

Workshop Summary

Lecture 1

Components of Radiation: Definition of Units, Measuring Radiation Transmission, Sensors

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Definitions

Transmittance -- ratio of transmitted radiant energy to that incident

Absorbance -- ratio of the absorbed radiant energy to that incident

Reflectance -- ratio of the reflected radiant energy to that incident

Direct radiation -- straight beam radiation directly arriving from the sun to the sensor or plant

Diffuse radiation -- solar radiation, which is reflected by the atmosphere or greenhouse structure before reaching the sensor or the plant

Clearness Index (CI) -- ratio of the irradiance at the surface of the earth to the irradiance above the atmosphere; the “transmissivity” of the atmosphere for solar radiation

Electromagnetic spectrum -- all the wavelengths of radiation from the sun

PAR, Photosynthetically Active Radiation (400-700 nm) -- waveband of the electromagnetic spectrum used by the plant for photosynthesis

PPF, Photosynthetic Photon Flux density -- number of photons in the PAR waveband that are incident on a surface in a give time period. The units are $\mu\text{mol m}^{-2} \text{s}^{-1}$

PI, Photosynthetic Irradiance -- radiant energy stream in the PAR waveband, incident on a surface in a given time period. The units are W m^{-2}

Photons – measure of radiation (smallest “particles” of light; quanta)

Photon frequency – the energy of a photon is proportional to its characteristic frequency

Pyranometer -- sensor measuring solar radiation usually from 280-2,800 nm. Units are W m^{-2}

Quantum Sensor -- sensor measuring PAR waveband (400-700 nm). Units are $\mu\text{mol m}^{-2} \text{s}^{-1}$

Spectroradiometer -- instrument that can measure the irradiance of photons in each wavelength of a waveband

Spectral Irradiance (SI) -- energy value or distribution for each wavelength within a waveband is measured as $\mu\text{mol m}^{-2} \text{s}^{-1} \text{nm}^{-1}$ or $\text{W m}^{-2} \text{nm}^{-1}$

$\mu\text{mol m}^{-2} \text{s}^{-1}$ -- micromoles per square meter per second (intensity)
 W m^{-2} -- Watt per square meter

wavelength -- way to measure and describe the photon of light

waveband -- a grouping of wavelengths; PAR is a waveband from 400 to 700 nm

nm or nanometer -- unit of measure of the wavelength of light; one billionth of a meter

μm or micrometer -- unit of measure of the wavelength of light; one millionth of a meter

Some Perspective

The goal should be to provide the environment for the most optimum growth of the plant, or the highest quality final plant product, one that will demand the greatest return on investment. The plant response should remain dominant in all the discussions.

Measurement and reporting procedures of the appropriate radiation wavelengths or waveband that are important to the growth and development of plants should become the focus.

Consider the concept of “more is better”. The plant growth rate will increase with additional light, but it does so at a decreasing rate. As more light is added, the unit return becomes less. Ultimately the growth curve levels off, meaning that more light energy will no longer provide any increase of plant growth rate.

In the evaluation of a particular glazing for a greenhouse application, it may be more valuable to determine the total amount of photosynthetic energy transmitted to the plant canopy during an extended period of time (day, crop cycle, season, or year), than to determine an instantaneous value.

Defining the Components of Radiation

Radiation from the sun can be described by its quantity and quality.

The quality depends on the waveband of the light, as well as, the distribution and intensity of the wavelengths within the waveband.

The quantity is the amount of energy within the radiation. This quantity can be measured as the number of photons of light [moles of photons] per square meter per second, $\mu\text{mol m}^{-2} \text{s}^{-1}$, or as a total energy value of the light, Watts per square meter [W m^{-2}].

Radiation can be described by its wavelength or its frequency.

Wavelength has units of meters, typically nanometers (nm) [one billionth of a meter] or micrometers (μm) [one millionth of a meter], frequency has units of cycles per second, and each can be used to describe the energy value and the quality of the photon of light.

Wavelength and frequency are related by the constant c, the speed of light.

Frequency is equal to the speed of light multiplied by the wavelength.

The energy of a wavelength of light is determined by its frequency or its wavelength.

As the wavelength increases, the energy of the light wave decreases, and as the wavelength decreases, its energy increases. It is an inverse relationship.

Thus short wavelength blue light has more energy than longer wavelength red light, and likewise ultraviolet radiation has more energy than infrared radiation.

The radiation spectrum contains various wavebands of interest:

Ultra-Violet or UV is the wavelengths less than 400 nm. These high energy wavelengths can cause skin damage [sunburn].

Visible light, which is based on the sensitivity of the human eye, is within the 380-770 nm waveband, but based on its usefulness for plants it is within the PAR (400-700 nm) waveband.

The “colors” of visible radiation to humans can be approximately divided into the following wavebands:

Waveband	Color	Function in the Plant
380-436 nm	violet	=> uncertain, but may support effect of blue light
436-495 nm	blue	=> a minimal quantity is necessary to prevent tall, weak plants
495-566 nm	green	=> unnecessary, but contributes to photosynthesis
566-589 nm	yellow	=> unnecessary, but contributes to photosynthesis
589-627 nm	orange	=> Optimize for maximum photosynthesis
627-770 nm	red	=> Optimize for maximum photosynthesis; enhances flowering, stem elongation; Red/Far-red ratio is important

Infrared or IR are wavelengths greater than 770 nm and consist of a useful waveband for plants known as the Near Infrared or NIR which is 770-850 nm. Infrared wavelengths (770-1,400 nm) have the heating effect. These can provide warming to a plant leaf surface, or to our skin.

The PAR, Photosynthetically Active Radiation, is 400 to 700 nm waveband, which is the primary wavelengths important for providing the energy for plant photosynthesis.

Red: Far-red (R:FR) ratio consists of two narrow wavebands which influence plant growth responses.

The leaf is designed to absorb nearly 95% of wavelengths between 400 – 700 nm, but only 5% of the 700-850 nm waveband is absorbed. Of the remaining 95% of the 700-850 nm waveband, ~45% is reflected, and 45% is transmitted.

In the table below, the quantity or intensity of the radiation from 400-800 nm is shown as the Photon Irradiance (first column) for a very clear day. The quality or distribution of the wavebands of radiation is shown as a percentage of each waveband of light. These are contrasted for direct sunlight, and for under dense leaf shade (Kendrick and Kronenberg, eds., 1986).

Photon Irradiance (400 – 800 nm) $\mu\text{mol m}^{-2} \text{s}^{-1}$	Proportion of total light within each waveband				
	Blue (400-500 nm)	Green (500-600 nm)	Red (600-700 nm)	Far-red (700-800 nm)	
Direct sunlight	1700	23%	26%	26%	25%
Leaf Shade	60	4%	15%	11%	70%

Definition of Units of Measurements

Irradiance is the measure of the quantity or intensity of radiation. It is an energy per unit area value with units of Watt per square meter, or W m^{-2} . The pyranometer is used to measure this value

The PPF, Photosynthetic Photon Flux density is the number of photons in the PAR waveband that are incident on a surface in a give time period. The units are $\mu\text{mol m}^{-2} \text{s}^{-1}$. The quantum sensor will measure this value. A very clear sky will approach 2,000 $\mu\text{mol m}^{-2} \text{s}^{-1}$ PAR.

The PI, Photosynthetic Irradiance, is the radiant energy stream incident on a surface in a given time period. The very clear sky value will approach 1,000 W m^{-2} (for the 280-2800 nm waveband). The relationship between these two terms PPF and PI cannot be generalized, since they depend on the spectral properties (radiation distribution) of the radiation source.

Spectral irradiance (SI) can have units of $\mu\text{mol m}^{-2} \text{s}^{-1} \text{nm}^{-1}$ or $\text{W m}^{-2} \text{nm}^{-1}$ and can be determined from a spectroradiometer where the number or energy value of photons is measured at every wavelength.

Measuring Radiation Transmission

Radiation can either be reflected, absorbed or transmitted once it impacts a surface.

Extra-terrestrial solar radiation has a greater intensity and spectral distribution than ground level solar radiation because of the wavelengths of light which are absorbed while passing through the atmosphere. Major atmospheric components that absorb or reflect certain wavelengths of light include: ozone (O_3), carbon dioxide (CO_2), methane (CH_4), water vapor (H_2O), and CFC's (chlorofluorocarbons).

The Clearness Index (CI) indicates the percentage of the radiation which passes through the atmosphere. It quantitatively is the transmittance of the atmosphere, and essentially describes the "cloudiness" of the day. It is determined by the ratio of the intensity of radiation measured at the ground to that calculated to be above the atmosphere, using the same units for both. It can have units of either $\mu\text{mol m}^{-2} \text{s}^{-1}$ or W m^{-2} , that is, in terms of number of photons, or in energy terms, respectively. A CI of 0.75 is a very clear day, while a CI of 0.25 is a cloudy day.

Transmittance is a ratio of the intensity of the transmitted (below the surface) radiation within a given waveband, to incident (above the surface) radiation at the same waveband. A maximum value of transmission can be measured when the beam radiation is perpendicular (directly overhead of a horizontal surface) to the surface, and the sensor beneath the surface is located directly under it.

Transmittance measured within the greenhouse will be significantly different than when measured in the laboratory for a particular glazing material.

The value of transmittance in the greenhouse will vary depending on the location of measurement.

Two locations of importance are at the glazing level, and at the canopy level.

The glazing level transmittance value gives an indication of the glazing transmission performance in field conditions. The canopy level transmittance value gives an indication of the system (glazing and greenhouse structure) effectiveness in providing sunlight to the crop.

The proportion of direct (straight beam) radiation and diffuse (reflected) solar radiation will vary within the atmosphere in part due to the Clearness Index. A cloudy day will provide more diffuse

radiation, and less direct radiation than a clear day. A diffuse day essentially means that the light energy is not as concentrated from one direction (location of the sun in the sky), and light appears to arrive from all overhead directions with nearly equal intensity. In practical terms, there will be less clear, distinct shadows on the greenhouse crops which will result from the overhead structural members, when compared to a clear sky.

The diffuse radiation can be determined from the direct component of radiation with the use of a shadow-band instrument. This instrument continually places a small opaque piece between the sensor and the location of the sun, thus always keeping it in the shadow. It therefore approximates the diffuse component of the solar radiation. If simultaneously the total radiation is measured, then by subtracting the value of the diffuse from this total value, the direct component can be determined.

Sensors

Pyranometer sensors are for measuring solar radiation over most of its entire waveband, usually from 280-2,800 nm. Note that 97% of the sun's spectral distribution is within this waveband. This value could be considered "total solar" radiation. Units are $W m^{-2}$

A quantum sensor is limited to the PAR waveband (400-700 nm), and the units are typically expressed as $\mu mol m^{-2} s^{-1}$ or $W m^{-2}$

A spectroradiometer is an instrument that can split the incoming light into individual wavelengths or prescribed wavebands, and then measure the irradiance of photons in each wavelength. It typically measures spectral irradiance $\mu mol m^{-2} s^{-1} nm^{-1}$ or $W m^{-2} nm^{-1}$

A net Radiometer measures the difference of the radiation arriving from above to that being reflected from below. It is important for energy evaluations of the greenhouse.

Lecture 2

Plant Physiology: Environmental Factors and Photosynthesis

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Definitions

Anthesis – flowering

Air Temperature -- day or nighttime environmental temperature of the plant canopy

Hypocotyls -- plant stem of young seedling after germination

Photosynthates -- the initial chemical products of the photosynthesis; these are utilized to build complex molecules and ultimately the plant biomass

Photoperiodism -- plant growth in response to the length of the day; an example of plant response to daylength is flowering.

Stomate -- small openings on the leaf which allow carbon dioxide to enter the leaf for photosynthesis, and moisture and oxygen to exit to the atmosphere.

Transpiration -- water evaporating from the leaf; it is the natural cooling process for the plant, as well as, the process to move water (with dissolved nutrients) through the plant

I. Temperature

Most plants function in a relatively narrow range of temperatures. The extremes of this range may be considered killing frosts at about 32°F (0°C) and death by heat and desiccation at about 113°F (45°C).

Optimum Air Temperature - Each kind of crop grows and develops most rapidly at a favorable range of temperatures. This is called the optimum temperature range.

Soil Temperature - Soil temperature has direct dramatic effects on microbial growth and development, organic matter decay, seed germination, root development, and water and nutrient absorption by roots. It is defined as the temperature of the root zone environment of the plant.

Chilling Injury - Most crops are injured at temperatures at or slightly below freezing. Plant death or damage at temperatures above freezing but below 50°F (10°C) can occur for tropical plants.

Heat (High Temperature) Stress - When temperatures rise too high, heat destruction of the protoplast results in desiccation or plant cell death. This occurs in the range of 113-122°F (45-55°C).

Vernalization - Vernalization is the exposure of plants to low temperatures for extended periods of time, which then induces or accelerates flowering (or bolting). Bolting is unwanted flowering.

II. Light

All light is made up of energy.

Light to humans is the wavelengths of radiant energy in the electromagnetic spectrum that activates the light receptors in our eyes.

Light to plants is all the wavelengths of the electromagnetic spectrum including the wavelengths that humans can see (visible light) and the wavelengths that humans can't see (such as ultraviolet and infrared light).

Light Quality - Sunlight is often referred to as white light and is composed of all colors of light. A color of light would be the relative distribution of wavelengths from a radiation or reflective source.

Light Intensity - Light intensity is the quantity or amount of light received by plants in a particular region and is an important factor in determining the rate of photosynthesis of the plant.

Light Duration - Due to the tilt of the earth's axis (23° from vertical) and its travel around the sun, the length of the light period (also called photoperiod or daylength) varies according to the season of the year and latitude.

Photosynthesis - One of the main roles of light in the life of plants is to serve as an energy source that plants can capture through the process of photosynthesis. Using water and carbon dioxide through photosynthesis, plants produce the foodstuffs (photosynthates) necessary for growth and survival. Atmospheric carbon dioxide is consumed, oxygen is given off, water is required, and energy is stored.

Photomorphogenesis - Photomorphogenesis is defined as the ability of light to regulate plant growth and development (shape, size, proportion of the plant), independent of photosynthesis. Plant processes that appear to be photomorphogenic include internode elongation, chlorophyll development, flowering, abscission, lateral bud outgrowth, and root and shoot growth.

Water

Most plants are about 80 to 90 percent water. Since they contain so much water, their yields and quality suffer very quickly from drought. Most plants require a constant and somewhat abundant supply of moisture (approximately 65% field capacity) throughout the growing season.

Waterlogging - Under waterlogged conditions, all pores in the soil or soil mix are filled with water, so that the oxygen supply is almost completely deprived. As a result, plant roots cannot obtain oxygen for respiration to maintain their activities for nutrient and water uptake.

Water Balance - When the balance of water is affected either because there is insufficient available moisture in the soil (or soil mix) or the transpiration of water through the stomata exceeds the plant's capacity to compensate for the internal loss, the plant comes under stress.

Drought - Drought is generally considered to be a meteorological term and is defined as a period without significant rainfall or moisture

IV. Wind

A slight wind is necessary to replenish carbon dioxide (CO₂) near the plant surface. CO₂ can be rapidly depleted at the leaf surface.

V. Growing Media

The **growing media** must provide: moisture holding capacity, nutrient exchange capacity, gas exchange of oxygen and carbon dioxide, and physical support for the plant.

Plant Fertility – The root zone is the main source of nutrients for plants, which are incorporated into the plant through the roots.

Lecture 3

Glazing Materials, Structural Design, and Other Factors Affecting Light Transmission in Greenhouses

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Definitions

Single-span -- an independent, single-bay structure, separate from adjacent structures

multi-bay or gutter-connected -- construction where modular structural units are connected at the gutters to cover large ground areas

lean-to -- structure which is attached to another building along the ridgeline

over-wintering -- temporary, unheated structure for winter protection of hardy crops

single-layer -- cover or glazing composed of one layer of rigid or flexible film material

multi-layer -- cover or glazing consisting of two or more layers of rigid or flexible film materials

air inflated -- separation of two layers of flexible film by sealing the edges and inflating with pressurized air

roof slope -- angle of the face of the roof relative to the horizontal

arch roof -- continuous curved roof face

gable roof -- flat roof face

truss -- structural framework used to support the roof

purlin -- longitudinal members of the structural framework that support the glazing material on the roof

bow or hoop -- pipe or tube framework used to support the glazing of an arched roof

pipe or post or column -- vertical structural member which supports the gutters and endwalls

gutter -- water transport channel, supported by posts or columns, and providing attachment for the roof bows

ridge -- peak or high point of the roof that spans the long length of the structure

headhouse -- separate or attached building to the structure used as a preparation area

Transmission of Radiation through Glazings

The primary purpose of a greenhouse covering is to provide a translucent barrier between two environments. One is normally conducive to plant growth and the other is not. Light energy from the sun passes through the glazing providing energy for the photosynthetic process, converting CO₂ and H₂O to a form of C₆H₁₂O₆ (carbohydrate) and O₂.

Light energy or radiation which strikes a surface is either absorbed, reflected or transmitted. The angle of roof as it is presented to the sun determines the amount of energy which is reflected and the amount which is transmitted.

Laboratory tests indicate that measured total transmittance, direct and diffuse for new polyethylene film in the PAR waveband is approximately 90% for a single layer and 80% for two layers.

As with most films much of the transmitted radiation is diffused because of its translucent nature. For example, the diffuse component of the total solar energy measured beneath the glazing is 29% and 40% respectively for single and double layers of polyethylene.

Influence of greenhouse orientation

Guidelines for 40°N Latitude

- Free-standing greenhouse should be oriented East-West.
- Multi-bay, gutter-connected, or ridge and furrow greenhouse should be oriented North-South.

Free-standing greenhouses

The need for the most PAR transmission into the greenhouse is from October to March when there is less light available because of the seasonal change to a low sun angle. To achieve this goal, a free-standing greenhouse will receive more light with an East-West orientation of its ridge during this critical period.

Multi-bay, gutter connected or ridge and furrow greenhouses

Although an East-West orientation allows more light to enter the greenhouse there are permanent shadows throughout the greenhouse caused by the structural members, particularly the gutter and thermal screen installations.. A North-South orientation, however, will cause the shadows to move from the west side of any gutter section in the morning to the east side of the gutter section in the afternoon. This moving shadow pattern is more desirable for crop growth because there is no part of the crop subjected to shadow throughout the entire day

Influence of structural design

Roof slope is an important parameter in greenhouse design. The maximum amount of light energy transmitted occurs when the glazing surface is perpendicular to the sun. Essentially this happens only for a short time of the day. In current design practice, a roof slope of 27°- 30° or a slope of 1 in 2 is used. Some glazings have less unit weight but the design of the greenhouse structural members should be essentially the same because the primary loads are live loads of wind and snow and the dead load of the glazing is small in comparison to the total loads experienced by the greenhouse.

Influence of Location

The available light for the winter crop in November, December and January at 40° N is only one third of that available during the summer months. No engineering design can remedy this situation, but it must be recognized by the engineer as a potential limiting factor in any system.

Influence of interior greenhouse components and systems.

With the advent of thermal screens, supplemental lighting and other greenhouse handling system along with traditional overhead heating systems, concern has been expressed for obstruction of sunlight which is caused by these components. Under bench heating and in-floor heating systems have reduced the number of overhead heating pipes necessary to meet the heating demand load. Thermal screens which are installed and move gutter to gutter can reduce shading because the thermal screen shares the shadow pattern with the shadow caused by the structural gutter and does not add an additional shadow which is caused by the system which moves from truss to truss.

Influence of weathering on glazing

The design of sophisticated greenhouse glazing films has nearly eliminated this problem. However, it is also true that not all wavebands are attenuated the same over time of exposure of greenhouse glazings. There are distinct differences between the new and weathered film, particularly in the lower PAR region.

Influence of condensation on the glazing

Condensation is found on most glazings and is useful at night for reducing energy loss for direct radiation to the sky from polyethylene film covered greenhouses which are not glazed with IR film. Condensation between the two layers of polyethylene film can be reduced or eliminated by using outside air to supply the fan used to inflate and separate the two layers of film

Lecture 4

Greenhouse Glazing Effects on Heat Transfer for Winter Heating and Summer Cooling

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Definitions

Conduction heat transfer -- transfer of energy through materials by heat movement from molecule to adjacent molecule across the material.

Conductivity coefficient -- property of a material directly related to its ability to transfer heat; opposite of insulation (resistance) value.

Convection heat transfer -- transfer of energy by movement of a fluid from location to location, or by movement of the fluid across another layer of fluid.

Convection coefficient -- physical property of the fluid to transfer heat through physically moving from one position to another; opposite (inverse) of the convective resistance

Convective resistance -- the sum of the resistance to heat movement by convection; the opposite (inverse) of the convection coefficient

Condensation -- the change of vapor to liquid; heat is given off

Evaporation -- the change of liquid to vapor; heat is consumed

Natural convection heat transfer -- movement of heat by fluid flow without the use of a fan or pump

Forced convection heat transfer -- movement of heat by fluid flow with the use of a fan or pump

Infiltration -- unwanted heat loss through air exchange across the greenhouse glazing

Insulation -- resistance to heat flow; opposite of conductivity

Latent heat -- energy associated with the moisture in the air; energy associated with the change of liquid to vapor; evaporation is an example of latent heat exchange

Net radiation -- the difference of the energy (heat) received to that lost by radiation

Radiation heat transfer -- energy lost through the greenhouse glazing that is primarily dependent upon the emissivity and the transmissivity of the glazing; there is no movement of air mass.

Reciprocal -- mathematically the inverse; to determine the inverse, divide the value into one

Transpiration -- loss of plant moisture through openings in the leaves; it is an evaporative process which also cools the leaves

I. Energy (heat) transfer in the greenhouse occurs in a combination of four ways: Conduction/Convection, Radiation, Latent, and Infiltration.

Radiation heat loss may be the most important for thin film, continuous glazing.

The formulation and manufacture of the film will determine its transmission of heat by radiation.

The others, especially infiltration and latent heat loss, can be minimized only by the design and management of the greenhouse operation.

Light is the only form of radiation that is visible to humans, but all radiation is energy, and energy is synonymous with heat. The amount of heat within an object determines its temperature, and thus the input/output flows of heat from the greenhouse, or from the plant itself, are important.

The thermal environment (air temperature) of the greenhouse is based on the radiant energy transmitted into the greenhouse, to that re-emitted through the glazing (solar energy “in” compared to heat energy “out”). If more heat enters than leaves, the greenhouse air temperature will tend to rise. If more heat leaves than enters, the air temperature will fall.

Conduction and Convection heat gain and losses are practically the same for all plastic single film glazing materials, and there is little that can be done to reduce them, except increase the number of layers.

Conduction is defined as the transfer of energy through materials and can be envisioned as the transfer of heat from molecule to molecule across the material.

Convection is the transfer of energy by movement of a fluid from location to location, or by movement of the fluid across another layer of fluid.

Radiation heat transfer can be conceptualized as photons transporting energy from the object to its environment and other photons transporting energy from the environment to the object.

Energy losses by radiation in the greenhouse are primarily dependent upon the emissivity and the transmissivity (in the infrared waveband) of the greenhouse covering material.

The net radiation, that is, the difference of the energy received and lost by radiation, is important for determining the greenhouse air temperature. During the day, solar radiation generally assures a net gain of energy, with a subsequent greenhouse air temperature rise. At night, the warm plants and components within the greenhouse lose energy by transmission of long wave (infrared) radiation to the cold sky above.

The rate of this loss depends, not only on the temperature of the plants, and the atmospheric conditions (cloud cover, carbon dioxide, and ozone content), but also on the properties of the glazing. The

capability of the glazing to transmit long wave radiation (wavelengths greater than 850 nm) directly affects radiation energy losses.

Infiltration and ventilation involve the transfer of heat by the movement of air through the greenhouse covering.

Latent heat loss is related to the amount of moisture in the air. As moist air is lost to infiltration across the greenhouse glazing, the energy (heat) that was consumed during the process of evaporation of the liquid water to form the gaseous vapor is also lost. In the process, the greenhouse air was cooled.

Latent heat loss also occurs when water vapor in the air condenses to liquid water on a cold surface (such as the glazing), in the process, heat is generated, and is released directly to the glazing and then out to the environment.

II. Radiation fundamentals related to greenhouse environmental control

In conceptualizing radiation heat transfer as the movement of photons to and from an object the characteristics of the photons need to be considered. The energy of a photon is directly related (proportional) to the frequency of that photon.

The practical way to measure and describe the photon of light is by its wavelength.

The wavelength of the photon can be determined by dividing its frequency by the speed of light.

The human eye can visualize only those photons with wavelengths between 400 (red) and 700 nm (blue). The eye cannot “see” other wavelengths such as the ultraviolet (UV) or infrared (IR).

It is the IR and longer wavelengths that are important for heat loss from an object by radiation.

III. Energy transfer on a cold night requires heat to maintain the greenhouse air temperature

The plant constantly gains and loses heat attempting to maintain a balance with its surrounding environment. A cooler leaf will gain heat from the warmer air.

Transpiration will transfer latent heat by evaporation from the plant to the air.

The plant may receive net radiation from warmer portions of its environment such as heating pipes, radiant heaters and possibly a warm floor or bench top. It will lose heat by radiation to the colder glazing, or lose heat by radiation directly to the cold outside sky.

If the glazing is not transparent to radiation at the wavelengths being emitted by the plant (ie it is an infrared barrier film), then this heat loss will be reduced, and the leaf temperature will be warmer.

IV. Energy transfer during a sunny day requires cooling to reduce greenhouse air temperature

There are significant differences between the energy balance of the plant and greenhouse in the daytime and at night. With sunlight, the plant is actively engaged in photosynthesis and transpiration becomes a major mechanism for moving latent heat from the plant to the greenhouse air.

The plant receives radiation over a much larger waveband than it will actually use for photosynthesis.

The PAR is a portion of the total light spectrum, which is necessary for photosynthesis. Less than 5% of the PAR energy is converted to stored chemical energy by photosynthesis, therefore, at least 95% of the PAR and all of the other non-PAR radiation (shorter [less than 400 nm] and longer wavelengths [greater than 700 nm]) have only to contribute to raising the plant leaf and air temperatures.

Given that only 44% of the incoming radiation from the sun is in the PAR waveband, the remaining 56% contributes to heating the greenhouse and the plant leaf surface.

Lecture 5

Plant Physiology: Manipulating Plant Growth with Solar Radiation

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Definitions

Chlorophyll -- green pigment photoreceptor cells that capture light energy for use in photosynthesis

Color -- distribution of wavelengths of light coming from a radiation source, or reflected from a reflective object.

EOD treatment -- End-of-Day application of red wavelength of light (R) or far red wavelength

Red light wavelength (R) -- 600 to 660 nm wavelengths of the electromagnetic spectrum

Far red light wavelength (FR) -- 700 to 740 nm wavelengths of the electromagnetic spectrum

Morphology of the plant -- physical size, shape and distribution of the plant architecture

nm or nanometer -- unit of measure of the wavelength of light; one billionth of a meter

Photosynthetically Active Radiation (PAR) -- the photons of radiation in the 400 to 700 nm waveband. PAR is a general term that can describe either the photosynthetic photon flux density (PPF), or the photosynthetic irradiance (PI).

Photosynthetic Photon Flux Density (PPF) -- the number of photons in the 400 to 700 nm (PAR) waveband contacting a unit surface area over a given time period. Abbreviated as $\mu\text{mol m}^{-2} \text{s}^{-1}$

Photosynthetic Irradiance (PI) -- the energy of the radiation in the 400-700 nm waveband which is contacting a unit surface area over a given period of time. Abbreviated as W m^{-2} .

Photomorphogenesis -- the ability of the plant to monitor light and regulate its growth and development (shape, size, proportion of the plant), independently of photosynthesis

Photon or Quanta -- packet of energy associated with a wavelength of light

Photosynthetic wavelengths (PAR) -- 400-700 nm

Photosynthesis -- plant process where light is transformed into carbon molecules (plant matter); carbon dioxide is consumed, oxygen is given off, water is required, and energy is stored.

Photoreceptors -- plant cells that can sense light or and capture light energy

Photoreceptors Pr and Pfr -- Red and Far red forms of the photoreceptor which influences Photomorphogenesis

R:FR -- the ratio of the measured intensity of Red wavelength of light to the Far-red wavelength.
Spectroradiometric data -- the measured energy intensity of each wavelength of light

I. Light – Radiant Energy

Light is all the wavelengths of the electromagnetic spectrum including the wavelengths that humans can see (visible light) and the wavelengths that humans can't see (such as ultraviolet and infrared light).

Light for the plant is not only used for information about its environment, but also for producing its energy through the process of photosynthesis.

The characteristics of light in the plant's environment is transferred to the plant through the interception and activation of pigment systems. This information affects the morphological development (root and shoots) of the plant.

II. Color - The Wavelength Distribution of Radiant Energy

Color is "the quality of an object or object with respect to light reflected by it, usually determined visually by measurement of hue, saturation, and brightness of the reflected light".

The appropriate plant physiological definition of color is the relative distribution of wavelengths from a radiation or reflective source.

III. Perception of Light and Color By Humans And Animals

Light sensitive cells (photoreceptors) exist in almost all organisms.

The prime function of the cones of the eye is to perceive colors.

Three different types of cones in the eye, respond to blue, green, and red light.

Intermediate colors other than blue, green, and red are perceived by simultaneous stimulation of two or more types of cones.

IV. Plant Uses Of Radiant Energy And Plant “Vision”

Plants utilize specialized pigments (photoreceptors) to intercept and capture radiant energy.

Plants also monitor radiant energy as an indication about their environment and for adjusting plant growth.

This monitoring of the light environment may be considered plant “vision” and would be more correctly termed photomorphogenesis.

V. Light Energy Capture By Plants - Photosynthesis

Light energy captured by the chlorophyll pigments (green-colored photoreceptor) is used by plants for growth and development through photosynthesis.

Carbohydrates such as starches and sugars, and stored chemical energy are produced by photosynthesis.

VI. Photosynthetic Radiation

Photosynthetically Active Radiation (PAR) is defined as the radiation in the 400 to 700 nanometer (nm) waveband.

The PAR waveband of light is the energy source for photosynthesis.

Photosynthetic Photon Flux Density (PPFD) is the rate of interception of photons of radiation in the 400 to 700 nm waveband (PAR waveband). It is measured in micromoles per square meter per second, and abbreviated as $\mu\text{mol m}^{-2} \text{s}^{-1}$.

Photosynthetic Irradiance (PI) is the energy of the radiation in the 400-700 nm waveband which is intercepting a unit surface area over a given period of time. It is measured in Watts per square meter, and abbreviated as W m^{-2} .

VII. Light Regulated Plant Development - Photomorphogenesis

Photomorphogenesis is defined as the ability of light to regulate plant growth and development. It is independent of photosynthesis.

Plant processes that are photomorphogenic include internode elongation, chlorophyll development, flowering, abscission, lateral bud outgrowth, and root and shoot growth.

VII. Photomorphogenic Radiation

Radiation wavelengths which influence photomorphogenic plant responses include the Phytochrome Wavelengths (Red and Far-red light), and the "Cryptochrome" Wavelengths (Blue light).

Phytochrome, a colorless photoreceptor, can exist in two forms; an active phytochrome far red form (Pfr), and inactive phytochrome red (Pr) form. It can readily change from one form to the other.

The proportion of each form at any given time in the plant leaf is dependent on the amount of the far red (730 nm) and Red (660 nm) wavelengths of light received by the leaf.

"Cryptochrome" is an undetermined photoreceptor that responds to blue wavelength of light (400 to 500 nm) received by the plant leaf.

IX. Current Methods To Regulate The Growth Of Plants

Current methods for growth regulation of plants include the use of chemical plant growth regulators, temperature regulation of day and night temperatures ("DIF"), or applying mechanical (seismic) stress.

X. Using Light To Regulate Plant Growth In The Greenhouse

Exposing the Plants to R and FR Light

Daily exposing seedling plants to End-of-Day (EOD) red (R) or far red (FR) light for several weeks in the greenhouse prior to field transplanting can alter the plant height and the total leaf area.

Supplementing the Greenhouse Light Environment with Fluorescent Light

Daily exposing seedling plants to cool-white fluorescent light for one hour before the end of the natural photoperiod for several weeks can alter plant height and total leaf area.

Filtering out FR Light Using the Greenhouse Covering

Removal of FR from solar radiation, using liquid copper sulfate (CuSO_4) filters, reduced plant height.

Panels of rigid polycarbonate (PMMA) containing a FR intercepting dye have been developed and tested for controlling plant height.