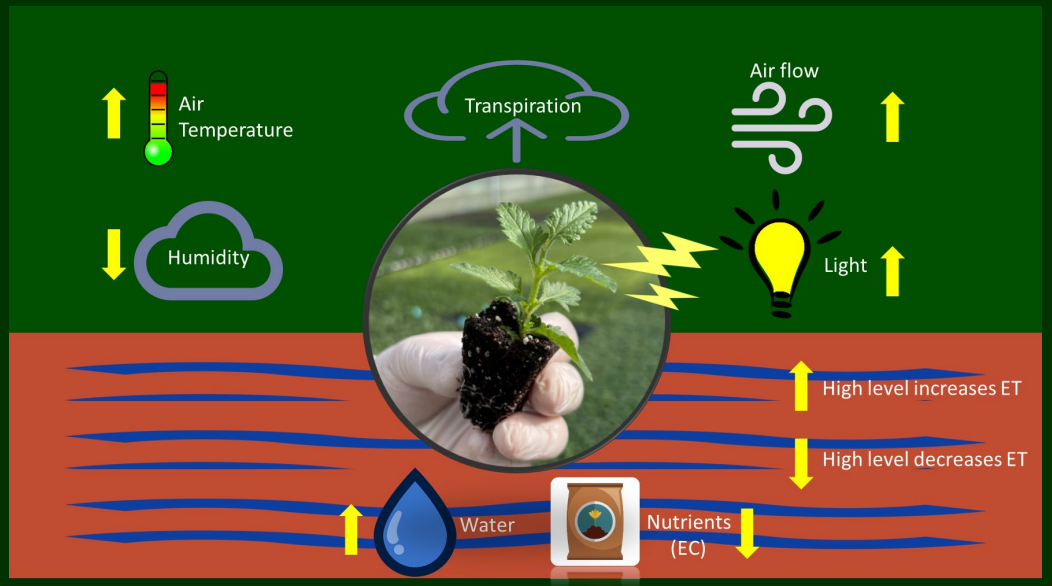
Greenhouse Climate Control

To VPD, or not to VPD…





Paul Fisher, Ph.D. pfisher@ufl.edu, 352 226 4410

UF IFAS
UNIVERSITY of FLORIDA

Key Points

- Plant science has come a long way. Is greenhouse climate control in the US keeping up?
- Example: water use in cutting propagation (VPD, etc.)
- Crop losses a driver to propagate in vertical farms
- Most greenhouses using manual or very simple set point control
- Very few sensors indoors – not enough to optimize
- We need more equipment talking to each other
- Few growers fully understand their environmental control systems



The rule of 10

- When researchers measure water use and leaching, the least efficient growers use at least 10 times more water than others

- Santos and Fisher (UF): Grower's leached between **0.6 to 6.0** liters/tray when propagating petunias and calibrachoa cuttings over 4 weeks

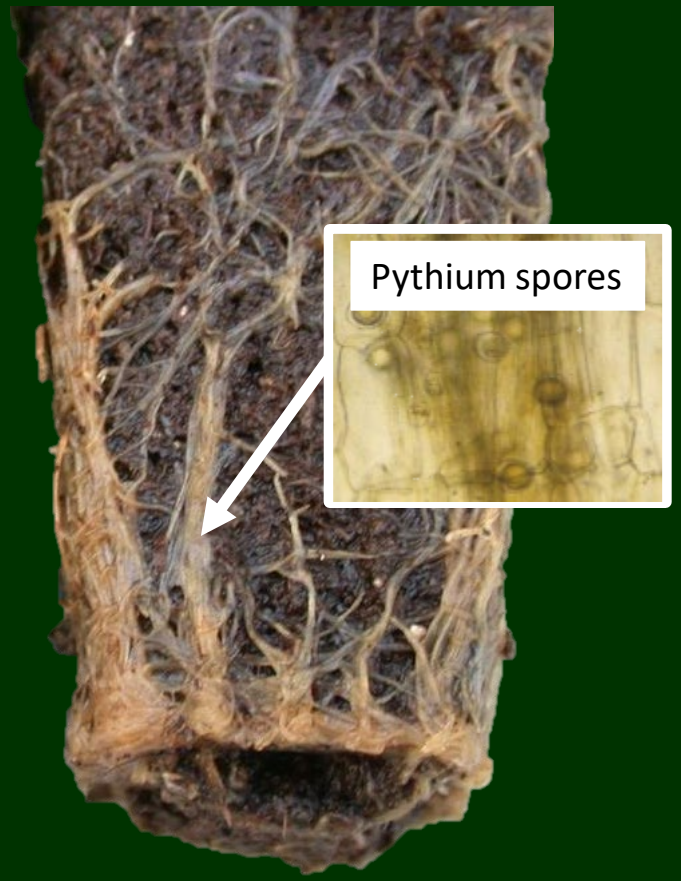


- Faust (Clemson University): Growers applied between **0.6 to 8.0** liters/tray for annuals & **0.4 to 15.5** liters/tray for geraniums over 10-day propagation cycle in late winter



The rule of 10: Why?

- Water is cheap
- But losses especially from over-watering are expensive
- Growers are smart
- But irrigation decisions & environmental factors are complex



Dr. Rob Wick
University of Massachusetts

Many factors go into irrigation timing

Species differences, crop stage, weather, day of week, water pressure…






It Depends..

Stress = Variability = $$$!

- Crop losses
- Fixing trays = labor
- We need uniformity

  within a tray,

  across the bench,

  and over time



- Plant factories manufacturing transplants, with little room for “art”

Growers are looking more at indoor production: Why?

- More expensive space
- But consistent climate & results
- Higher productivity
- Less shrinkage



Greenhouse Grower 1, 2

Indoor seedling plugs, rooted cuttings, and tissue-culture transplants



Shenandoah Growers



Battlefield Farms



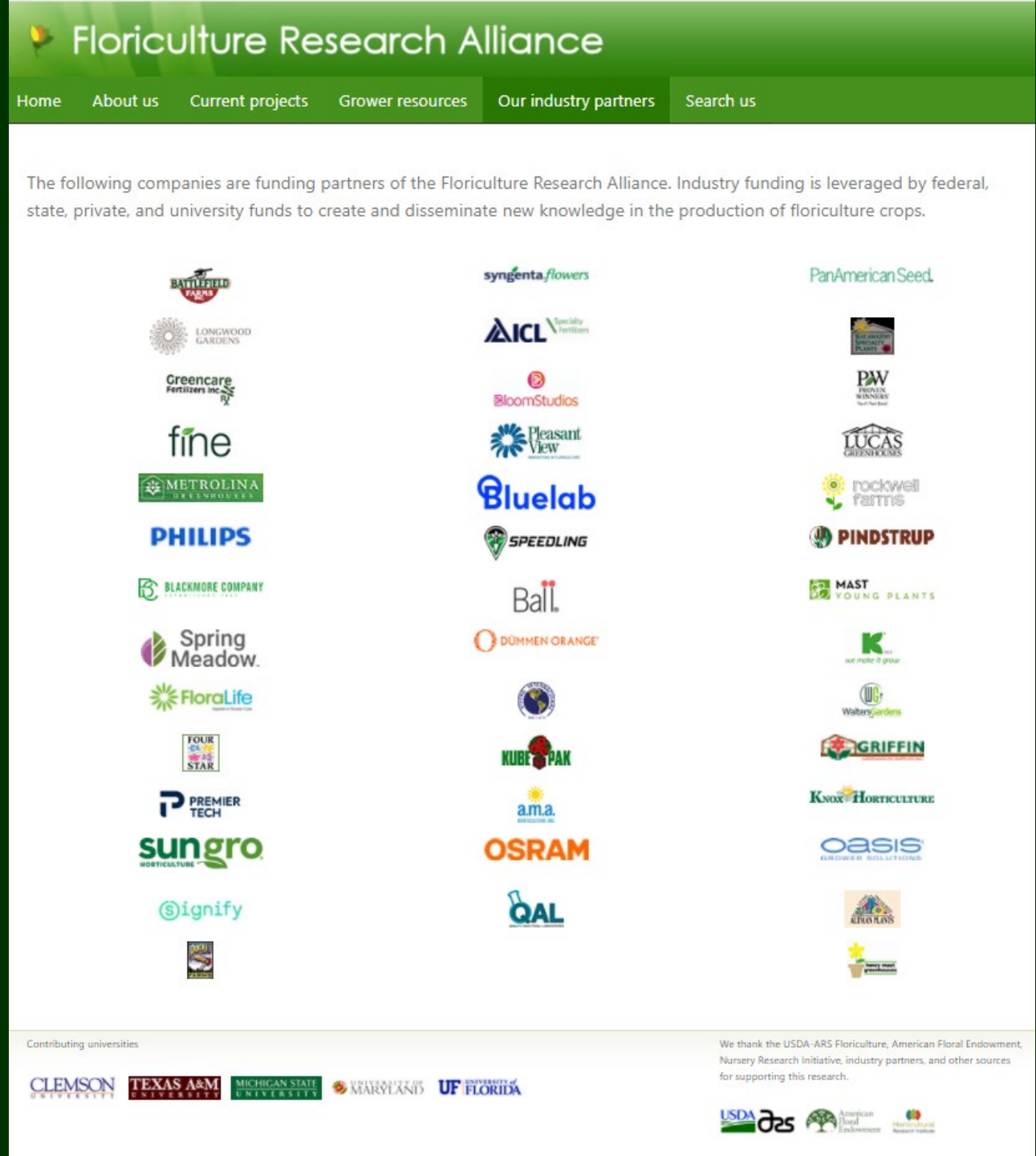
Metrolina

Short height, relatively short production times, low energy demand per plant, and high economic value per square foot week

Floriculture Research Alliance university/industry consortium

Donors 2021:

Thank you for your support!



Example: blueberry tissue culture plants



Tissue culture laboratory stage (4 weeks)



Greenhouse rooting stage (8-12 weeks)

Trial on light level with blueberries



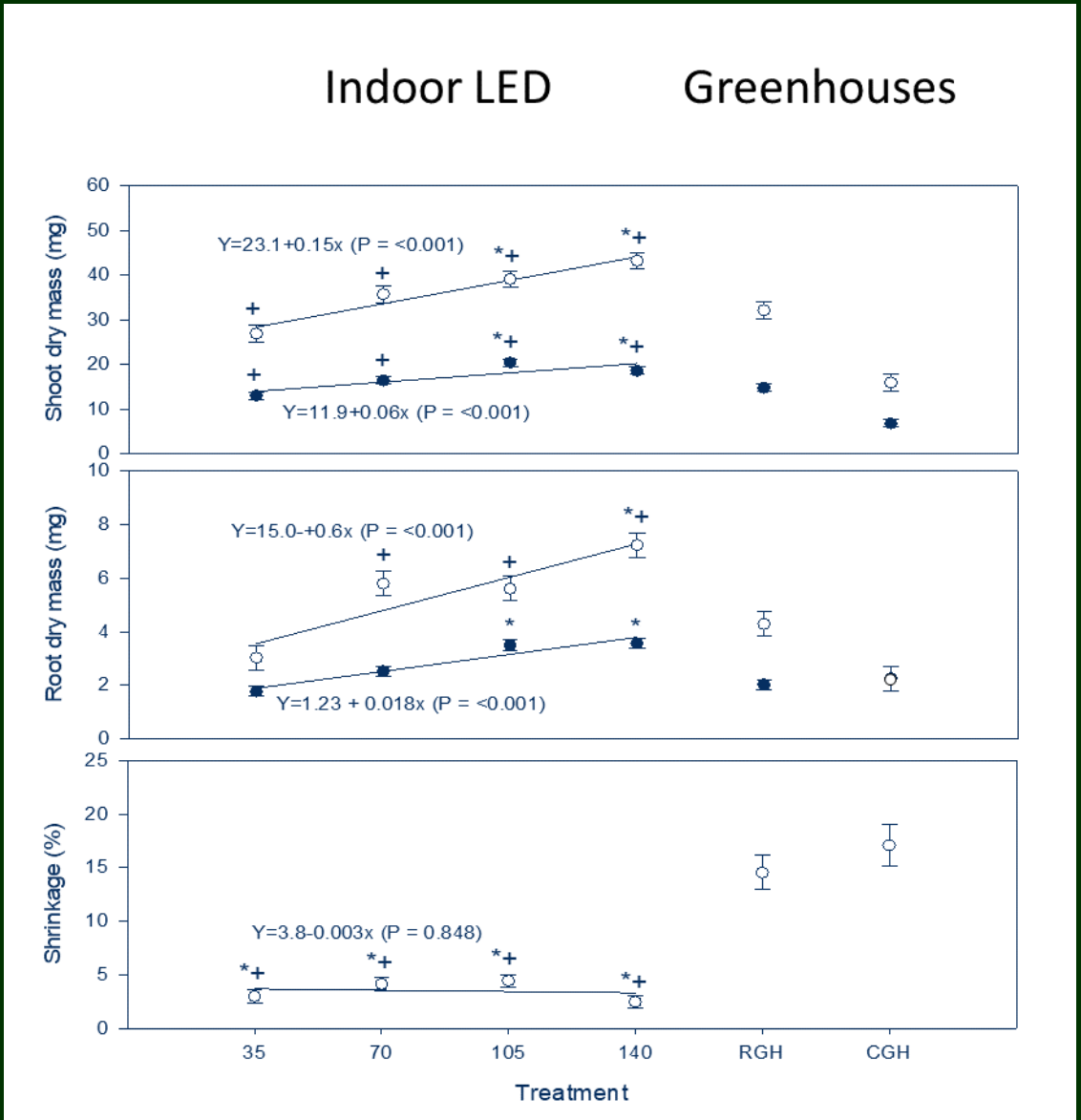
Indoors: Four light intensities
(35 to 140 µmol·m^{-2}·s^{-1})





Commercial and research greenhouses

Improved survival Indoors versus Greenhouse



Shrinkage at week 8

4% Indoor propagation

15% Research greenhouse (RGH)

17% Commercial greenhouse (CGH)

At week 4, biomass was already higher than in a commercial greenhouse (CGH) at week 8



Greenhouse **Indoor propagation**

Blueberry 'Emerald' at week 4

UF trials in parallel with growers

Indoor Fog and Mist



Light Cart & Dome



Greenhouse





Percent Rooting	Campanula at 39 days	Olive at 42 days	Lavender at 29 days				
			Big Time Blue	Papilli on Purple	Super Blue	Spirit Deep Purple	Imperi al
Indoor Fog	100%	82%	92%	95%	100%	93%	93%
Dome	98%	68%	93%	77%	100%	93%	85%
Greenhouse	81%	23%	92%	85%	100%	95%	85%

Pilot data on energy & economics



Dr. Ying Zhang
CEA engineer







Thanks to Sarah Lehning,
Emilio Suárez Romero, &
Marc Verdel, Battlefield Farms

Pilot data on energy and economics

- $1.00 assumed indoor propagation cost per tray per week:
  - $0.48 lights + electrical from preliminary Battlefield Farms data, OR
  - $0.59 lights + electrical + cart based on light cart
  - PLUS depreciation of other capital costs (germination room and HVAC), supplemental CO_2, & extra labor
- Break even reduction in shrinkage (# plugs) to pay for indoor lighting:
  - Example blueberry:
    - 4 weeks indoors = $4 additional cost
    - Net value per plant = $0.50
    - 8 additional plants per 288 tray that survive
    - = 3% less shrinkage



- Favors short time in indoor propagation, high-valued crop, small cell size, high shrinkage in greenhouse

Is indoor propagation the future?

- Primarily for niche crops
- Scalability and cost
- Turn this question around:
  - *Why is greenhouse climate control failing with sensitive crops?*





Greenhouse production in northern winter can be like sole-source lighting indoors

- Some growers will even close energy curtains on a cloudy cold day to conserve heating fuel



Greenhouse production in northern winter can be like sole-source lighting indoors

Sunny open shade





Cloudy open shade + LED



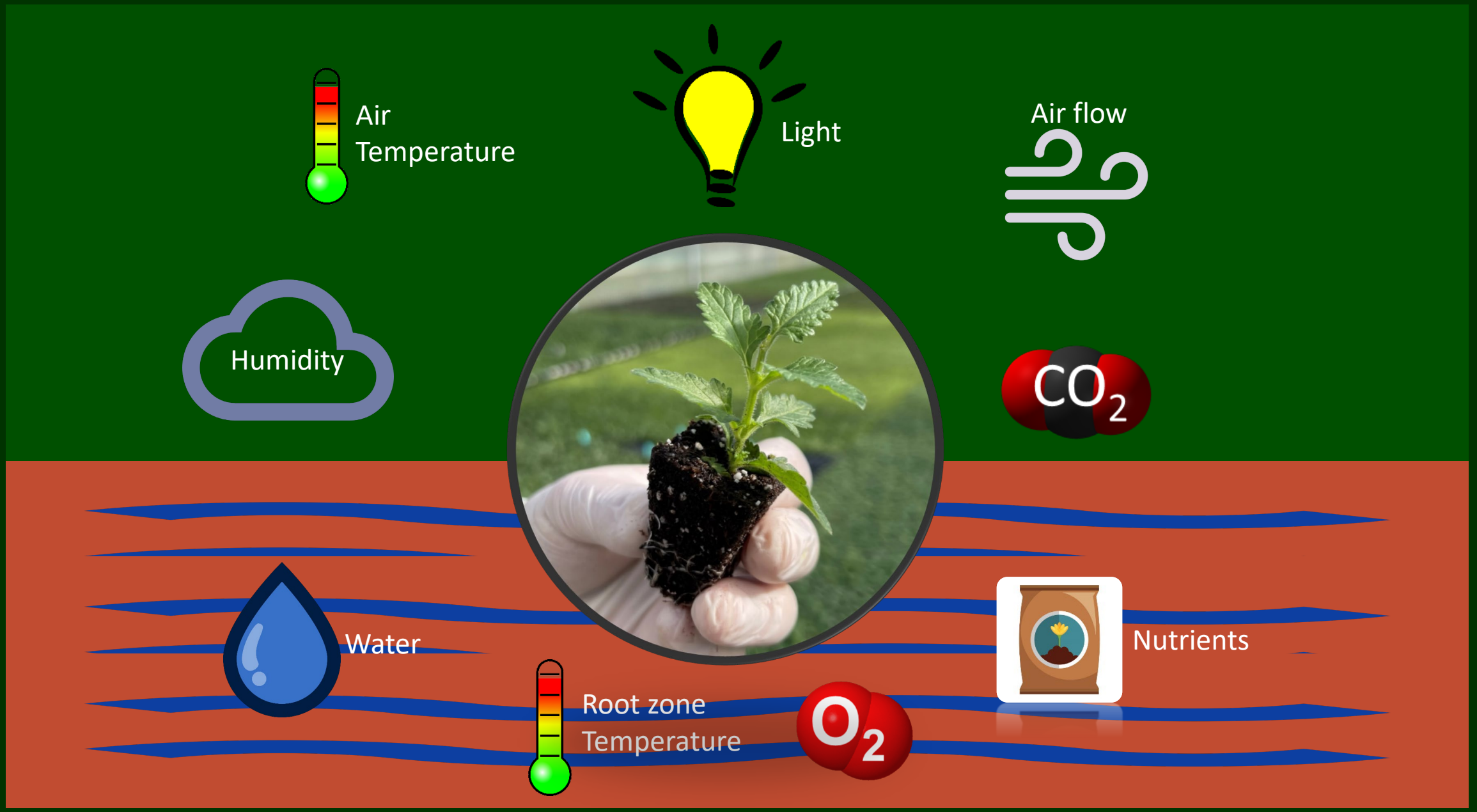


Cloudy open shade + HPS

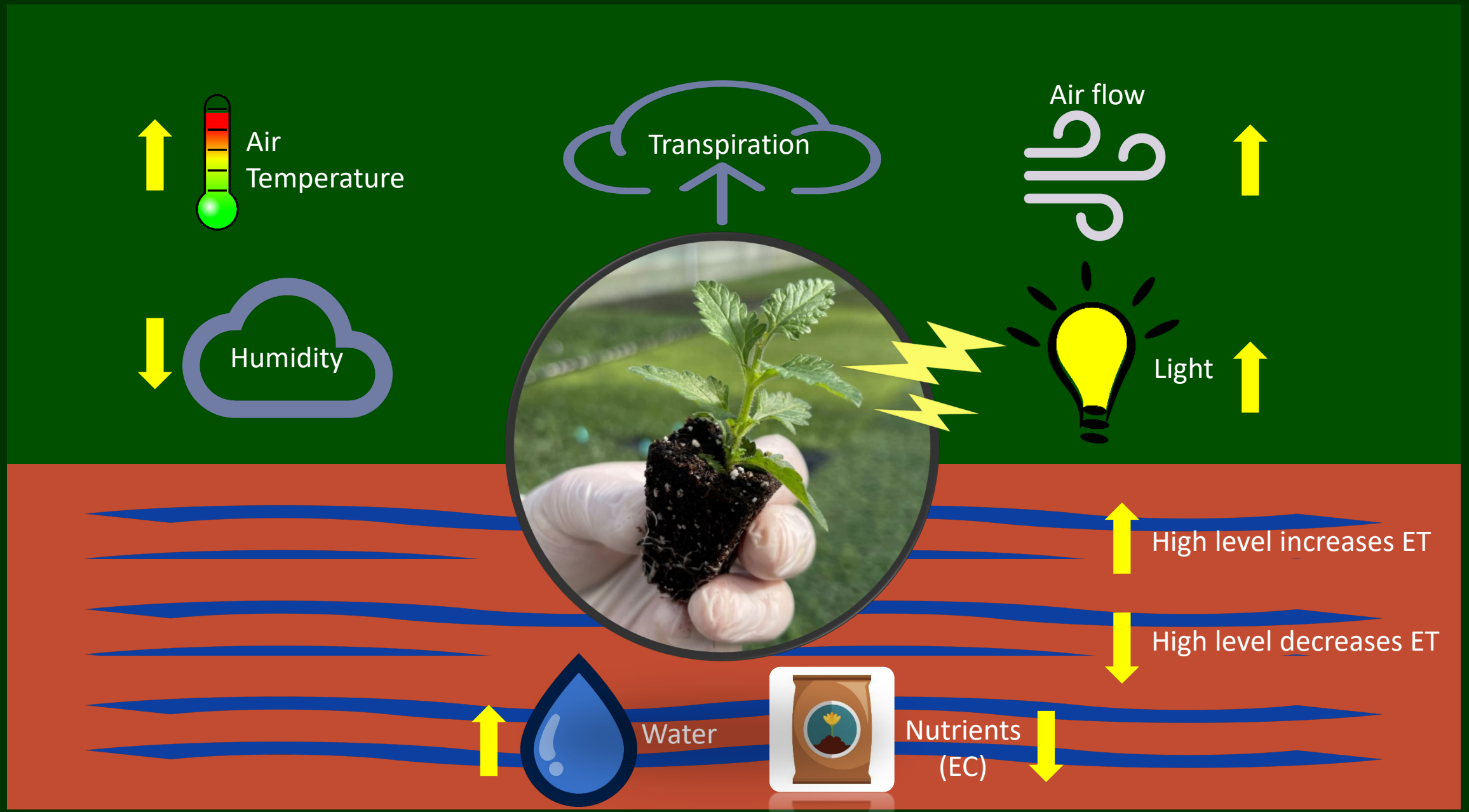




Nine key factors



Factors Affecting Evapotranspiration



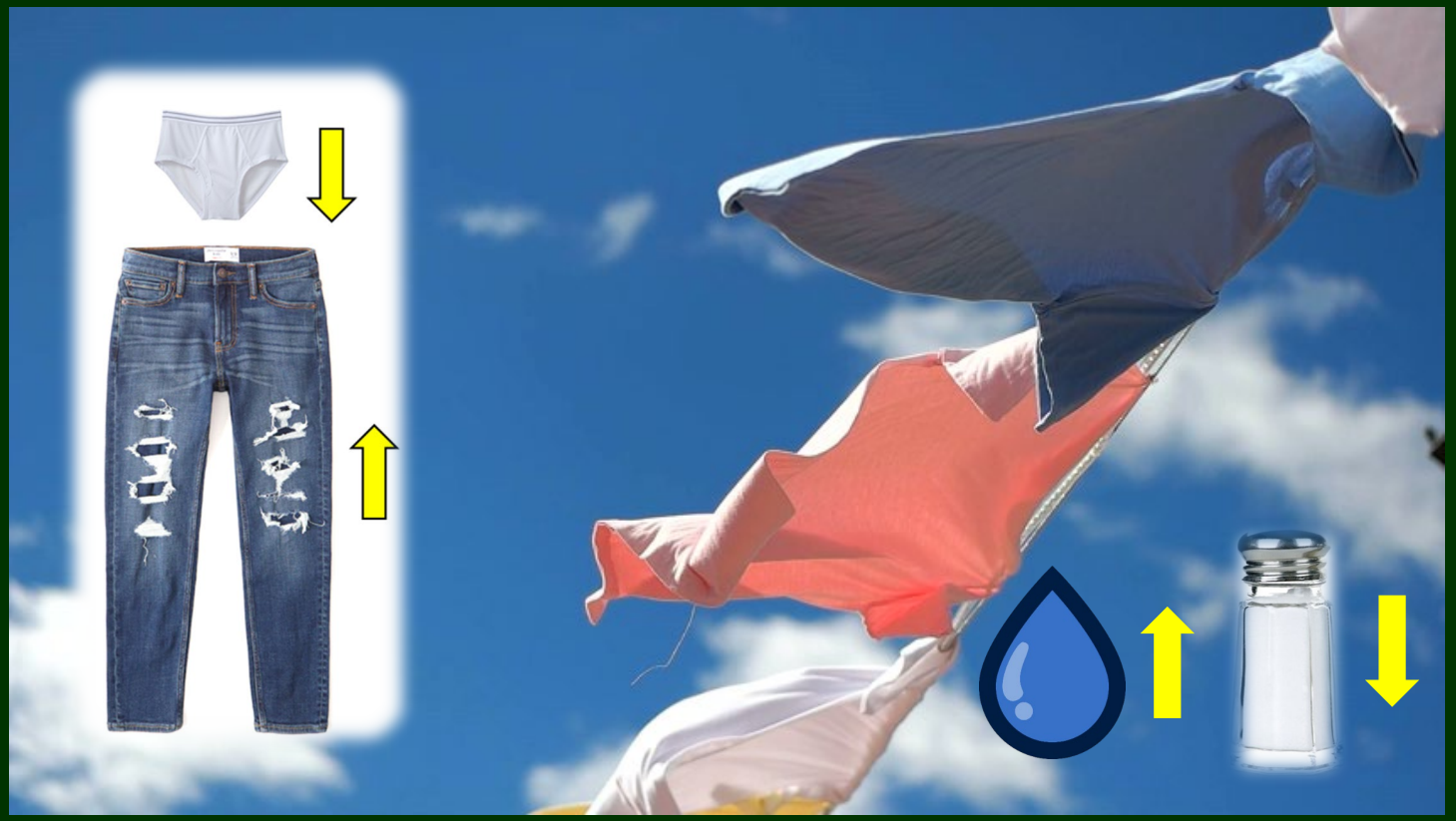
Air Temperature

Humidity

Evaporation

Air flow

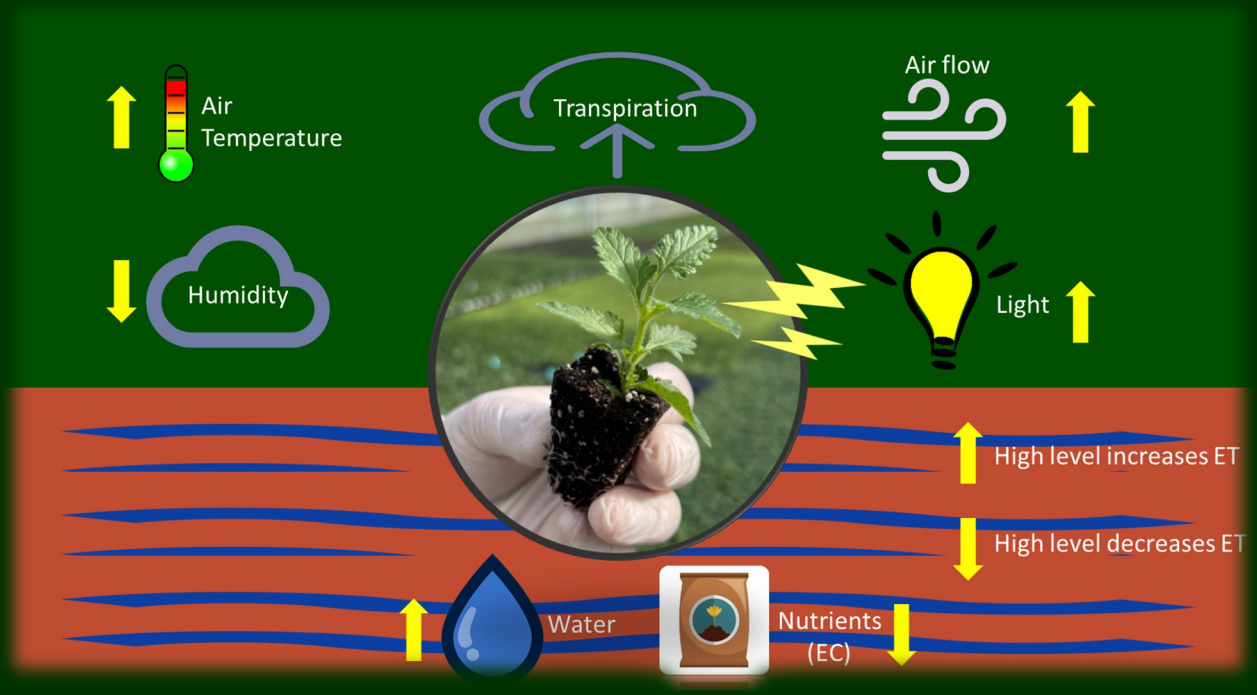
Light



High level increases ET

High level decreases ET

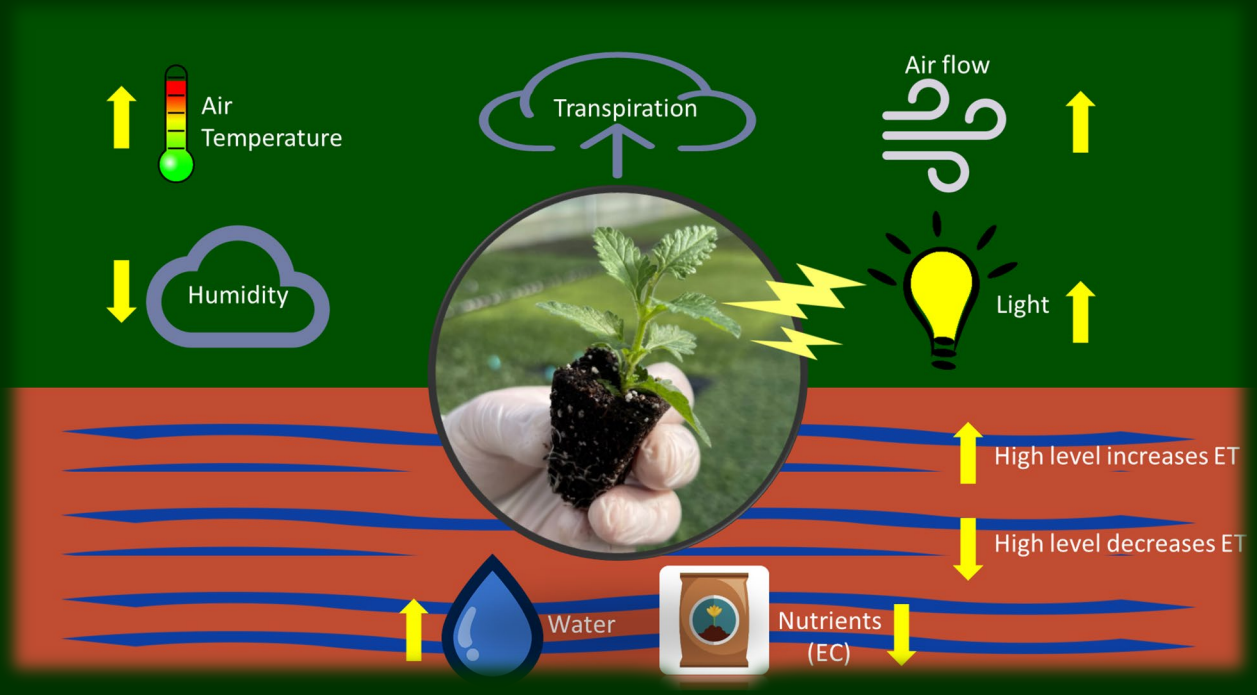
Extreme hot, dry, high air flow





- Wilting (ET demand > supply from roots)
- Stomates close to conserve water
- Photosynthesis reduced
- Less water and nutrient uptake
- Drought stress
- Higher plant temperature

Extreme cool, moist, low air flow

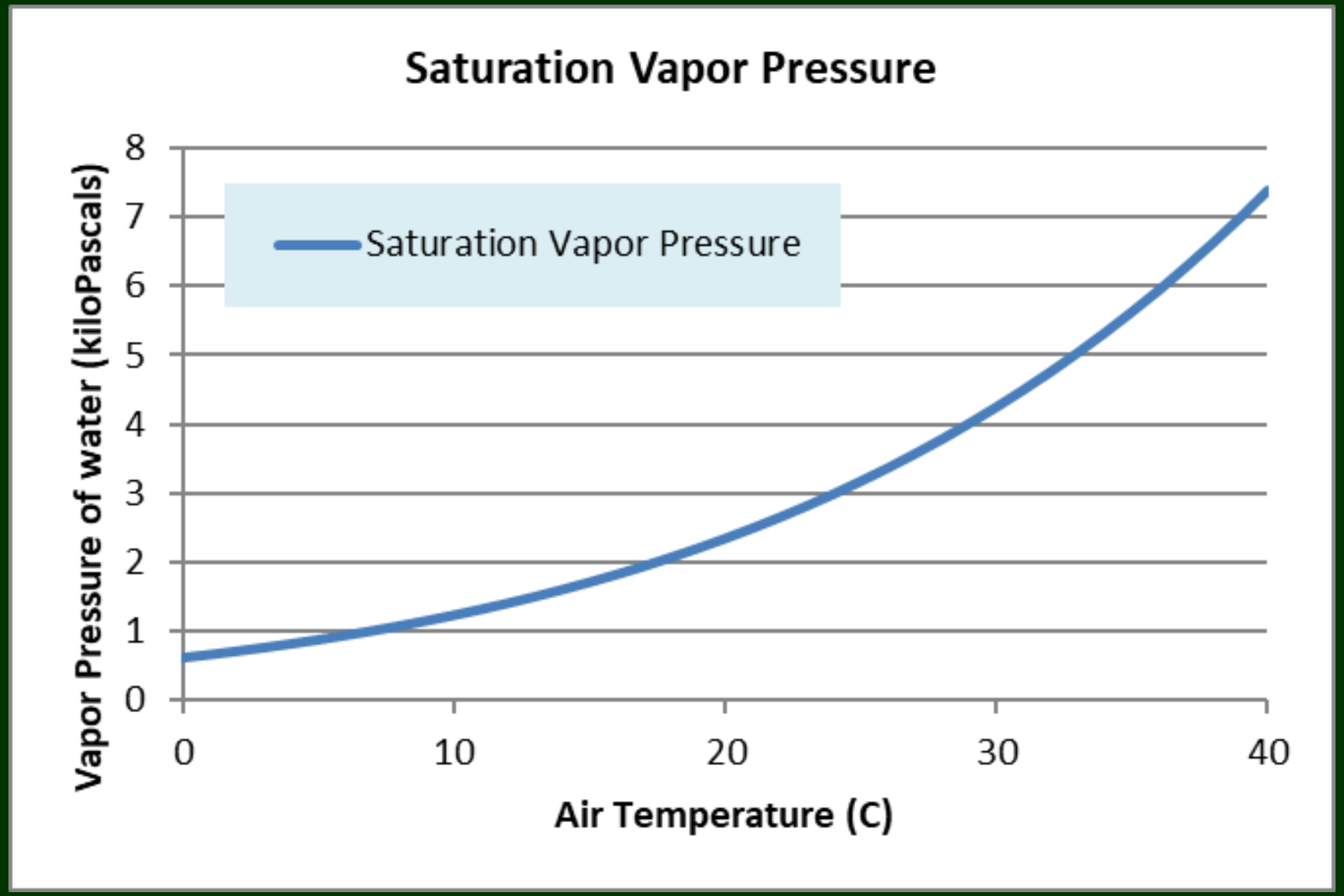






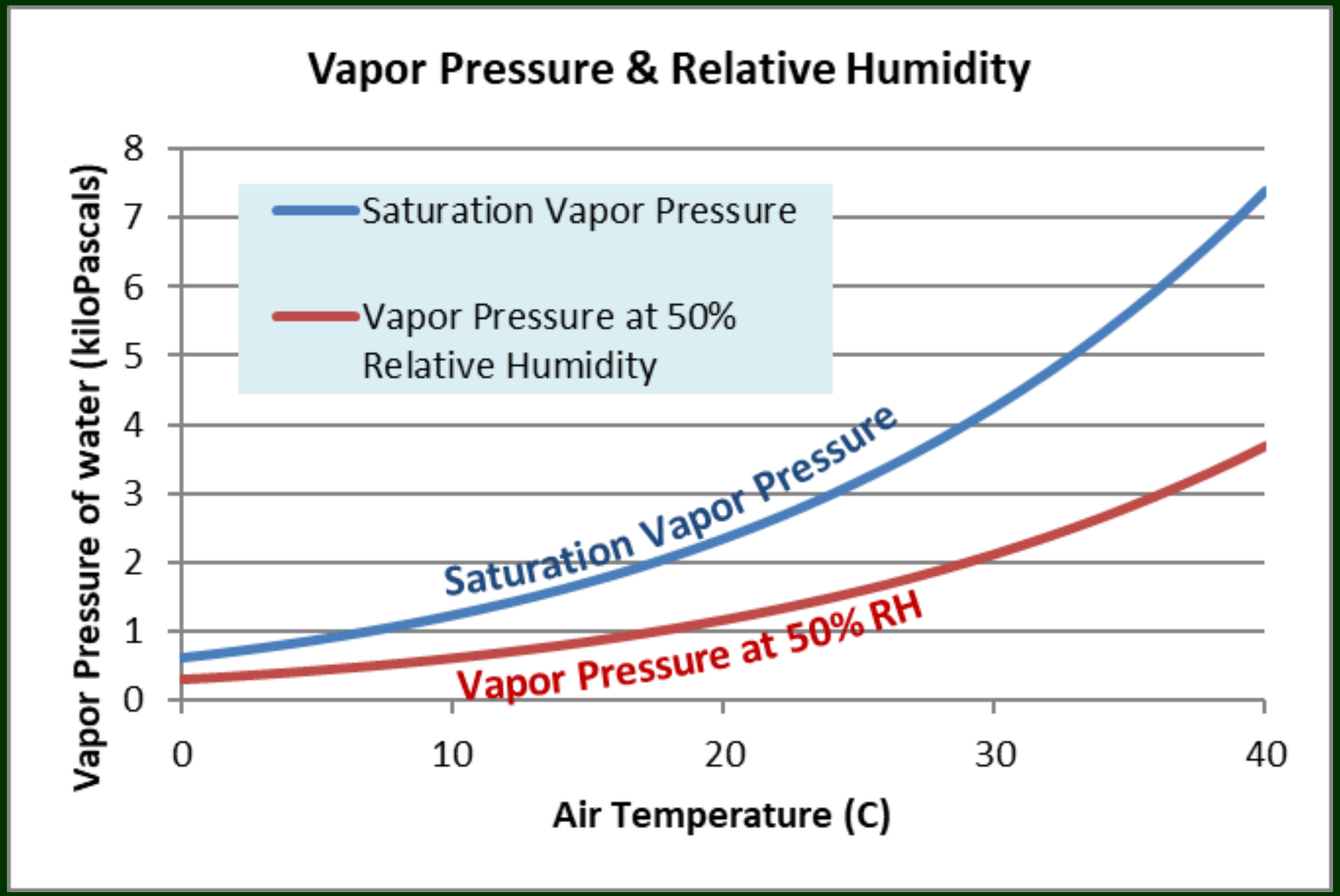
- Less ET: No gradient to drive water and nutrient uptake
- Ca deficiency (tip burn & blossom end rot)
- Higher plant temperature

Saturation Vapor Pressure: The most water vapor that air can hold



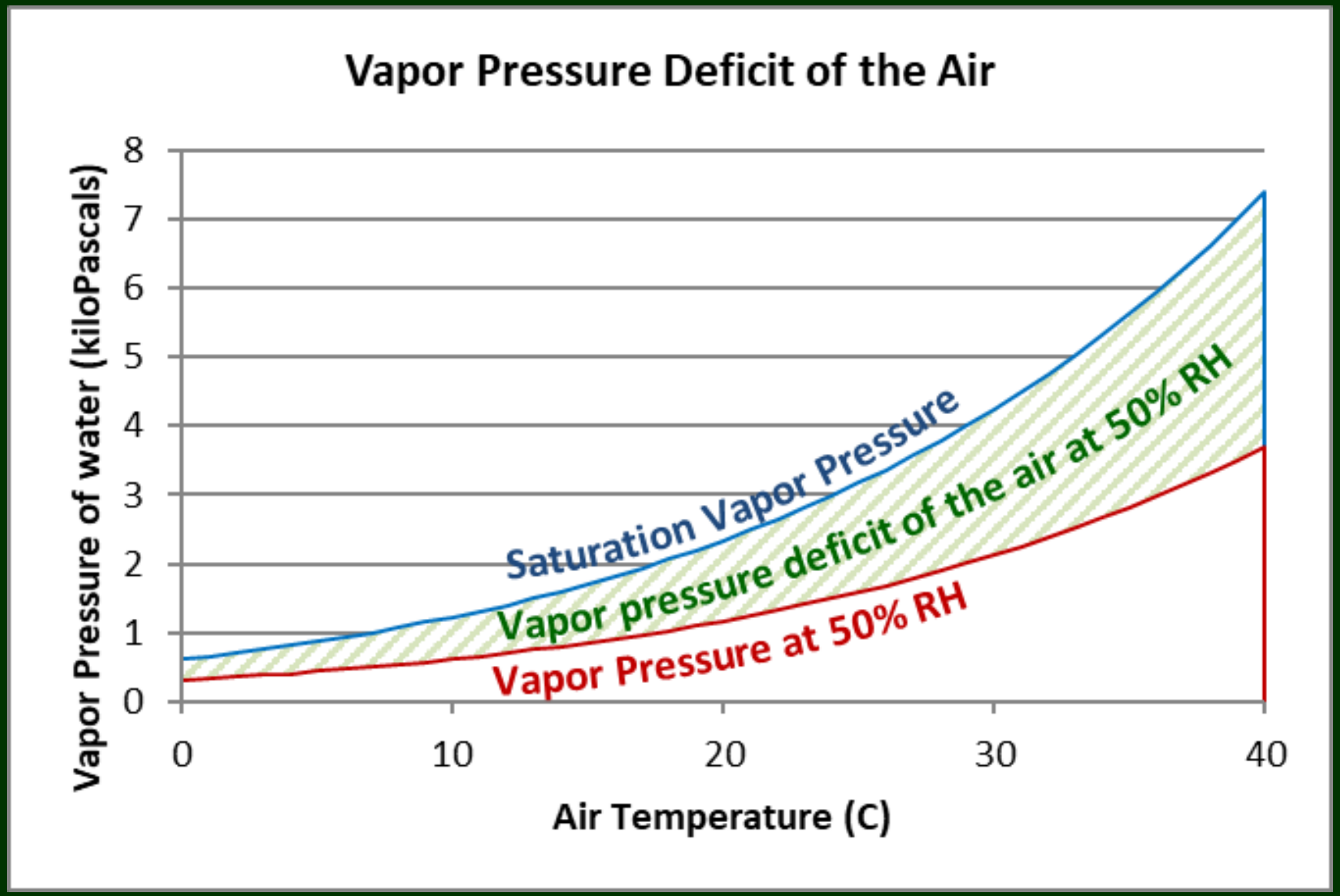
- Warm air holds more water vapor (gas) than cold air
- At saturation vapor pressure, relative humidity is 100%
- If you added more water vapor, it would condense as liquid

Relative humidity: How much water vapor is being held compared with the maximum?



Relative humidity
is relative to
saturation vapor pressure
as a percentage
at that temperature

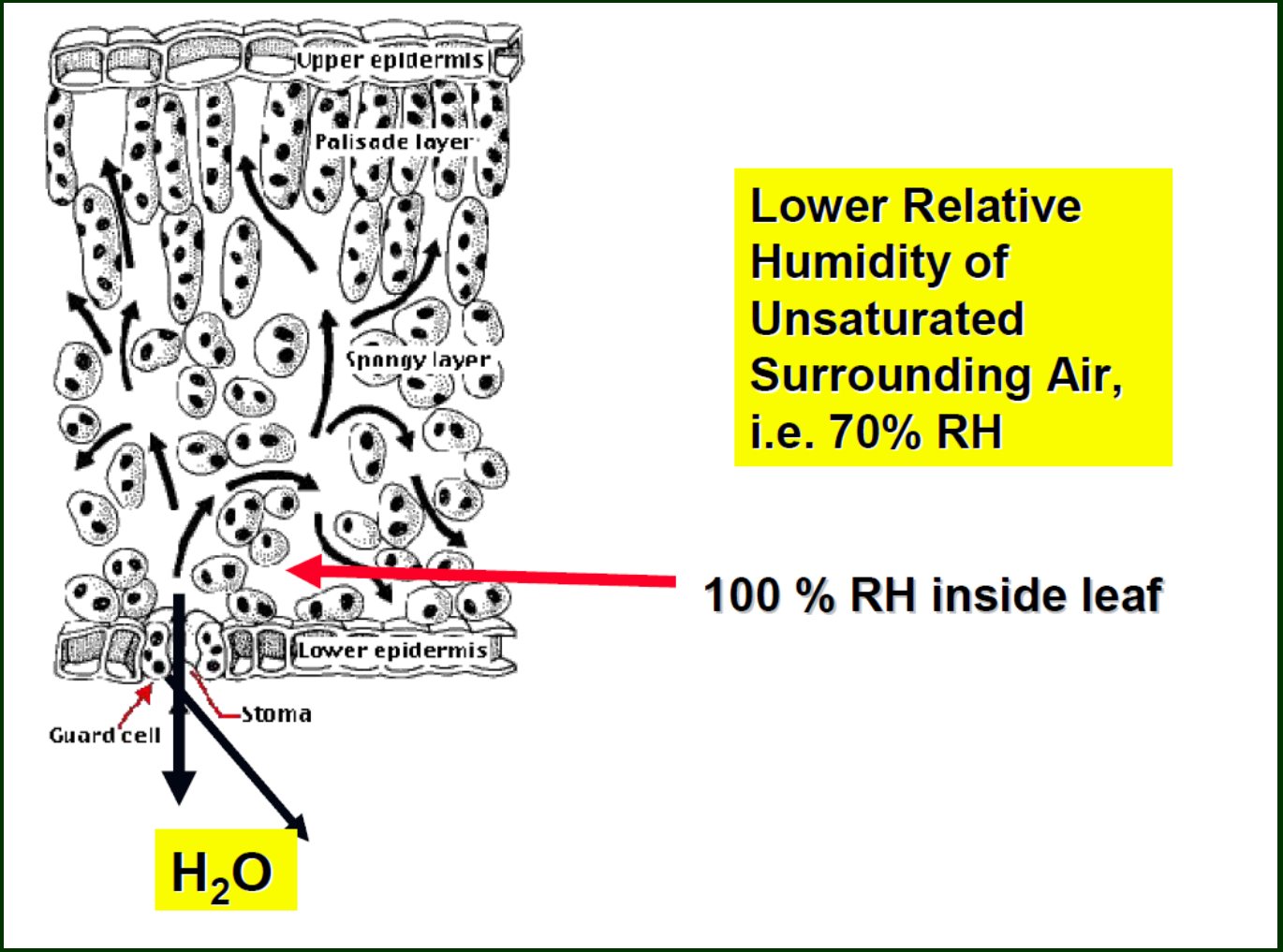
Vapor Pressure Deficit of the Air (VPD_{air})



The difference between actual vapor pressure and the saturation vapor pressure is known as the VPD

VPD is higher at a given RH as temperature increases

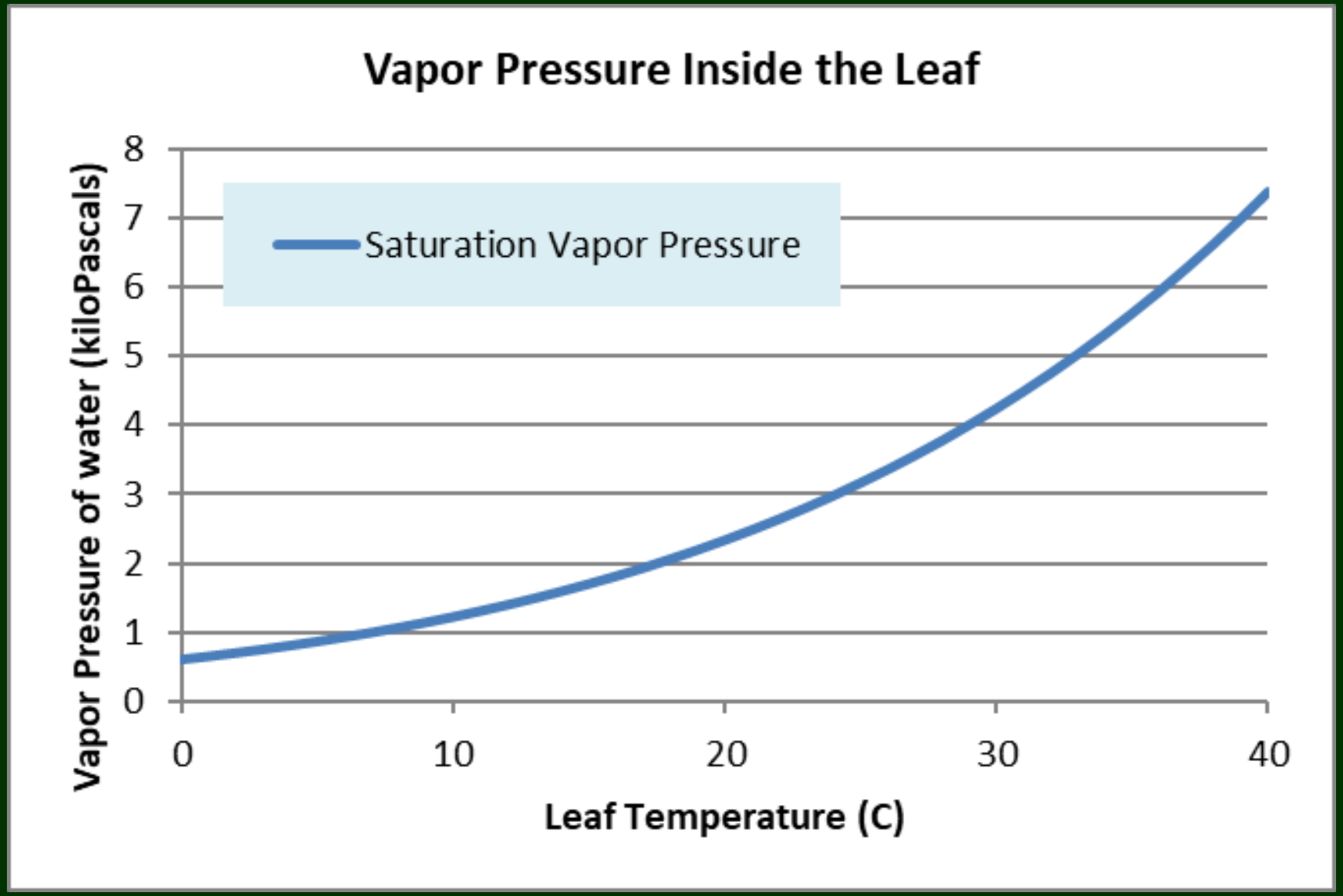
Vapor Pressure of a Leaf: Always at 100% RH



- Inside a leaf, there are intercellular spaces
- These spaces are at 100% relative humidity

Dr. Fred Davies, Texas A&M University – a great article about VPD & moisture loss of cuttings.
https://rngr.net/publications/fnn/2007-winter/new-nursery-literature/optimizing-the-water-relations-of-cuttings-during-propagationa9/at_download/file

Vapor Pressure of a Leaf: Always at 100% RH



- Leaf temperature tells us the vapor pressure inside the leaf



Vapor Pressure Deficit of the Leaf (VPD_{leaf})

- The leaf is at saturation (VP_{leaf}). This vapor pressure increases as the leaf heats up
- The air has a vapor pressure (VP_{air}) that increases when warm (high temperature) and dry (low RH)
- The difference between leaf and air vapor pressure (VPD_{leaf}) drives evapotranspiration

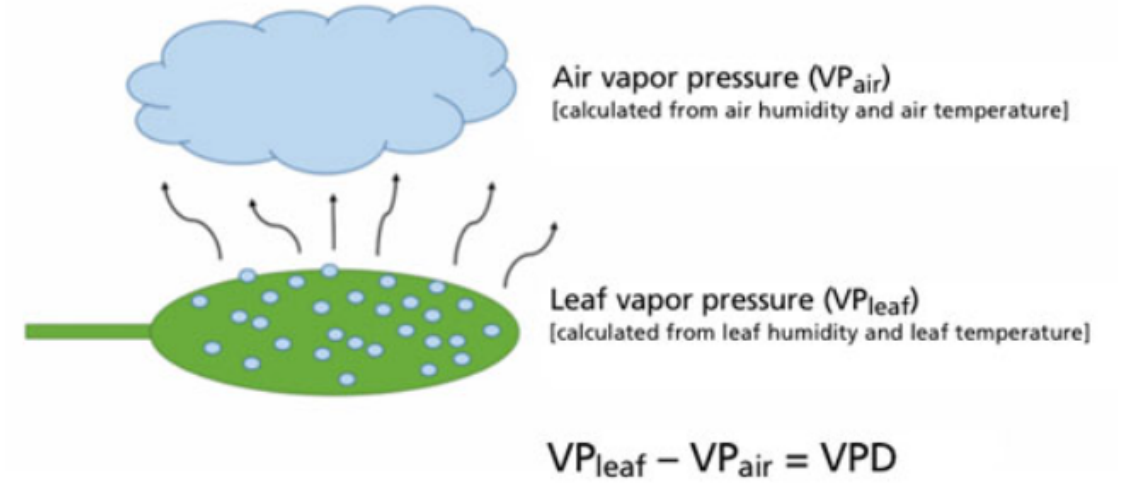
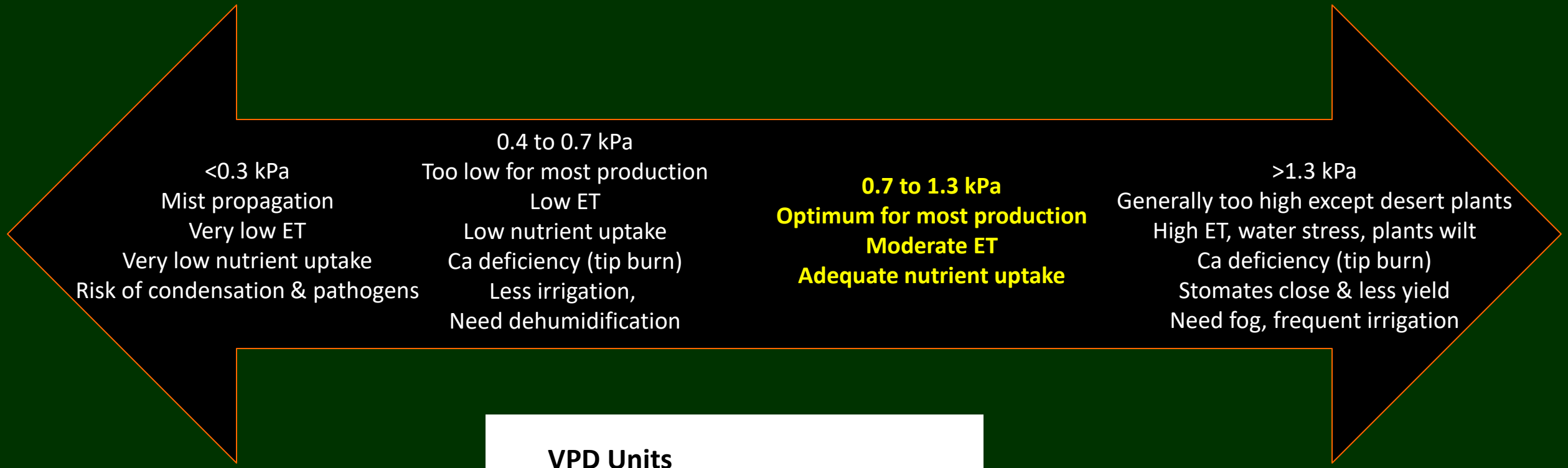


Figure 1. Vapor pressure deficit (VPD) is calculated by subtracting the water vapor pressure of the air from the water vapor pressure of the leaf. Water vapor pressure is calculated based on the temperature and humidity of the water in the air or leaf.

Jim Faust (2017) Clemson University: VPD and Mist Propagation

Typical VPD targets



VPD Units

kiloPascals (kPa)	1
Pascals (Pa)	1000
Millibars (mbar)	10
Bars (bar)	0.01
Atmospheres (atm)	0.0099

Typical VPD targets

Temperature and relative humidity targets assuming equal leaf and air temperature

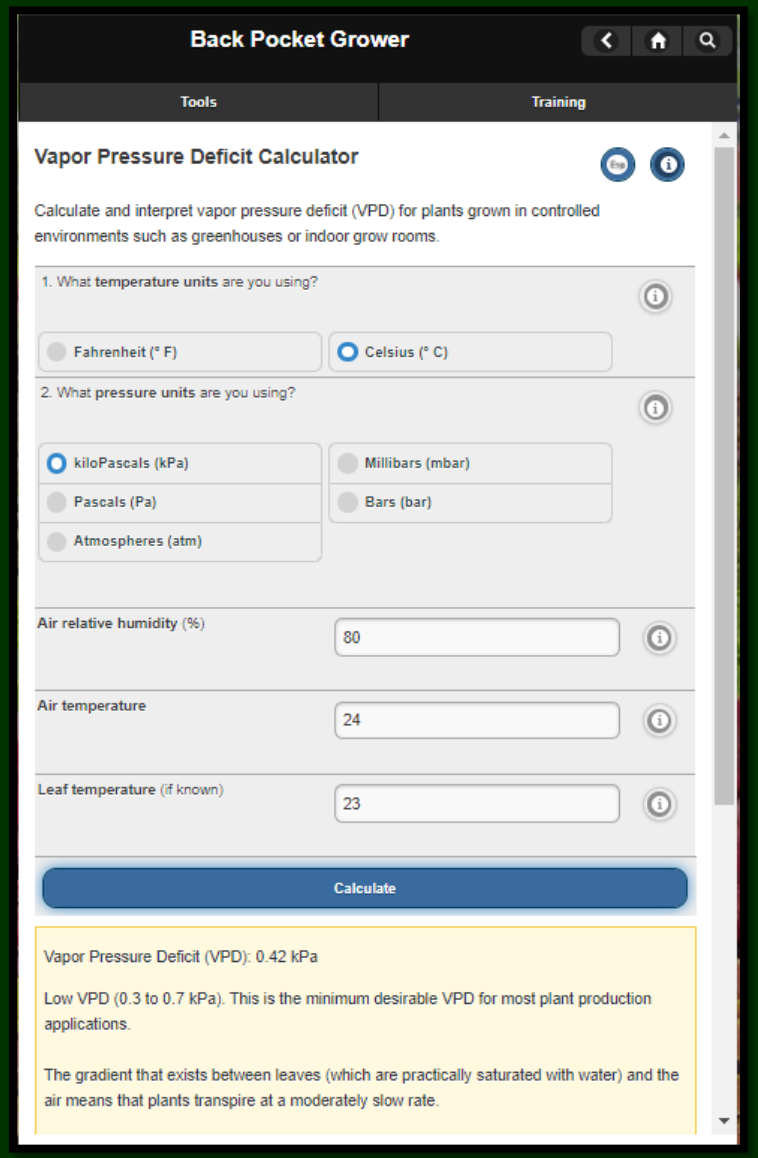
Relative humidity / Temperatura relativa (%)																	
C	F	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%	100%
15	59	1.3	1.2	1.1	1.0	0.9	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.3	0.2	0.1	0.0
16	61	1.4	1.3	1.2	1.1	1.0	0.9	0.8	0.7	0.6	0.5	0.5	0.4	0.3	0.2	0.1	0.0
17	63	1.5	1.4	1.3	1.2	1.1	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1	0.0
18	64	1.5	1.4	1.3	1.2	1.1	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1	0.0
19	66	1.6	1.5	1.4	1.3	1.2	1.1	1.0	0.9	0.8	0.7	0.5	0.4	0.3	0.2	0.1	0.0
20	68	1.8	1.6	1.5	1.4	1.3	1.2	1.1	0.9	0.8	0.7	0.6	0.5	0.4	0.2	0.1	0.0
21	70	1.9	1.7	1.6	1.5	1.4	1.2	1.1	1.0	0.9	0.7	0.6	0.5	0.4	0.2	0.1	0.0
22	72	2.0	1.9	1.7	1.6	1.5	1.3	1.2	1.1	0.9	0.8	0.7	0.5	0.4	0.3	0.1	0.0
23	73	2.1	2.0	1.8	1.7	1.5	1.4	1.3	1.1	1.0	0.8	0.7	0.6	0.4	0.3	0.1	0.0
24	75	2.2	2.1	1.9	1.8	1.6	1.5	1.3	1.2	1.0	0.9	0.7	0.6	0.4	0.3	0.1	0.0
25	77	2.4	2.2	2.1	1.9	1.7	1.6	1.4	1.3	1.1	1.0	0.8	0.6	0.5	0.3	0.2	0.0
26	79	2.5	2.4	2.2	2.0	1.8	1.7	1.5	1.3	1.2	1.0	0.8	0.7	0.5	0.3	0.2	0.0
27	81	2.7	2.5	2.3	2.1	2.0	1.8	1.6	1.4	1.2	1.1	0.9	0.7	0.5	0.4	0.2	0.0
28	82	2.8	2.6	2.5	2.3	2.1	1.9	1.7	1.5	1.3	1.1	0.9	0.8	0.6	0.4	0.2	0.0
29	84	3.0	2.8	2.6	2.4	2.2	2.0	1.8	1.6	1.4	1.2	1.0	0.8	0.6	0.4	0.2	0.0
30	86	3.2	3.0	2.8	2.5	2.3	2.1	1.9	1.7	1.5	1.3	1.1	0.8	0.6	0.4	0.2	0.0
31	88	3.4	3.1	2.9	2.7	2.5	2.2	2.0	1.8	1.6	1.3	1.1	0.9	0.7	0.4	0.2	0.0
32	90	3.6	3.3	3.1	2.9	2.6	2.4	2.1	1.9	1.7	1.4	1.2	1.0	0.7	0.5	0.2	0.0
33	91	3.8	3.5	3.3	3.0	2.8	2.5	2.3	2.0	1.8	1.5	1.3	1.0	0.8	0.5	0.3	0.0
34	93	4.0	3.7	3.5	3.2	2.9	2.7	2.4	2.1	1.9	1.6	1.3	1.1	0.8	0.5	0.3	0.0
35	95	4.2	3.9	3.7	3.4	3.1	2.8	2.5	2.3	2.0	1.7	1.4	1.1	0.8	0.6	0.3	0.0
36	97	4.5	4.2	3.9	3.6	3.3	3.0	2.7	2.4	2.1	1.8	1.5	1.2	0.9	0.6	0.3	0.0
37	99	4.7	4.4	4.1	3.8	3.5	3.1	2.8	2.5	2.2	1.9	1.6	1.3	0.9	0.6	0.3	0.0
38	100	5.0	4.6	4.3	4.0	3.6	3.3	3.0	2.7	2.3	2.0	1.7	1.3	1.0	0.7	0.3	0.0
39	102	5.2	4.9	4.5	4.2	3.8	3.5	3.1	2.8	2.4	2.1	1.7	1.4	1.0	0.7	0.3	0.0
40	104	5.5	5.2	4.8	4.4	4.1	3.7	3.3	3.0	2.6	2.2	1.8	1.5	1.1	0.7	0.4	0.0

Production

Propagation

An online tool to calculate VPD

https://www.backpocketgrower.org/vpd.asp



Growing environment energy balance



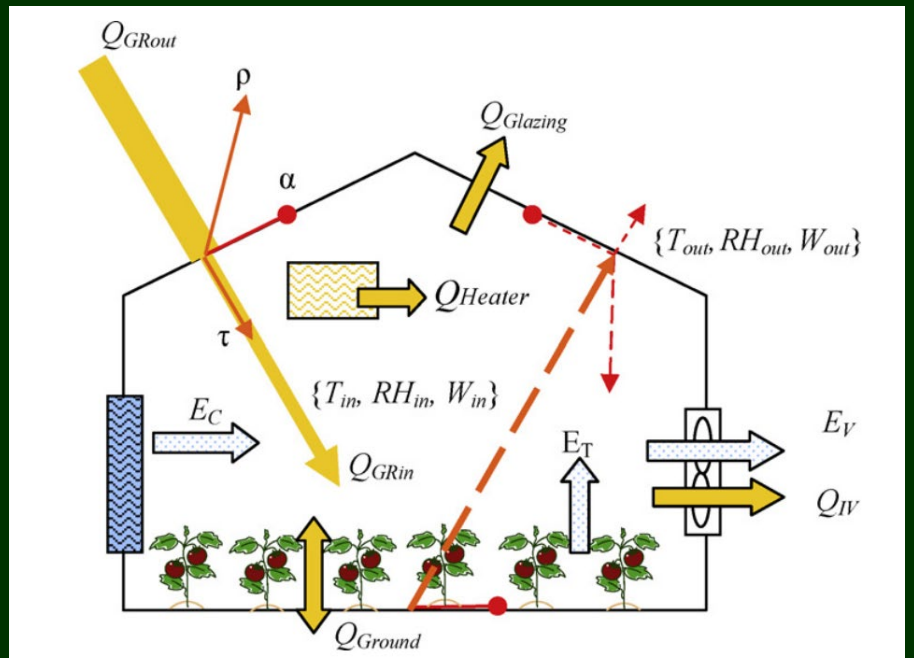


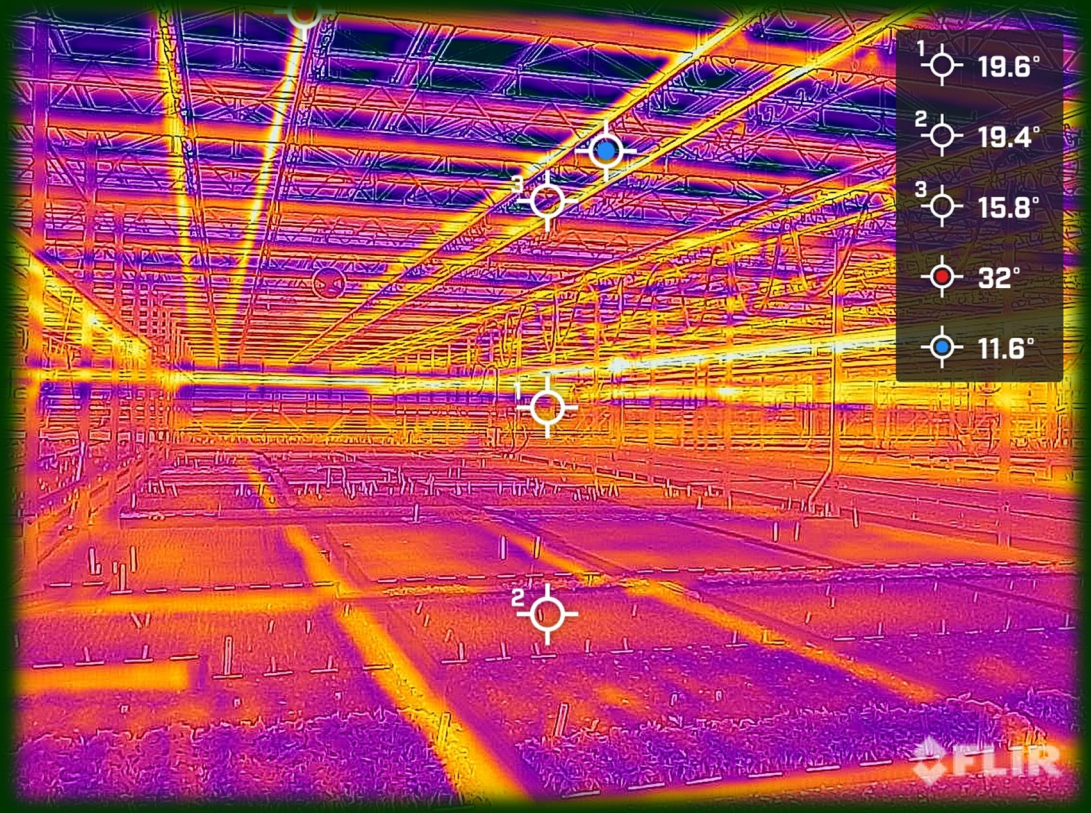
Fig. 3. Energy and water vapor fluxes within the greenhouse which define the energy and mass balance equations.

Fitz-Rodriguez et al. (2010)

Greenhouse cutting propagation facility

Growing environment exchanges energy with the crop

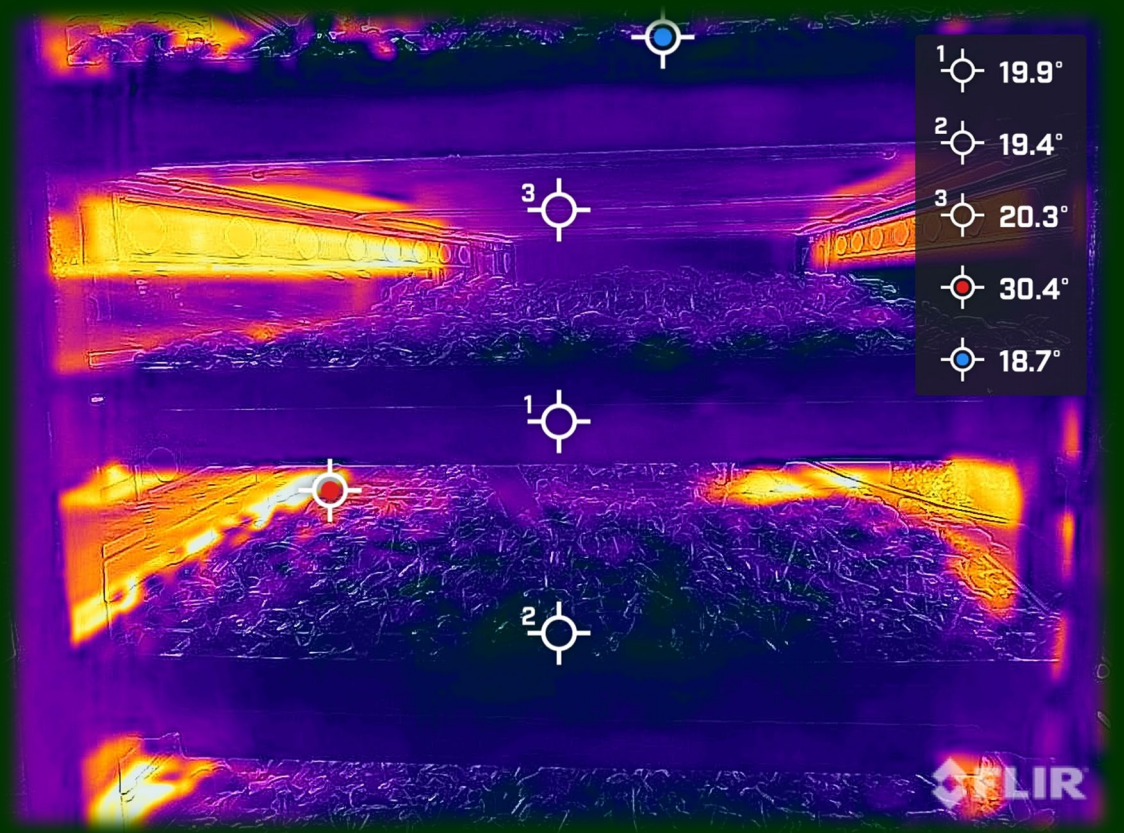




Greenhouse cutting propagation facility

Growing environment exchanges energy with the crop





Indoor cutting propagation facility

The leaf is rarely the same temperature as the air



Dr. Celina Gómez



Structure: 12.1C

RH 76%

Air: 25.4C

VPD Air: 0.78 kPa

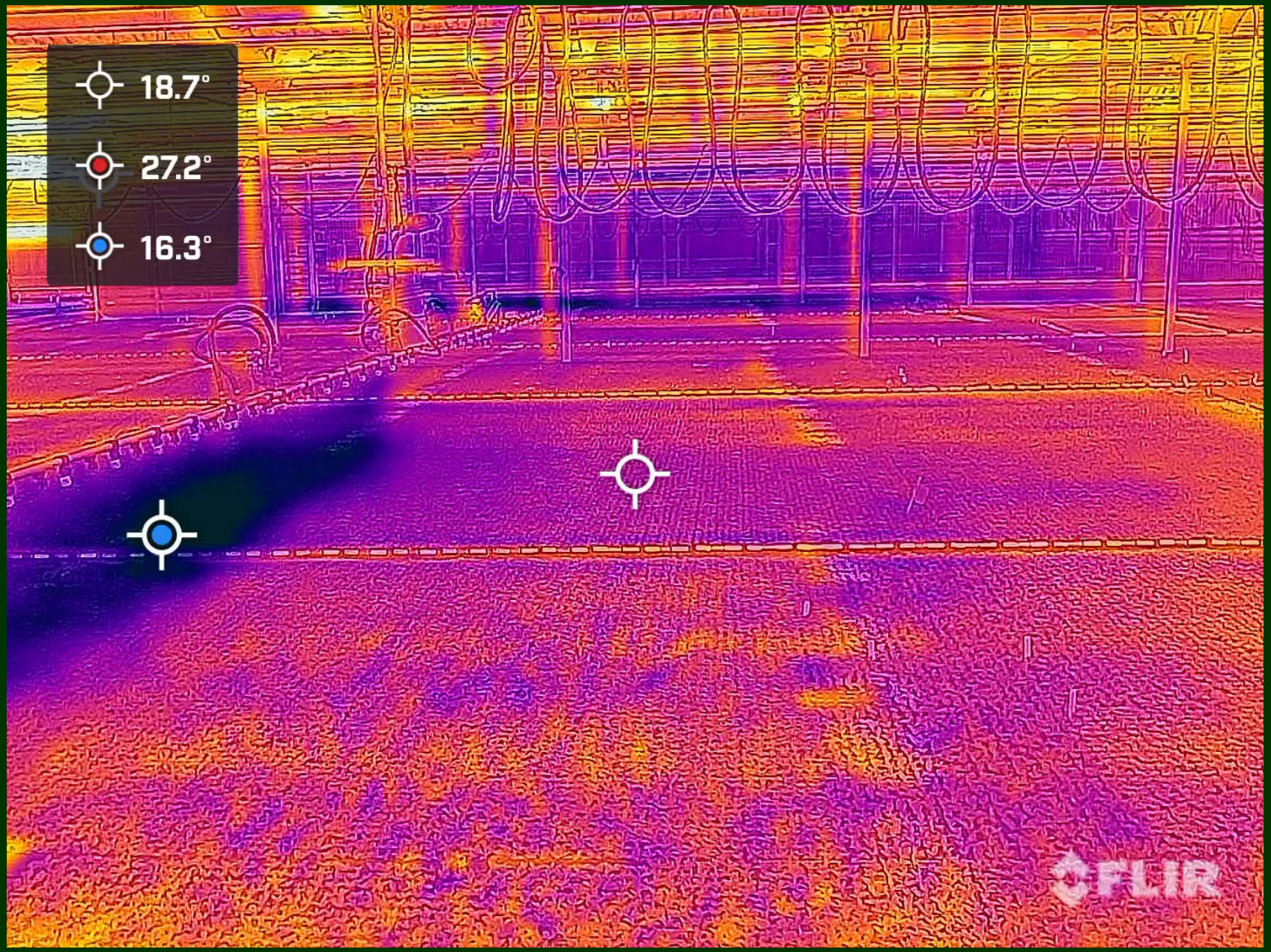
Soil: 24.0C

Leaf: 23.6C

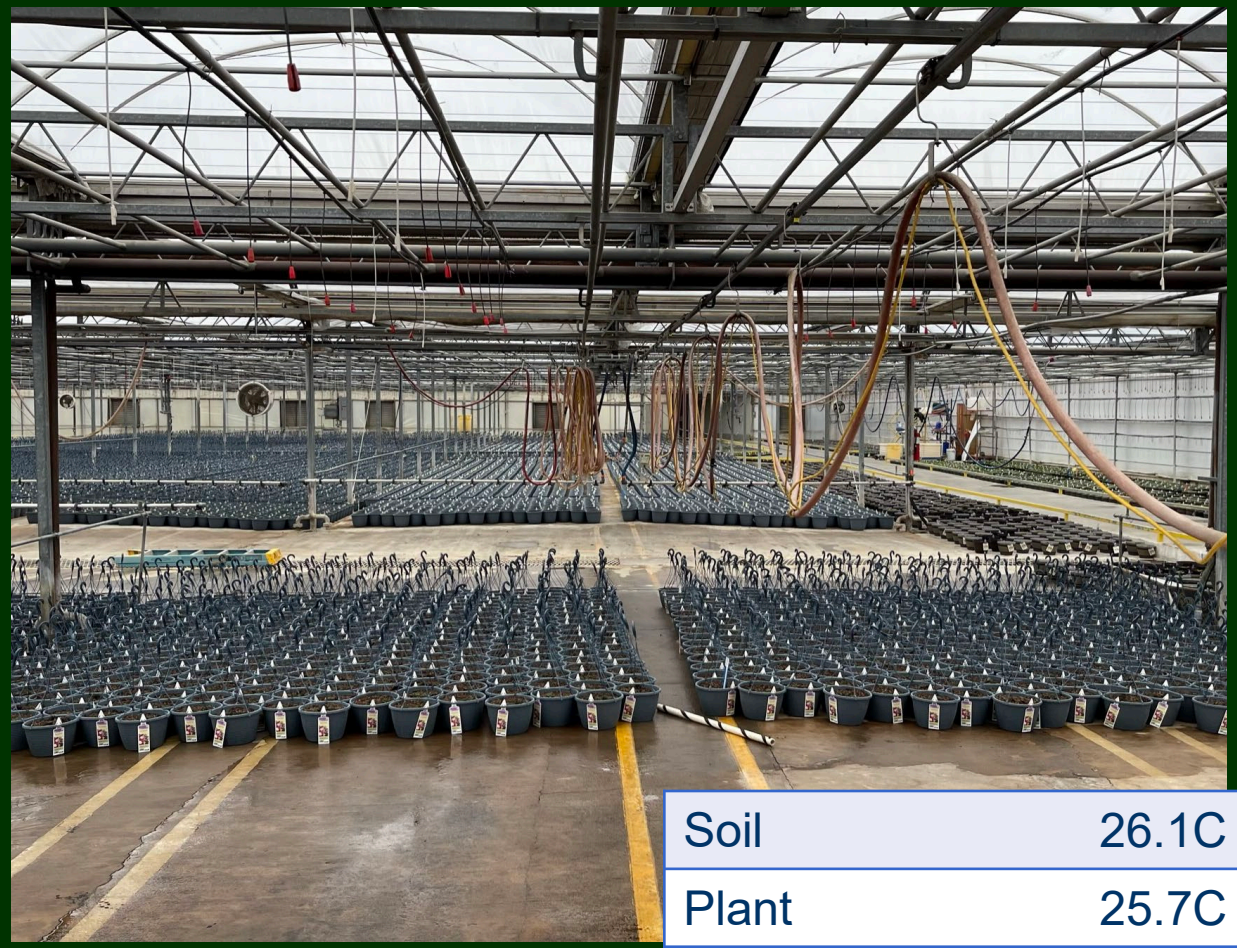
VPD Leaf: 0.45 kPa

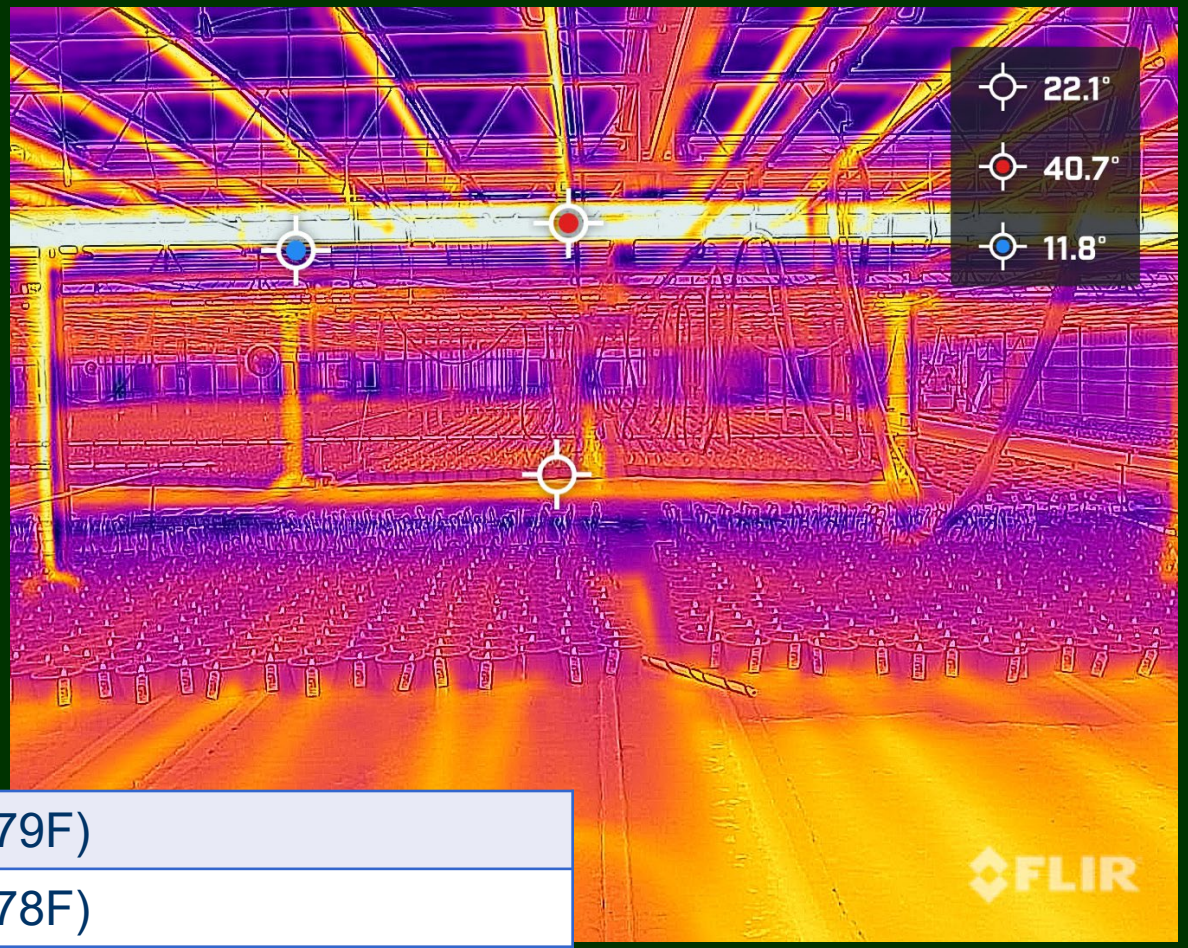
Floor: 27.4C

Crop temperature changes dynamically



Crop temperature is close to soil temperature with floor heat

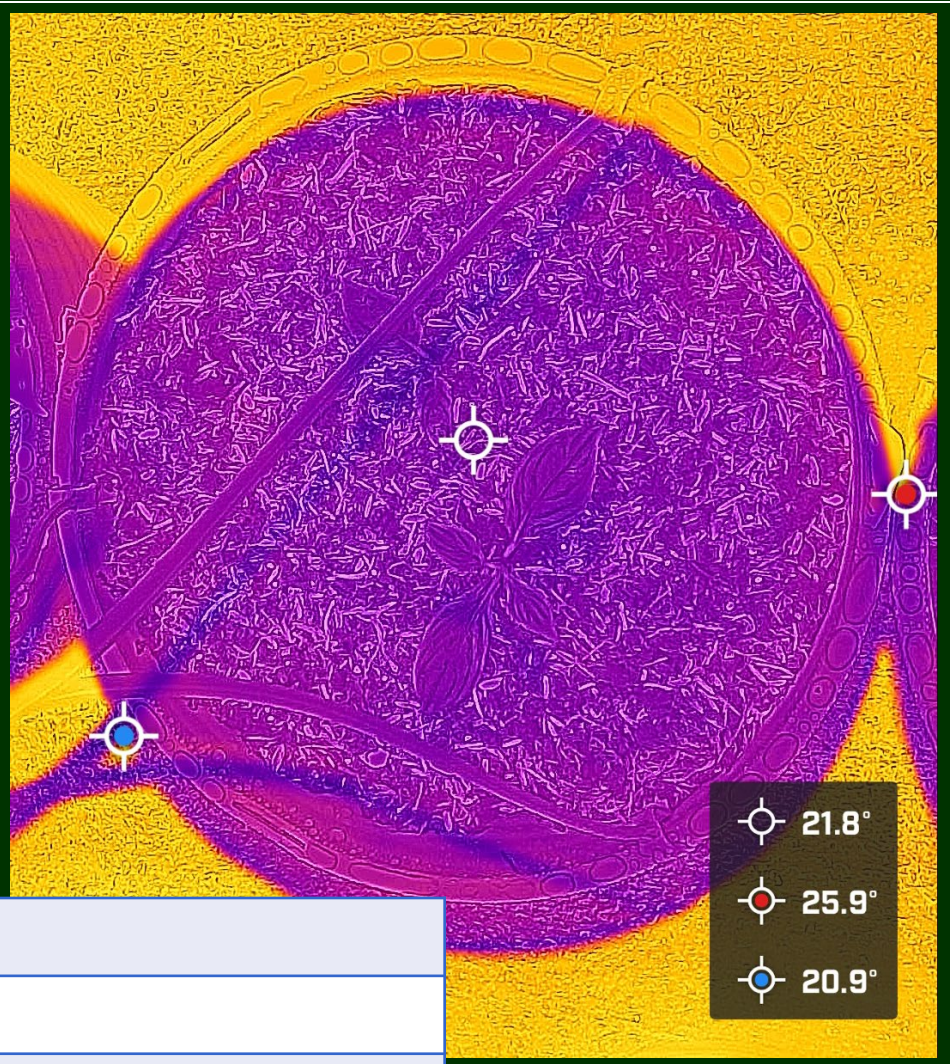




Soil	26.1C (79F)
Plant	25.7C (78F)
Air	23.6C (74F)
Relative humidity	63%
VPD	1.47 kPa (high for propagation)

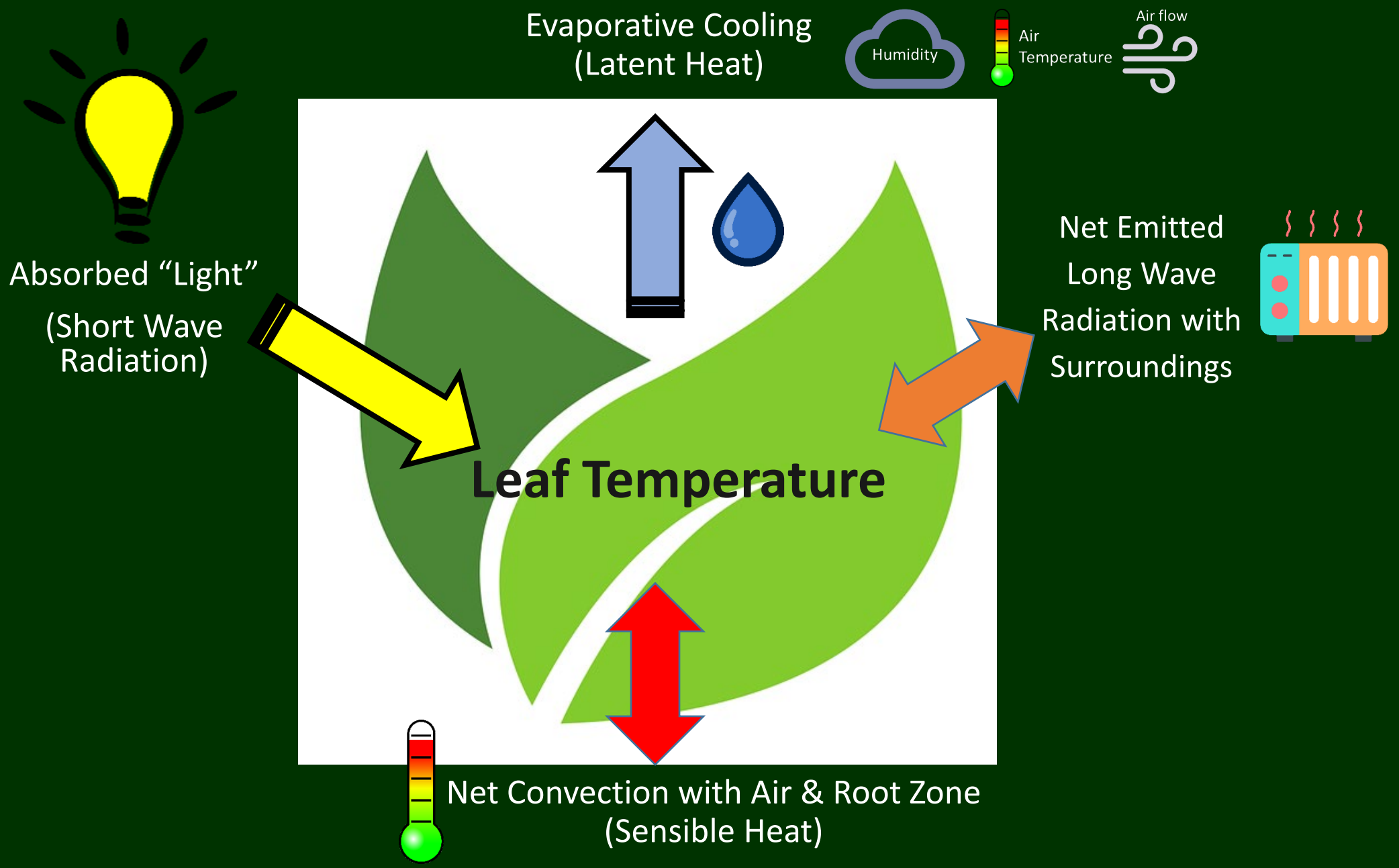
Crop temperature is close to soil temperature with floor heat





Soil	26.1C (79F)
Plant	25.7C (78F)
Air	23.6C (74F)
Relative humidity	63%
VPD	1.47 kPa (high for propagation)

Energy balance



Modeling energy balance, leaf temperature & evapotranspiration

Indoor Plant Energy Balance Model

Based on Campbell and Norman (1998) and Faust & Heins (1998), Version 1.3 Dec 3 2021

PAR Light (PPFD, micromoles/m^2/s)	100
Incoming Short Wave Radiation (W/m^2)	25.3
Air Temperature (C)	20
Enclosure Surface Temperature (C)	21.5
Relative Humidity	80%
Wind Speed (u) in m/s	0.5
Atmospheric pressure in kPa (P_a)	100
Leaf width (cm)	3
Leaf Temperature (C)	**19.9**

Change Leaf Temperature & Balance Energy

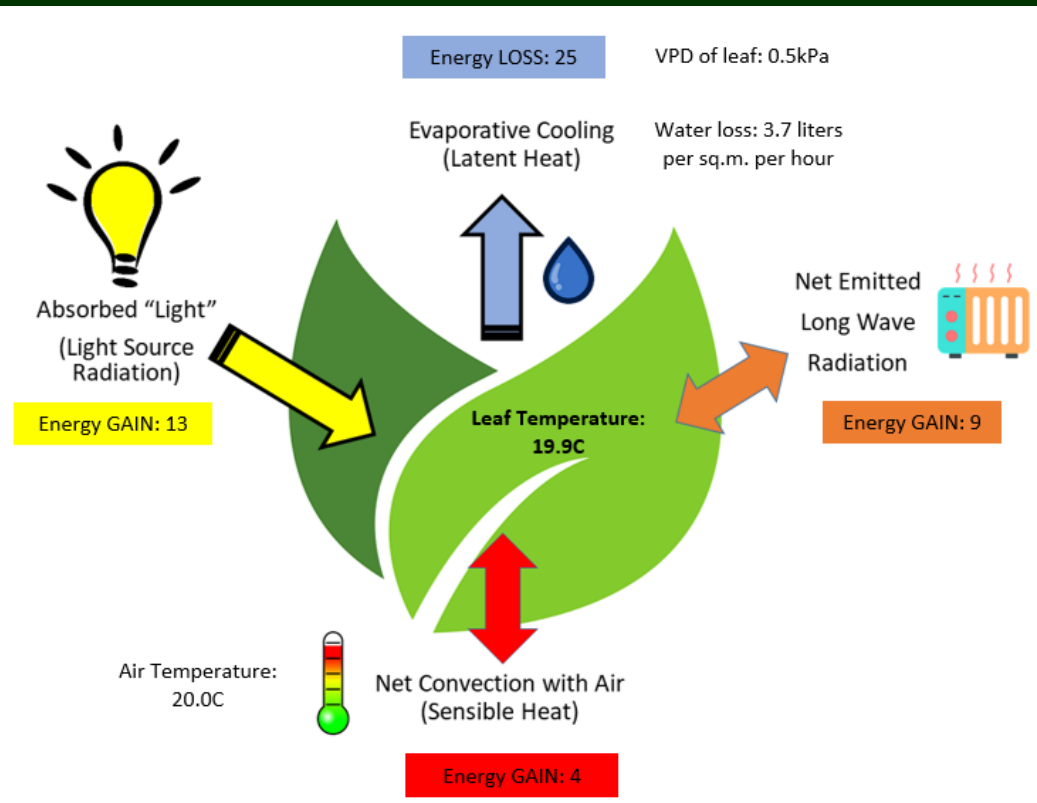
Change EvapoTranspiration & Balance Energy

Energy Balance Calculations

R_{abs} - R_{emit} - C - λE = 0	0	Should equal zero after balancing energy exchanges
R_{abs}	13	Short wave radiation absorbed in W/m^2, R_{abs}
R_{emit}	-9	Net long wave radiation emitted by leaf in W/m^2, R_{emit}
C	-4	Convection with air (sensible heat flux, C)
λE	**25**	Evaporative cooling (latent heat transfer)

Vapor Pressure Calculations

e_sTa	2.34	Saturation vapor pressure of air in kPa
$e_s T_L$	2.32	Saturation vapor pressure of leaf in kPa
e_a	1.87	Partial pressure of water vapor in air in kPa
VPD of leaf	0.45	Vapor pressure deficit of leaf in kPa
VPD of air (symbolized as D)	0.47	Vapor pressure deficit of air in kPa



Okay, at this point the professor has lost the plot..

$$ET_o = \frac{0.048\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)},$$

where

ET_o	is reference crop evapotranspiration, in millimeters per day,
R_n	is net radiation at the crop surface, in megajoules per square meter per day,
G	is soil heat flux density, in megajoules per square meter per day,
T	is mean daily air temperature at 2 meter height, in degrees Celsius,
u_2	is wind speed at 2 meter height, in meters per second,
e_s	is saturation vapor pressure, in kilopascals,
e_a	is actual vapor pressure, in kilopascals,
$e_s - e_a$	is saturation vapor pressure deficit, in kilopascals,
Δ	is slope vapor pressure curve, in kilopascals per degrees Celsius, and
γ	is psychrometric constant, in kilopascals per degrees Celsius.

Greenhouses: simple sensors & controls







What did we see with leading growers?

- 12 leading growers FL, MI, NC, NH, NJ
- 8 program booms based on time, 4 with VPD
- All have environmental control systems (3 brands)
- No full integration between ECS and booms



- Temperature and RH only inline sensors in greenhouse, shielded but many not aspirated (no fans)
- Several using standalone weather stations for daily light integral (DLI)

Take home messages

- We need more sensors:
  - Infrared (at least leaf+soil temperature, ideally also structure temperature)



Image: Apogee Instruments



  - Light inside greenhouse (at least quantum sensor for PAR light, ideally also pyranometer for SW radiation)

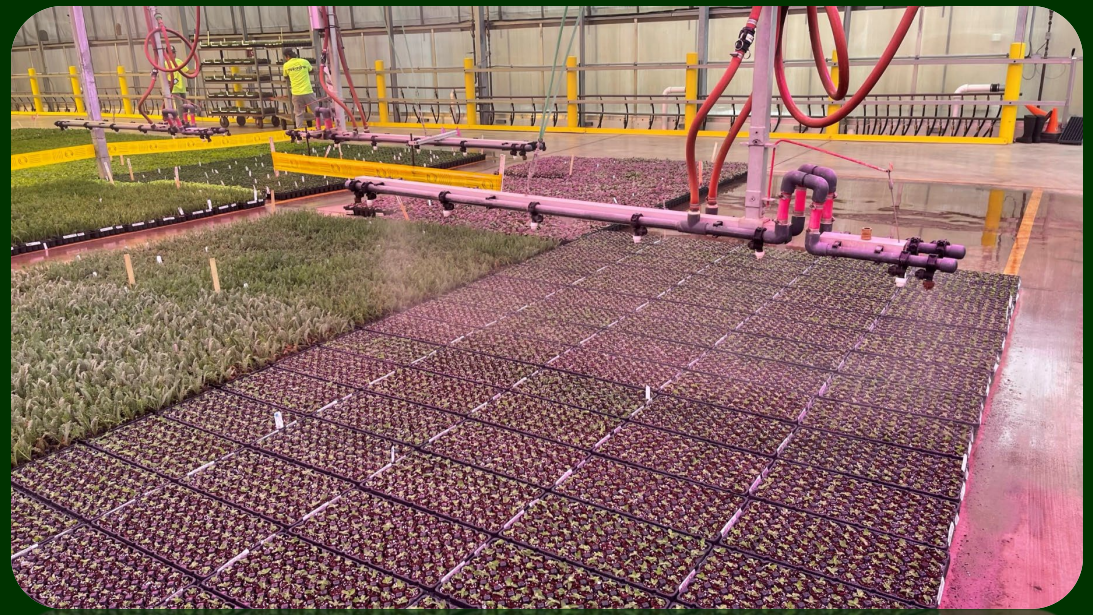


Image: Campbell Scientific



Take home messages

- We need more equipment talking to each other
- Especially control system <> booms
- Indoor growing is partly an expensive admission of failure of greenhouse climate control



Take home messages

- Few growers fully understand their environmental control systems
- We don't just need more numbers
- Need training and research on interpretation of data – what is the clear value added?

Greenhouse Training Online

hort.ifas.ufl.edu/training

Course Name	Start	End	Level/Nivel	Cost/Costo
Greenhouse 101 / Invernadero 101	30-May-22	24-Jun-22	•	$249
Nutrient Management 1 (Intro) / Manejo de Nutrientes 1 (Intro)	11-Jul-22	5-Aug-22	••	$249
Nutrient Management 2 (Advanced) / Manejo de Nutrientes 2 (Avanzado)	22-Aug-22	16-Sep-22	•••	$249
Disease Management / Manejo de Enfermedades	19-Sep-22	14-Oct-22	••	$249
Weed Management / Manejo de Malezas	17-Oct-22	11-Nov-22	••	$249
Hydroponic Vegetable Production / Producción Hidropónica de Vegetales	17-Oct-22	11-Nov-22	••	$249
Irrigation Water Quality & Treatment / Calidad y Remediación de Agua	14-Nov-22	16-Dec-22	•••	$249
Costing and Profitability / Costos y Rentabilidad	Next course 2023		•••	$499

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