based on 200 litre stock tanks and a 1:200 injection ratio.

Accounting for nutrients in raw water

Assuming the water quality analysis has determined the water is suitable for greenhouse crop production, the first step is to account for the nutrients already contained in the water. This information comes directly from the water analysis report.

Accounting for nutrients provided by pH adjustment of water

Next, determine if the pH needs adjusting, and if so, decide on the amount of acid (or base) required to meet the target pH of 5.8. Once the amount of acid to be added has been determined, the levels of nutrients present in the acid have to be accounted for.

Using the example in the previous section on pH, where it was determined that 161 ml of 85 per cent phosphoric acid would be required to adjust the pH from 8.1 to 5.8 for every 1,000 litres of water, the amount of acid required for 40,000 litres would be (161 ml/1,000 litres x 40,000 litres =) 6,440 mls. Knowing the volume of acid required and the specific gravity of the acid makes it is possible to calculate the weight of acid that will be used.

6,440 mls (85% phosphoric acid) x 1.41 grams/ml = 9,080 grams of phosphoric acid

Table 8. The specific gravity of 85 per cent phosphoric acid and 67 per cent nitric acid.

Phosphoric acid (85 per cent)	1.14 grams/ml
Nitric acid (67 per cent)	1.28 grams/ml

Having the weight of the acid, it is now possible to determine the amount of phosphorus contributed to the pH-adjusted water by 85 per cent phosphoric acid. One more piece of information is required; phosphoric acid contains 32 per cent available phosphorus, which is also referred to as the fertilizer grade of the acid.

Table 9. Fertilizer "grades" of phosphoric and nitric acid.

Phosphoric acid	32 per cent available phophorous (PO_4-P)
Nitric acid	22 Per cent available nitrogen (NO_3- N)

Now, using the following formula:

Formula 1 (from Mirza and Younus, 1994)

$$\text{ppm} = \frac{\text{grams of acid} \times \text{grade of acid} \times 10}{\text{litres of water}}$$

the amount of phosphorus (in ppm) contributed by 7,857 grams of 85% phosphoric acid

$$= \frac{9{,}080 \text{ grams} \times 32\% \times 10}{40{,}000}$$

= 73 ppm of phosphorus, actual "P"

This same sequence of calculations can be used to determine the amount of nitrogen contributed if 67 per cent nitric acid was used. In this example, 49 ppm of nitrogen would be contributed if 67 per cent nitric acid was used.

Determining fertilizers amounts to meet feed targets

For the purposes of this discussion of designing a fertilizer program, only component fertilizers will be considered. A list of the common component fertilizers for greenhouse crop production is presented in Table 10. The fertilizers are identified by their chemical name and their fertilizer number designation, i.e. 0-53-35 for monopotassium phosphate. The "grade" of the fertilizer with respect to the different nutrients supplied by the fertilizer is also provided.

It is important to know that the three-number designation of the fertilizer represents the percentages or grade of nitrogen (N), phosphorus (P) and potassium (K), in that order, present in the fertilizer. However, it is very important to note when the percentages for phosphorus and potassium are used, the number on the bag represents the percentages of phosphate (P_2O_5) and potash (K_2O) and not actual phosphorus and potassium. Phosphate is only 43 per cent actual phosphorus and potash is only 83 per cent actual potassium. For this reason, monopotassium phosphate, 0-53-35, is listed as containing 23 per cent phosphorus (53 per cent x 0.43 = 23 per cent), and 29 per cent potassium (35 per cent x 0.83 = 29 per cent).

Blended or premixed fertilizers are also used by some growers. A common premixed fertilizer is 20-20-20. If these fertilizers are used, it is important to account for all the nutrients provided in the fertilizer, both macro and micronutrients. As well, although the fertilizer 20-20-20 contains 20 per cent nitrogen, for the purposes of calculating actual phosphorus (P) and actual potassium (K), 20-20-20 should actually be considered as 20-8.6-16.6.

In determining the amount of fertilizer to add, it is important to remember that as salts, fertilizers often contain more than just one plant nutrient. For example, calcium nitrate ($Ca(NO_3)_2$) provides both calcium and nitrogen. Calcium nitrate is commonly used in commercial vegetable greenhouses as the only source of calcium. The amount of calcium nitrate added depends on how much is required to meet the calcium target.

However, since nitrogen is also present in calcium nitrate, it is important to keep track of how much nitrogen is contributed. After all, there is also an optimum target for nitrogen. Calcium nitrate is 19 per cent calcium and 15.5 per cent nitrogen, so for every 100 grams of calcium nitrate, there will be 19 grams of calcium and 15.5 grams of nitrogen.

The percentage of the relative nutrient components of a fertilizer is also sometimes referred to as the "grade." As the fertilizer calculations are made, an ongoing tally is kept on what nutrients are being supplied by the various fertilizers until all the feed targets have been met.

With the information of stock tank size, injector ratio and the nutrients contributed by each fertilizer, the same relatively simple formula (Formula 1) can be modified and used to determine the amount of each fertilizer required to meet the parts per million (ppm) feed targets of the essential nutrients.

Formula 2 (from Mirza and Younus, 1994)

$$\text{grams of fertilizer required} = \frac{\text{ppm desired} \times \text{litres of water}}{\text{grade of fertilizer} \times 10}$$

This formula can be rearranged to calculate ppm if the amount of fertilizer added is known.

$$\text{ppm} = \frac{\text{grams of fertilizer} \times \text{grade of fertilizer} \times 10}{\text{litres of water}}$$

Assumptions with the example include using 200 litre stock tanks, a 200:1 injector ratio, meeting a calcium target in the nutrient solution of 180 ppm and obtaining all the calcium from calcium nitrate. The formula can be used to determine the amount of calcium nitrate required to meet the calcium target, as well as determining the levels of nitrogen (in ppm) contributed by the calcium nitrate.

Calcium required = 180 ppm, from calcium nitrate, 19% calcium, 15.5% nitrogen.

grams of calcium nitrate required =

$$\frac{180 \text{ ppm} \times (200 \times 200) \text{ litres of water}}{19\% \times 10}$$

$$= \frac{180 \text{ ppm} \times 40{,}000 \text{ litres of water}}{190}$$

= 37,894 grams

= 37.9 kilograms

The amount of nitrogen contributed:

$$\text{ppm of nitrogen} = \frac{37{,}894 \text{ grams} \times 15.5\% \times 10}{40{,}000 \text{ litres}}$$

= 146.8 = 147 ppm of nitrogen

By repeating this type of calculation using the various component fertilizers, including the micronutrient chelates, all the individual nutrients coming from each fertilizer can be accounted for until all the nutrient targets are met and balanced in the final feed program.

Table 10. Some component fertilizers for formulating nutrient feed programs for hydroponic greenhouse vegetable crops.

Element			Element		
Macronutrients	Fertilizer	Nutrients	Macronutrients	Fertilizer	Nutrients
Nitrogen	Calcium nitrate 15.5-0-0	15.5% nitrogen (NO_3 - N) 19% calcium	**Calcium**	Calcium nitrate 15.5-0-0	19% calcium 15.5% (NO_3 - N)
	Potassium nitrate 13-0-44	13 % nitrogen (NO_3 - N) 37% potassium		Calcium chloride $CaCl_2$ - $2H_2O$	27% calcium 48% chlorine
	Ammonium nitrate 34-0-0	17% nitrogen (NO_3 - N) 17% nitrogen (NH_4 - N)	**Magnesium**	Magnesium sulfate $MgSO_4$ - $7H_2O$	10% magnesium 13% sulfur
Phosphorus	Monopotassium phosphate 0-53-35	23% phosphorus 29% potassium		Magnesium nitrate $Mg\ (NO_3)_2$- $6H_2O$	10% magnesium 11% nitrogen (NO_3 - N)
Potassium	Potassium nitrate 13-0-44	37% potassium 13% nitrogen (NO_3 - N)	**Sulfur**	Magnesium sulfate $MgSO_4$ - $7H_2O$	10% magnesium 13% sulfur
	Potassium sulfate 0-0-50	41.5% potassium 17% sulfur		Potassium sulfate 0-0-50	41.5% potassium 17% sulfur
	Monopotassium phosphate 0-53-35	23% phosphorus 29% potassium	**Chlorine**	Calcium chloride $CaCl_2$ - $2H_2O$	48% chlorine 27% calcium
	Potassium chloride 0-0-60	49% potassium 26% chlorine		Potassium chloride 0-0-60	26% chlorine 49% potassium
Micronutrients	Fertilizer	Nutrients	Micronutrients	Fertilizer	Nutrients
Iron	Iron chelate	13% iron	**Zinc**	Zinc chelate	13% zinc
Manganese	Manganese chelate	13% manganese	**Molybdenum**	Sodium molybdate	39% molybdenum
Copper	Copper chelate	14% copper	**Boron**	Borax	15% boron

Rules for Mixing Fertilizers

Once the amounts of the various fertilizers have been determined, the next step is to mix the fertilizers in the stock tanks. Most commercial vegetable greenhouses use a two-stock-tank system for mixing fertilizers, although some systems involve three stock tanks with the third tank containing the acid or bicarbonate for pH adjustment.

Before mixing fertilizers, ensure that a dust mask and gloves are worn to avoid inhaling the fertilizer dusts or coming into contact with the fertilizer concentrates.

The first rule in mixing fertilizers is to always use high quality, water soluble "greenhouse grade" fertilizers. Second, when working with stock tank concentrates, never mix calcium containing fertilizers (e.g. calcium nitrate) with any fertilizers containing phosphates (e.g. monopotassium phosphate) or sulfates (e.g. potassium sulfate, magnesium sulfate). When fertilizers containing calcium, phosphates or sulfates are mixed together as concentrates, the result is insoluble precipitates of calcium phosphate and calcium sulfate. Essentially, the calcium combines with the phosphate or sulfate in the solution and comes out of the solution as a solid. This solid forms a "sludge" at the bottom of the fertilizer tank, which can plug the irrigation lines.

This reaction between calcium, phosphate and sulfate can be avoided if a one-times strength fertilizer is being mixed, as it is considerably more dilute. However, mixing fertilizers to make a one-times strength fertilizer solution is impractical for a commercial greenhouse operation since it would mean that someone would be mixing fertilizers almost continuously.

The third rule for mixing fertilizers is to dissolve the fertilizers for each tank together in **hot** water. The components of tank one are dissolved together as are the components of tank two. The micronutrients are added to the tanks when the solution is warm, not hot. The fourth rule is to continually agitate the solution in the stock tanks as the fertilizers are being added.

Using the two-stock tank system, the fertilizers should be mixed as follows:

Using the two-tank stock tank system, the fertilizer should be mixed as follows:

Tank A	Tank B
calcium nitrate	potassium nitrate (one half the total amount)
potassium nitrate (one half the total amount)	magnesium sulfate
iron chelate	monopotassium phosphate
	potassium sulfate
	manganese chelate
	zinc chelate
	copper chelate
	sodium molybdate
	boric acid

If other fertilizers are used, ensure that mixing calcium-containing fertilizers with phosphate or sulfate-containing fertilizers is avoided. Generally, other nitrate fertilizers can be added to the "A" tank, while with all others mixed in the "B" tank. Note that iron is always added to the "A" tank to avoid mixing it with phosphate fertilizers, which can cause the precipitation of iron phosphates, resulting in iron deficiency in the plants. If acids are used for pH correction, they can be added to either the "A" or "B" tank, or they can be added to a third stock tank, a "C" tank. If potassium bicarbonate is required for pH correction, it should be added to a third tank, the "C" tank, to avoid the risk of raising the pH in the other stock tanks, which could result in the other fertilizers coming out of solution.

The fertilizer feed program is designed to supply specific quantities of the nutrient elements to the plants per every unit volume of nutrient feed delivered to the plant. The absolute quantities of these nutrients is measured by the parts per million (ppm) targets. In addition to the absolute quantities of the nutrients in the feed, the relative ratios of one nutrient to another (particularly the N:P:K ratio) are also an important component of the feed program.

Direct measurement of the various component nutrients contained in the feed solution and the determination of the relative ratio of the nutrients comes from a lab analysis of the feed solution. It is useful to have the feed solution tested regularly to monitor the actual nutrient levels being delivered to the plants. Lab analysis of the feed solution takes time, and it is also important to be able to monitor the feed on a ongoing basis throughout the day. Measuring the electrical conductivity (E.C.) of the feed solution is a very useful tool in the day-to-day management of the fertilizer feed solution.

Measuring the E.C. of the fertilizer feed solution delivered to the plants can be used as an indirect measure of the level of nutrients reaching the plants. The feed program contains the appropriate quantities of dissolved fertilizer salts required to meet the nutrient requirements of the plants, and this solution has a corresponding E.C. In fact, the corresponding E.C. of most feed solutions delivered to the plants, when based on a nitrogen target of 200 ppm, is about 2.5 mmho. Of course, the other nutrients are present in their relative amounts with respect to nitrogen. Once the feed solution has been mixed to meet the targets, measuring the E.C. of the one-times strength solution can serve as the point of reference for delivering the nutrients to the plants.

The day-to-day management of the delivery of feed to the crop can vary and is based on the salt level of the feed solution. The feed solution can be used as a management tool to direct the development of the crop towards a vegetative or generative direction. The basis for this approach is that the higher the level of salts delivered to the root zone, the more stress is placed on the plants. The more stress the plant is under, the more emphasis the plant puts on producing fruit and the less emphasis on stems and leaves.

There are limits to the salt stresses that can be placed on the plants while still maintaining optimum production, as a high sustained yield is obtained through a balance of leaves and fruit throughout the season. However, using the feed solution to help optimize plant balance is a management tool. On cloudy days, plants can make use of higher fertilizer levels, more so than on sunny days when the plant has greater demands for water. Raising the feed E.C. (0.3 mmho) on a cloudy day will provide more nutrients to the plants; lowering the fertilizer E.C. on a sunny day will provide a greater relative proportion of water to the plants. The saltier the fertilizer solution, the harder the plant has to work to extract the water from the root zone.

Management of the daily application of fertilizer to the crop is based on varying the E.C. of the feed solution. The general rules for managing the feed E.C. and the total amount of nutrient solution volume delivered to the crop on a daily basis is presented in the next section.

Fertilizer and water application

Water and fertilizer are delivered simultaneously to the crop through the nutrient solution, and the amounts of water and fertilizer delivered vary with the changing requirements of the plants. The plants requirements change as they develop from seedlings to mature plants and in accordance with the day-to-day changes in the growing environment. To manage the delivery of nutrients and water to the plant, it is important to have a way of determining the crop's requirements for fertilizer and water.

Feed monitoring stations are established throughout the crop. One or two stations per every 0.4 hectare (1 acre) of greenhouse area are usually sufficient, but having one monitoring station for every watering "zone" of the greenhouse is a good idea. The purpose of the monitoring station is to measure the volume of feed delivered to the individual plants and to determine the volume of feed solution leachate, or "overdrain," flowing past the plants and out of the root zone over the course of the day. The E.C. and pH of the feed solution are taken on a daily basis, as are the E.C. and pH of the leachate (Figure 15).

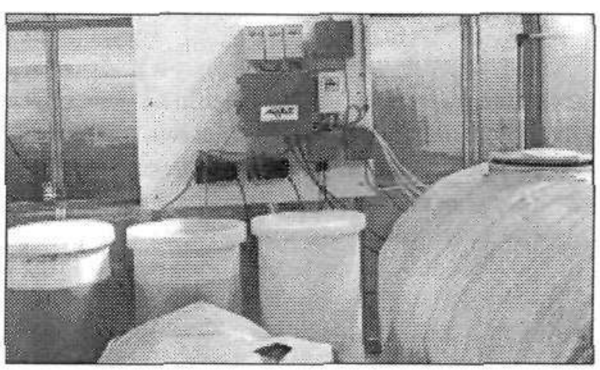

Figure 15. Typical fertilizer feed system with two fertilizer stock tanks and computerized control of pH and E.C.

The daily monitoring of the percentage of feed solution volume flowing through the root zone environment, the sawdust bags or rockwool slabs, etc. is used to adjust the volume of feed solution delivered to the plants. The E.C. of the leachate is used to make adjustments to the feed solution E.C. Monitoring the pH of the feed and leachate helps to ensure the correct pH is being fed to the crop. It also gives an indication of what is happening in the root zone with respect to pH.

Optimum feed pH is approximately 5.8, and this pH optimum also applies to the root environment as well. Generally, the activity of the roots tends to raise the pH in the root environment, and feeding at a lower pH can help counteract this rise in pH.

The amount of nutrient solution delivered to the plant on a daily basis can be determined by the percentage overdrain or leachate recovered from the plants over the course of the day. Leaching, or allowing a certain percentage of nutrient solution applied to the crop to pass through the root system, allows for a flushing of the root zone to avoid the accumulation of salts.

Generally, when the plants are young, a percentage leachate of 10 to 15 per cent is a good target. As the plants develop, the amount of water required to attain this overdrain target increases. As the season progresses and the light levels increase and the plants mature and begin to bear fruit, the overdrain targets increase to 20 to 30 per cent. Generally, these higher overdrain targets apply as the high light period of the year begins, usually in June. As the percentage overdrain decreases, the leachate E.C. increases, that is, the amount of salts in the root zone increases. The general rule for managing the level of salts in the root zone is that the root zone E.C. should not be greater than 1.0 mmho above the feed E.C.

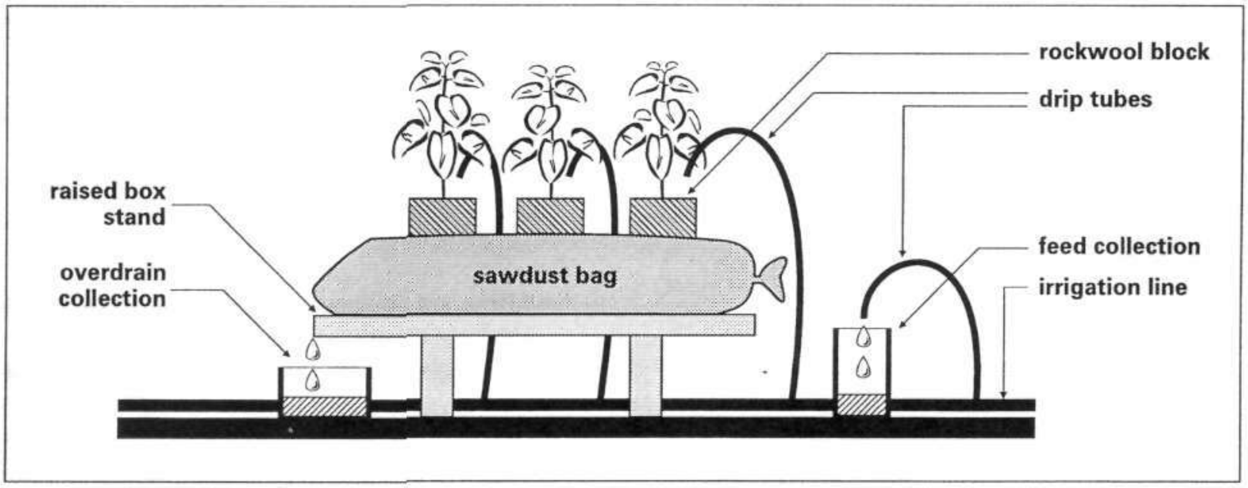

Figure 16. General schematic of a nutrient feed monitoring station

It is not a good idea to feed at a pH of lower than 5.5 when attempting to lower the pH in the root zone. In addition to feeding at a pH of 5.5, ammonium nitrate at 2 to 5 ppm of ammonium nitrogen (NH_4 - N) will help lower the pH of the root zone, due to the acidifying effect of this fertilizer.

A schematic of a typical feed monitoring station is presented in Figure 16. In addition to monitoring the feed and leachate, recording the leachate percentage, feed and leachate E.C. and pH can be used as a tool to chart the performance of the crop with respect to these recorded values over time and in relationship to other parameters, including the amount and intensity of available light.

Feed solution design is based on delivering adequate nutrition to the plants, and these feed programs usually have an E.C. 2.5 mmho (this largely depends on the E.C. of the irrigation water). With the optimum feed solution E.C. at approximately 2.5 - 3.0 mmho, the salt levels in the root zone should be maintained at around 3.5 - 4.0 mmho.

Early in the crop cycle, the salt levels in the root zone can be maintained at the proper target fairly easily by increasing the volume of nutrient solution delivered to the plant to ensure a 10 to 15 per cent overdrain. As the season progresses and the water has been increased so that the upper limit of 30 per cent overdrain has been reached, and the E.C. of the overdrain continues to climb above the target of 3.5 - 4.0 mmhos, the E.C. of the solution can be dropped.

The reduction in feed solution E.C. is accomplished in stages, with gradual, incremental reductions in feed E.C. in the order of 0.2 mmho every two to three days. It is never advisable to apply straight water to the plants to lower the root zone E.C. since the rapid reduction in root zone E.C. and increased pH can compromise the health of the roots and reduce the performance of the crop.

During periods when the plants are in a rapid stage of growth, the E.C. in the root zone can be below that of the feed solution. For example, the feed can be at 2.5 mmho while the leachate E.C. may be at 2.0 mmho. This result is an indicator that the plants require more nutrients, and the feed E.C. should be increased in increments in the order of 0.2 mmho/day until the E.C. in the root zone begins to approach the upper target limit of 4.0 mmho.

By varying the volume and E.C. of nutrient solution delivered to the plants, in accordance with the leachate overdrain and E.C. targets, it is possible to optimize the delivery of water and nutrients to the crop without overwatering and over-fertilizing. Applying too much or too little water can compromise the health and performance of the crop.

Water delivery to the plants occurs over the course of the entire day. Watering can be scheduled by using a time clock, or in more sophisticated systems, watering can be triggered by the amount of incoming light received by the greenhouse. In general, the greater the ability to control the delivery of water, the greater the ability to maximize crop performance.

A starting point for watering the crop early in the crop cycle would be to apply water every half hour from one half hour after sunrise to approximately one hour before sunset. The amount of water required to meet the overdrain target is divided among the waterings, based on the duration of the individual waterings.

For example, if a 40-second watering delivers 100 ml of water, then 10 watering events are required to deliver 1 litre of water. When more than a litre of water is required in one day, the duration of the individual watering events can be increased, or the number of watering events can be increased or both.

Generally, as the crop matures, it is better to increase the frequency of watering events than the duration of each event. If the watering system allows the variation of the frequency and duration of the watering events over the course of the day, then it is possible to increase the frequency and/or duration of the watering events during the high light period of the day, without necessarily increasing the duration of the early morning or late afternoon watering events.

Watering frequency can be used to help direct the vegetative/generative balance of the plant. For any given volume of water that is delivered to the plants, the more frequent the waterings throughout the day, the more the plant will be directed to grow vegetatively. The longer the duration between waterings, the stronger the generative signal sent to the plant. Frequent watering during the summer months in Alberta can help balance plants that are overly gener-ative due to the intense sunlight, high temperatures and low relative humidity.

With regard to the concept of per cent overdrain, it is preferable to obtain the majority of the overdrain during the high light period of the day. The first of the overdrain should start to occur at 10:00 a.m., and the greater part of the daily overdrain target should be reached by 2:00 to 3:00 p.m. Being able to vary the duration of the watering events over the course of the day allows for more nutrient feed being delivered to the plants between 10:00 a.m. and 2:00 to 3:00 p.m.

The use of overdrain targets is one way to ensure the plants are receiving adequate water throughout the day. A strong indicator of whether or not the plants have received adequate water during the previous day is whether the growing points or the tops of the plants have a light green color early in the morning. Over the course of the day when the plant is under transpiration stress, the color of the plants will progress from a light green to a darker blue- green. If the plants have received adequate water throughout the previous day, the light green color will return overnight as the plant recovers and improves its water status.

If the plants remain a darker bluish-green in the early morning, the amount of water delivered the previous day was inadequate. Usually, this result means that the overdrain targets for the previous day have not been met, and the amount of nutrient solution delivered to the plants has to be increased.

During the summer months, under continuous periods of intense light, the plants may not have recovered their water status overnight even when the daily overdrain targets have been met. The plants begin the day a dark blue-green color, an indication that they are already under water stress, even though the day has just begun. Under these circumstances the overdrain targets for the day could be increased, but there is the associated risk of overwatering and decreasing root health and performance.

In these cases, it is advisable to consider one or two night waterings, one at approximately 10:00 p.m. or one at 2:00 a.m. or both. Usually, the night waterings are the same length of time as the minimum watering duration applied during the day. Night watering can also help increase the rate of fruit development, but there is an associated risk of fruit splitting if too much water is applied at night. The night waterings should not be continued indefinitely, and the decision to use night watering events and to continue with night watering has to be based on the assessed needs of the crop.

Management of the feed solution and its delivery to the crop has to be relatively flexible to meet the changing crop needs. With experience, growers gain more confidence and skill in meeting and anticipating the changing crop needs throughout the crop cycle and through periods of fluctuating light levels. The general information presented in this section serves as a starting point. By following the principles of overdrain management, electrical conductivity and pH monitoring and correction, a successful strategy for water and nutrient delivery can be established.

As with many things, there is no one "right" way to apply water and nutrients to the crop. The use of leaching, although ensuring that salt levels do not accumulate to high levels in the root zone, does result in some "waste" of fertilizer solution as runoff.

Strategies can be employed to minimize the waste associated with leaching. Collection and recirculation of the leachate, with an associated partial sterilization or biofiltration of the nutrient solution, is one approach. The sterilization or biofiltration steps are required to minimize the disease risk associated with recycling nutrient solutions. Some estimates place the fertilizer cost savings at between 30 to 40 per cent when recirculation is used. In addition to being economical, recycling nutrient solutions is an environmentally sound practice.

There is a limit to how long nutrient solutions can be recirculated, because prolonged recycling of the same solution can negatively affect growth and yield. This result is primarily associated with the accumulation of sulfate ions in the solution. In addition to sulfates, chlorides and bicarbonates also have a tendency to accumulate and can influence crop growth. The progressive accumulation of sulfates in recirculating solutions requires occasional "refreshing" of the solution, where the solution would have to be allowed to leave the greenhouse as waste.

Conclusion

Commercial greenhouse management in Alberta growing conditions requires knowledge and the use of particular systems. Since greenhouse systems are complex, many growers simplify the many decisions they must make by using specific indicators.

Indicators quickly reveal changes in the greenhouse that may require changes in management strategies. Knowing and understanding these basic indicators will help in three ways:

- to evaluate the greenhouse environment
- to implement ways to enhance the greenhouse environment
- to achieve optimum crop performance

Anticipating crop needs and responding effectively to crop changes will lead to successful greenhouse crop production.

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