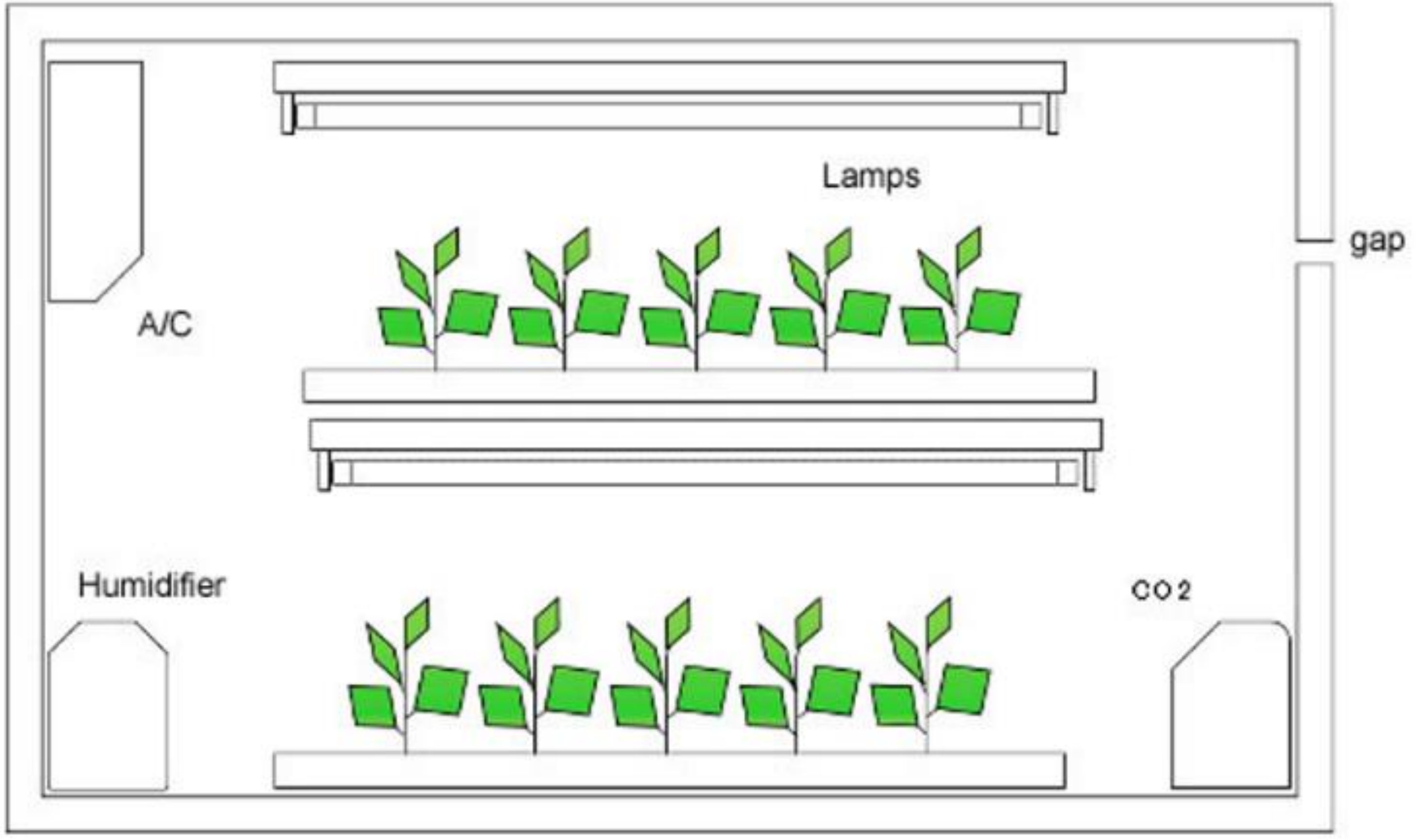


TUTOR FOR PFAL SIMULATOR

Wei FANG, Ph.D., Professor
Dept. of Biomechatronics Engineering
National Taiwan University

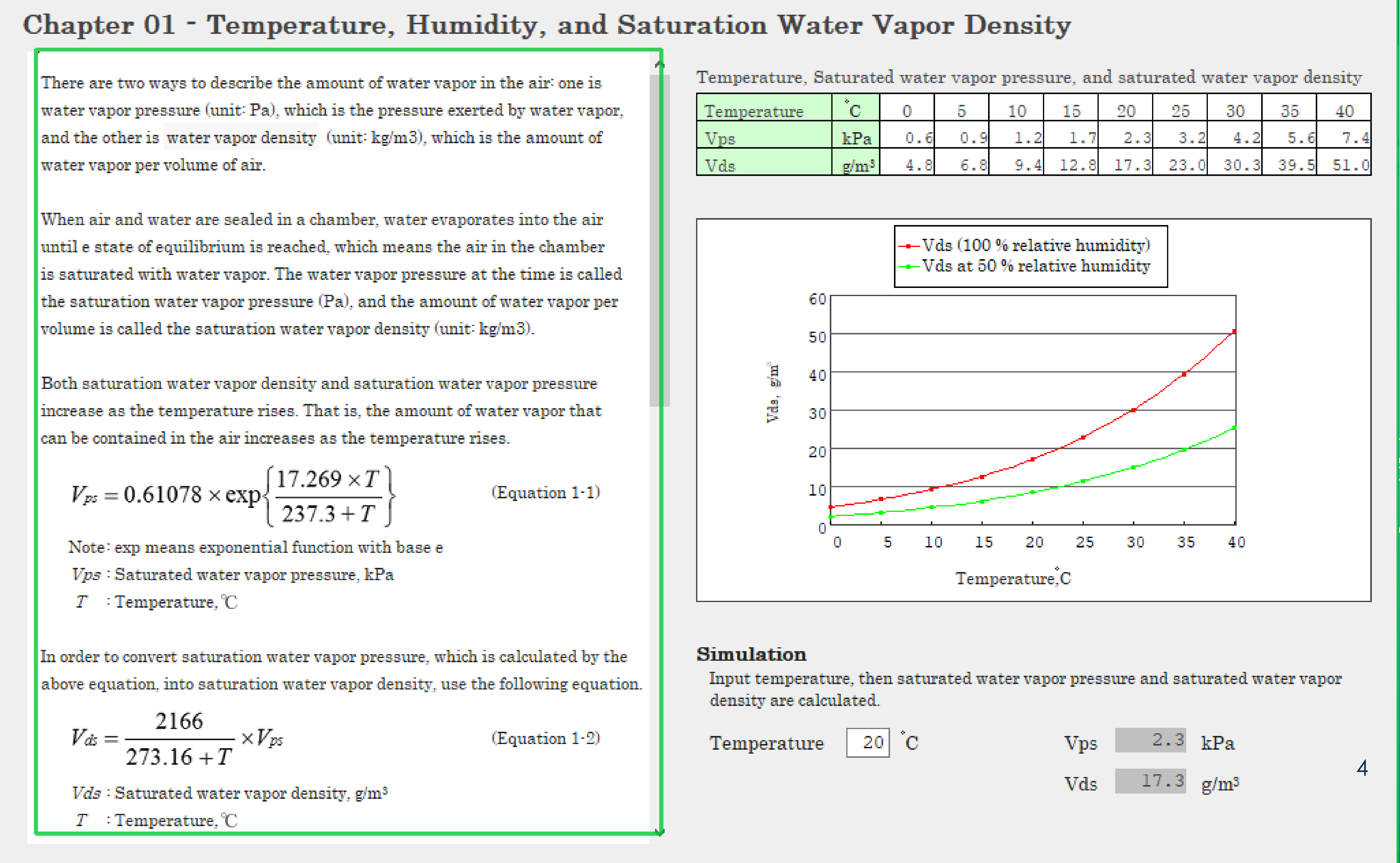
Plant Factory with Artificial Lighting (PFAL)

This is a tutorial for ‘E-learning System for Plant Factory’, a software developed by Chiba University, Japan.

Chapters 1 to16 related to plant physiology (phytophysiology).
Chapters 17 to 22 related to PFAL.

To run the software, you need to purchase a license.
An excel version was developed to cover the same information for education purpose without using the software.

CHAPTER 1
TEMPERATURE, HUMIDITY, AND SATURATION WATER VAPOR DENSITY



Chapter 01 - Temperature, Humidity, and Saturation Water Vapor Density

There are two ways to describe the amount of water vapor in the air: one is water vapor pressure (unit: Pa), which is the pressure exerted by water vapor, and the other is water vapor density (unit: kg/m3), which is the amount of water vapor per volume of air.

When air and water are sealed in a chamber, water evaporates into the air until e state of equilibrium is reached, which means the air in the chamber is saturated with water vapor. The water vapor pressure at the time is called the saturation water vapor pressure (Pa), and the amount of water vapor per volume is called the saturation water vapor density (unit: kg/m3).

Both saturation water vapor density and saturation water vapor pressure increase as the temperature rises. That is, the amount of water vapor that can be contained in the air increases as the temperature rises.

$$V_{ps} = 0.61078 \times \exp\left\{\frac{17.269 \times T}{237.3 + T}\right\} \qquad \text{(Equation 1-1)}$$

Note: exp means exponential function with base e

V_{ps} : Saturated water vapor pressure, kPa

T : Temperature, ℃

In order to convert saturation water vapor pressure, which is calculated by the above equation, into saturation water vapor density, use the following equation.

$$V_{ds} = \frac{2166}{273.16 + T} \times V_{ps} \qquad \text{(Equation 1-2)}$$

V_{ds} : Saturated water vapor density, g/m³

T : Temperature, ℃

Temperature, Saturated water vapor pressure, and saturated water vapor density

Temperature	°C	0	5	10	15	20	25	30	35	40
Vps	kPa	0.6	0.9	1.2	1.7	2.3	3.2	4.2	5.6	7.4
Vds	g/m³	4.8	6.8	9.4	12.8	17.3	23.0	30.3	39.5	51.0

Simulation

Input temperature, then saturated water vapor pressure and saturated water vapor density are calculated.

Temperature 20 °C

Vps 2.3 kPa

Vds 17.3 g/m³

Two ways to describe the amount of water vapor in the air

1. **Water vapor pressure (in Pa)**:
   the pressure exerted by water vapor

2. **Water vapor density (in kg/m^3)**:
   amount of water vapor per volume of air

When air and water are sealed in a chamber, water evaporates into the air until a **state of equilibrium** is reached , which means the air in the chamber is **saturated** with water vapor.

The water vapor pressure at the time is called the **saturated water vapor pressure** (V_{ps}, in Pa), and the amount of water vapor per volume is called the **saturated water vapor density** (V_{ds}, in kg/m^3)

V_{ps} and V_{ds} increase as the **temperature (T)** rises. That is, the amount of water vapor that can be contained in the air increases as the T rises.

$$V_{ps} = 0.61078 \times \exp\left\{\frac{17.269 \times T}{237.3 + T}\right\}$$

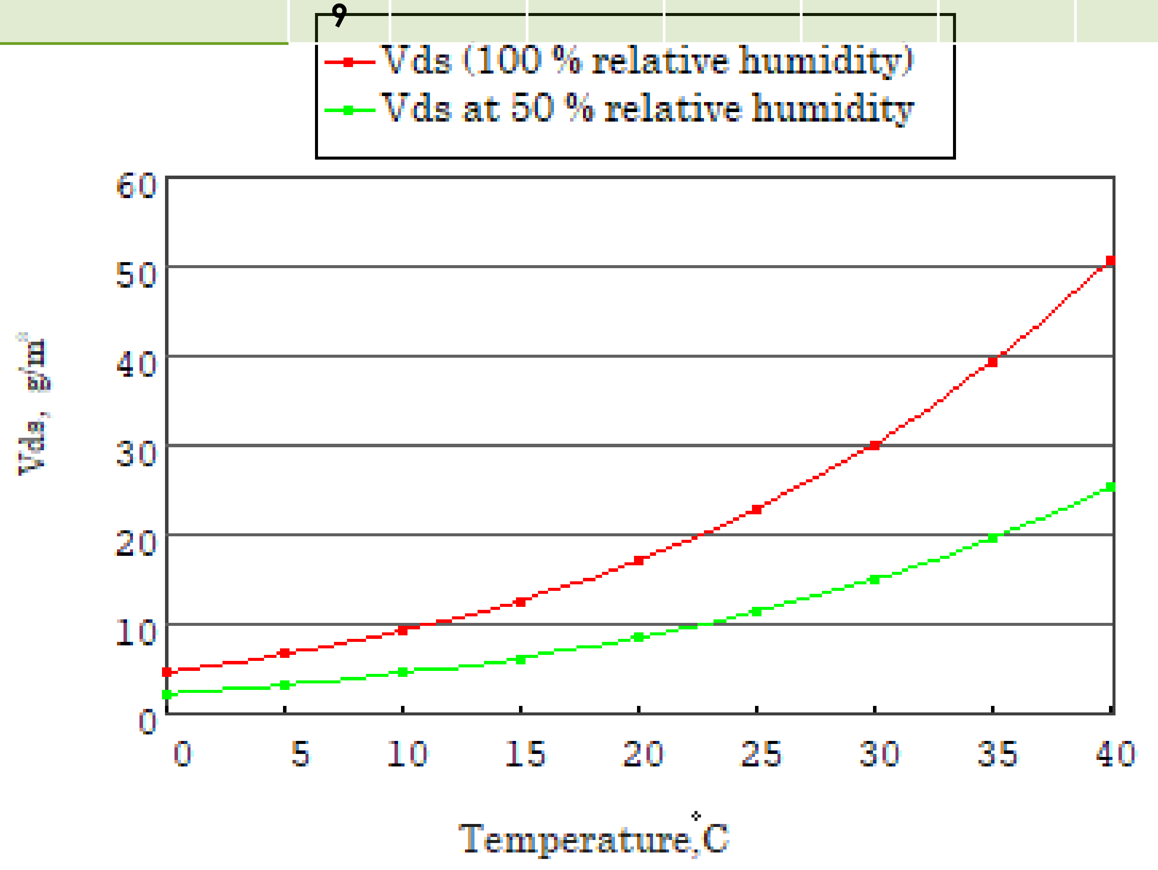
Transpiration rate is expressed as a water evaporation rate per unit of leaf area. It is more convenient to express the water status of the air in terms **of density** than pressure.

$$V_{ds} = \frac{2166}{273.16 + T} \times V_{ps}$$

$$V_{ps} = \frac{273.16 + T}{2166} \times V_{ds}$$

Temperature, Saturated water vapor pressure, and saturated water vapor density

Temperature	°C	0	5	10	15	20	25	30	35	40
Vps	kPa	0.6	0.9	1.2	1.7	2.3	3.2	4.2	5.6	7.4
Vds	g/m³	4.8	6.8	9.4	12.8	17.3	23.0	30.3	39.5	51.0
Abs. humidity (AH): g/kg		3.77	5.4	7.63	10.65					
Density of dry air (ρ): kg/m³		1.28	1.265	1.24	1.217					

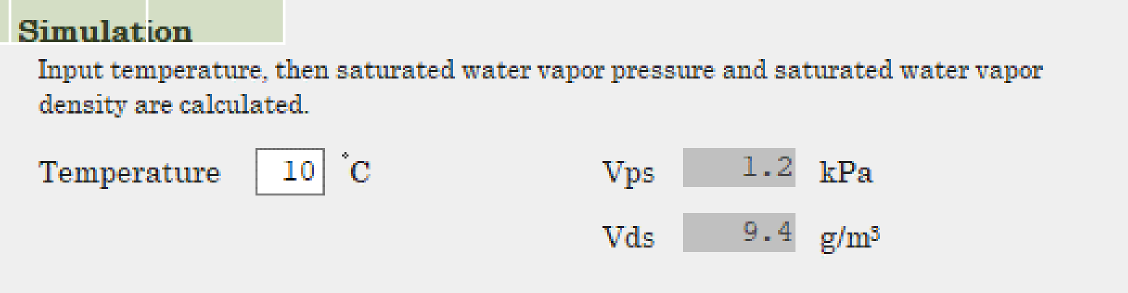


$$Vds = AHs * \rho$$
$$Vd = AH * \rho$$

When T=10,

Vps= 0.61078 * exp(17.269*T/237.3+T)=1.22 kPa

Vds= 2166*1.2278/(273.16+10)=9.39 g/m³



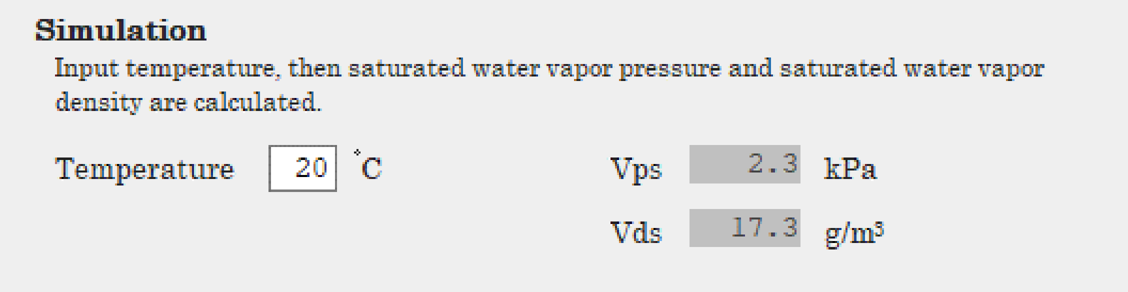
Simulation

Input temperature, then saturated water vapor pressure and saturated water vapor density are calculated.

Temperature 10 °C

Vps 1.2 kPa

Vds 9.4 g/m³



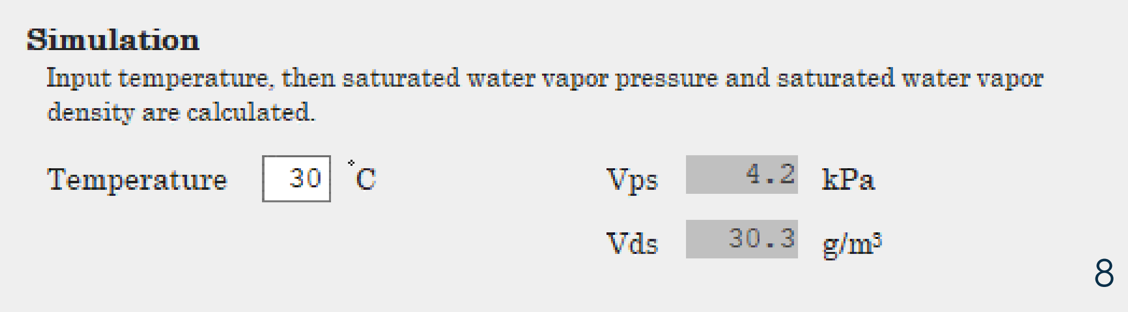
Simulation

Input temperature, then saturated water vapor pressure and saturated water vapor density are calculated.

Temperature 20 °C

Vps 2.3 kPa

Vds 17.3 g/m³



Simulation

Input temperature, then saturated water vapor pressure and saturated water vapor density are calculated.

Temperature 30 °C

Vps 4.2 kPa

Vds 30.3 g/m³

CHAPTER 2
PSYCHROMETRIC CHART

The air is usually not saturated with the water vapor and it is also seldom completely dry. Most of the time it is in between.

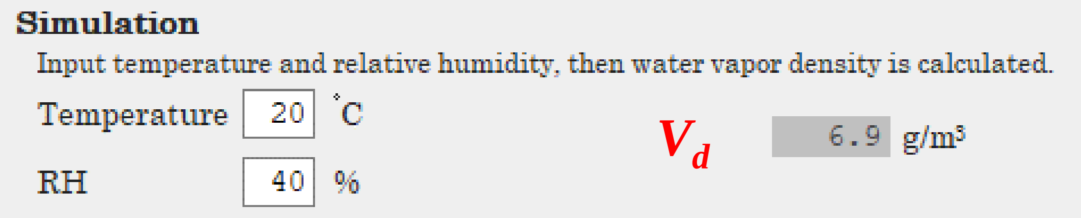
The relative humidity (RH) is the ratio of the water vapor density at the time to the saturation on water vapor density at the temperature of the time, expressed as a percentage.

$$\textbf{\textit{RH (Relative Humidity, in \%)}} = V_p/V_{ps} = V_d/V_{ds}$$

The Table shows water vapor density (V_d) at various T (0~40 deg.C) and RH levels. Vd increases as the T and/or RH rises.
T or RH alone can be determined value of Vd.

This table is the Psychrometric Chart.

When T=20,
Vps= 0.61078 * exp(17.269*T/(237.3+T))=2.338 kPa
Vds= 2166*2.338/(273.16+20)=17.274 g/m³
Vd= Vds * RH /100 = 6.909 g/m³



Simulation

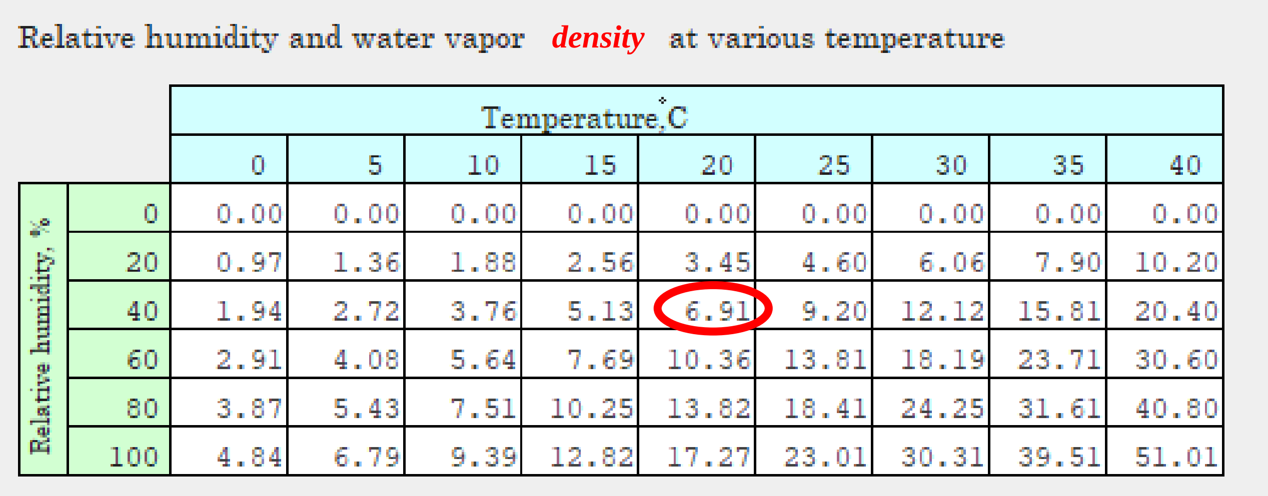
Input temperature and relative humidity, then water vapor density is calculated.

Temperature 20 °C

RH 40 %

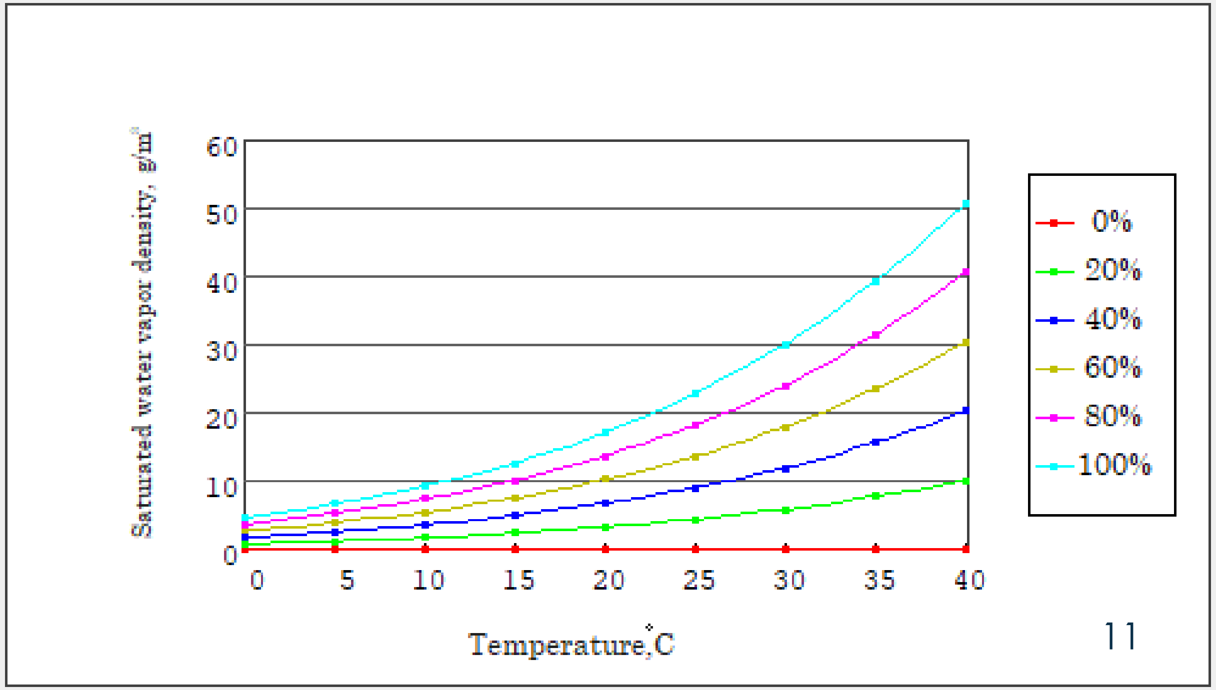
V_d 6.9 g/m³

There are several free APPs, such as: Psychrometric calculator, psychroApp, aRhoAir, Psychrometric, and freeware: psyc0226.



Relative humidity and water vapor *density* at various temperature

Relative humidity, %	Temperature,°C 0	5	10	15	20	25	30	35	40
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.97	1.36	1.88	2.56	3.45	4.60	6.06	7.90	10.20
40	1.94	2.72	3.76	5.13	6.91	9.20	12.12	15.81	20.40
60	2.91	4.08	5.64	7.69	10.36	13.81	18.19	23.71	30.60
80	3.87	5.43	7.51	10.25	13.82	18.41	24.25	31.61	40.80
100	4.84	6.79	9.39	12.82	17.27	23.01	30.31	39.51	51.01



1. **Absolute Humidity (AH):** The mass of water vapor in the air to the mass of the dry air, in g vapor/kg dry air.
2. Relative Humidity (RH)
3. Water vapor pressure (V_p, V_{ps})
4. Water vapor density (V_d, V_{ds})

FOUR TERMS RELATED TO THE WATER VAPOR IN THE AIR

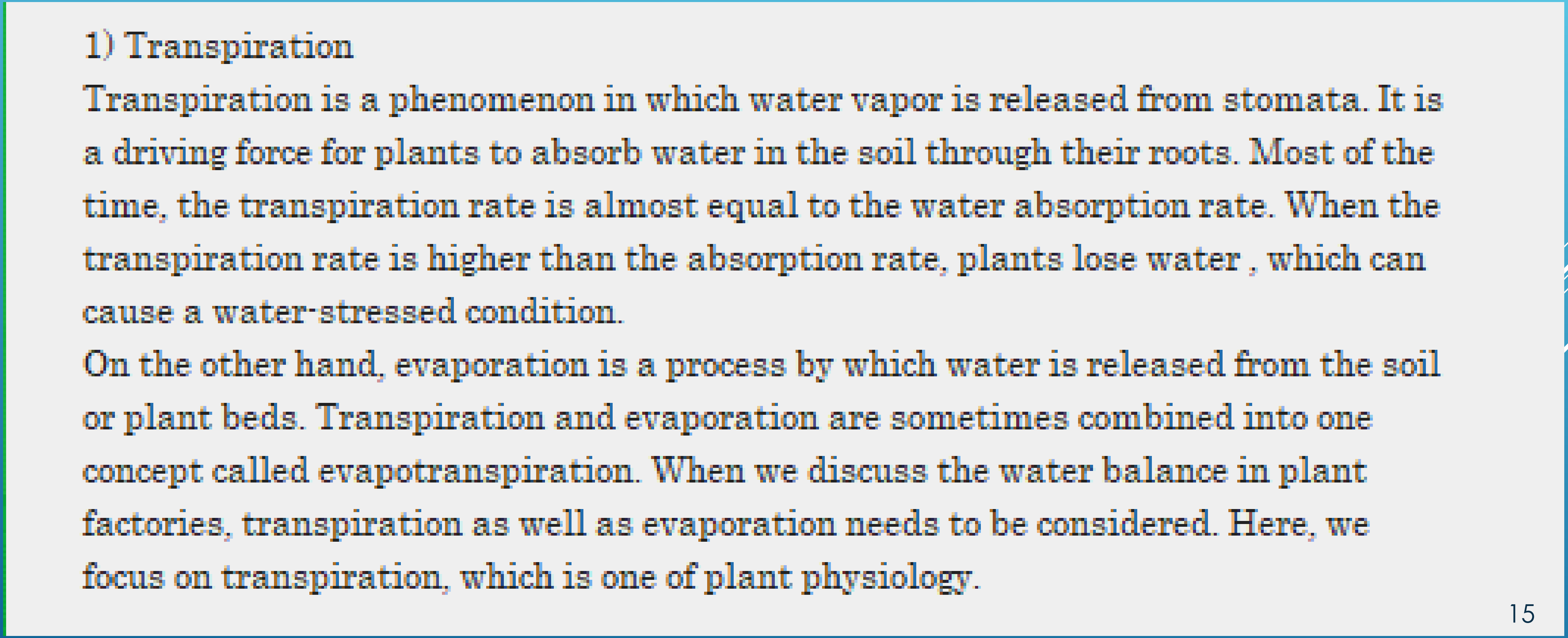
- The difference between actual water vapor pressure (**V_p**) and saturated water vapor pressure (**V_{ps}**) is called (water) vapor pressure deficit or **VPD**. Difference between V_{ds} and V_d is called **VDD**.
- If leaf temperature equals air temperature, VPD and VDD also represents the driving force of leaf transpiration.

$$VPD = V_{ps} - V_p$$

$$\text{VDD (Vapor Density Difference)} = V_{ds} - V_d \,.$$

CHAPTER 3
TRANSPIRATION

Evaporation, Transpiration, Evapotranspiration

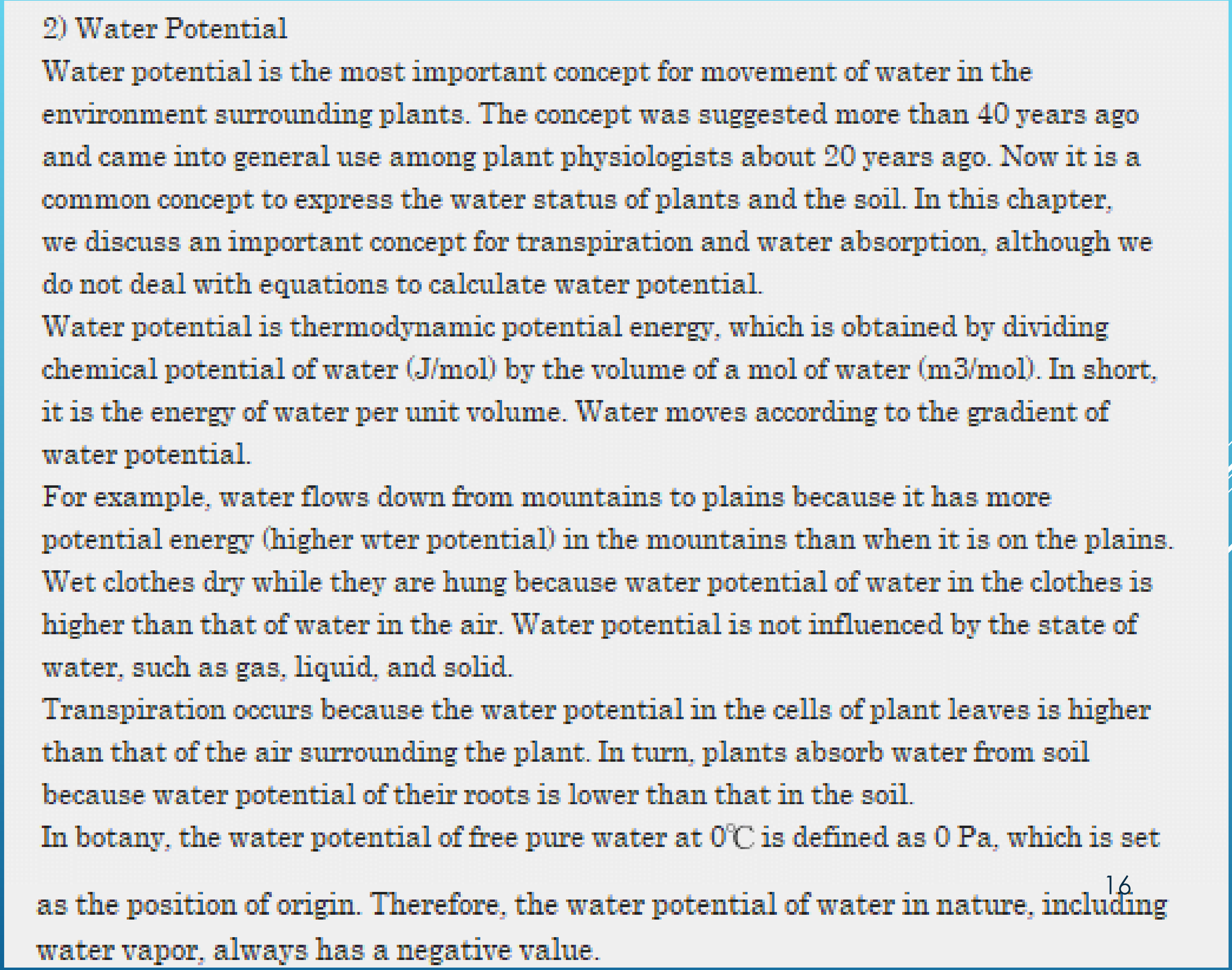


1) Transpiration

Transpiration is a phenomenon in which water vapor is released from stomata. It is a driving force for plants to absorb water in the soil through their roots. Most of the time, the transpiration rate is almost equal to the water absorption rate. When the transpiration rate is higher than the absorption rate, plants lose water , which can cause a water-stressed condition.

On the other hand, evaporation is a process by which water is released from the soil or plant beds. Transpiration and evaporation are sometimes combined into one concept called evapotranspiration. When we discuss the water balance in plant factories, transpiration as well as evaporation needs to be considered. Here, we focus on transpiration, which is one of plant physiology.

Water potential



2) Water Potential

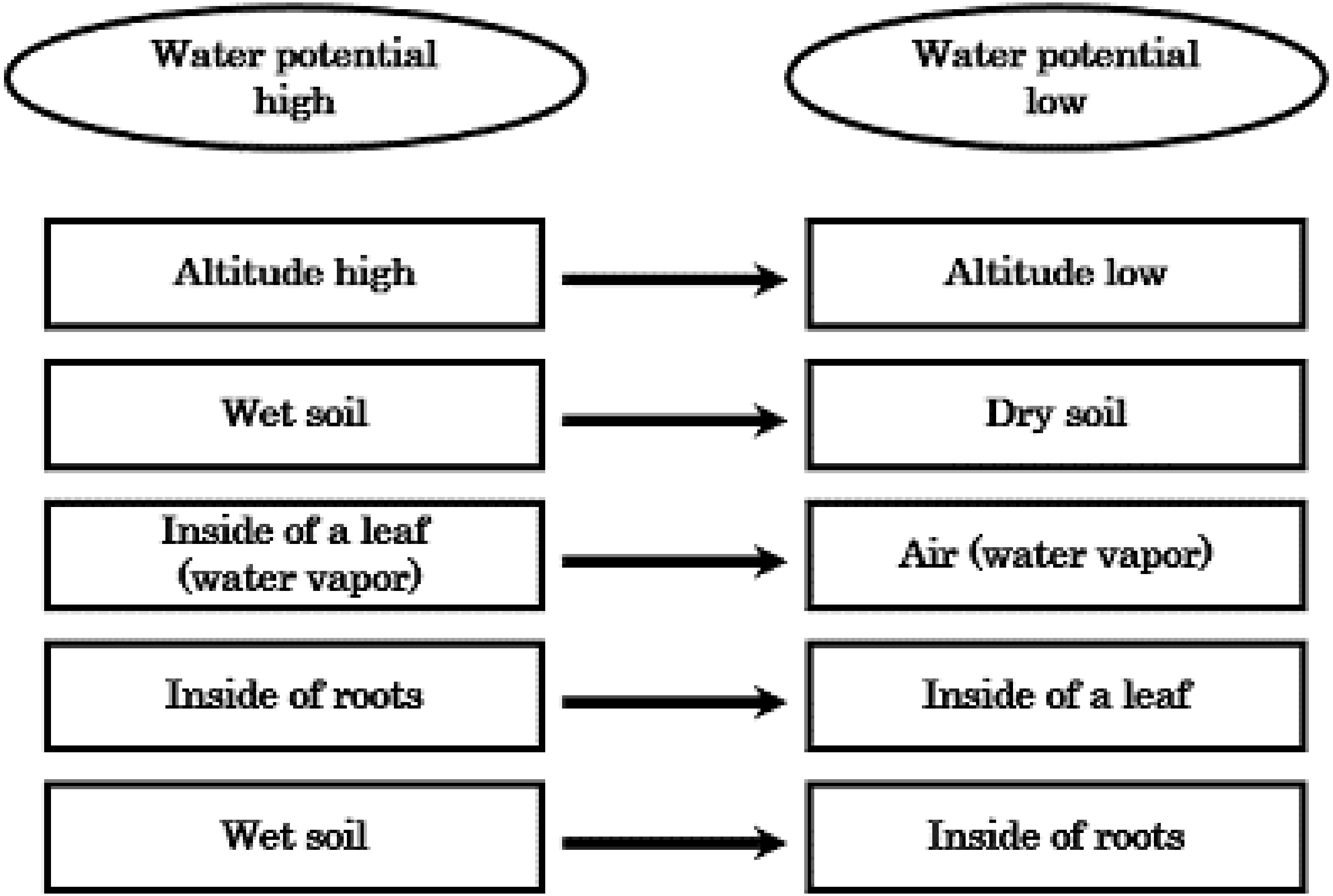
Water potential is the most important concept for movement of water in the environment surrounding plants. The concept was suggested more than 40 years ago and came into general use among plant physiologists about 20 years ago. Now it is a common concept to express the water status of plants and the soil. In this chapter, we discuss an important concept for transpiration and water absorption, although we do not deal with equations to calculate water potential.

Water potential is thermodynamic potential energy, which is obtained by dividing chemical potential of water (J/mol) by the volume of a mol of water (m3/mol). In short, it is the energy of water per unit volume. Water moves according to the gradient of water potential.

For example, water flows down from mountains to plains because it has more potential energy (higher wter potential) in the mountains than when it is on the plains. Wet clothes dry while they are hung because water potential of water in the clothes is higher than that of water in the air. Water potential is not influenced by the state of water, such as gas, liquid, and solid.

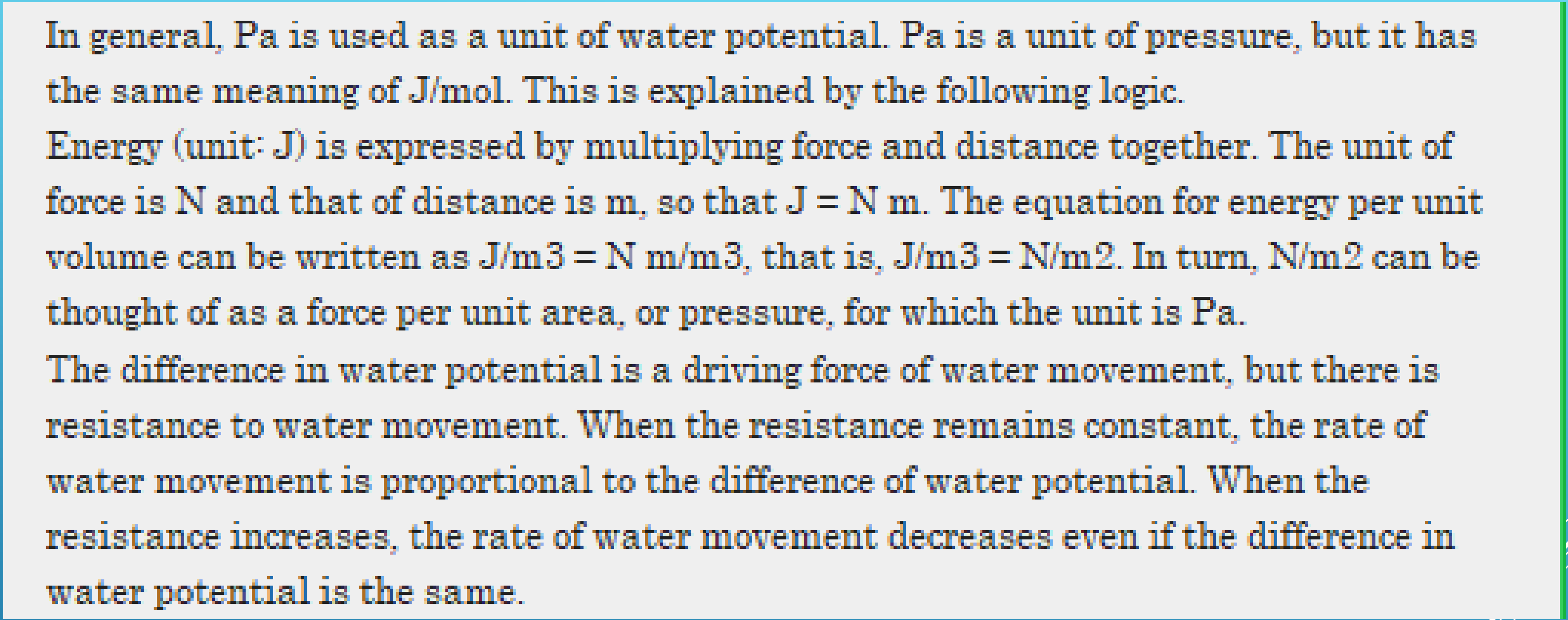
Transpiration occurs because the water potential in the cells of plant leaves is higher than that of the air surrounding the plant. In turn, plants absorb water from soil because water potential of their roots is lower than that in the soil.

In botany, the water potential of free pure water at 0℃ is defined as 0 Pa, which is set as the position of origin. Therefore, the water potential of water in nature, including water vapor, always has a negative value.



The difference of water potential in two points determines the direction of the water flow.

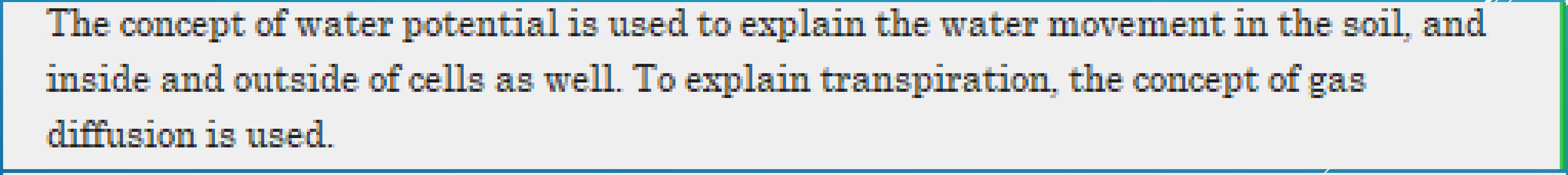
Figure 3-1 Concept of water potential



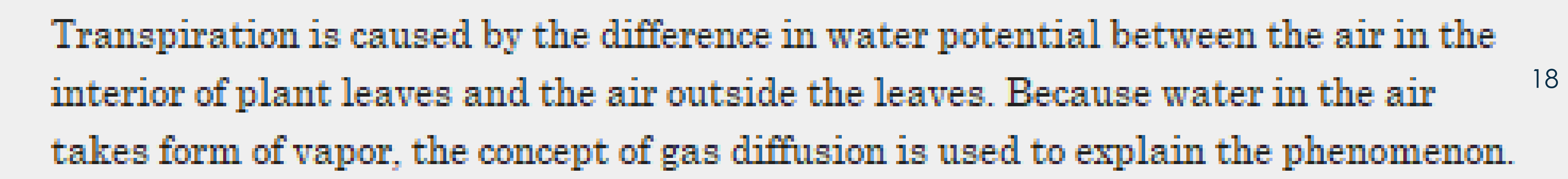
In general, Pa is used as a unit of water potential. Pa is a unit of pressure, but it has the same meaning of J/mol. This is explained by the following logic.

Energy (unit: J) is expressed by multiplying force and distance together. The unit of force is N and that of distance is m, so that J = N m. The equation for energy per unit volume can be written as J/m3 = N m/m3, that is, J/m3 = N/m2. In turn, N/m2 can be thought of as a force per unit area, or pressure, for which the unit is Pa.

The difference in water potential is a driving force of water movement, but there is resistance to water movement. When the resistance remains constant, the rate of water movement is proportional to the difference of water potential. When the resistance increases, the rate of water movement decreases even if the difference in water potential is the same.



The concept of water potential is used to explain the water movement in the soil, and inside and outside of cells as well. To explain transpiration, the concept of gas diffusion is used.



Transpiration is caused by the difference in water potential between the air in the interior of plant leaves and the air outside the leaves. Because water in the air takes form of vapor, the concept of gas diffusion is used to explain the phenomenon.

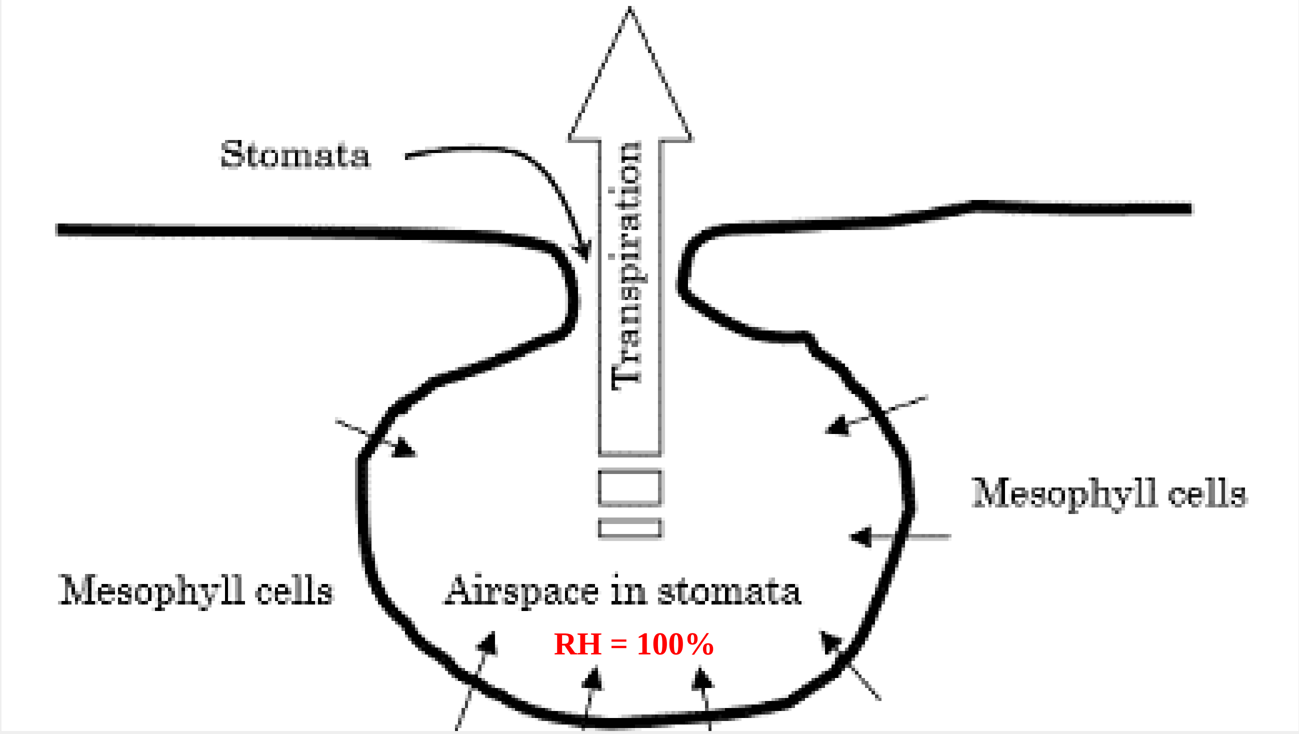


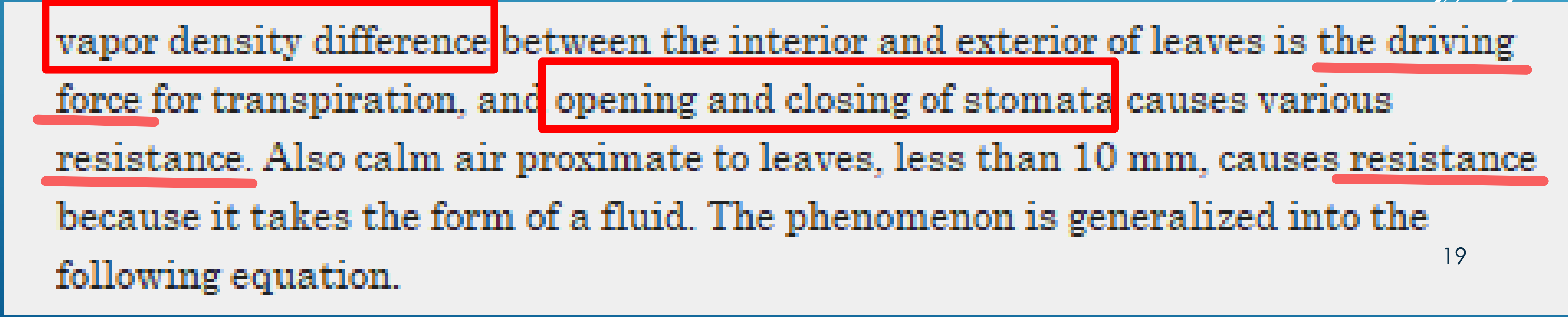
Figure 3-2 Conceptual diagram showing the water-vapor flow near stomata

T_r increases when driving force increase, T in leaf increase and RH in air decrease lead to higher T_r.

$$Tr = \frac{El - Ea}{Rlv + Rav} \qquad \text{(Equation 3-1)}$$

driving force
resistance

Tr : Transpiration rate, $mg/(m^2 s)$
El : Water vapor density in airspace within stomata, mg/m^3
Ea : Water vapor density in the air, mg/m^3
Rlv : Stomatal resistance, s/m
Rav : Aerodynamic resistance, s/m
Also termed Leaf boundary layer resistance

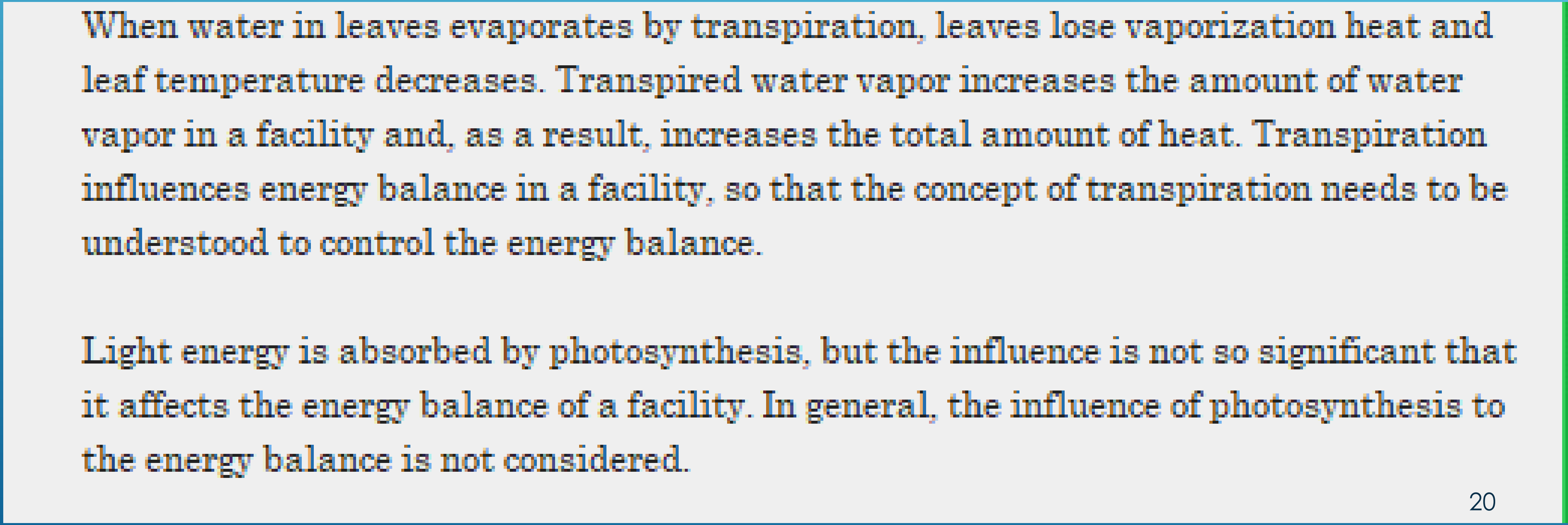


vapor density difference between the interior and exterior of leaves is the driving force for transpiration, and opening and closing of stomata causes various resistance. Also calm air proximate to leaves, less than 10 mm, causes resistance because it takes the form of a fluid. The phenomenon is generalized into the following equation.

R_{lv} (stomata resistance) increases at night because the stomata close (for C3, C4 plants)

R_{lv} influenced by CO_2 concentration, it increases as CO2 conc. Increases.

R_{av} (aerodynamic resistance) decreasing when wind velocity increases.



When water in leaves evaporates by transpiration, leaves lose vaporization heat and leaf temperature decreases. Transpired water vapor increases the amount of water vapor in a facility and, as a result, increases the total amount of heat. Transpiration influences energy balance in a facility, so that the concept of transpiration needs to be understood to control the energy balance.

Light energy is absorbed by photosynthesis, but the influence is not so significant that it affects the energy balance of a facility. In general, the influence of photosynthesis to the energy balance is not considered.

CHAPTER 4

PHOTOSYNTHETICALLY ACTIVE IRRADIANCE AND STOMATAL RESISTANCE

Amount of Energy per unit area per unit time (in W/m^2)

Photosynthetically active irradiance

Photosynthetically Active Radiation, PAR (400~700 nm)

Number of Photons per unit area per unit time (in $\mu mol/m^2/s$)

Photosynthetically active flux density (PPFD)

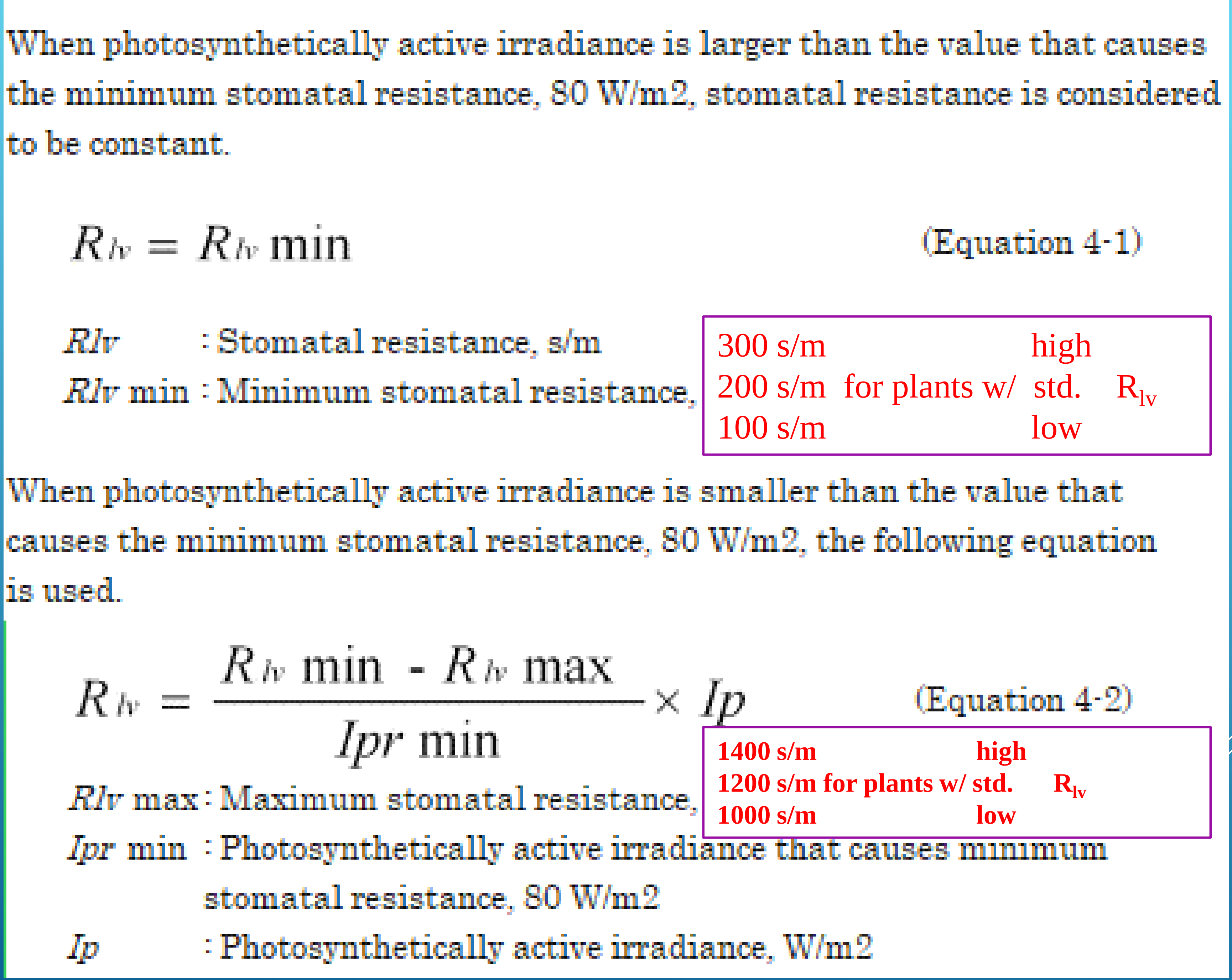
R_{lv} and R_{av} are resistance to water vapor diffusion

R_{lv} influenced by light intensity (*l* stands for leaf, v stands for vapor)

R_{av} influenced by wind velocity (a stands for aerodynamic, see next Chapter)

R_{lv} of common plant is 50 to 300 s/m when stomata are open.

R_{lv} is of 10 times, > 1000 s/m when stomata are closed in the dark period.



When photosynthetically active irradiance is larger than the value that causes the minimum stomatal resistance, 80 W/m2, stomatal resistance is considered to be constant.

$$R_{lv} = R_{lv}\min \qquad \text{(Equation 4-1)}$$

Rlv : Stomatal resistance, s/m
Rlv min : Minimum stomatal resistance,

300 s/m high
200 s/m for plants w/ std. R_{lv}
100 s/m low

When photosynthetically active irradiance is smaller than the value that causes the minimum stomatal resistance, 80 W/m2, the following equation is used.

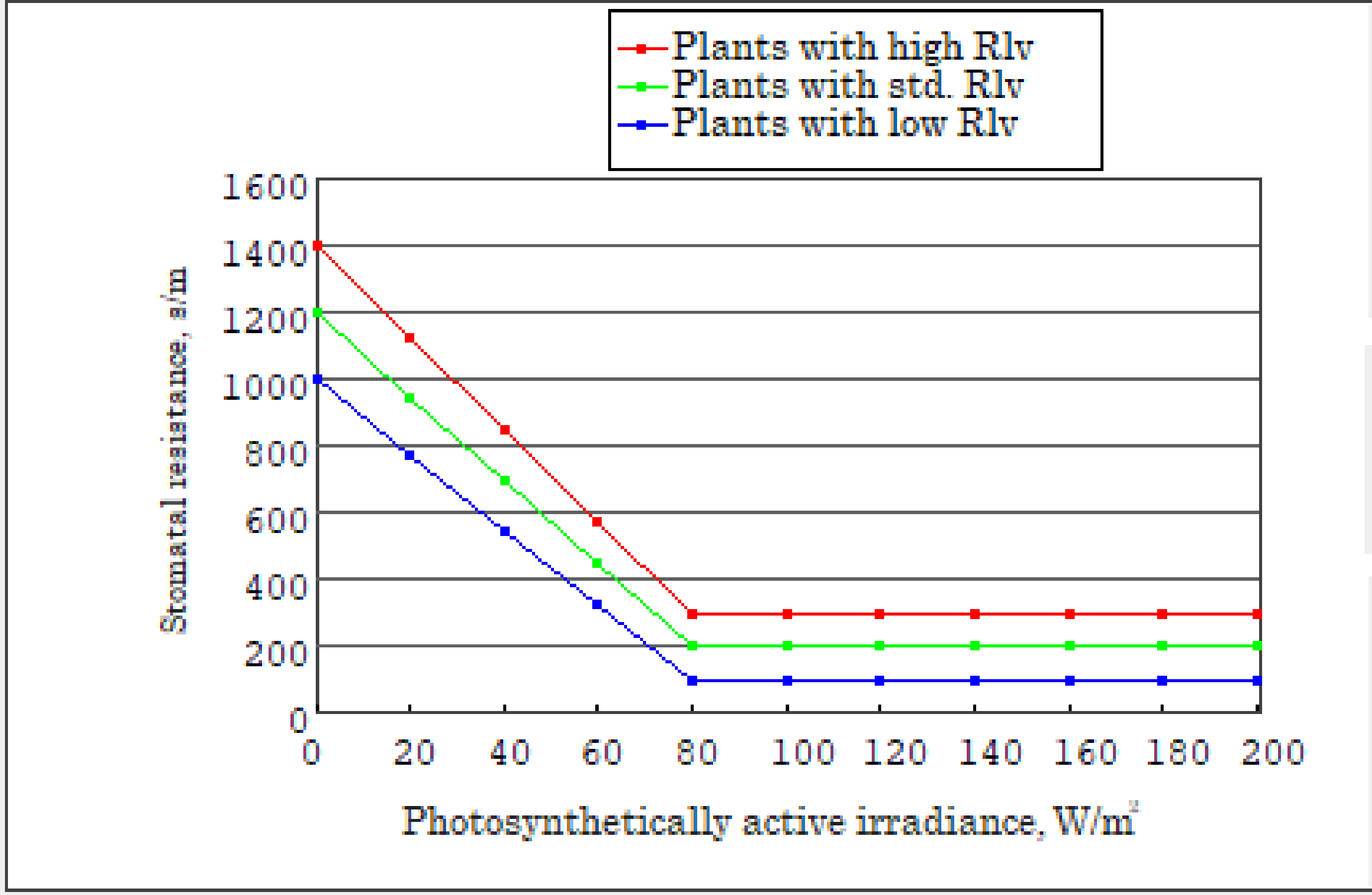
$$R_{lv} = \frac{R_{lv}\min - R_{lv}\max}{Ipr\min} \times Ip \qquad \text{(Equation 4-2)}$$

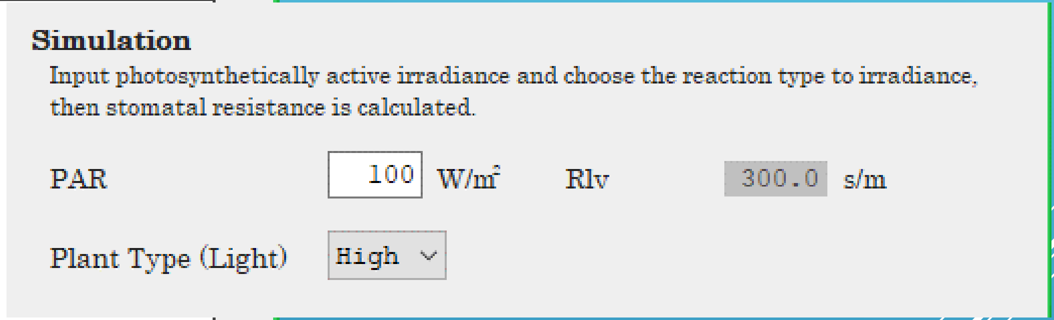
1400 s/m high
1200 s/m for plants w/ std. R_{lv}
1000 s/m low

Rlv max : Maximum stomatal resistance,
Ipr min : Photosynthetically active irradiance that causes minimum stomatal resistance, 80 W/m2
Ip : Photosynthetically active irradiance, W/m2

Photosynthetically active irradiance and Stomatal resistance

PAR	W/m²	0	20	40	60	80	100	120	140	160	180	200
Rlv:High	s/m	1400	1125	850	575	300	300	300	300	300	300	300
Rlv:Std.	s/m	1200	950	700	450	200	200	200	200	200	200	200
Rlv:Low	s/m	1000	775	550	325	100	100	100	100	100	100	100





Simulation

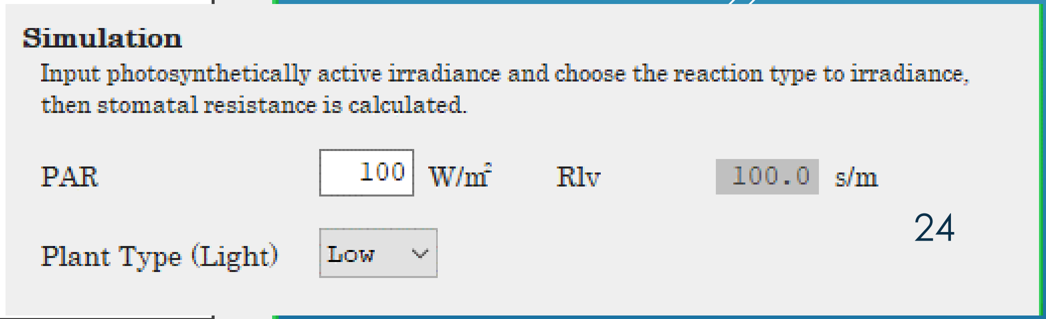
Input photosynthetically active irradiance and choose the reaction type to irradiance, then stomatal resistance is calculated.

PAR 100 W/m² Rlv 300.0 s/m

Plant Type (Light) High

PAR 100 W/m² Rlv 200.0 s/m

Plant Type (Light) Std.



Simulation

Input photosynthetically active irradiance and choose the reaction type to irradiance, then stomatal resistance is calculated.

PAR 100 W/m² Rlv 100.0 s/m

Plant Type (Light) Low

CHAPTER 5

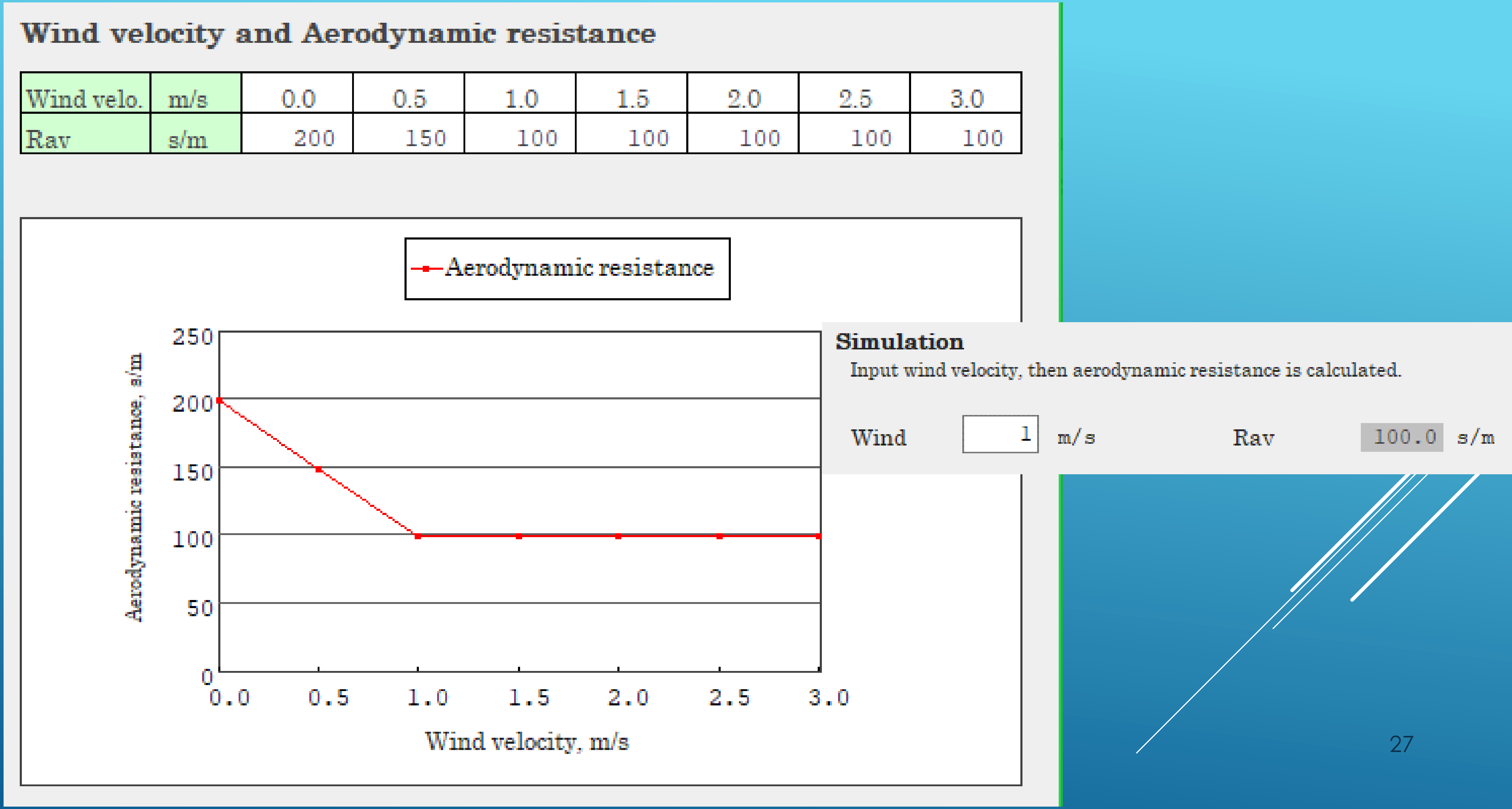
WIND VELOCITY AND RESISTANCE

- Aerodynamic resistance to water vapor (R_{av}) is greatly influenced by wind velocity (W). As W increases, R_{av} decreases sharply at first, however when W > 0.6 m/s, Rav does not increase much more.
- In this simulator, Rav.min = 100 s/m when W $\geq$1 m/s (expressed as Wr.min), Rav.max = 200 s/m when no wind.
- When W > 5 m/s, stomata may be closed under such high wind, but this will not occurred in PFAL or in greenhouses.

When W $\geq$ 1 m/s, Rav = Rav.min

When W < 1 m/s, Rav = (Rav.max – Rav.min) * W / Wr.min

= 100 * W / 1



Wind velocity and Aerodynamic resistance

Wind velo.	m/s	0.0	0.5	1.0	1.5	2.0	2.5	3.0
Rav	s/m	200	150	100	100	100	100	100

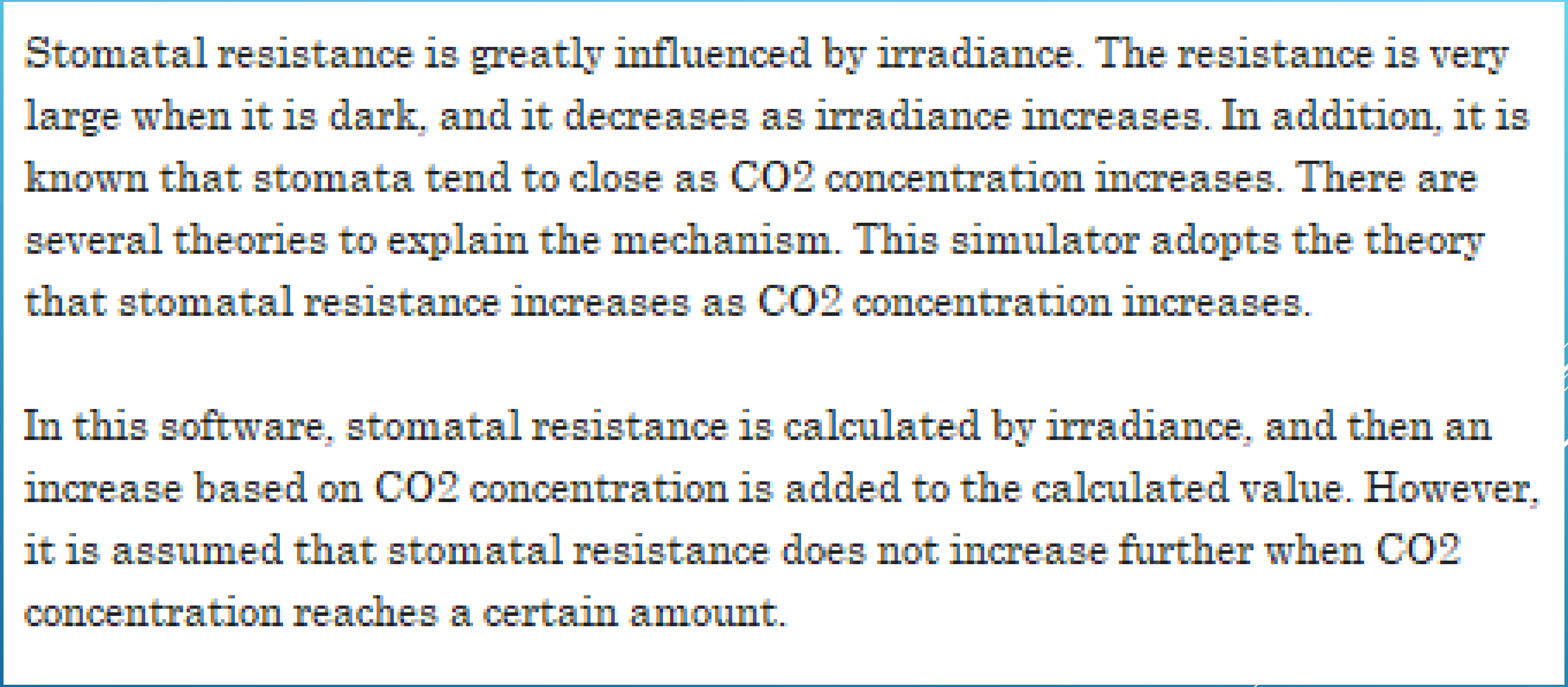
Simulation

Input wind velocity, then aerodynamic resistance is calculated.

Wind 1 m/s

Rav 100.0 s/m

CHAPTER 6
CO_2 CONCENTRATION AND STOMATAL RESISTANCE



Stomatal resistance is greatly influenced by irradiance. The resistance is very large when it is dark, and it decreases as irradiance increases. In addition, it is known that stomata tend to close as CO2 concentration increases. There are several theories to explain the mechanism. This simulator adopts the theory that stomatal resistance increases as CO2 concentration increases.

In this software, stomatal resistance is calculated by irradiance, and then an increase based on CO2 concentration is added to the calculated value. However, it is assumed that stomatal resistance does not increase further when CO2 concentration reaches a certain amount.

- When CO_2 conc. > $\rho_{cr.max}$ (2352 mg/m^3), stomata resistance increase ($_{Rlv.inc}$) due to CO_2 reaches its max and remain constant (200 or 400 s/m) even the CO_2 conc. still increase.

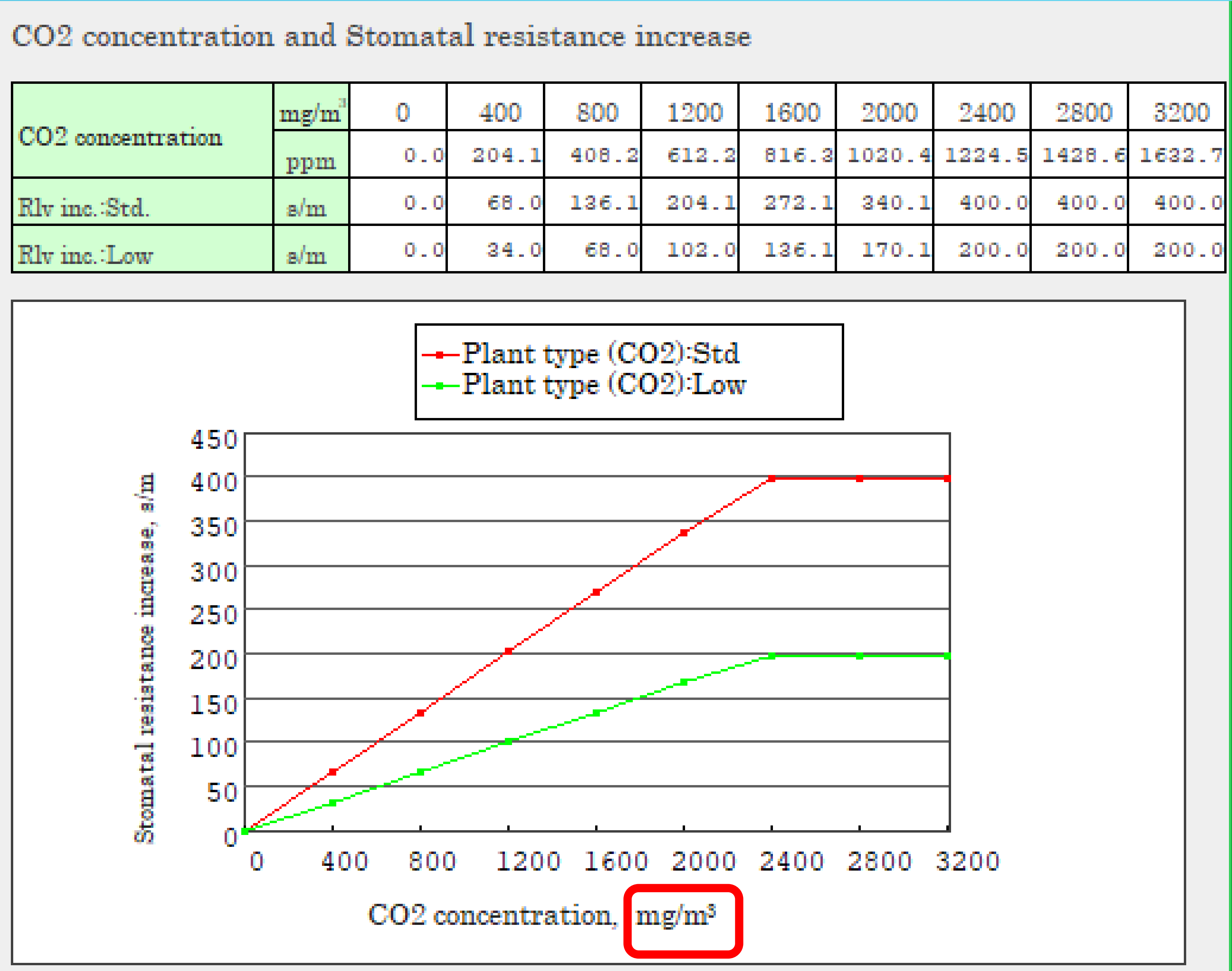
$$R_{lv.inc} = R_{lv.inc.max}$$

- When CO_2 conc. is lower than the value that gives the max stomata resistance increment, the following eq. is used.

$$R_{lv.inc} = \rho_{ca} * (R_{lv.max} / \rho_{cr.max})$$

ρ_{ca}: CO_2 concentration, mg/m^3

$\rho_{cr.max}$: CO_2 concentration that gives the max stomata resistance increment, 2352 mg/m^3 (1200 ppm).



CO2 concentration and Stomatal resistance increase

CO2 concentration	mg/m^3	0	400	800	1200	1600	2000	2400	2800	3200
	ppm	0.0	204.1	408.2	612.2	816.3	1020.4	1224.5	1428.6	1632.7
Rlv inc.:Std.	s/m	0.0	68.0	136.1	204.1	272.1	340.1	400.0	400.0	400.0
Rlv inc.:Low	s/m	0.0	34.0	68.0	102.0	136.1	170.1	200.0	200.0	200.0

$\rho_{cr.max}$ = 2352 mg/m^3

(1200 ppm)

(CO_2 density=1.96 kg/m^3)

when plant type is Std.

$R_{lv.max}$ = 400, slope=400/2352

CO_2 conc. = 800 mg/m^3

Rlv.inc=400/2352*800= 136.05

when plant type is low

$R_{lv.max}$ = 200, slope=200/2352

CO_2 conc. = 800 mg/m^3

Rlv.inc = 200/2352*800= 68

Discussion on the conversion factors related to ppm (vpm), mg/m^3 and mg/kg

$PV=nRT=(m/M)\ RT$

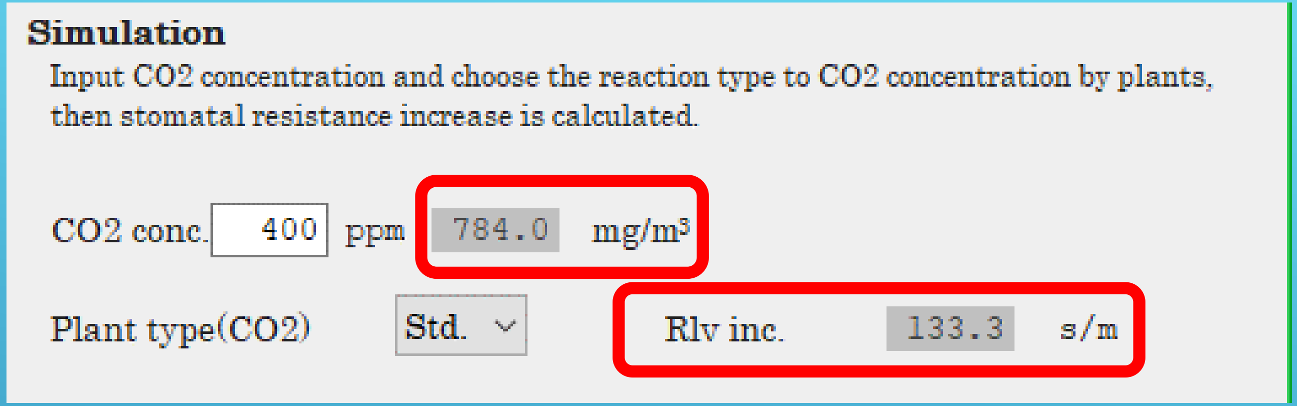
When $P=1$, density $= m/V = M/RT$

@$0^oC = 44/(0.0821*273.15) = 1.96$ mg CO_2/m^3 air

@$20^oC = 44/(0.0821*(273.15+20)) = 1.83$ mg CO_2/m^3 air

$\underline{1\ ppm = 1\ m^3\ CO_2/10^6\ m^3\ air = 1.96\ mg/m^3\ air\ @\ 0^oC}$

$\underline{= 1.96/density\ of\ air = 1.96/1.29 = 1.519\ mg/kg@\ 0^oC}$

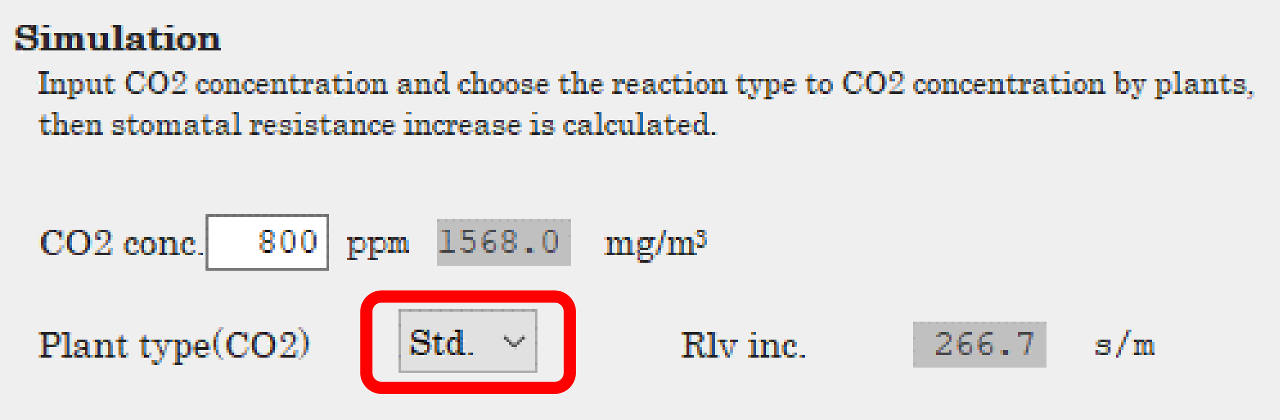


Simulation

Input CO2 concentration and choose the reaction type to CO2 concentration by plants, then stomatal resistance increase is calculated.

CO2 conc. 400 ppm 784.0 mg/m³

Plant type(CO2) Std. Rlv inc. 133.3 s/m

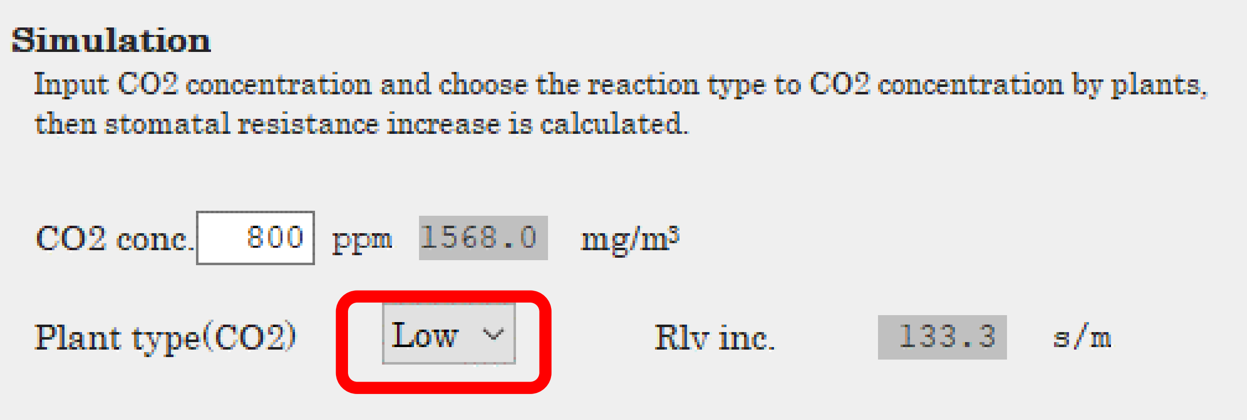


Simulation

Input CO2 concentration and choose the reaction type to CO2 concentration by plants, then stomatal resistance increase is calculated.

CO2 conc. 800 ppm 1568.0 mg/m³

Plant type(CO2) Std. Rlv inc. 266.7 s/m

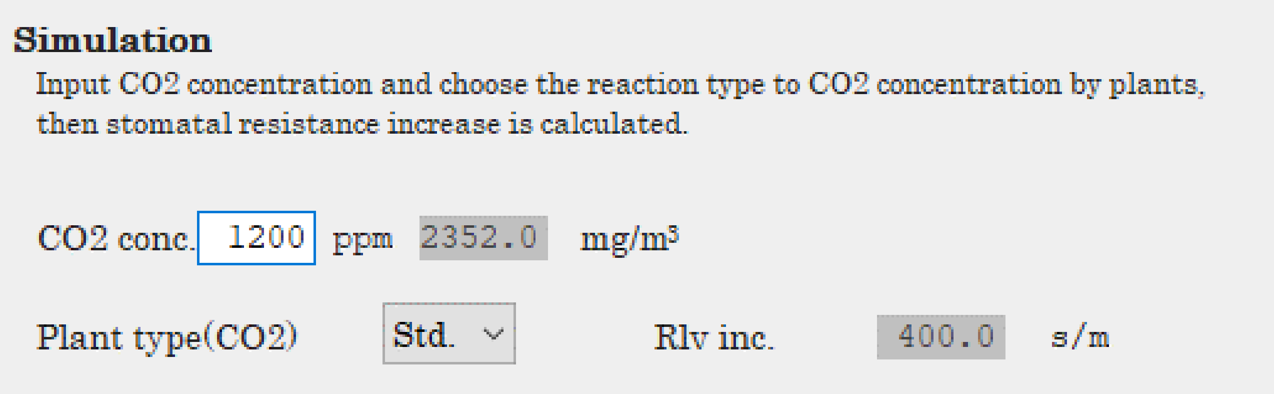


Simulation

Input CO2 concentration and choose the reaction type to CO2 concentration by plants, then stomatal resistance increase is calculated.

CO2 conc. 800 ppm 1568.0 mg/m³

Plant type(CO2) Low Rlv inc. 133.3 s/m

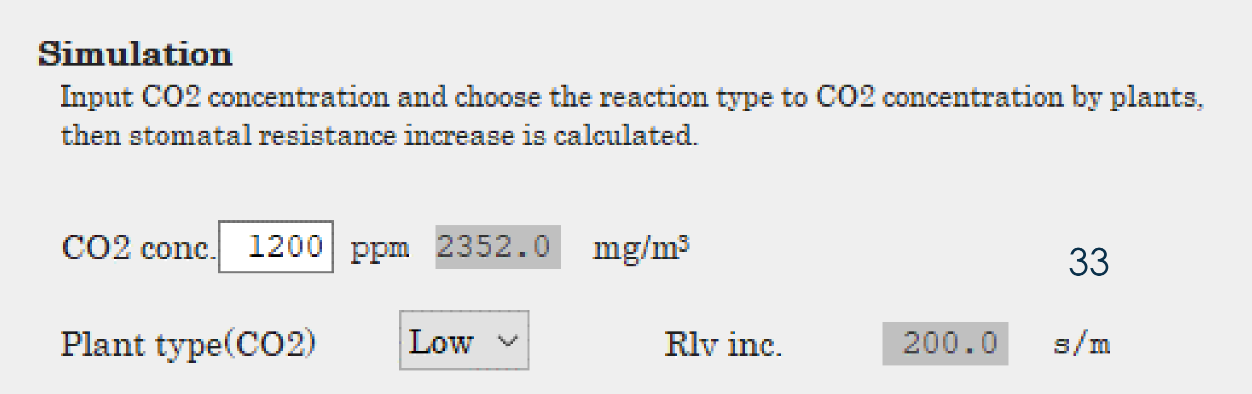


Simulation

Input CO2 concentration and choose the reaction type to CO2 concentration by plants, then stomatal resistance increase is calculated.

CO2 conc. 1200 ppm 2352.0 mg/m³

Plant type(CO2) Std. Rlv inc. 400.0 s/m



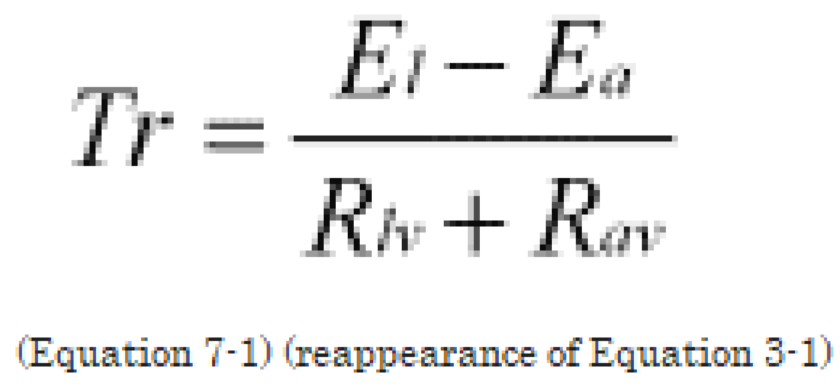
Simulation

Input CO2 concentration and choose the reaction type to CO2 concentration by plants, then stomatal resistance increase is calculated.

CO2 conc. 1200 ppm 2352.0 mg/m³

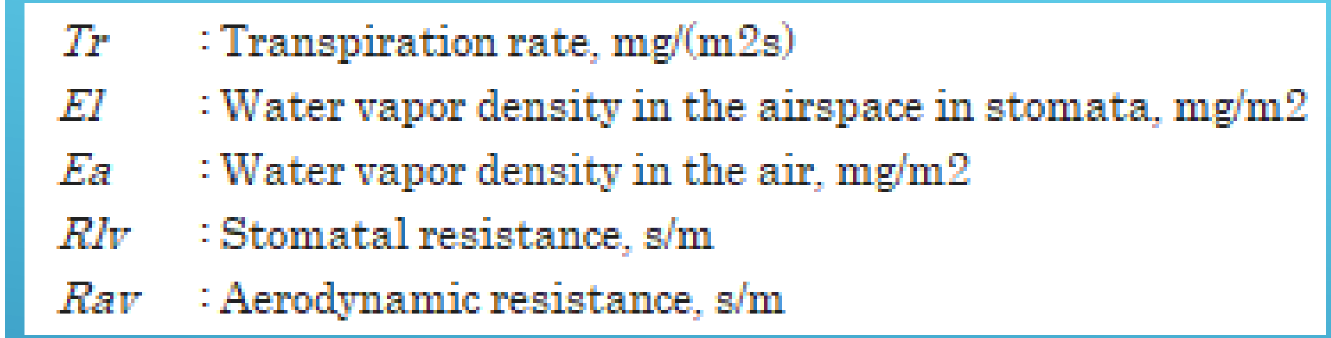
Plant type(CO2) Low Rlv inc. 200.0 s/m

CHAPTER 7
TRANSPIRATION RATE



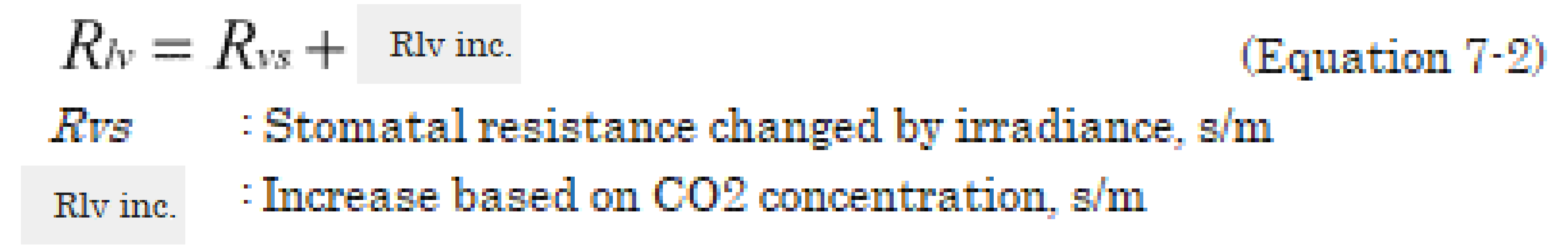
$$Tr = \frac{E_l - E_a}{R_{lv} + R_{av}}$$

(Equation 7-1) (reappearance of Equation 3-1)



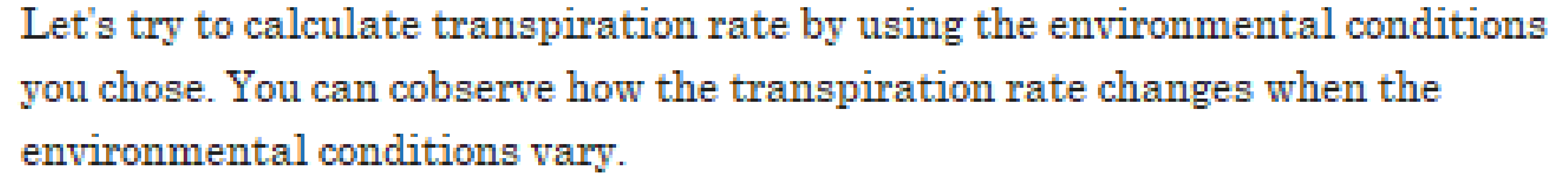
Tr : Transpiration rate, mg/(m2s)
El : Water vapor density in the airspace in stomata, mg/m2
Ea : Water vapor density in the air, mg/m2
Rlv : Stomatal resistance, s/m
Rav : Aerodynamic resistance, s/m

Stomatal resistance (affected by PAR) includes an increase based on CO_2 concentration.



$$R_{lv} = R_{vs} + \text{Rlv inc.} \qquad \text{(Equation 7-2)}$$

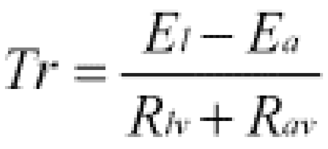
Rvs : Stomatal resistance changed by irradiance, s/m
Rlv inc. : Increase based on CO2 concentration, s/m



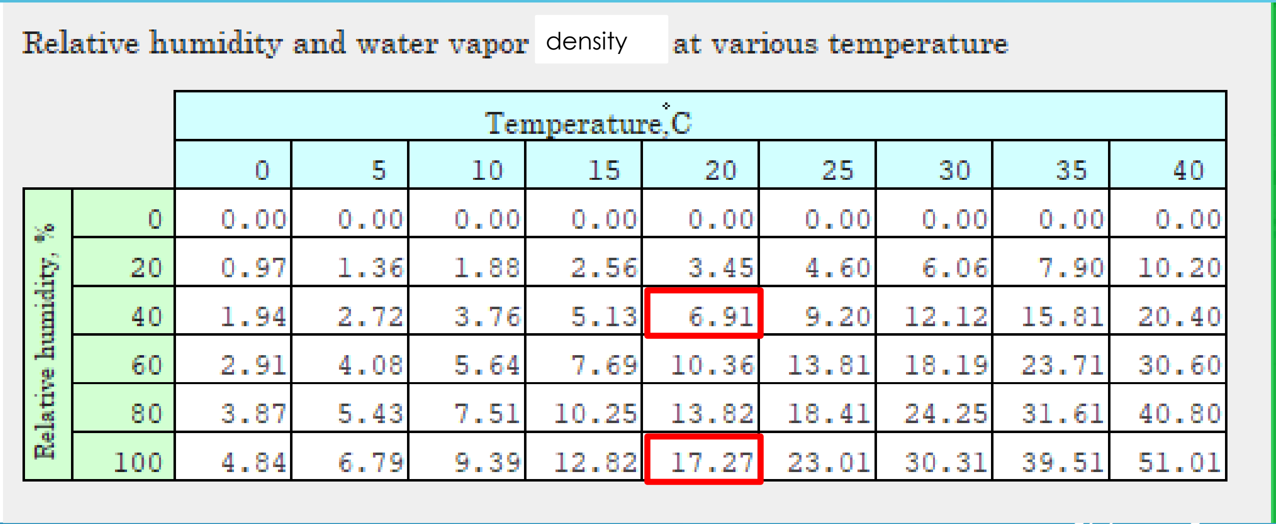
Let's try to calculate transpiration rate by using the environmental conditions you chose. You can cobserve how the transpiration rate changes when the environmental conditions vary.

Assuming T_{air} equals T_{leaf}.

VDD = 17.27 – 6.91 = 10.36 g/m^3 = 10360 mg/m^3
R = 100+200+124.5 = 424.5 s/m
Tr = VDD/R in mg*m/(m^3.s)
= 10360/424.5 = 24.40 mg/m^2.s

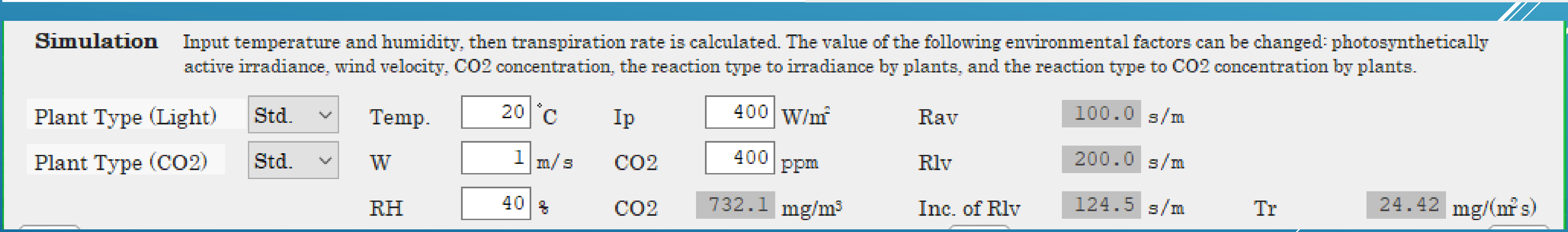


$$Tr = \frac{E_l - E_a}{R_{lv} + R_{av}}$$



Relative humidity and water vapor density at various temperature

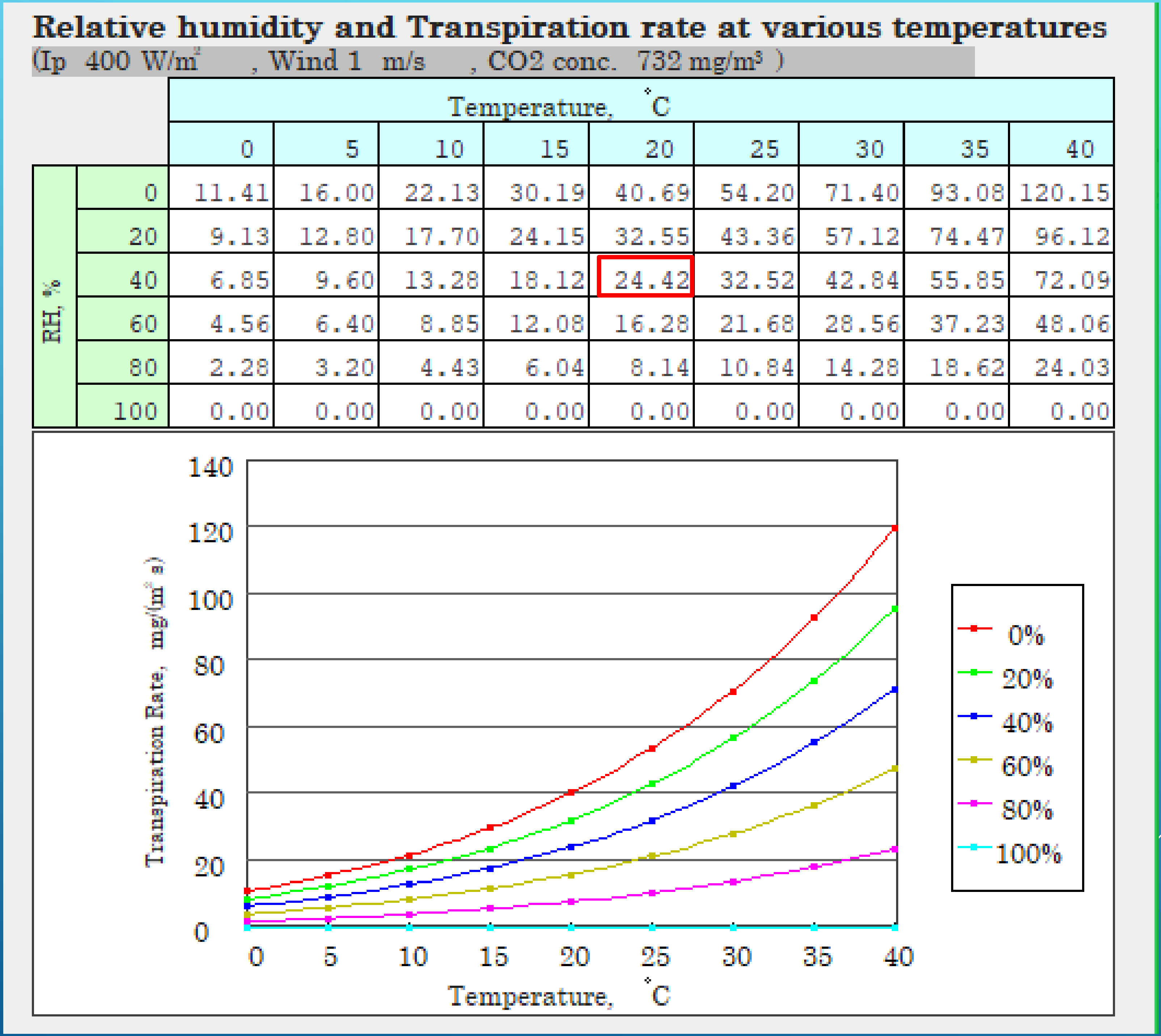
Relative humidity, %		Temperature,°C								
		0	5	10	15	20	25	30	35	40
	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	20	0.97	1.36	1.88	2.56	3.45	4.60	6.06	7.90	10.20
	40	1.94	2.72	3.76	5.13	6.91	9.20	12.12	15.81	20.40
	60	2.91	4.08	5.64	7.69	10.36	13.81	18.19	23.71	30.60
	80	3.87	5.43	7.51	10.25	13.82	18.41	24.25	31.61	40.80
	100	4.84	6.79	9.39	12.82	17.27	23.01	30.31	39.51	51.01



Simulation Input temperature and humidity, then transpiration rate is calculated. The value of the following environmental factors can be changed: photosynthetically active irradiance, wind velocity, CO2 concentration, the reaction type to irradiance by plants, and the reaction type to CO2 concentration by plants.

Plant Type (Light)	Std.	Temp.	20 °C	Ip	400 W/m²	Rav	100.0 s/m		
Plant Type (CO2)	Std.	W	1 m/s	CO2	400 ppm	Rlv	200.0 s/m		
		RH	40 %	CO2	732.1 mg/m³	Inc. of Rlv	124.5 s/m	Tr	24.42 mg/(m² s)

CO2 density at 20°C, d=M/RT = 44/(0.0821×(273.15+20)) = 1.83 kg/m^3



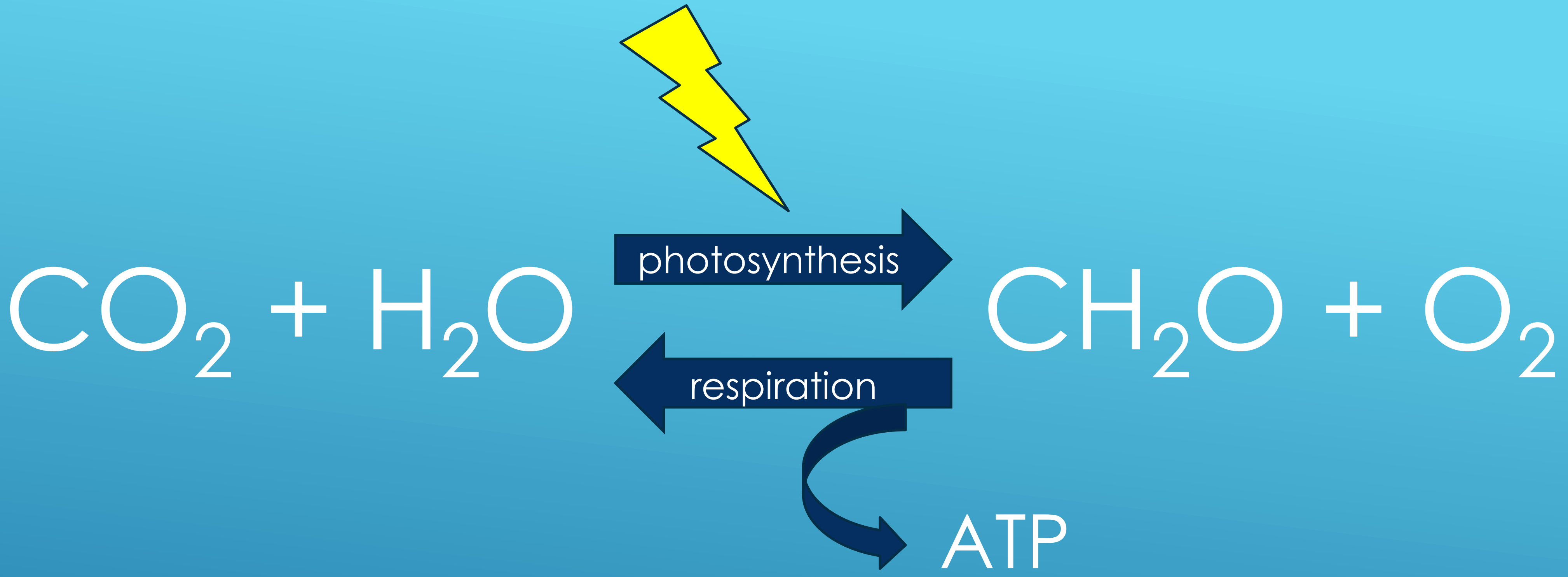
Relative humidity and Transpiration rate at various temperatures

(Ip 400 W/m^2 , Wind 1 m/s , CO2 conc. 732 mg/m^3)

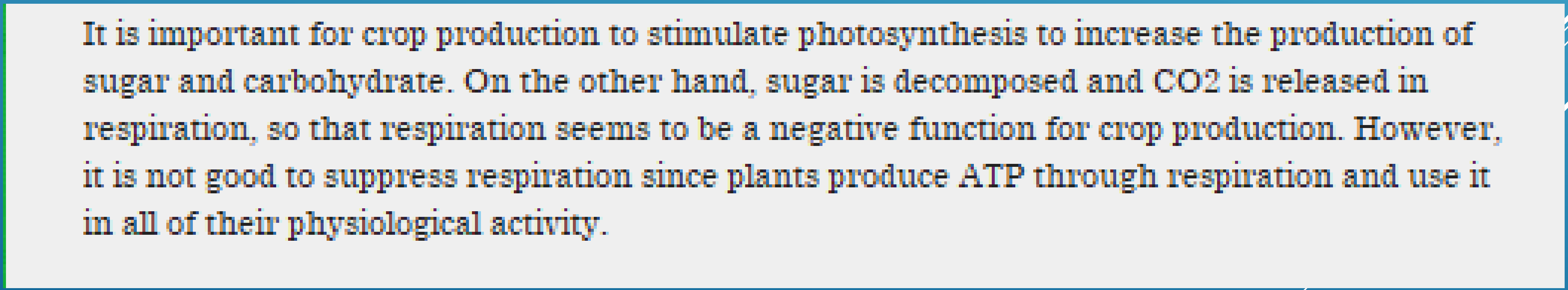
RH, %	Temperature, °C 0	5	10	15	20	25	30	35	40
0	11.41	16.00	22.13	30.19	40.69	54.20	71.40	93.08	120.15
20	9.13	12.80	17.70	24.15	32.55	43.36	57.12	74.47	96.12
40	6.85	9.60	13.28	18.12	24.42	32.52	42.84	55.85	72.09
60	4.56	6.40	8.85	12.08	16.28	21.68	28.56	37.23	48.06
80	2.28	3.20	4.43	6.04	8.14	10.84	14.28	18.62	24.03
100	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

CHAPTER 8

PHOTOSYNTHESIS AND RESPIRATION



$$CO_2 + H_2O \underset{\text{respiration}}{\overset{\text{photosynthesis}}{\rightleftharpoons}} CH_2O + O_2$$



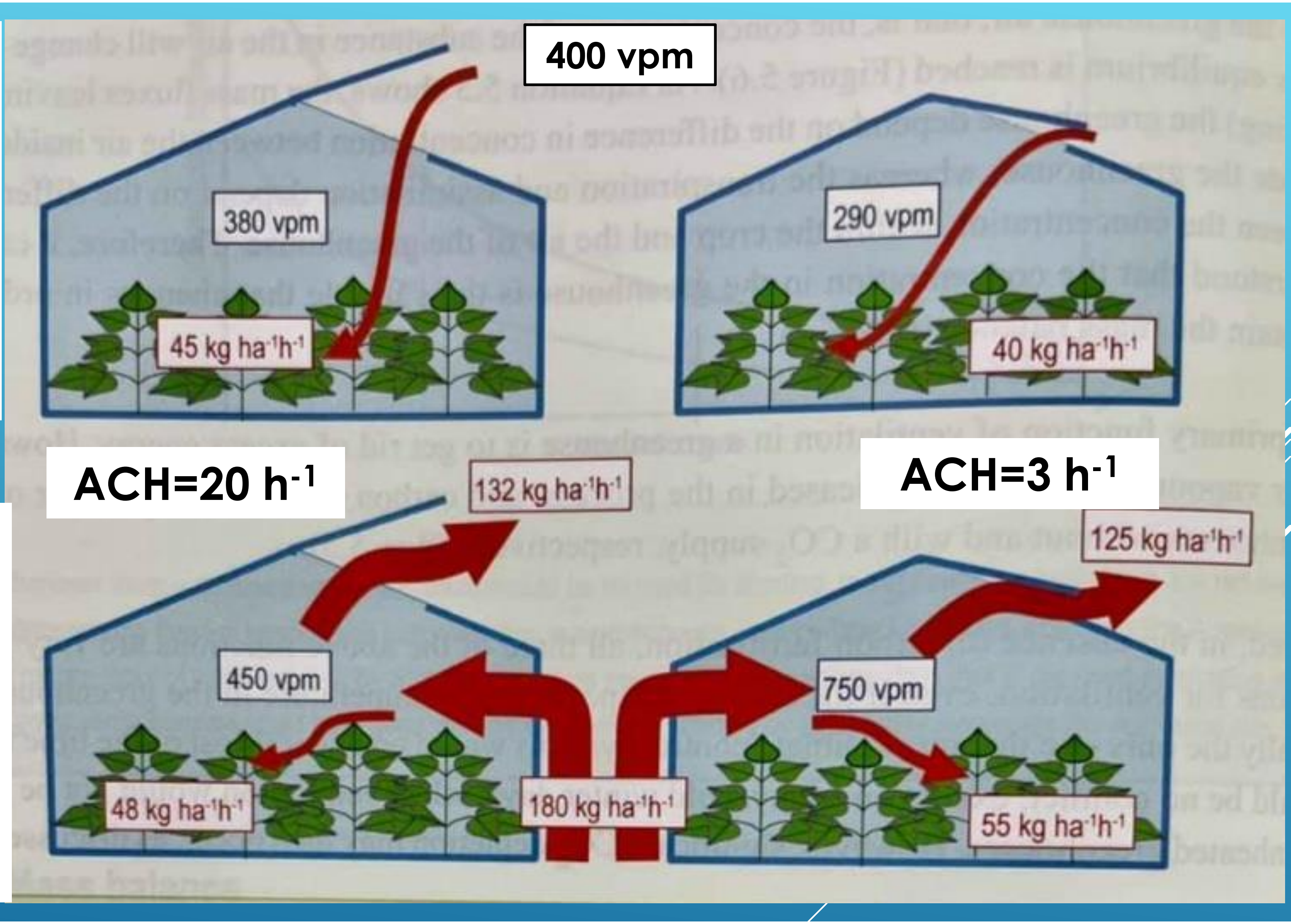
It is important for crop production to stimulate photosynthesis to increase the production of sugar and carbohydrate. On the other hand, sugar is decomposed and CO2 is released in respiration, so that respiration seems to be a negative function for crop production. However, it is not good to suppress respiration since plants produce ATP through respiration and use it in all of their physiological activity.

SUP

Crop Assimilation / Net Photosynthesis

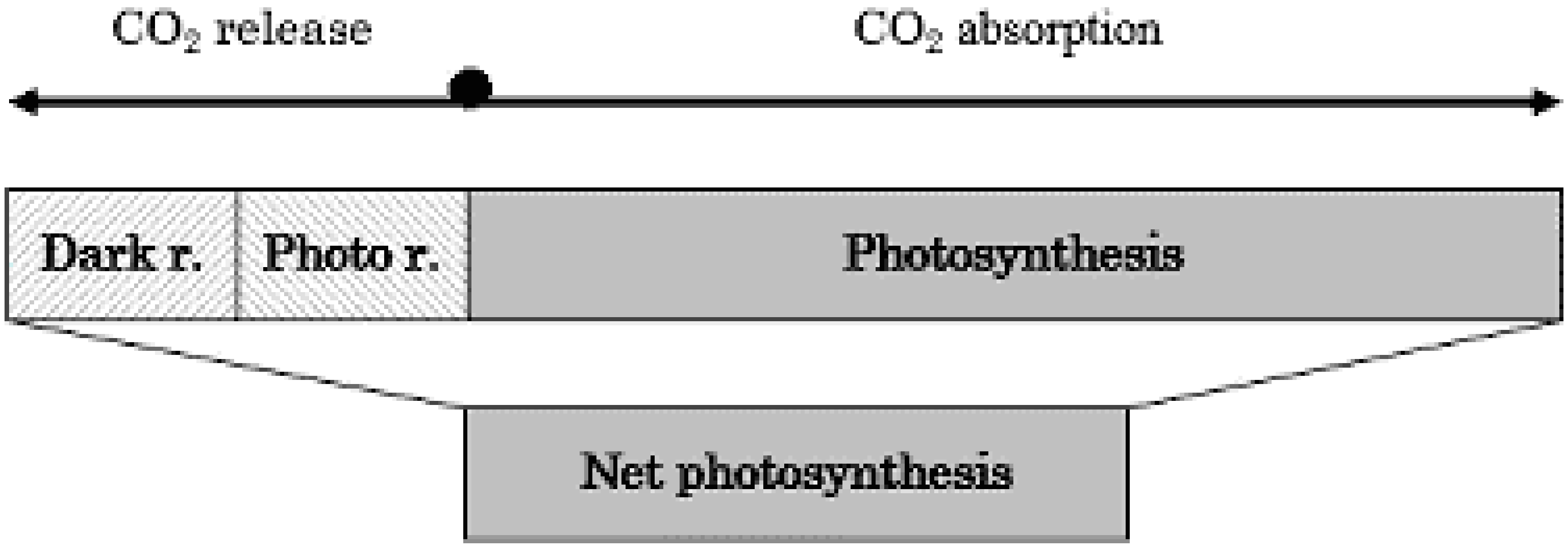
Without CO_2 enrichment
ACH=20 is better
Due to higher indoor CO_2 concentration and higher assimilation rate

with CO_2 enrichment
ACH=3 is better
Due to higher indoor CO_2 concentration and higher assimilation rate



Height of GH: 6 m, Max Assimilation rate: 72 kg $ha^{-1}h^{-1}$(2 mg $m^{-2}s^{-1}$)
Outdoor CO_2 concentration: 400 vpm

CO_2 absorption = Photosynthesis – (Photorespiration + Dark respiration)



Net photosynthesis is equal to the difference between CO2 release and CO2 absorption

Figure 8-1 Conceptual diagram to show CO2 balance in plants

Net photosynthesis rate = photosynthesis rate – (Photorespiration rate + Dark respiration rate)

SUP

Type	Dark respiration	Photorespiration	Photosynthesis
C3 plant	yes	yes	yes
C4 plant	yes	**No**	yes
CAM plant	yes	**No**	Yes
Dark period	yes	**No**	**No**
When in dark, Net photosynthesis rate = - Dark respiration rate			

Net photosynthesis rate = photosynthesis rate – (Photorespiration rate + Dark respiration rate)

Irradiance, in $J/(m^2.s) = W/m^2$

- Irradiance is light energy received by leaves per unit area per unit time.
- Only light within 400 ~ 700 nm is used for photosynthesis and is called **photosynthetically active radiation (PAR)**.
- PAR is only about half (0.46) of the total radiation in sunlight.

Influence of irradiance on net photosynthesis

- When in dark (x=0 @ Fig.8-2), net Pn (Y value) < 0
- Light compensation point: net Pn = 0
- In between: net Pn > 0, slope > 0
- Light saturation point: net Pn > 0 and slope = 0

- The light compensation/saturation point vary with plants.

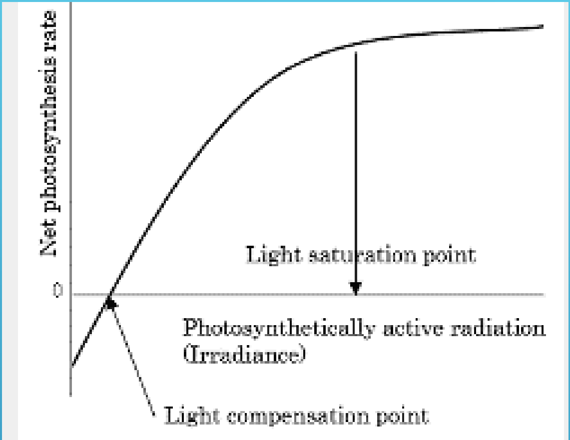


Figure 8-2 Light - Net photosynthesis curve

	Light compensation point
Foliage plants which can be grown indoor	**Low**
Many crop plant	High
Vegetables such as lettuce, spinach	**Low**
Vine crops such as Tomatoes, cucumbers	High

Plants with **low compensation point** are **more suitable** for PFALs

Other environmental factors also have influence on photosynthesis.

Influence of CO$_2$ on net photosynthesis

- In general, net Pn increases when CO2 concentration increases in the range of 0 ~ 2000 ppm (0 to 3.92 g/m^3)
- Fig. 8-3 is similar to Fig.8-2.
- No CO2, net Pn < 0
- CO2 compensation point: net Pn = 0
    - In between: net Pn > 0, slope > 0
- CO2 saturation point: net Pn > 0 and slope = 0
- The light compensation/saturation point vary with plants.

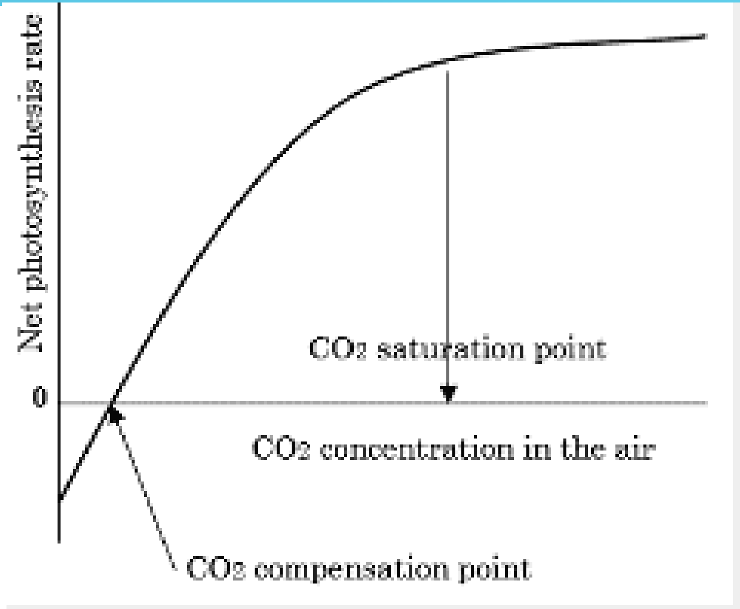


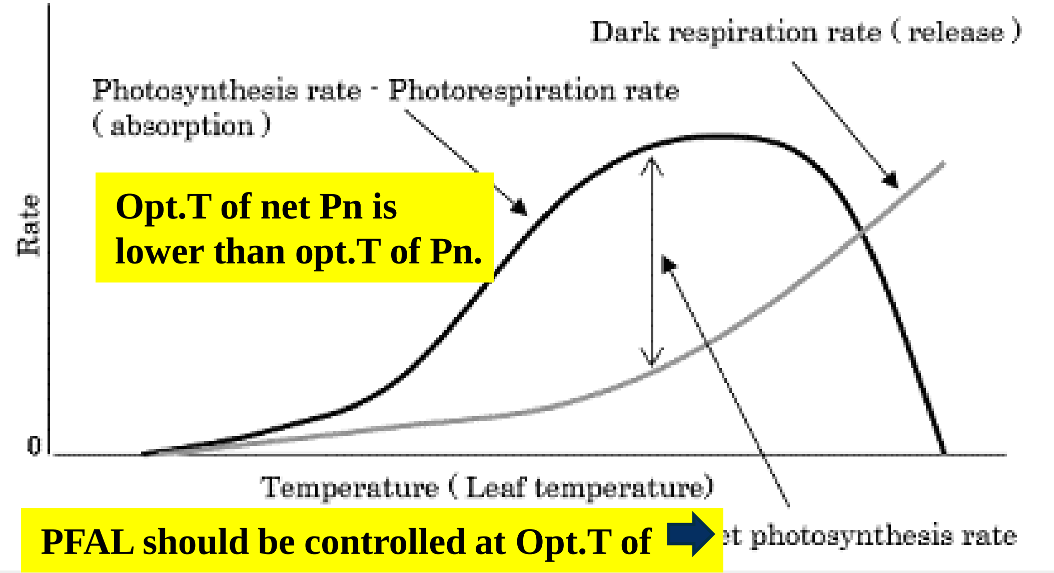
Figure 8-3 CO2 - Net photosynthesis curve

- C3 plants perform photorespiration and release CO2 when CO2 concentration is low.
- C4 plants do not perform photorespiration and do not release CO2 except when dark respiration takes place.
- The photorespiration of C3 plants is suppressed (decreased) under high CO2 concentration. This is the reason why the Pn of C3 plants increases when CO2 is high.

- CO_2 concentration in the atmosphere is about 380 ppm.
- The technique to artificially increase CO_2 concentration in a closed environment (greenhouse, plant factory, etc.) is called CO_2 enrichment.
- In PFAL, CO_2 is not supply from the outside air, thus, CO_2 enrichment is required. The environment need to be air-tight (ACH=0) or with very low (< 0.02 h^{-1}) air change per hour (ACH) to save CO_2 resource.

Influence of Temperature on net photosynthesis

- Photosynthesis is a biochemical reaction involved with many enzymes. Enzymes are highly influenced by temperature.
- Fig.8-4 shows response of photosynthesis to temperature (T).
- T increases, Pn increases due to elevation of enzyme activity.
- Pn starts to decrease sharply at a certain T due to enzymes are deactivated by high T. If T rises more, Pn will cease.
- Optimum T of Pn varies with plants and other environmental factors.
- When dark respiration rate > Net Pn, if condition continue, plants will die.
- In general, optimum T of corn, rice, melons, tomatoes, parprika and sunflowers is high, and that of lettuce, radish and spinach is low.



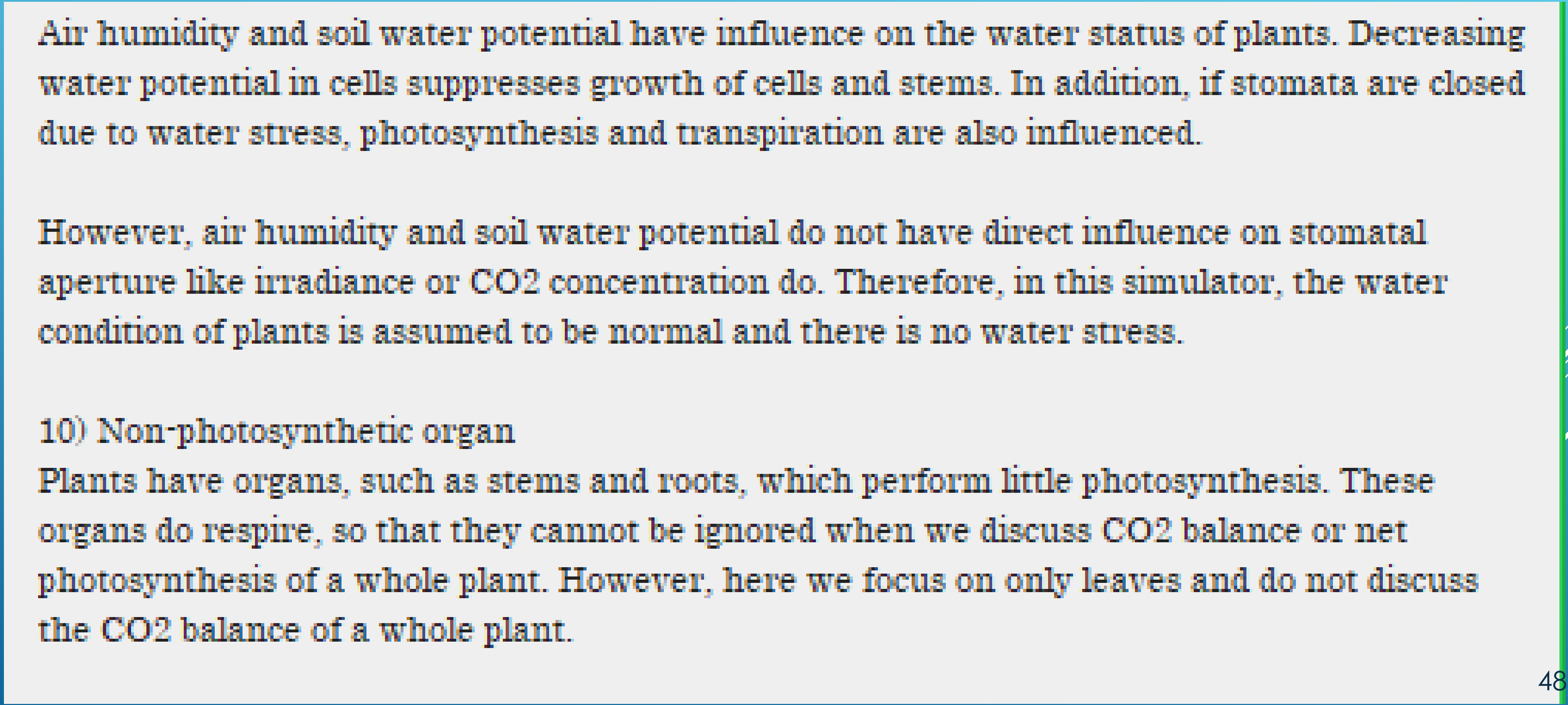
Opt.T of net Pn is lower than opt.T of Pn.

PFAL should be controlled at Opt.T of ➡

Figure 8-4 The influence of temperature on photosynthesis and respiration (Conceptual diagram)

- Influence of temperature on net photosynthesis rate is quite different from dark respiration rate.
- Dark respiration rate increase by almost double as T rises 10 ^{o}C.
- The dark respiration rate increases exponentially as T rises.
- The dark respiration rate consists of growth and maintenance respiration.

Air humidity and soil water



Air humidity and soil water potential have influence on the water status of plants. Decreasing water potential in cells suppresses growth of cells and stems. In addition, if stomata are closed due to water stress, photosynthesis and transpiration are also influenced.

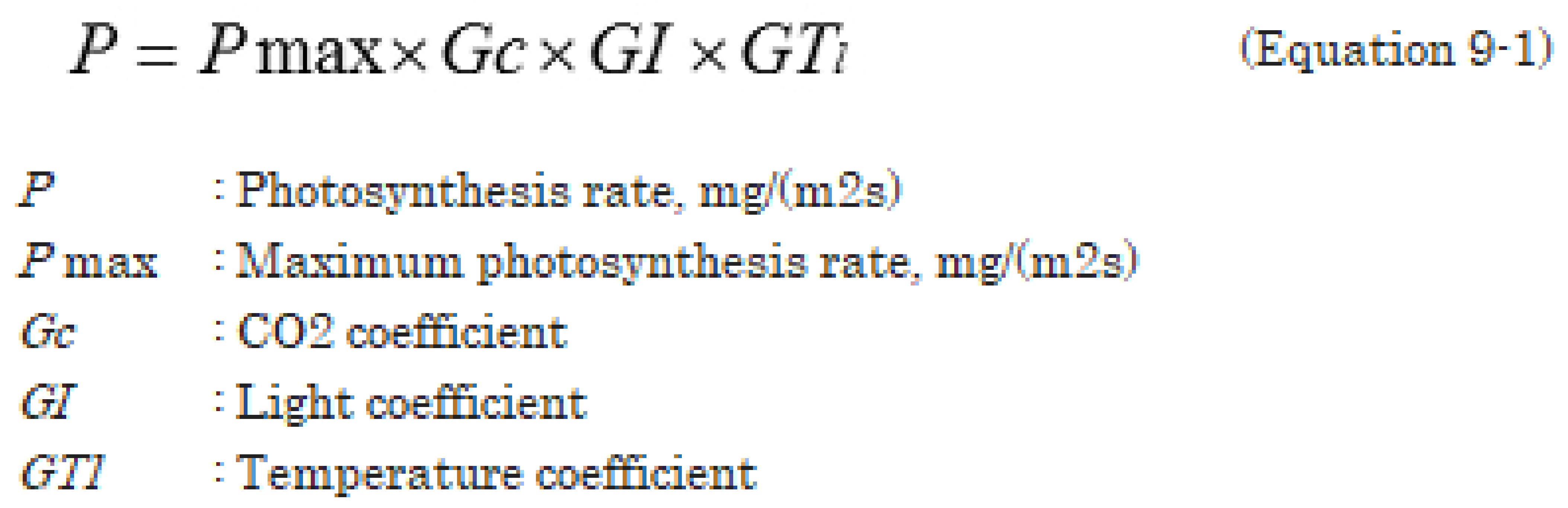
However, air humidity and soil water potential do not have direct influence on stomatal aperture like irradiance or CO2 concentration do. Therefore, in this simulator, the water condition of plants is assumed to be normal and there is no water stress.

10) Non-photosynthetic organ

Plants have organs, such as stems and roots, which perform little photosynthesis. These organs do respire, so that they cannot be ignored when we discuss CO2 balance or net photosynthesis of a whole plant. However, here we focus on only leaves and do not discuss the CO2 balance of a whole plant.

CHAPTER 9
LIGHT COEFFICIENT OF PHOTOSYNTHESIS

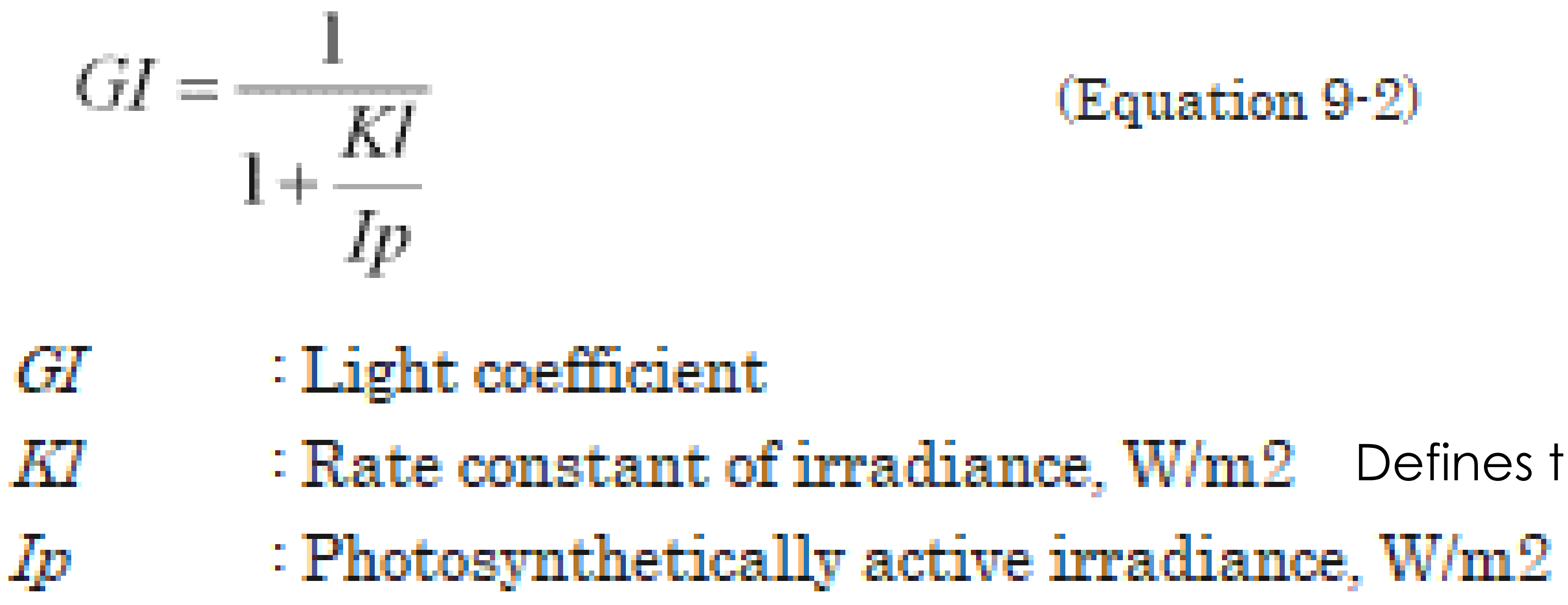
Photosynthesis is a biochemical reaction. Light energy and CO_2 are considered substance and temperature has influence on reaction rate. These three are factors (value from 0 to 1) limiting the photosynthesis reaches its maximum as shown in eq.9-1.



$$P = P\max \times Gc \times GI \times GT_i \qquad \text{(Equation 9-1)}$$

P : Photosynthesis rate, mg/(m2s)
$P\max$: Maximum photosynthesis rate, mg/(m2s)
Gc : CO2 coefficient
GI : Light coefficient
GTI : Temperature coefficient

Light coefficient, *GI*



$$GI = \frac{1}{1 + \frac{KI}{Ip}} \qquad \text{(Equation 9-2)}$$

GI : Light coefficient

KI : Rate constant of irradiance, W/m2

Defines the slope of the curve

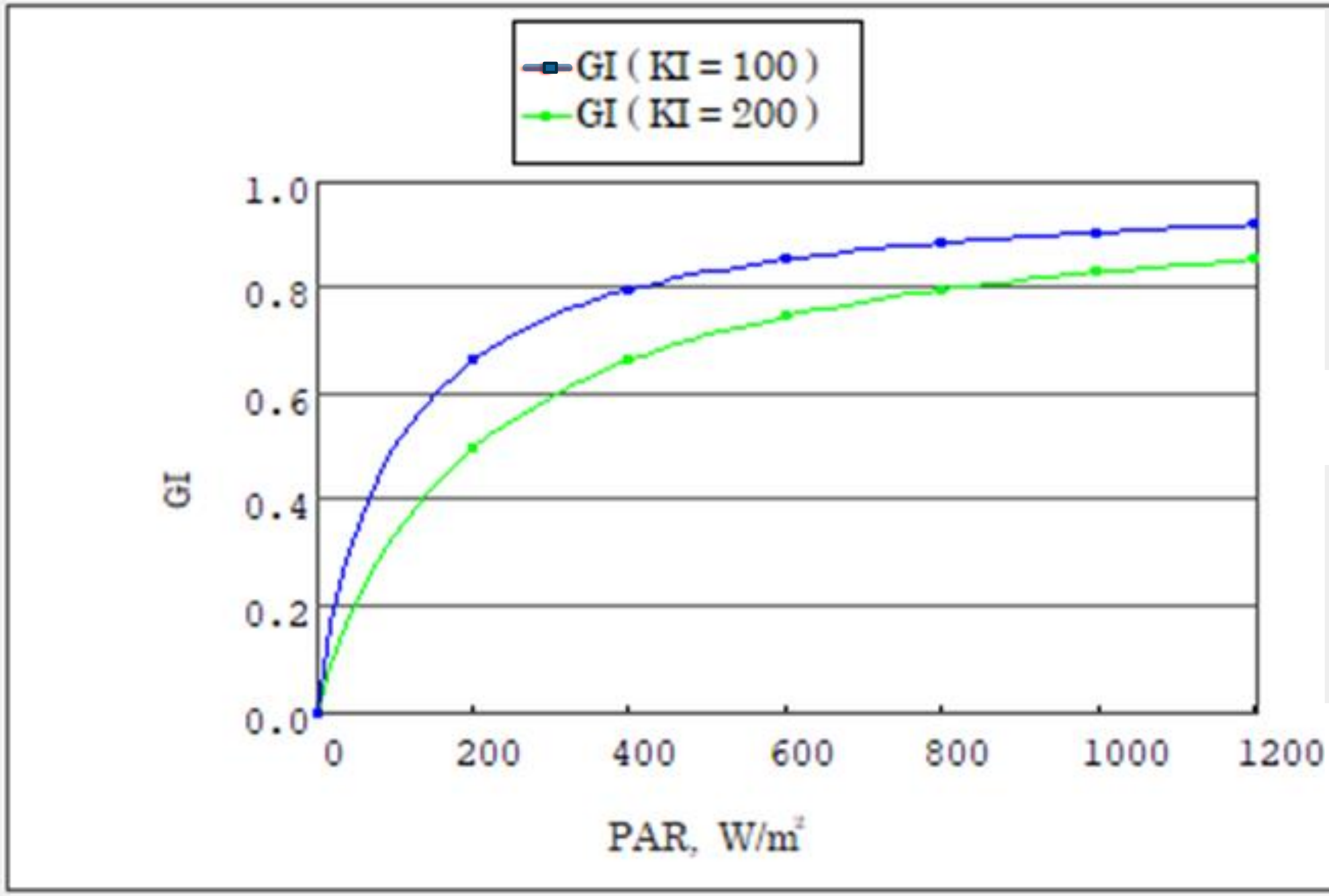
Ip : Photosynthetically active irradiance, W/m2

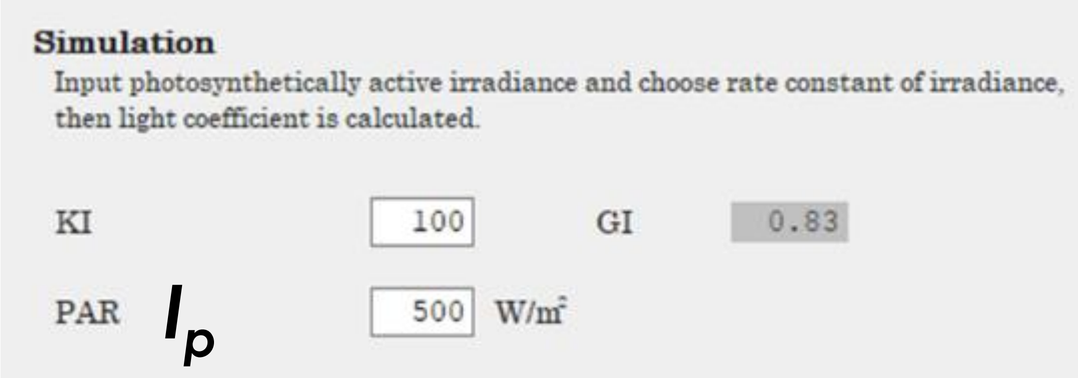
When irradiance is very strong, I_p is big, GI is 1

When I_p equals KI, GI is 0.5
Small KI steeper slope

Photosynthetically active radiation and Light coefficient

PAR	0	100	200	300	400	500	600	700	800	900	1000	1100	1200
GI (KI = 100)	0.00	0.50	0.67	0.75	0.80	0.83	0.86	0.88	0.89	0.90	0.91	0.92	0.92
GI (KI = 200)	0.00	0.33	0.50	0.60	0.67	0.71	0.75	0.78	0.80	0.82	0.83	0.85	0.86





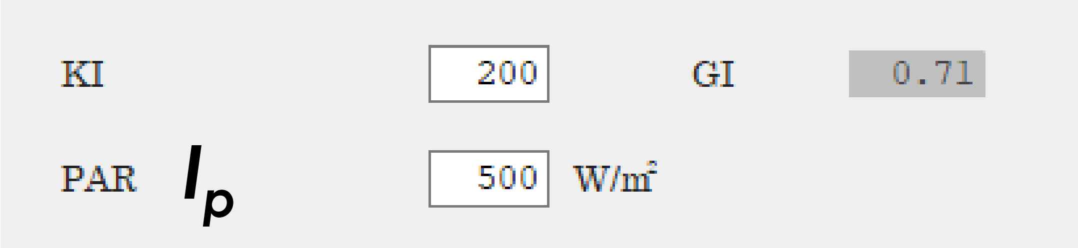
Simulation

Input photosynthetically active irradiance and choose rate constant of irradiance, then light coefficient is calculated.

KI 100 GI 0.83

PAR I_p 500 W/m²

GI = 1/(1+100/500)=1/1.2= 0.83



KI 200 GI 0.71

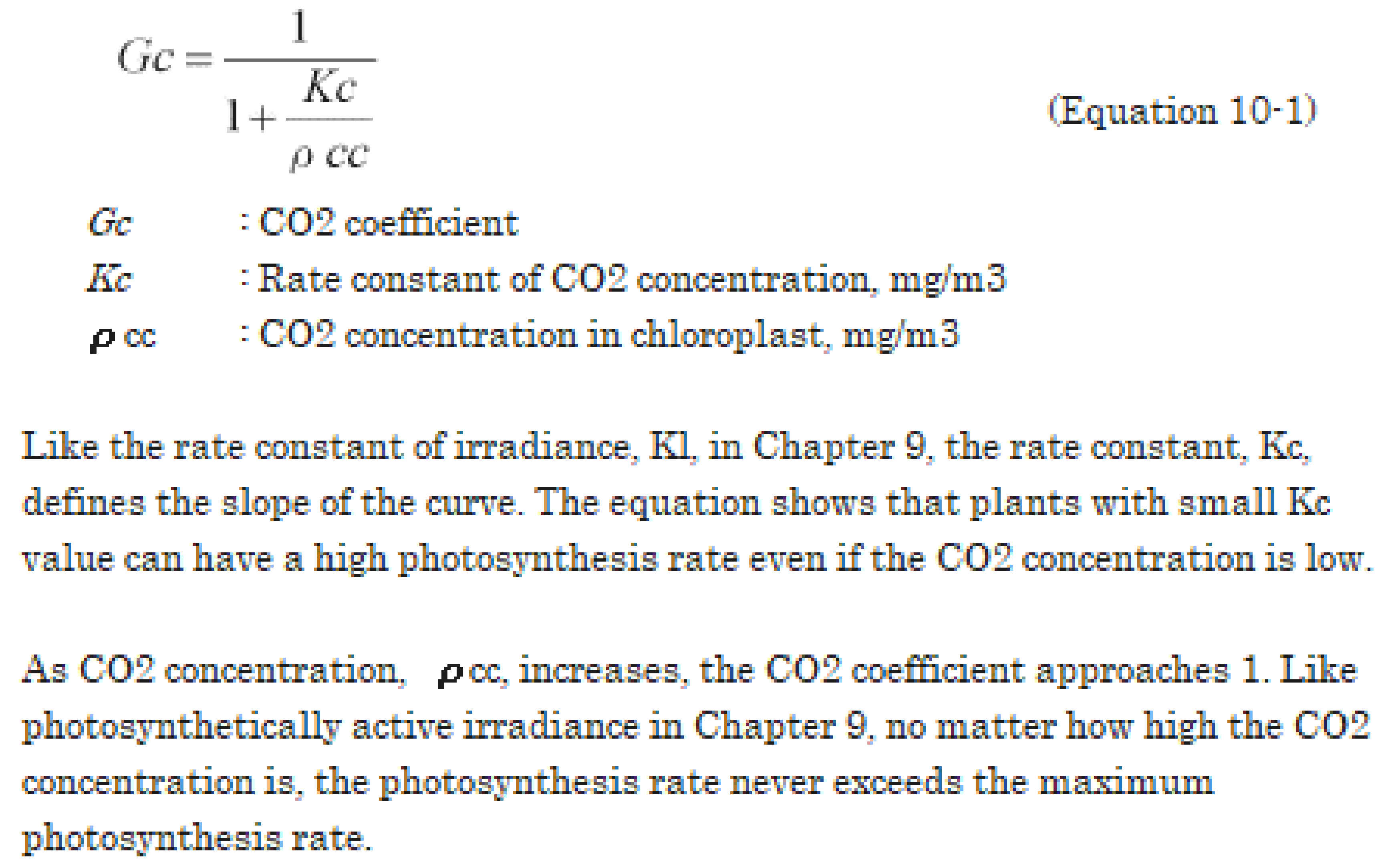
PAR I_p 500 W/m²

GI = 1/(1+200/500)=1/1.4 = 0.71

CHAPTER 10

CO_2 COEFFICIENT OF PHOTOSYNTHESIS

CO_2 coefficient, *Gc*



$$Gc = \frac{1}{1 + \frac{Kc}{\rho\, cc}} \qquad \text{(Equation 10-1)}$$

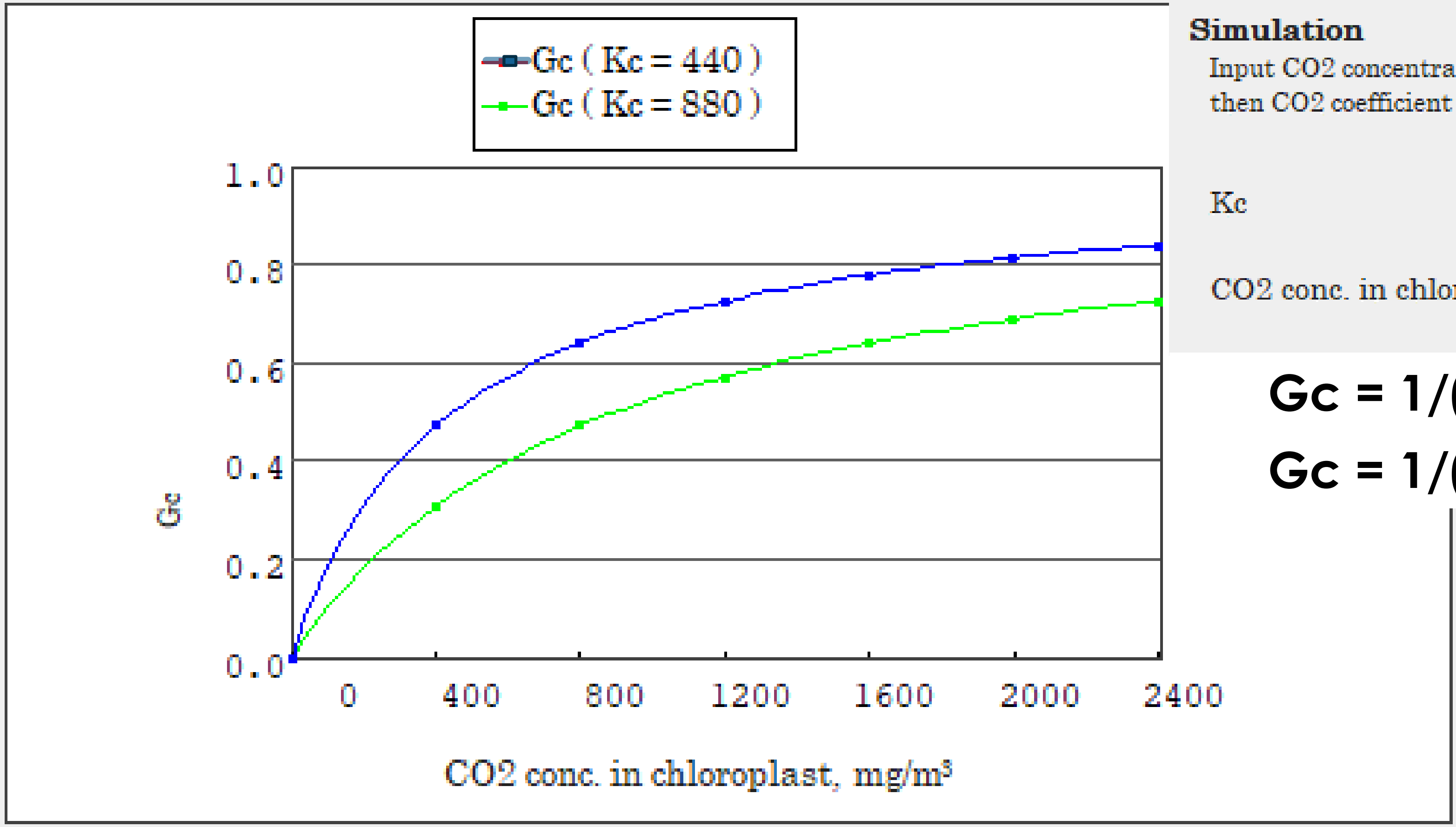
Gc : CO2 coefficient
Kc : Rate constant of CO2 concentration, mg/m3
ρ cc : CO2 concentration in chloroplast, mg/m3

Like the rate constant of irradiance, KI, in Chapter 9, the rate constant, Kc, defines the slope of the curve. The equation shows that plants with small Kc value can have a high photosynthesis rate even if the CO2 concentration is low.

As CO2 concentration, ρcc, increases, the CO2 coefficient approaches 1. Like photosynthetically active irradiance in Chapter 9, no matter how high the CO2 concentration is, the photosynthesis rate never exceeds the maximum photosynthesis rate.

CO2 concentration in chloroplast and CO2 coefficient

CO2 conc. in chloropls	0	200	400	600	800	1000	1200	1400	1600	1800	2000	2200	2400
Gc, Small	0.00	0.31	0.48	0.58	0.65	0.69	0.73	0.76	0.78	0.80	0.82	0.83	0.85
Gc, Large	0.00	0.19	0.31	0.41	0.48	0.53	0.58	0.61	0.65	0.67	0.69	0.71	0.73



Simulation

Input CO2 concentration in chloroplast and rate constant of CO2 concentration, then CO2 coefficient is calculated.

Kc 440 mg/m³ Gc 0.7

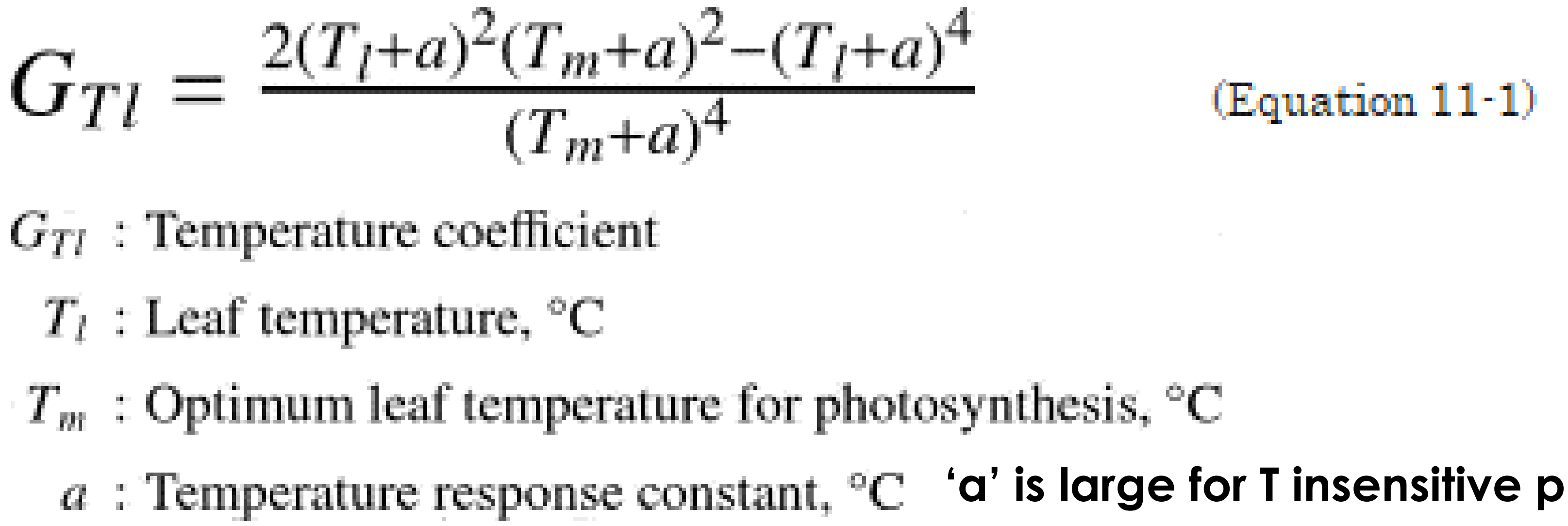
CO2 conc. in chloroplas 500 ppm 980.0 mg/m³

Gc = 1/(1+440/980)=1/1.4489 = 0.70

Gc = 1/(1+880/980)=1/1.4489 = 0.53

CHAPTER 11
TEMPERATURE COEFFICIENT OF PHOTOSYNTHESIS

Temperature coefficient, G_{Tl}



$$G_{Tl} = \frac{2(T_l+a)^2(T_m+a)^2-(T_l+a)^4}{(T_m+a)^4} \qquad \text{(Equation 11-1)}$$

G_{Tl} : Temperature coefficient

T_l : Leaf temperature, °C

T_m : Optimum leaf temperature for photosynthesis, °C

a : Temperature response constant, °C

‘a’ is large for T insensitive plants

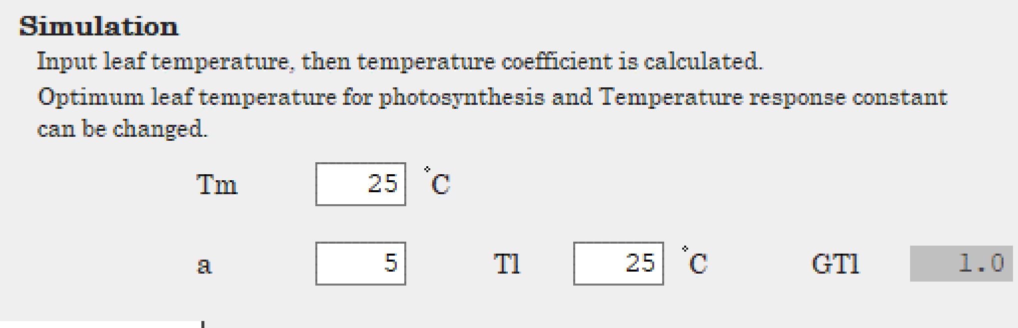
- **When T*l* equals T*m*, G_{Tl} equals 1**
- **When T*l* decreases from T*m*, G_{Tl} decreases to 0**
- **When T*l* increases more than T*m*, enzyme activities suddenly decrease and the slope of the curves descends sharply.**

Leaf temperature and Temperature coefficient

Leaf temp.	0	5	10	15	20	25	30	35	40
GTl (Plant A)	0.05	0.21	0.44	0.69	0.91	1.00	0.87	0.40	0.00
GTl (Plant B)	0.16	0.33	0.55	0.76	0.93	1.00	0.91	0.57	0.00

Given Tm=25, Tl=10,
a=5 (plant A)

$G_{Tl} = [2*(10+5)^2*(25+5)^2 - (10+5)^4] / (25+5)^4 = 0.4375$



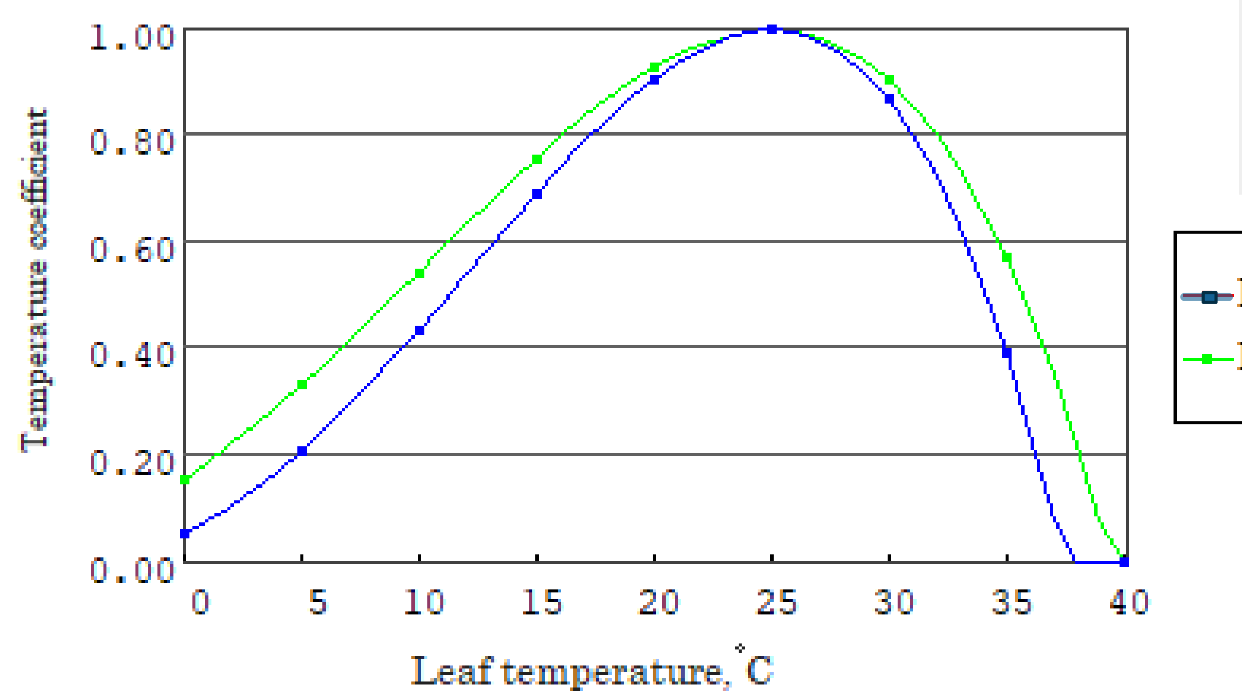
Simulation

Input leaf temperature, then temperature coefficient is calculated.

Optimum leaf temperature for photosynthesis and Temperature response constant can be changed.

Tm 25 °C

a 5 Tl 25 °C GTl 1.0



Given Tm=25, Tl=10,
a=10 (plant B)

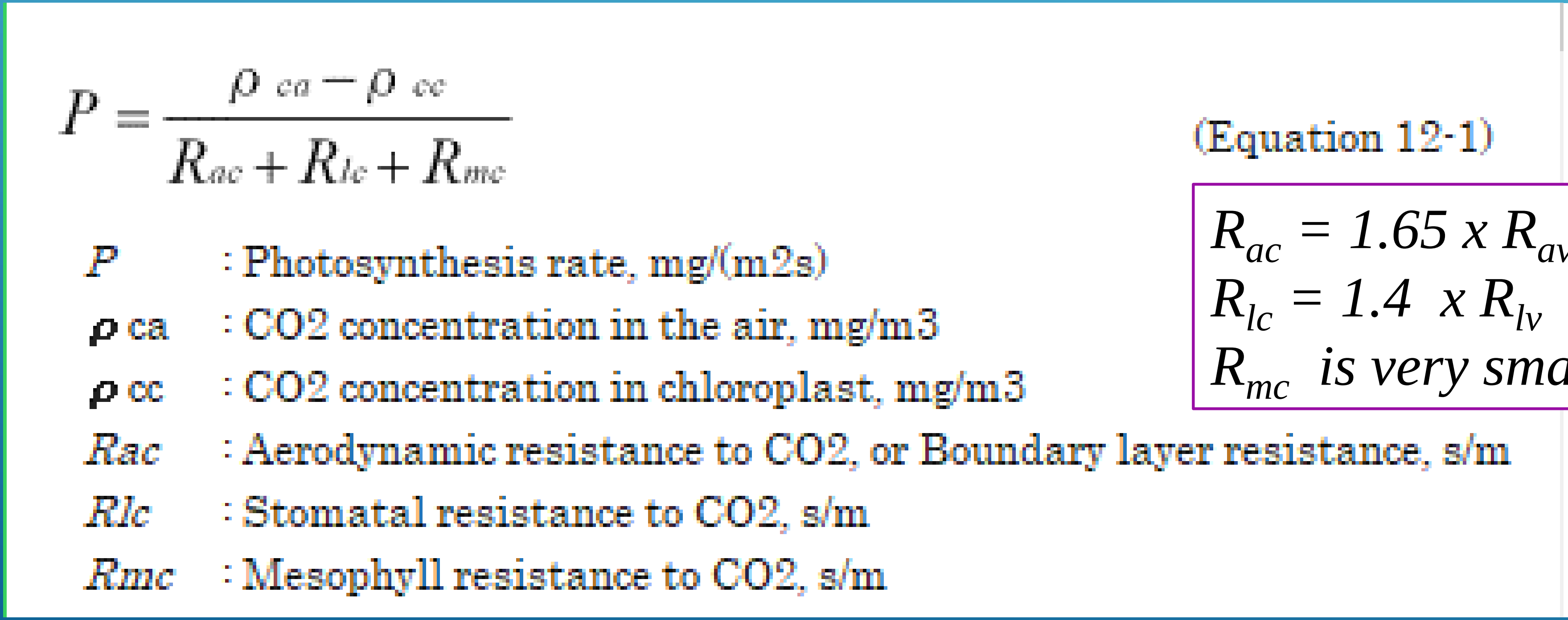
$G_{Tl} = [2*(10+10)^2*(25+10)^2 - (10+10)^4] / (25+10)^4 = 0.5464$

CHAPTER 12
PHOTOSYNTHESIS RATE

Photosynthetic rate can be calculated using eq. 12-1. It is the driving force divided by the resistance to diffusion.

The driving force is CO_2 difference between outside and inside of a leaf.

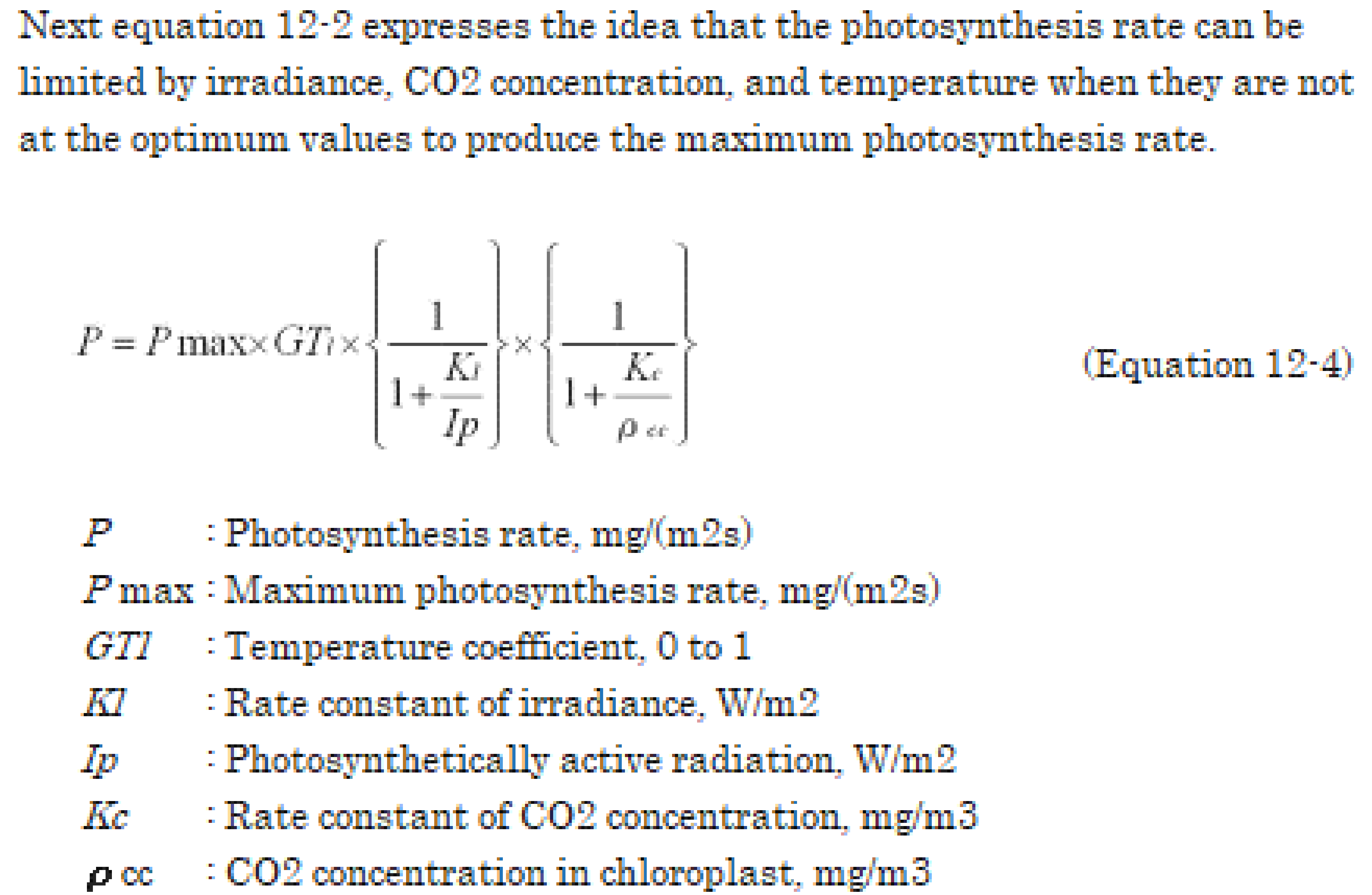
The resistance to diffusion is the sum of aerodynamic resistance, stomatal resistance and mesophyll resistance to CO_2.



$$P = \frac{\rho_{ca} - \rho_{cc}}{R_{ac} + R_{lc} + R_{mc}} \quad \text{(Equation 12-1)}$$

P : Photosynthesis rate, mg/(m2s)
ρ ca : CO2 concentration in the air, mg/m3
ρ cc : CO2 concentration in chloroplast, mg/m3
Rac : Aerodynamic resistance to CO2, or Boundary layer resistance, s/m
Rlc : Stomatal resistance to CO2, s/m
Rmc : Mesophyll resistance to CO2, s/m

$R_{ac} = 1.65 \times R_{av}$
$R_{lc} = 1.4 \times R_{lv}$
R_{mc} is very small, close to 0



Next equation 12-2 expresses the idea that the photosynthesis rate can be limited by irradiance, CO2 concentration, and temperature when they are not at the optimum values to produce the maximum photosynthesis rate.

$$P = P\max \times GT_I \times \left\{ \frac{1}{1 + \frac{K_I}{Ip}} \right\} \times \left\{ \frac{1}{1 + \frac{K_c}{\rho_{cc}}} \right\} \qquad \text{(Equation 12-4)}$$

P : Photosynthesis rate, mg/(m2s)
$P\max$: Maximum photosynthesis rate, mg/(m2s)
GTI : Temperature coefficient, 0 to 1
KI : Rate constant of irradiance, W/m2
Ip : Photosynthetically active radiation, W/m2
Kc : Rate constant of CO2 concentration, mg/m3
ρ_{cc} : CO2 concentration in chloroplast, mg/m3

$P = (\rho_{ca} - \boldsymbol{\rho_{cc}})/Rc$ ……………... from eq.12-1

Define $P_m = P_{max} * G_{Tl} * G_I$, require Value of P_{max}

$P = Pm * \boldsymbol{\rho_{cc}} / (\boldsymbol{\rho_{cc}} + Kc)$ ….. from eq.12-4

ρ_{cc} unknown and can be cancelled by substituting eq.12-1 into eq.12-4

$P = Pm * (\rho_{ca} - P * Rc)/(\rho_{ca} - P * Rc + Kc)$

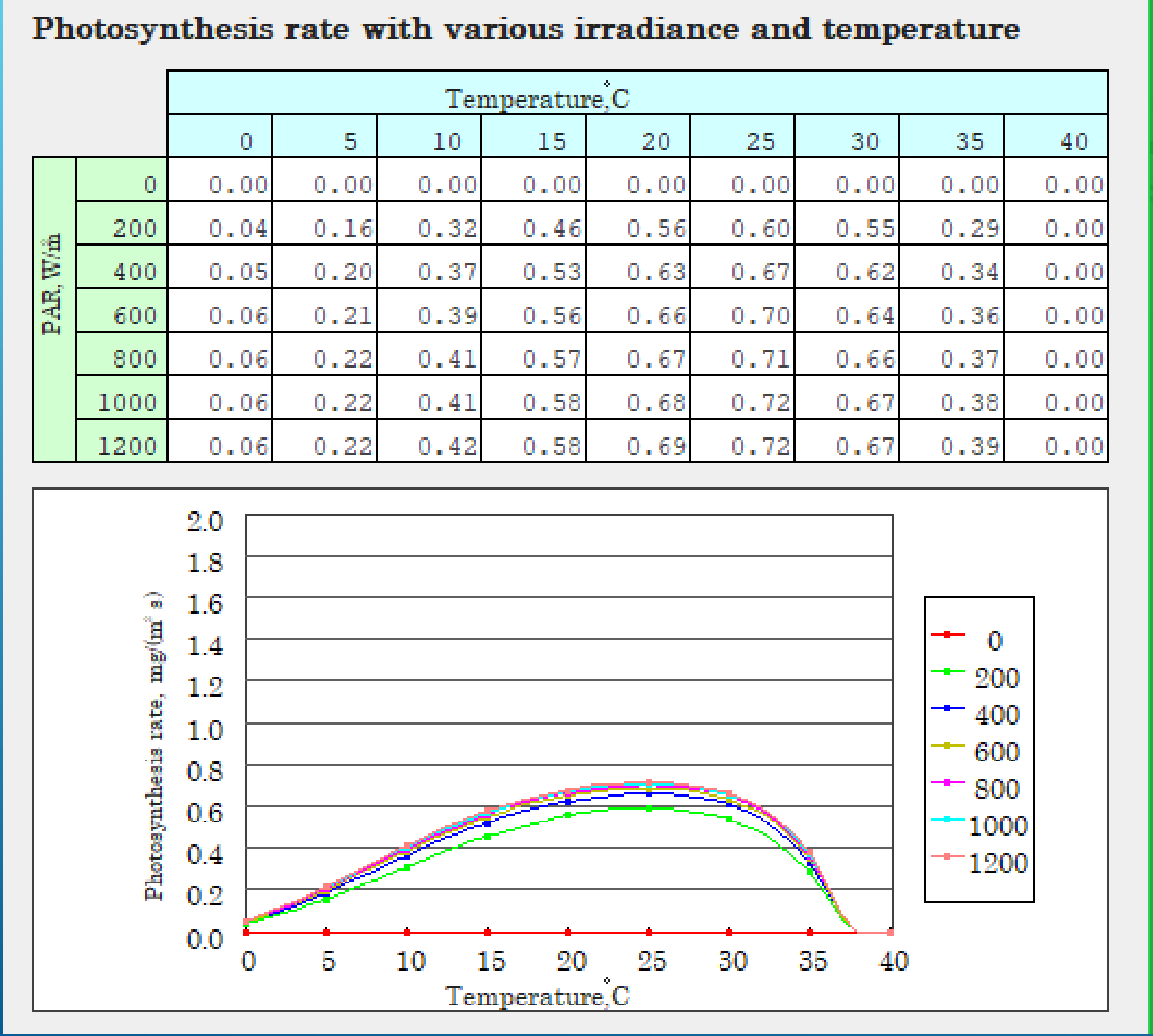
a 2nd order polynomial equation of P is formed, thus P can be derived.

$P * \rho_{ca} - P^2 * Rc + P * Kc = Pm * \rho_{ca} - P * Rc * Pm$

$Rc * P^2 - (\rho_{ca} + Kc + Rc * Pm) * P + Pm * \rho_{ca} = 0$

$$P = \frac{(\rho_{ca} + K_c + R_c P_m) - \sqrt{(\rho_{ca} + K_c + R_c P_m)^2 - 4\rho_{ca} R_c P_m}}{2R_c}$$

(Equation 12-5)

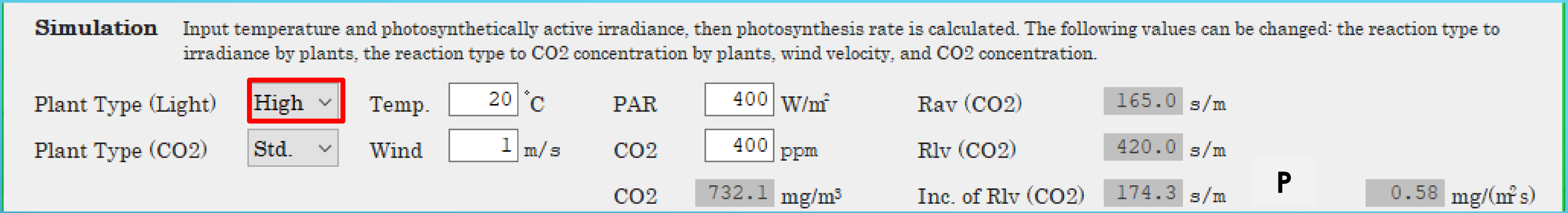


Photosynthesis rate with various irradiance and temperature

		Temperature,°C								
		0	5	10	15	20	25	30	35	40
PAR, W/m²	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	200	0.04	0.16	0.32	0.46	0.56	0.60	0.55	0.29	0.00
	400	0.05	0.20	0.37	0.53	0.63	0.67	0.62	0.34	0.00
	600	0.06	0.21	0.39	0.56	0.66	0.70	0.64	0.36	0.00
	800	0.06	0.22	0.41	0.57	0.67	0.71	0.66	0.37	0.00
	1000	0.06	0.22	0.41	0.58	0.68	0.72	0.67	0.38	0.00
	1200	0.06	0.22	0.42	0.58	0.69	0.72	0.67	0.39	0.00

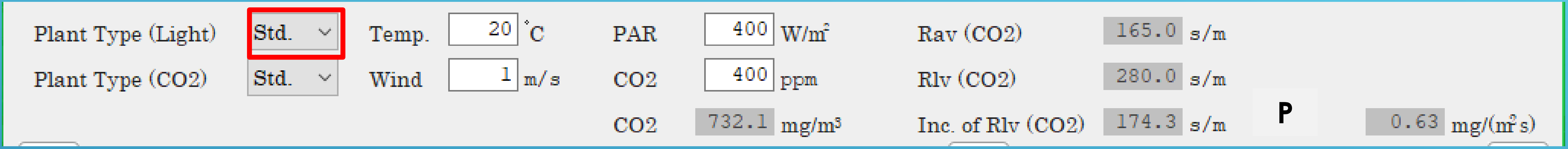
Plant type (Light): std
Plant type (CO_2): std
CO_2: 400 ppm
Kl = 200
Kc = 440
Rc not constant

PAR	Pn@Tl=10	Pn@Tl=20
200	0.287	0.52
400	0.366	0.63
600	0.403	0.67
800	0.424	0.694
1000	0.438	0.709
1200	0.448	0.72

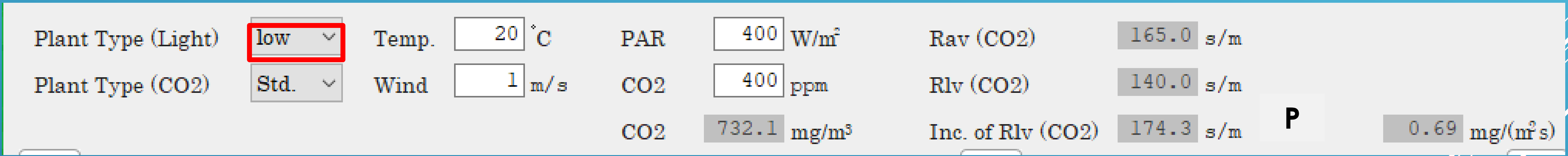


Simulation Input temperature and photosynthetically active irradiance, then photosynthesis rate is calculated. The following values can be changed: the reaction type to irradiance by plants, the reaction type to CO2 concentration by plants, wind velocity, and CO2 concentration.

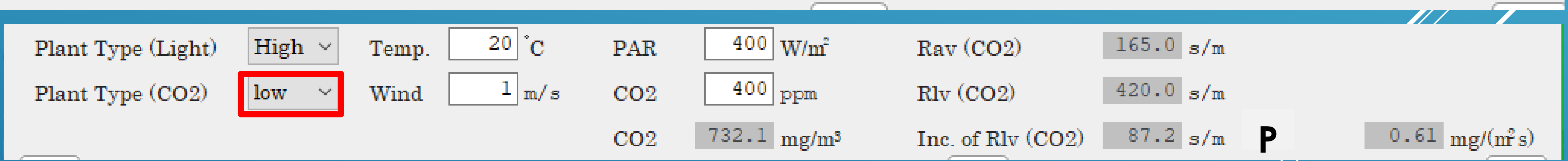
Plant Type (Light)	High	Temp.	20 °C	PAR	400 W/m^2	Rav (CO2)	165.0 s/m		
Plant Type (CO2)	Std.	Wind	1 m/s	CO2	400 ppm	Rlv (CO2)	420.0 s/m		
				CO2	732.1 mg/m^3	Inc. of Rlv (CO2)	174.3 s/m	P	0.58 mg/(m^2 s)



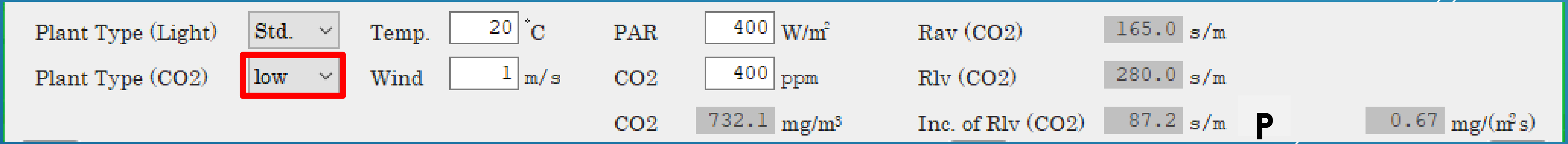
Plant Type (Light)	Std.	Temp.	20 °C	PAR	400 W/m^2	Rav (CO2)	165.0 s/m		
Plant Type (CO2)	Std.	Wind	1 m/s	CO2	400 ppm	Rlv (CO2)	280.0 s/m		
				CO2	732.1 mg/m^3	Inc. of Rlv (CO2)	174.3 s/m	P	0.63 mg/(m^2 s)



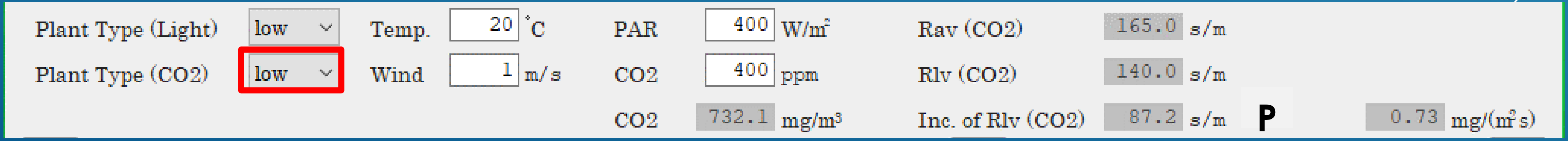
Plant Type (Light)	low	Temp.	20 °C	PAR	400 W/m^2	Rav (CO2)	165.0 s/m		
Plant Type (CO2)	Std.	Wind	1 m/s	CO2	400 ppm	Rlv (CO2)	140.0 s/m		
				CO2	732.1 mg/m^3	Inc. of Rlv (CO2)	174.3 s/m	P	0.69 mg/(m^2 s)



Plant Type (Light)	High	Temp.	20 °C	PAR	400 W/m^2	Rav (CO2)	165.0 s/m		
Plant Type (CO2)	low	Wind	1 m/s	CO2	400 ppm	Rlv (CO2)	420.0 s/m		
				CO2	732.1 mg/m^3	Inc. of Rlv (CO2)	87.2 s/m	P	0.61 mg/(m^2 s)



Plant Type (Light)	Std.	Temp.	20 °C	PAR	400 W/m^2	Rav (CO2)	165.0 s/m		
Plant Type (CO2)	low	Wind	1 m/s	CO2	400 ppm	Rlv (CO2)	280.0 s/m		
				CO2	732.1 mg/m^3	Inc. of Rlv (CO2)	87.2 s/m	P	0.67 mg/(m^2 s)



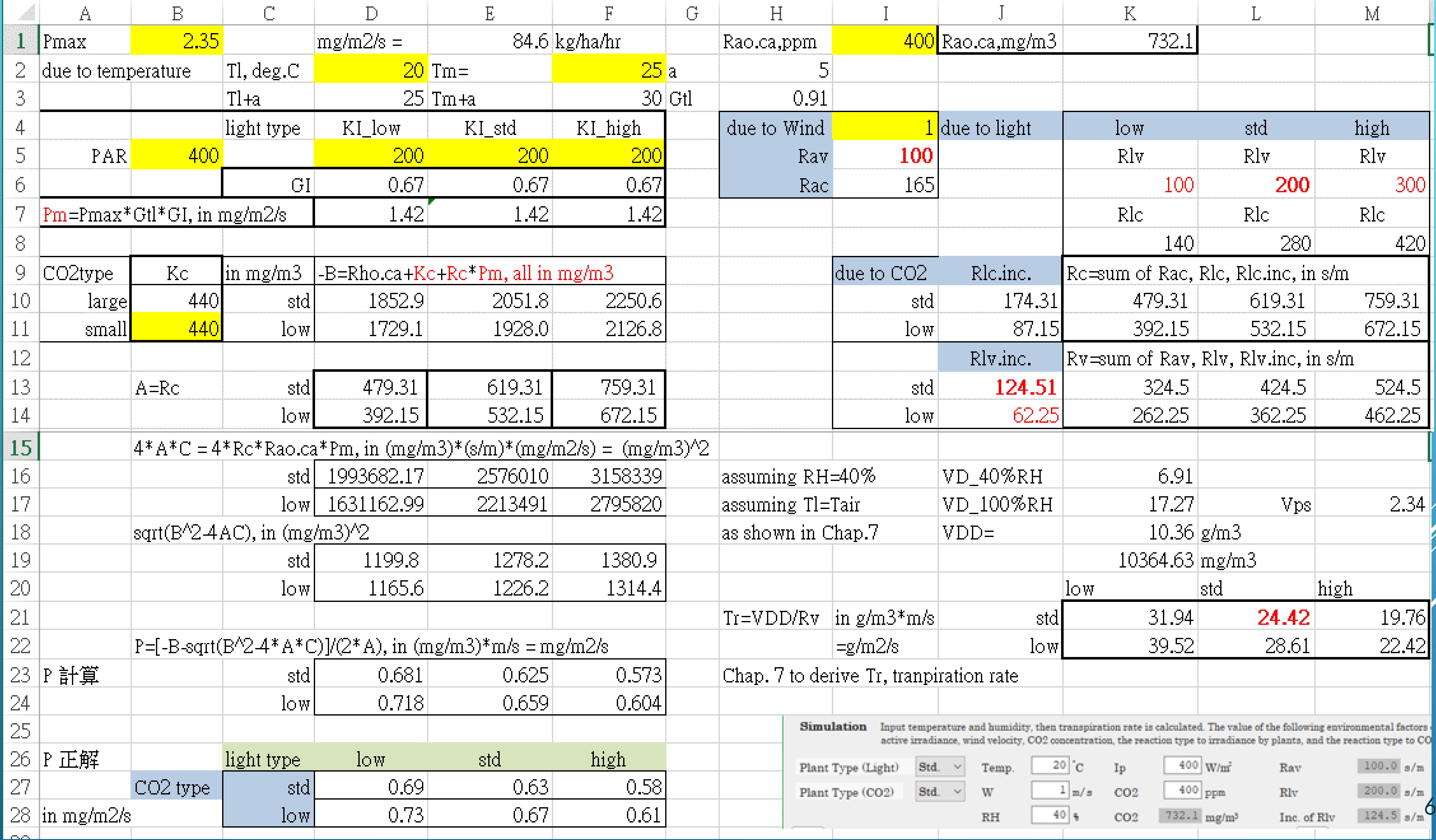
Plant Type (Light)	low	Temp.	20 °C	PAR	400 W/m^2	Rav (CO2)	165.0 s/m		
Plant Type (CO2)	low	Wind	1 m/s	CO2	400 ppm	Rlv (CO2)	140.0 s/m		
				CO2	732.1 mg/m^3	Inc. of Rlv (CO2)	87.2 s/m	P	0.73 mg/(m^2 s)

$$R_{ac} = 1.65\ x\ R_{av}$$

$$R_{lc} = 1.4\ \ x\ R_{lv}$$

due to Wind	1	due to light	low	std	high
Rav	100		Rlv	Rlv	Rlv
Rac	165		100	200	300
			Rlc	**Rlc**	**Rlc**
			140	280	420
due to	CO2	**Rlc.inc.**	**Rc=sum of Rac, Rlc, Rlc.inc, in s/m**		
	std	174.31	479.31	619.31	759.31
	low	87.15	392.15	532.15	672.15
		Rlv.inc.	Rv=sum of Rav, Rlv, Rlv.inc, in s/m		
	std	124.51	324.5	424.5	524.5
	low	62.25	262.25	362.25	462.25

P 計算	light	Type	low	std	high
	CO2	std	0.681	0.625	0.573
	type	low	0.718	0.659	0.604
P 正解					
		Std	0.69	0.63	0.58
in mg/m2/s		low	0.73	0.67	0.61



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Pmax	2.35		mg/m2/s =	84.6	kg/ha/hr		Rao.ca,ppm	400	Rao.ca,mg/m3	732.1		
2	due to temperature		Tl, deg.C	20	Tm=	25	a	5					
3			Tl+a	25	Tm+a	30	Gtl	0.91					
4			light type	Kl_low	Kl_std	Kl_high		due to Wind	1	due to light	low	std	high
5	PAR	400		200	200	200		Rav	100		Rlv	Rlv	Rlv
6			GI	0.67	0.67	0.67		Rac	165		100	200	300
7	Pm=Pmax*Gtl*GI, in mg/m2/s			1.42	1.42	1.42					Rlc	Rlc	Rlc
8											140	280	420
9	CO2type	Kc	in mg/m3	-B=Rho.ca+Kc+Rc*Pm, all in mg/m3					due to CO2	Rlc.inc.	Rc=sum of Rac, Rlc, Rlc.inc, in s/m		
10	large	440	std	1852.9	2051.8	2250.6			std	174.31	479.31	619.31	759.31
11	small	440	low	1729.1	1928.0	2126.8			low	87.15	392.15	532.15	672.15
12										Rlv.inc.	Rv=sum of Rav, Rlv, Rlv.inc, in s/m		
13		A=Rc	std	479.31	619.31	759.31			std	124.51	324.5	424.5	524.5
14			low	392.15	532.15	672.15			low	62.25	262.25	362.25	462.25
15		4*A*C = 4*Rc*Rao.ca*Pm, in (mg/m3)*(s/m)*(mg/m2/s) = (mg/m3)^2											
16			std	1993682.17	2576010	3158339		assuming RH=40%		VD_40%RH	6.91		
17			low	1631162.99	2213491	2795820		assuming Tl=Tair		VD_100%RH	17.27	Vps	2.34
18		sqrt(B^2-4AC), in (mg/m3)^2						as shown in Chap.7		VDD=	10.36	g/m3	
19			std	1199.8	1278.2	1380.9					10364.63	mg/m3	
20			low	1165.6	1226.2	1314.4					low	std	high
21								Tr=VDD/Rv	in g/m3*m/s	std	31.94	24.42	19.76
22		P=[-B-sqrt(B^2-4*A*C)]/(2*A), in (mg/m3)*m/s = mg/m2/s							=g/m2/s	low	39.52	28.61	22.42
23	P 計算		std	0.681	0.625	0.573		Chap. 7 to derive Tr, tranpiration rate					
24			low	0.718	0.659	0.604							
25													
26	P 正解		light type	low	std	high							
27		CO2 type	std	0.69	0.63	0.58							
28	in mg/m2/s		low	0.73	0.67	0.61							

Simulation Input temperature and humidity, then transpiration rate is calculated. The value of the following environmental factors active irradiance, wind velocity, CO2 concentration, the reaction type to irradiance by plants, and the reaction type to CO

Plant Type (Light)	Std.	Temp.	20	°C	Ip	400	W/m²	Rav	100.0	s/m
Plant Type (CO2)	Std.	W	1	m/s	CO2	400	ppm	Rlv	200.0	s/m
		RH	40	%	CO2	732.1	mg/m³	Inc. of Rlv	124.5	s/m

Check the Pn_simulation.xlsx for details

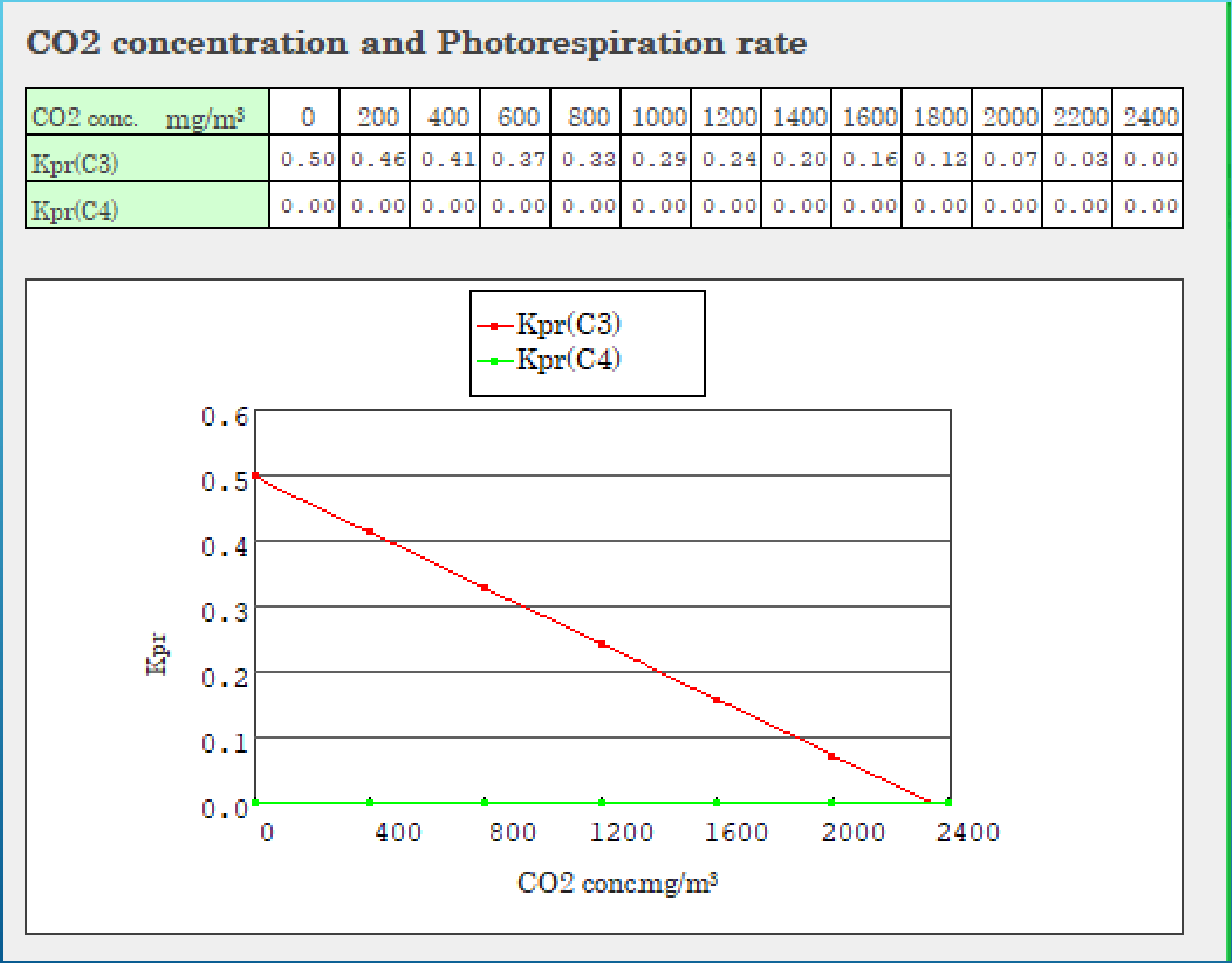
CHAPTER 13
PHOTORESPIRATION RATE

- Photorespiration occurred in photosynthesis of C3 plants, rarely occurred in C4 plants.
- It is a phenomenon in which RuBP is oxidized by RuBisco, and CO_2 is released.
- K_{pr} is the proportion of photorespiration rate to photosynthesis rate increases as CO_2 concentration decreases, and it decreases as CO_2 increases as shown below:

$K_{pr} = 0$ when $CO_2 \geq \rho_{cstop}$ or C4 plants eq.13-1

$K_{pr} = -K_{pr.max} \ (\rho_{ca} - \rho_{cstop}) / \rho_{cstop}$......eq.13-2

- Assumed $K_{pr.max} = 0.5$ and $\rho_{cstop} = 2352 \text{ mg/m}^3$ (1200 ppm)

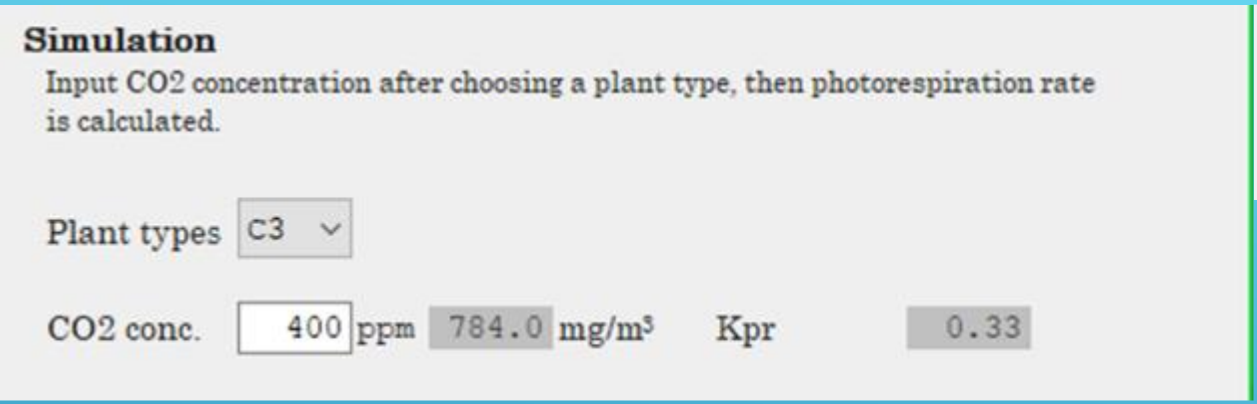


CO2 concentration and Photorespiration rate

CO2 conc. mg/m³	0	200	400	600	800	1000	1200	1400	1600	1800	2000	2200	2400
Kpr(C3)	0.50	0.46	0.41	0.37	0.33	0.29	0.24	0.20	0.16	0.12	0.07	0.03	0.00
Kpr(C4)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Plant type is C4, Kpr = 0
Plant type is C3, Kpr = $0.5*(2352-\rho_{ca})/2352$
$= (2352-\rho_{ca})/4704$

mg/m3	
Rho.ca	Kpr of C3
0	0.50
200	0.46
400	0.41
600	0.37
800	0.33
1000	0.29
1200	0.24
1400	0.20
1600	0.16
1800	0.12
2000	0.07
2200	0.03
2352	0.00

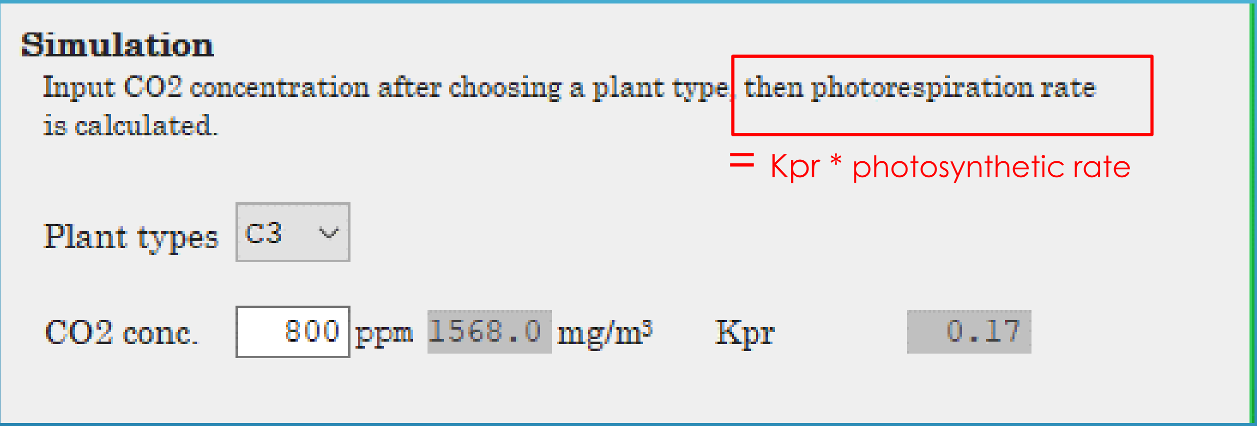


Simulation

Input CO2 concentration after choosing a plant type, then photorespiration rate is calculated.

Plant types: C3

CO2 conc. 400 ppm 784.0 mg/m³ Kpr 0.33



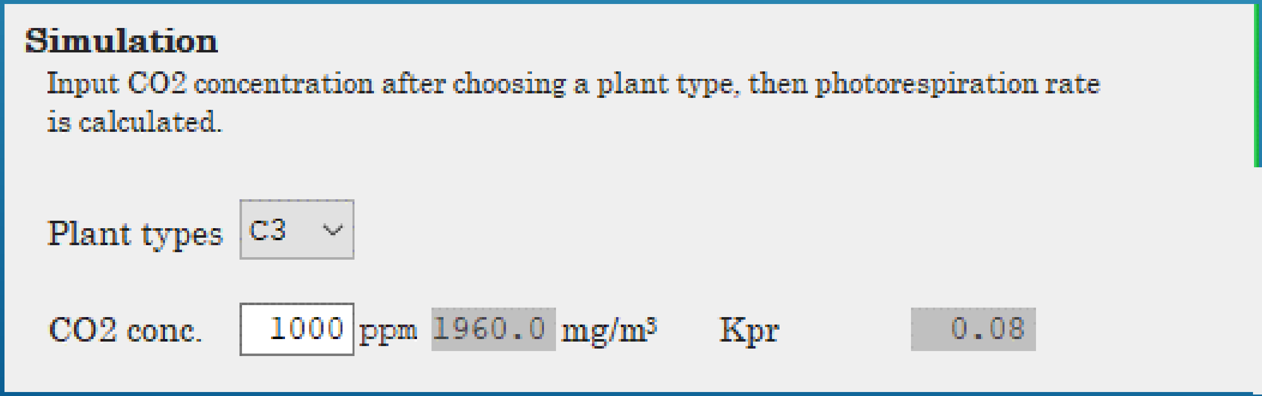
Simulation

Input CO2 concentration after choosing a plant type, then photorespiration rate is calculated.

= Kpr * photosynthetic rate

Plant types: C3

CO2 conc. 800 ppm 1568.0 mg/m³ Kpr 0.17

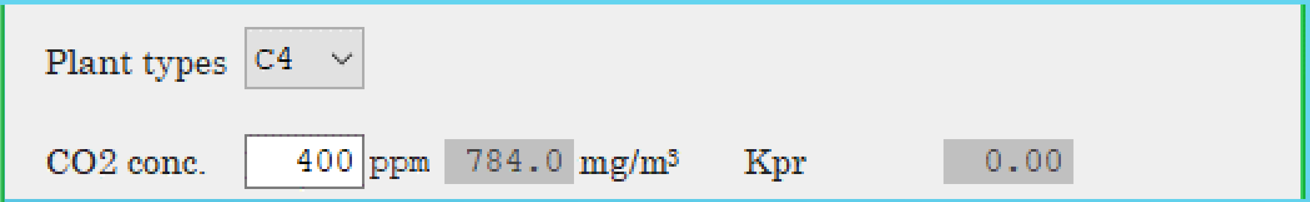


Simulation

Input CO2 concentration after choosing a plant type, then photorespiration rate is calculated.

Plant types: C3

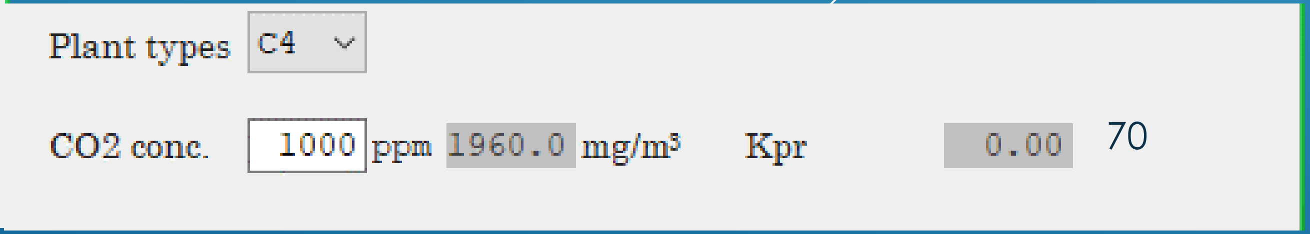
CO2 conc. 1000 ppm 1960.0 mg/m³ Kpr 0.08



Plant types: C4

CO2 conc. 400 ppm 784.0 mg/m³ Kpr 0.00

ppm	
Rho.ca	Kpr of C3
0	0.50
100	0.46
200	0.42
300	0.38
400	0.33
500	0.29
600	0.25
700	0.21
800	0.17
900	0.13
1000	0.08
1100	0.04
1200	0.00

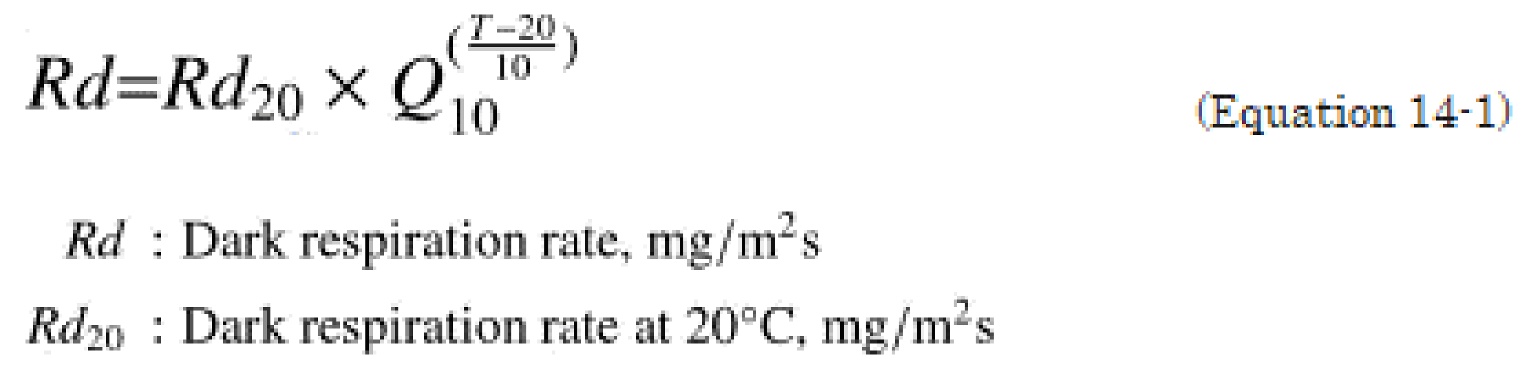


Plant types: C4

CO2 conc. 1000 ppm 1960.0 mg/m³ Kpr 0.00

CHAPTER 14
DARK RESPIRATION RATE

- **Dark respiration is a physiological function needed to maintain living organisms. It is greatly influenced by Temperature, but not CO_2 concentration and irradiance.**
- **The change of dark respiration rate (Rd) is expressed by a coefficient Q10, which shows how many times larger the value becomes with each 10 C change.**
- **Q10 in here equals 2.**



$$Rd = Rd_{20} \times Q_{10}^{\left(\frac{T-20}{10}\right)} \qquad \text{(Equation 14-1)}$$

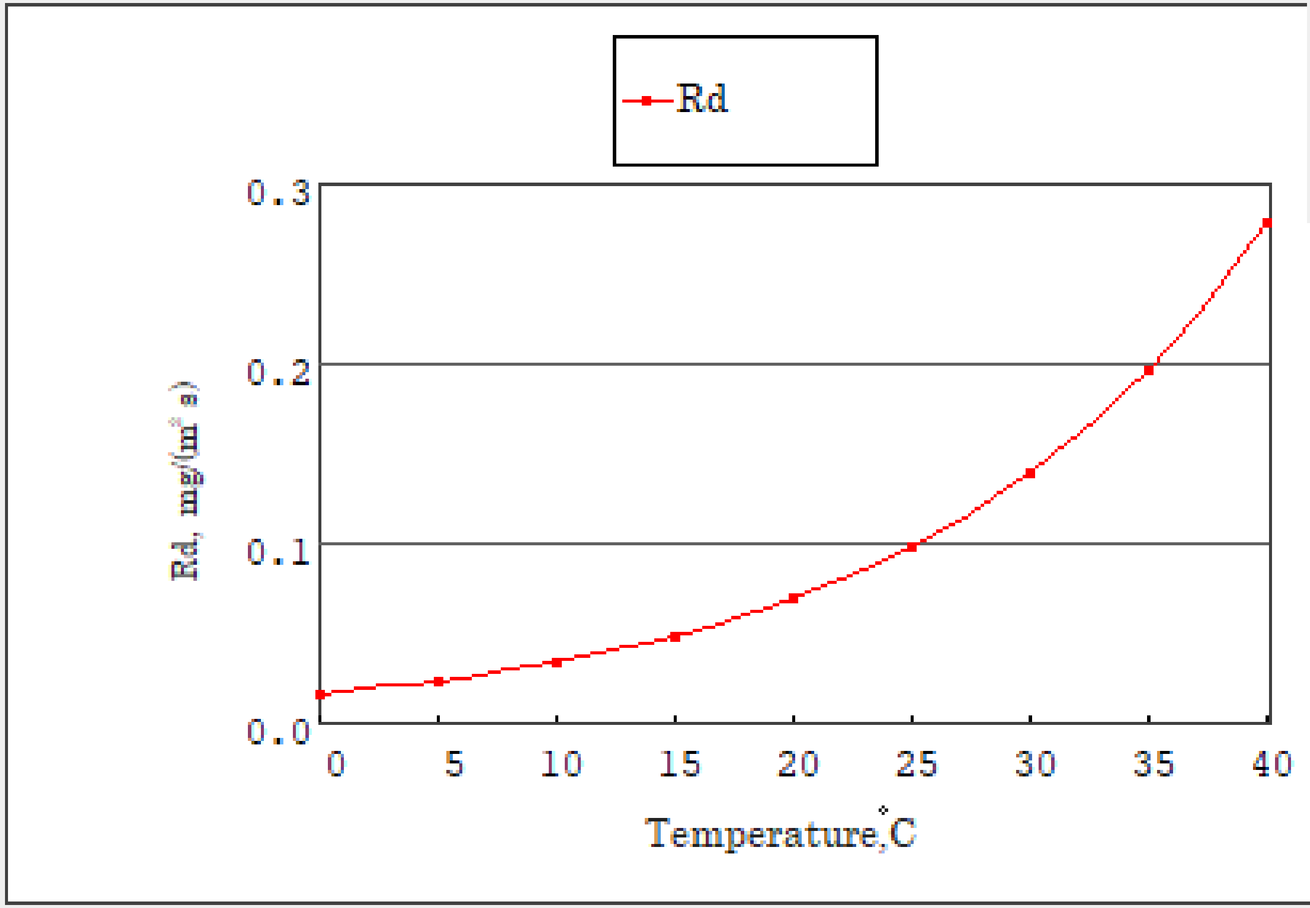
Rd : Dark respiration rate, mg/m^{2}s

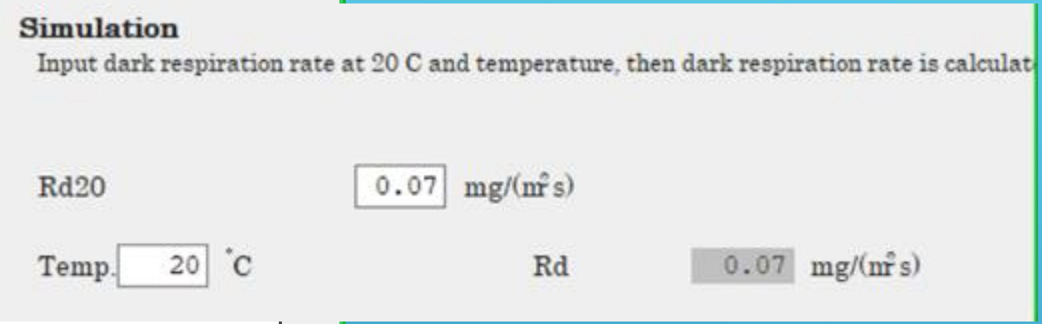
Rd_{20} : Dark respiration rate at 20°C, mg/m^{2}s

Temperature and Dark respiration rate

(Rd20=0.07)

Temp.	0	5	10	15	20	25	30	35	40
Rd, mg/(m²s)	0.02	0.02	0.04	0.05	0.07	0.10	0.14	0.20	0.28





Simulation

Input dark respiration rate at 20 C and temperature, then dark respiration rate is calculat

Rd20 0.07 mg/(m²s)

Temp. 20 °C

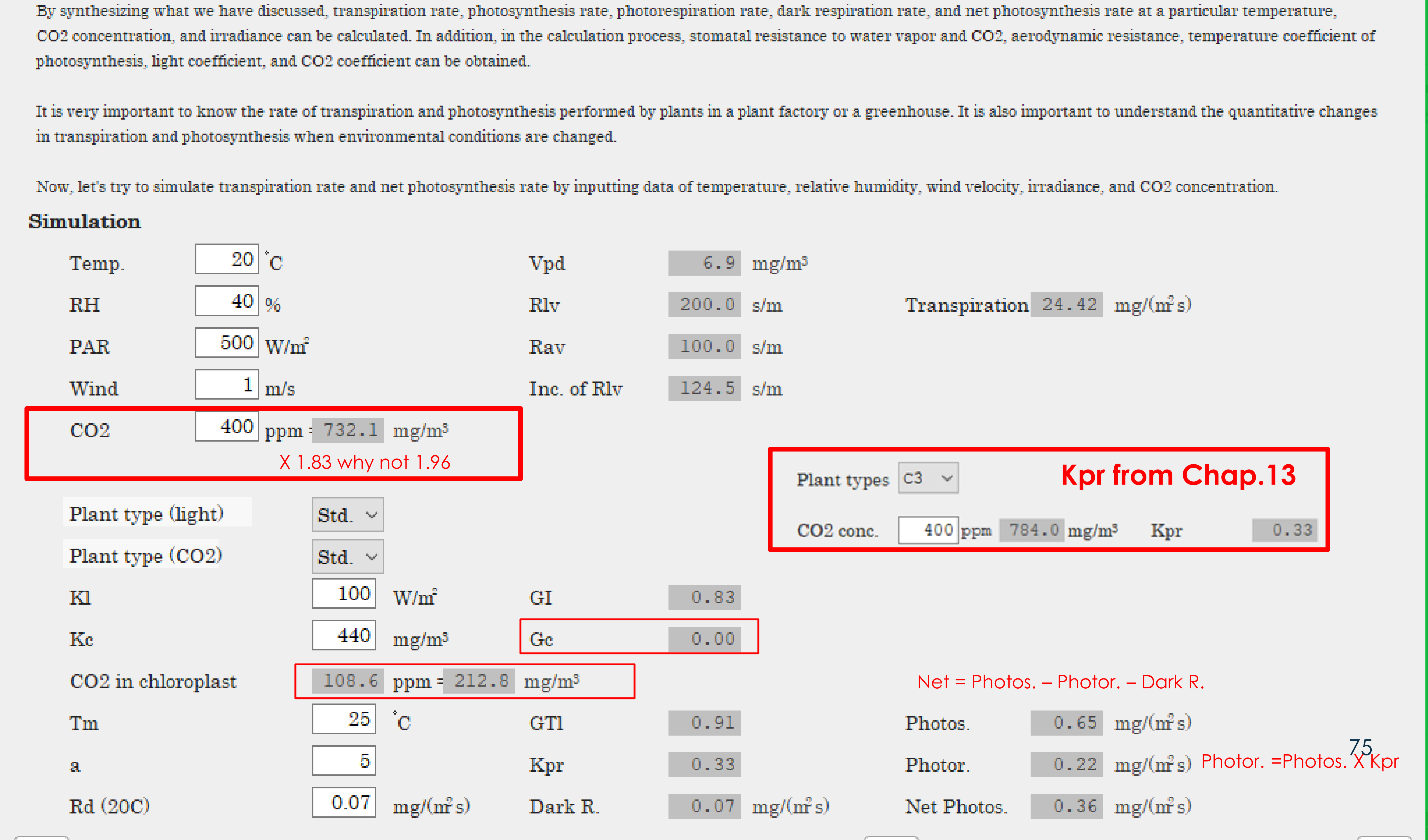
Rd 0.07 mg/(m²s)

Given Rd20 = 0.07

Rd@40 C = 0.07*2^((40-20)/10) = 0.28
Rd@30 C = 0.07*2^1 = 0.14
Rd@20 C = 0.07*2^0 = 0.07
Rd@10 C = 0.07*2^-1 = 0.035
Rd@ 5 C = 0.07*2^-1.5 = 0.0247
Rd@ 0 C = 0.07*2^-2 = 0.0175

CHAPTER 15

SIMULATION OF TRANSPIRATION AND PHOTOSYNTHESIS



By synthesizing what we have discussed, transpiration rate, photosynthesis rate, photorespiration rate, dark respiration rate, and net photosynthesis rate at a particular temperature, CO2 concentration, and irradiance can be calculated. In addition, in the calculation process, stomatal resistance to water vapor and CO2, aerodynamic resistance, temperature coefficient of photosynthesis, light coefficient, and CO2 coefficient can be obtained.

It is very important to know the rate of transpiration and photosynthesis performed by plants in a plant factory or a greenhouse. It is also important to understand the quantitative changes in transpiration and photosynthesis when environmental conditions are changed.

Now, let's try to simulate transpiration rate and net photosynthesis rate by inputting data of temperature, relative humidity, wind velocity, irradiance, and CO2 concentration.

Simulation

Temp. 20 °C
RH 40 %
PAR 500 W/m²
Wind 1 m/s
CO2 400 ppm = 732.1 mg/m³

X 1.83 why not 1.96

Vpd 6.9 mg/m³
Rlv 200.0 s/m
Rav 100.0 s/m
Inc. of Rlv 124.5 s/m

Transpiration 24.42 mg/(m² s)

Plant types C3

Kpr from Chap.13

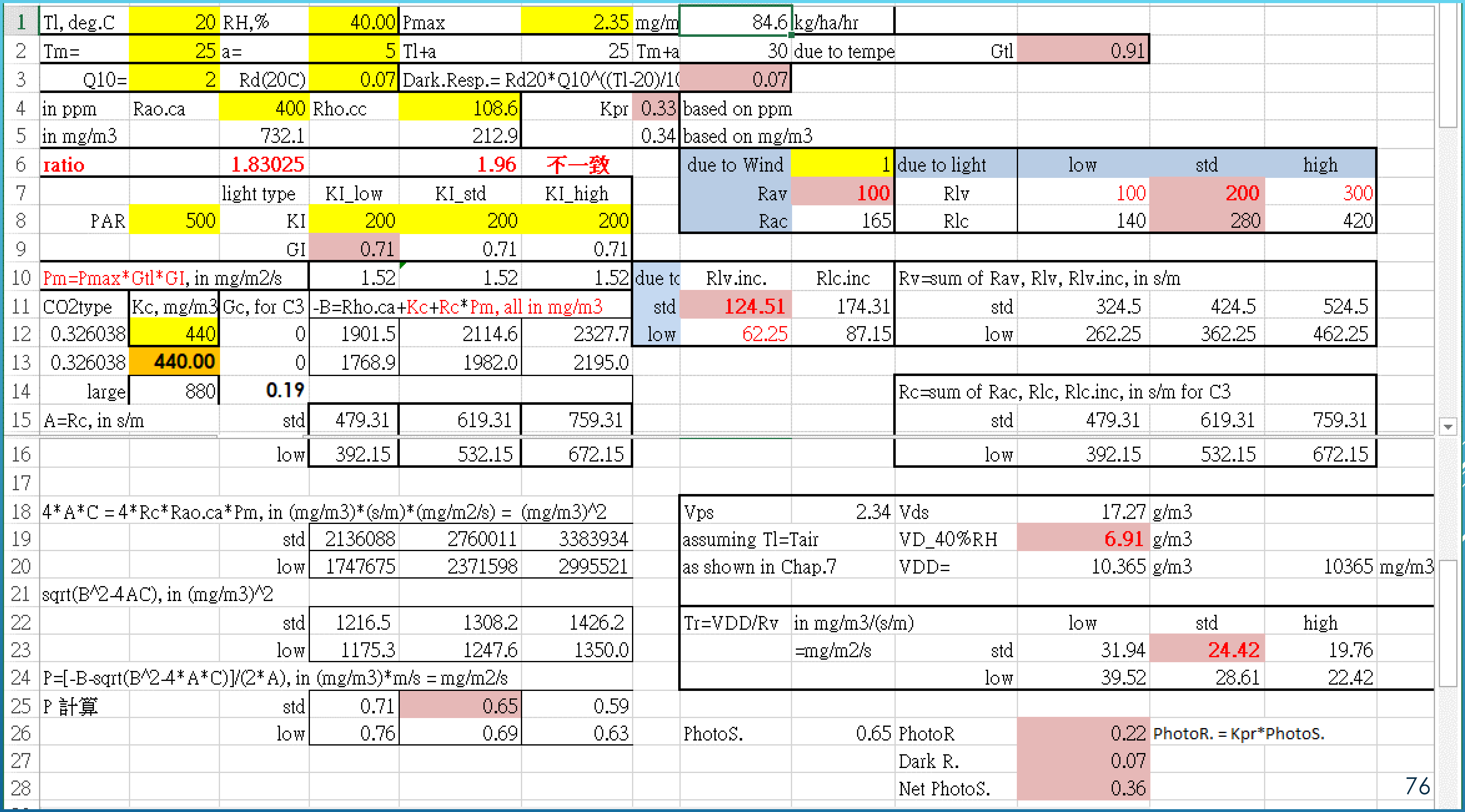
CO2 conc. 400 ppm 784.0 mg/m³ Kpr 0.33

Plant type (light) Std.
Plant type (CO2) Std.
Kl 100 W/m²
Kc 440 mg/m³
CO2 in chloroplast 108.6 ppm = 212.8 mg/m³
Tm 25 °C
a 5
Rd (20C) 0.07 mg/(m² s)

Gl 0.83
Gc 0.00
GTl 0.91
Kpr 0.33
Dark R. 0.07 mg/(m² s)

Net = Photos. – Photor. – Dark R.

Photos. 0.65 mg/(m² s)
Photor. 0.22 mg/(m² s) Photor. =Photos. X Kpr
Net Photos. 0.36 mg/(m² s)

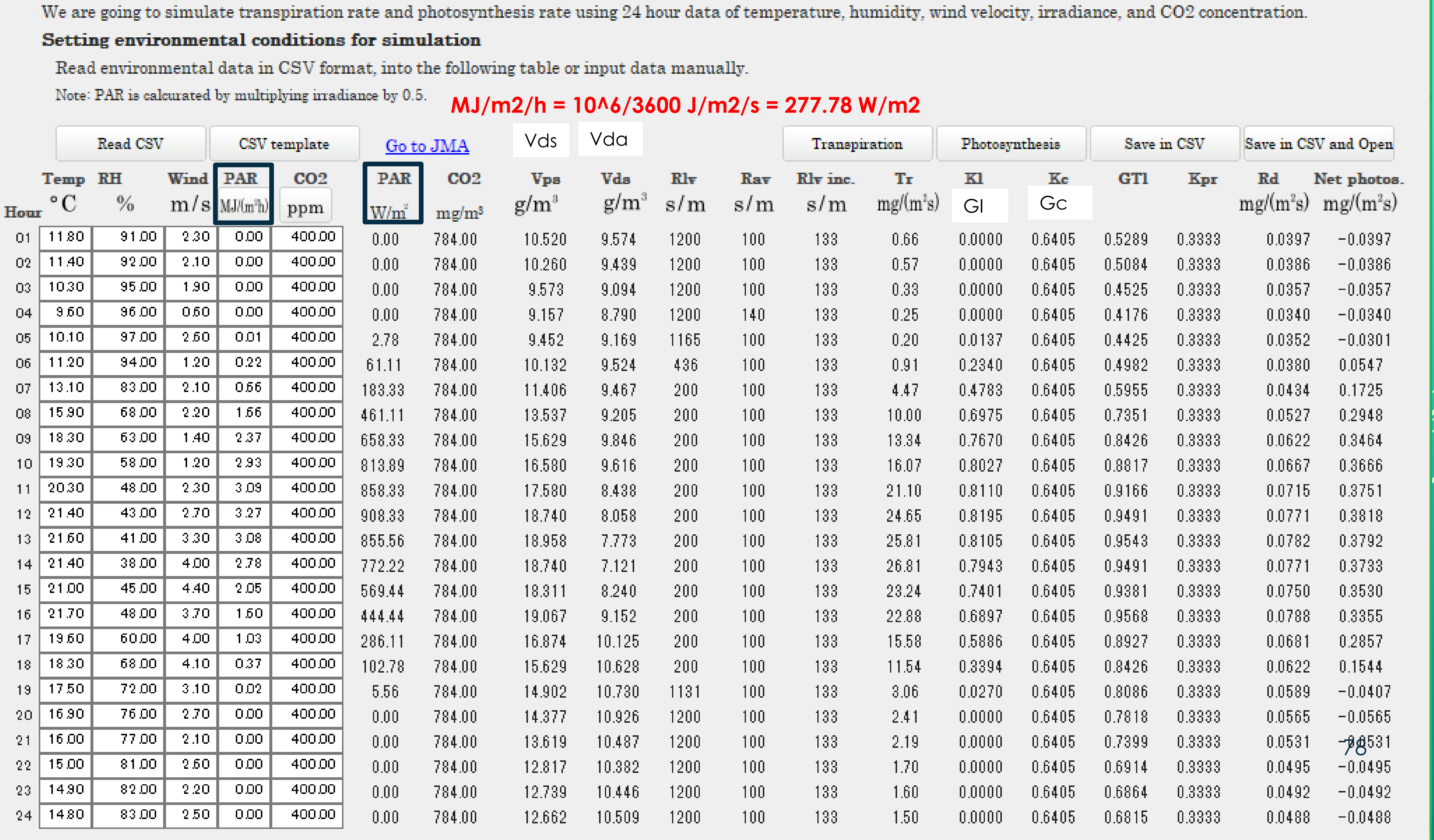


1	Tl, deg.C	20	RH,%	40.00	Pmax	2.35	mg/m	84.6	kg/ha/hr					
2	Tm=	25	a=	5	Tl+a	25	Tm+a	30	due to tempe	Gtl	0.91			
3	Q10=	2	Rd(20C)	0.07	Dark.Resp.= Rd20*Q10^((Tl-20)/1(			0.07						
4	in ppm	Rao.ca	400	Rho.cc	108.6	Kpr	0.33	based on ppm						
5	in mg/m3		732.1		212.9		0.34	based on mg/m3						
6	ratio		1.83025		1.96	不一致		due to Wind	1	due to light	low	std	high	
7			light type	KI_low	KI_std	KI_high		Rav	100	Rlv	100	200	300	
8	PAR	500	KI	200	200	200		Rac	165	Rlc	140	280	420	
9			GI	0.71	0.71	0.71								
10	Pm=Pmax*Gtl*GI, in mg/m2/s			1.52	1.52	1.52	due tc	Rlv.inc.	Rlc.inc	Rv=sum of Rav, Rlv, Rlv.inc, in s/m				
11	CO2type	Kc, mg/m3	Gc, for C3	-B=Rho.ca+Kc+Rc*Pm, all in mg/m3			std	124.51	174.31	std	324.5	424.5	524.5	
12	0.326038	440	0	1901.5	2114.6	2327.7	low	62.25	87.15	low	262.25	362.25	462.25	
13	0.326038	440.00	0	1768.9	1982.0	2195.0								
14	large	880	0.19							Rc=sum of Rac, Rlc, Rlc.inc, in s/m for C3				
15	A=Rc, in s/m		std	479.31	619.31	759.31				std	479.31	619.31	759.31	
16			low	392.15	532.15	672.15				low	392.15	532.15	672.15	
17														
18	4*A*C = 4*Rc*Rao.ca*Pm, in (mg/m3)*(s/m)*(mg/m2/s) = (mg/m3)^2							Vps	2.34	Vds	17.27	g/m3		
19			std	2136088	2760011	3383934		assuming Tl=Tair		VD_40%RH	6.91	g/m3		
20			low	1747675	2371598	2995521		as shown in Chap.7		VDD=	10.365	g/m3	10365	mg/m3
21	sqrt(B^2-4AC), in (mg/m3)^2													
22			std	1216.5	1308.2	1426.2		Tr=VDD/Rv	in mg/m3/(s/m)		low	std	high	
23			low	1175.3	1247.6	1350.0			=mg/m2/s	std	31.94	24.42	19.76	
24	P=[-B-sqrt(B^2-4*A*C)]/(2*A), in (mg/m3)*m/s = mg/m2/s									low	39.52	28.61	22.42	
25	P 計算		std	0.71	0.65	0.59								
26			low	0.76	0.69	0.63		PhotoS.	0.65	PhotoR	0.22	PhotoR. = Kpr*PhotoS.		
27										Dark R.	0.07			
28										Net PhotoS.	0.36			

Check the Pn_simulation.xlsx for details

CHAPTER 16

24 HOURS SIMULATION OF TRANSPIRATION AND PHOTOSYNTHESIS



We are going to simulate transpiration rate and photosynthesis rate using 24 hour data of temperature, humidity, wind velocity, irradiance, and CO2 concentration.

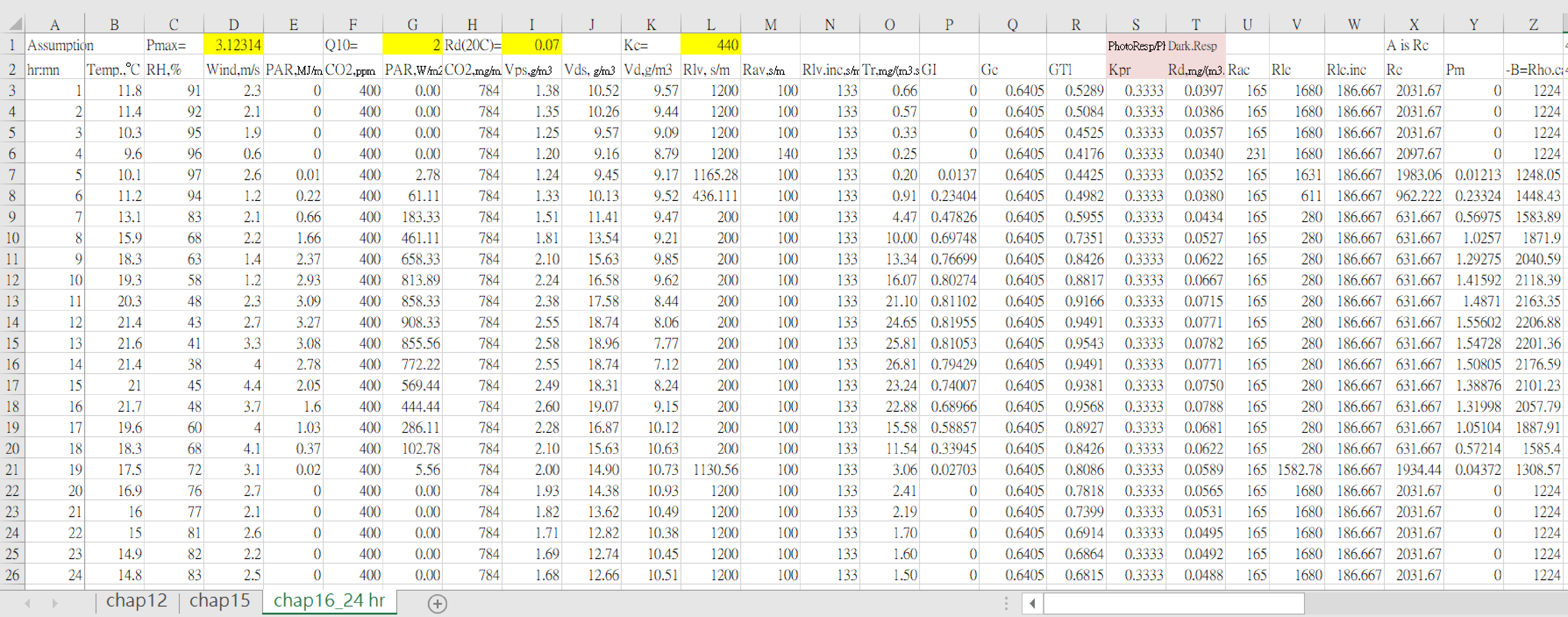
Setting environmental conditions for simulation

Read environmental data in CSV format, into the following table or input data manually.

Note: PAR is calcurated by multiplying irradiance by 0.5.

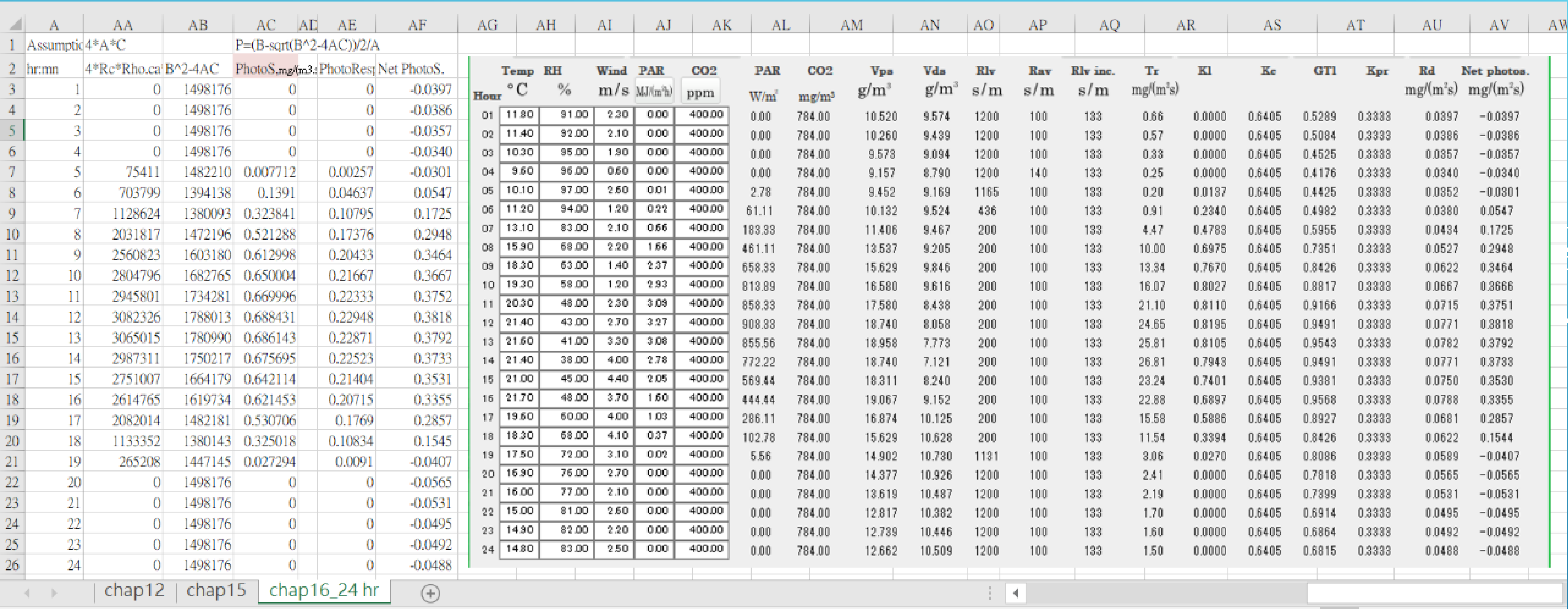
MJ/m2/h = 10^6/3600 J/m2/s = 277.78 W/m2

Hour	Temp °C	RH %	Wind m/s	PAR MJ/(m²h)	CO2 ppm	PAR W/m²	CO2 mg/m³	Vds Vps g/m³	Vda Vda g/m³	Rlv s/m	Rav s/m	Rlv inc. s/m	Tr mg/(m²s)	Kl Gl	Kc Gc	GTl	Kpr	Rd mg/(m²s)	Net photos. mg/(m²s)
01	11.80	91.00	2.30	0.00	400.00	0.00	784.00	10.520	9.574	1200	100	133	0.66	0.0000	0.6405	0.5289	0.3333	0.0397	−0.0397
02	11.40	92.00	2.10	0.00	400.00	0.00	784.00	10.260	9.439	1200	100	133	0.57	0.0000	0.6405	0.5084	0.3333	0.0386	−0.0386
03	10.30	95.00	1.90	0.00	400.00	0.00	784.00	9.573	9.094	1200	100	133	0.33	0.0000	0.6405	0.4525	0.3333	0.0357	−0.0357
04	9.60	96.00	0.60	0.00	400.00	0.00	784.00	9.157	8.790	1200	140	133	0.25	0.0000	0.6405	0.4176	0.3333	0.0340	−0.0340
05	10.10	97.00	2.60	0.01	400.00	2.78	784.00	9.452	9.169	1165	100	133	0.20	0.0137	0.6405	0.4425	0.3333	0.0352	−0.0301
06	11.20	94.00	1.20	0.22	400.00	61.11	784.00	10.132	9.524	436	100	133	0.91	0.2340	0.6405	0.4982	0.3333	0.0380	0.0547
07	13.10	83.00	2.10	0.66	400.00	183.33	784.00	11.406	9.467	200	100	133	4.47	0.4783	0.6405	0.5955	0.3333	0.0434	0.1725
08	15.90	68.00	2.20	1.66	400.00	461.11	784.00	13.537	9.205	200	100	133	10.00	0.6975	0.6405	0.7351	0.3333	0.0527	0.2948
09	18.30	63.00	1.40	2.37	400.00	658.33	784.00	15.629	9.846	200	100	133	13.34	0.7670	0.6405	0.8426	0.3333	0.0622	0.3464
10	19.30	58.00	1.20	2.93	400.00	813.89	784.00	16.580	9.616	200	100	133	16.07	0.8027	0.6405	0.8817	0.3333	0.0667	0.3666
11	20.30	48.00	2.30	3.09	400.00	858.33	784.00	17.580	8.438	200	100	133	21.10	0.8110	0.6405	0.9166	0.3333	0.0715	0.3751
12	21.40	43.00	2.70	3.27	400.00	908.33	784.00	18.740	8.058	200	100	133	24.65	0.8195	0.6405	0.9491	0.3333	0.0771	0.3818
13	21.60	41.00	3.30	3.08	400.00	855.56	784.00	18.958	7.773	200	100	133	25.81	0.8105	0.6405	0.9543	0.3333	0.0782	0.3792
14	21.40	38.00	4.00	2.78	400.00	772.22	784.00	18.740	7.121	200	100	133	26.81	0.7943	0.6405	0.9491	0.3333	0.0771	0.3733
15	21.00	45.00	4.40	2.05	400.00	569.44	784.00	18.311	8.240	200	100	133	23.24	0.7401	0.6405	0.9381	0.3333	0.0750	0.3530
16	21.70	48.00	3.70	1.60	400.00	444.44	784.00	19.067	9.152	200	100	133	22.88	0.6897	0.6405	0.9568	0.3333	0.0788	0.3355
17	19.60	60.00	4.00	1.03	400.00	286.11	784.00	16.874	10.125	200	100	133	15.58	0.5886	0.6405	0.8927	0.3333	0.0681	0.2857
18	18.30	68.00	4.10	0.37	400.00	102.78	784.00	15.629	10.628	200	100	133	11.54	0.3394	0.6405	0.8426	0.3333	0.0622	0.1544
19	17.50	72.00	3.10	0.02	400.00	5.56	784.00	14.902	10.730	1131	100	133	3.06	0.0270	0.6405	0.8086	0.3333	0.0589	−0.0407
20	16.90	76.00	2.70	0.00	400.00	0.00	784.00	14.377	10.926	1200	100	133	2.41	0.0000	0.6405	0.7818	0.3333	0.0565	−0.0565
21	16.00	77.00	2.10	0.00	400.00	0.00	784.00	13.619	10.487	1200	100	133	2.19	0.0000	0.6405	0.7399	0.3333	0.0531	−0.0531
22	15.00	81.00	2.60	0.00	400.00	0.00	784.00	12.817	10.382	1200	100	133	1.70	0.0000	0.6405	0.6914	0.3333	0.0495	−0.0495
23	14.90	82.00	2.20	0.00	400.00	0.00	784.00	12.739	10.446	1200	100	133	1.60	0.0000	0.6405	0.6864	0.3333	0.0492	−0.0492
24	14.80	83.00	2.50	0.00	400.00	0.00	784.00	12.662	10.509	1200	100	133	1.50	0.0000	0.6405	0.6815	0.3333	0.0488	−0.0488



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
1	Assumption		Pmax=	3.12314		Q10=	2	Rd(20C)=	0.07		Kc=	440							PhotoResp/Pl	Dark.Resp				A is Rc		
2	hr:mn	Temp.,°C	RH,%	Wind,m/s	PAR,MJ/m	CO2,ppm	PAR,W/m2	CO2,mg/m	Vps,g/m3	Vds, g/m3	Vd,g/m3	Rlv, s/m	Rav,s/m	Rlv.inc,s/m	Tr,mg/(m3.s	GI	Gc	GTl	Kpr	Rd,mg/(m3.	Rac	Rlc	Rlc.inc	Rc	Pm	-B=Rho.c
3	1	11.8	91	2.3	0	400	0.00	784	1.38	10.52	9.57	1200	100	133	0.66	0	0.6405	0.5289	0.3333	0.0397	165	1680	186.667	2031.67	0	1224
4	2	11.4	92	2.1	0	400	0.00	784	1.35	10.26	9.44	1200	100	133	0.57	0	0.6405	0.5084	0.3333	0.0386	165	1680	186.667	2031.67	0	1224
5	3	10.3	95	1.9	0	400	0.00	784	1.25	9.57	9.09	1200	100	133	0.33	0	0.6405	0.4525	0.3333	0.0357	165	1680	186.667	2031.67	0	1224
6	4	9.6	96	0.6	0	400	0.00	784	1.20	9.16	8.79	1200	140	133	0.25	0	0.6405	0.4176	0.3333	0.0340	231	1680	186.667	2097.67	0	1224
7	5	10.1	97	2.6	0.01	400	2.78	784	1.24	9.45	9.17	1165.28	100	133	0.20	0.0137	0.6405	0.4425	0.3333	0.0352	165	1631	186.667	1983.06	0.01213	1248.05
8	6	11.2	94	1.2	0.22	400	61.11	784	1.33	10.13	9.52	436.111	100	133	0.91	0.23404	0.6405	0.4982	0.3333	0.0380	165	611	186.667	962.222	0.23324	1448.43
9	7	13.1	83	2.1	0.66	400	183.33	784	1.51	11.41	9.47	200	100	133	4.47	0.47826	0.6405	0.5955	0.3333	0.0434	165	280	186.667	631.667	0.56975	1583.89
10	8	15.9	68	2.2	1.66	400	461.11	784	1.81	13.54	9.21	200	100	133	10.00	0.69748	0.6405	0.7351	0.3333	0.0527	165	280	186.667	631.667	1.0257	1871.9
11	9	18.3	63	1.4	2.37	400	658.33	784	2.10	15.63	9.85	200	100	133	13.34	0.76699	0.6405	0.8426	0.3333	0.0622	165	280	186.667	631.667	1.29275	2040.59
12	10	19.3	58	1.2	2.93	400	813.89	784	2.24	16.58	9.62	200	100	133	16.07	0.80274	0.6405	0.8817	0.3333	0.0667	165	280	186.667	631.667	1.41592	2118.39
13	11	20.3	48	2.3	3.09	400	858.33	784	2.38	17.58	8.44	200	100	133	21.10	0.81102	0.6405	0.9166	0.3333	0.0715	165	280	186.667	631.667	1.4871	2163.35
14	12	21.4	43	2.7	3.27	400	908.33	784	2.55	18.74	8.06	200	100	133	24.65	0.81955	0.6405	0.9491	0.3333	0.0771	165	280	186.667	631.667	1.55602	2206.88
15	13	21.6	41	3.3	3.08	400	855.56	784	2.58	18.96	7.77	200	100	133	25.81	0.81053	0.6405	0.9543	0.3333	0.0782	165	280	186.667	631.667	1.54728	2201.36
16	14	21.4	38	4	2.78	400	772.22	784	2.55	18.74	7.12	200	100	133	26.81	0.79429	0.6405	0.9491	0.3333	0.0771	165	280	186.667	631.667	1.50805	2176.59
17	15	21	45	4.4	2.05	400	569.44	784	2.49	18.31	8.24	200	100	133	23.24	0.74007	0.6405	0.9381	0.3333	0.0750	165	280	186.667	631.667	1.38876	2101.23
18	16	21.7	48	3.7	1.6	400	444.44	784	2.60	19.07	9.15	200	100	133	22.88	0.68966	0.6405	0.9568	0.3333	0.0788	165	280	186.667	631.667	1.31998	2057.79
19	17	19.6	60	4	1.03	400	286.11	784	2.28	16.87	10.12	200	100	133	15.58	0.58857	0.6405	0.8927	0.3333	0.0681	165	280	186.667	631.667	1.05104	1887.91
20	18	18.3	68	4.1	0.37	400	102.78	784	2.10	15.63	10.63	200	100	133	11.54	0.33945	0.6405	0.8426	0.3333	0.0622	165	280	186.667	631.667	0.57214	1585.4
21	19	17.5	72	3.1	0.02	400	5.56	784	2.00	14.90	10.73	1130.56	100	133	3.06	0.02703	0.6405	0.8086	0.3333	0.0589	165	1582.78	186.667	1934.44	0.04372	1308.57
22	20	16.9	76	2.7	0	400	0.00	784	1.93	14.38	10.93	1200	100	133	2.41	0	0.6405	0.7818	0.3333	0.0565	165	1680	186.667	2031.67	0	1224
23	21	16	77	2.1	0	400	0.00	784	1.82	13.62	10.49	1200	100	133	2.19	0	0.6405	0.7399	0.3333	0.0531	165	1680	186.667	2031.67	0	1224
24	22	15	81	2.6	0	400	0.00	784	1.71	12.82	10.38	1200	100	133	1.70	0	0.6405	0.6914	0.3333	0.0495	165	1680	186.667	2031.67	0	1224
25	23	14.9	82	2.2	0	400	0.00	784	1.69	12.74	10.45	1200	100	133	1.60	0	0.6405	0.6864	0.3333	0.0492	165	1680	186.667	2031.67	0	1224
26	24	14.8	83	2.5	0	400	0.00	784	1.68	12.66	10.51	1200	100	133	1.50	0	0.6405	0.6815	0.3333	0.0488	165	1680	186.667	2031.67	0	1224

Check the Pn_simulation.xlsx for details

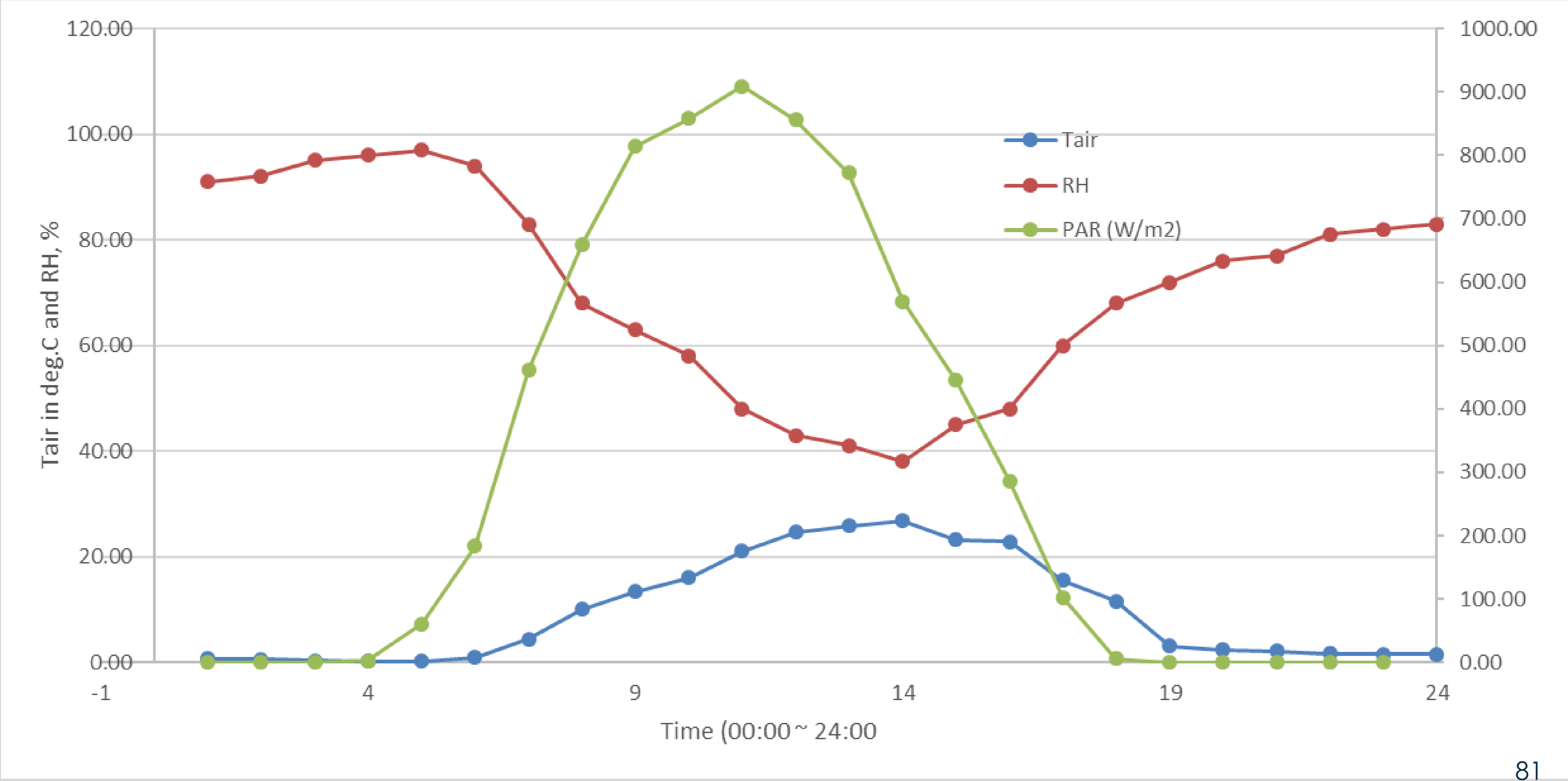


	A	AA	AB	AC	AD	AE	AF
1	Assumptic	4*A*C		P=(B-sqrt(B^2-4AC))/2/A			
2	hr:mn	4*Rc*Rho.ca	B^2-4AC	PhotoS.mg/(m3.:		PhotoResp	Net PhotoS.
3	1	0	1498176	0		0	-0.0397
4	2	0	1498176	0		0	-0.0386
5	3	0	1498176	0		0	-0.0357
6	4	0	1498176	0		0	-0.0340
7	5	75411	1482210	0.007712		0.00257	-0.0301
8	6	703799	1394138	0.1391		0.04637	0.0547
9	7	1128624	1380093	0.323841		0.10795	0.1725
10	8	2031817	1472196	0.521288		0.17376	0.2948
11	9	2560823	1603180	0.612998		0.20433	0.3464
12	10	2804796	1682765	0.650004		0.21667	0.3667
13	11	2945801	1734281	0.669996		0.22333	0.3752
14	12	3082326	1788013	0.688431		0.22948	0.3818
15	13	3065015	1780990	0.686143		0.22871	0.3792
16	14	2987311	1750217	0.675695		0.22523	0.3733
17	15	2751007	1664179	0.642114		0.21404	0.3531
18	16	2614765	1619734	0.621453		0.20715	0.3355
19	17	2082014	1482181	0.530706		0.1769	0.2857
20	18	1133352	1380143	0.325018		0.10834	0.1545
21	19	265208	1447145	0.027294		0.0091	-0.0407
22	20	0	1498176	0		0	-0.0565
23	21	0	1498176	0		0	-0.0531
24	22	0	1498176	0		0	-0.0495
25	23	0	1498176	0		0	-0.0492
26	24	0	1498176	0		0	-0.0488

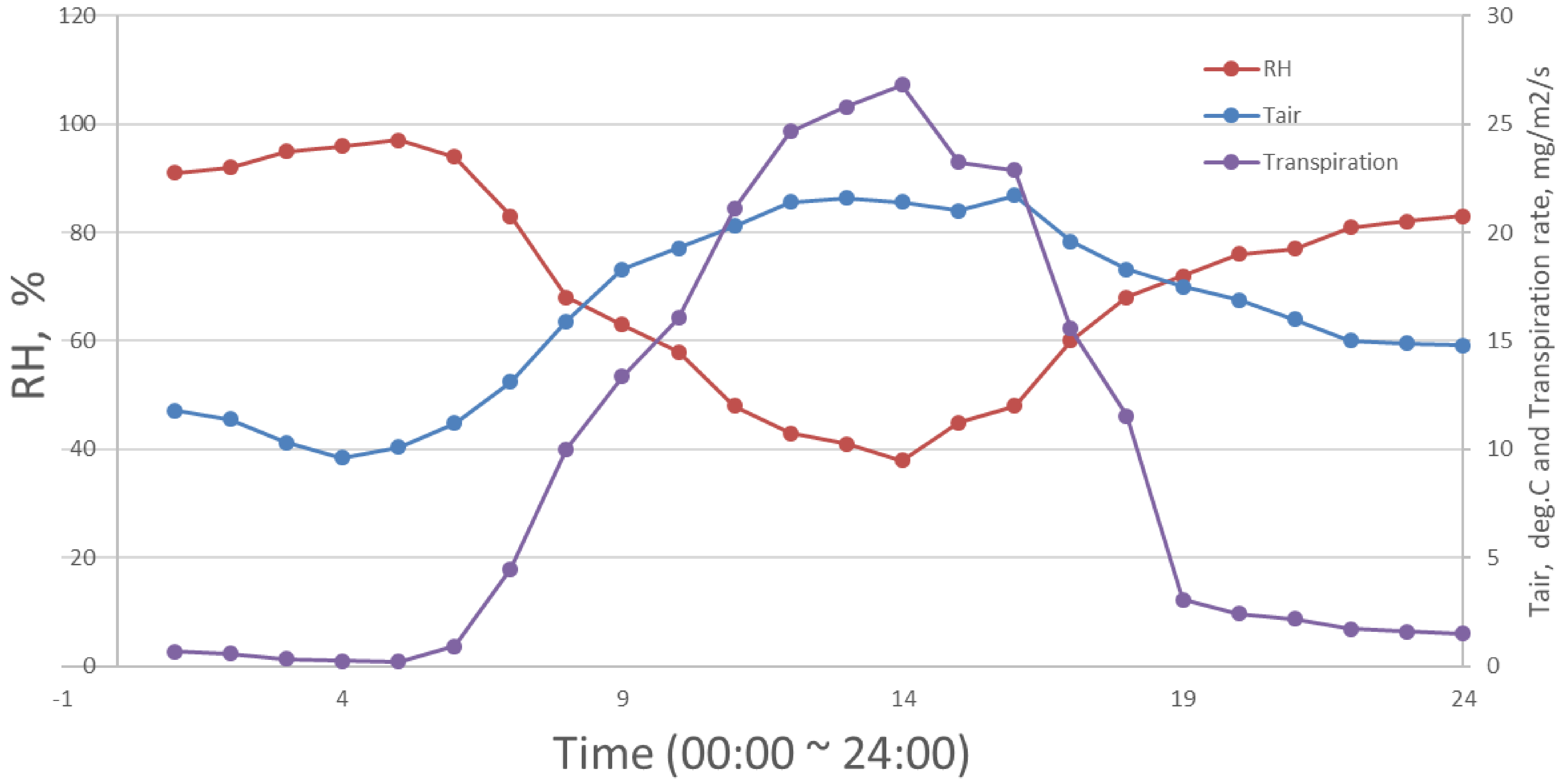
Hour	Temp °C	RH %	Wind m/s	PAR MJ/(m^2h)	CO2 ppm	PAR W/m^2	CO2 mg/m^3	Vps g/m^3	Vds g/m^3	Rlv s/m	Rav s/m	Rlv inc. s/m	Tr mg/(m^2s)	Kl	Kc	GTl	Kpr	Rd mg/(m^2s)	Net photos. mg/(m^2s)
01	11.80	91.00	2.30	0.00	400.00	0.00	784.00	10.520	9.574	1200	100	133	0.66	0.0000	0.6405	0.5289	0.3333	0.0397	−0.0397
02	11.40	92.00	2.10	0.00	400.00	0.00	784.00	10.260	9.439	1200	100	133	0.57	0.0000	0.6405	0.5084	0.3333	0.0386	−0.0386
03	10.30	95.00	1.90	0.00	400.00	0.00	784.00	9.573	9.094	1200	100	133	0.33	0.0000	0.6405	0.4525	0.3333	0.0357	−0.0357
04	9.60	96.00	0.60	0.00	400.00	0.00	784.00	9.157	8.790	1200	140	133	0.25	0.0000	0.6405	0.4176	0.3333	0.0340	−0.0340
05	10.10	97.00	2.60	0.01	400.00	2.78	784.00	9.452	9.169	1165	100	133	0.20	0.0137	0.6405	0.4425	0.3333	0.0352	−0.0301
06	11.20	94.00	1.20	0.22	400.00	61.11	784.00	10.132	9.524	436	100	133	0.91	0.2340	0.6405	0.4982	0.3333	0.0380	0.0547
07	13.10	83.00	2.10	0.66	400.00	183.33	784.00	11.406	9.467	200	100	133	4.47	0.4783	0.6405	0.5955	0.3333	0.0434	0.1725
08	15.90	68.00	2.20	1.66	400.00	461.11	784.00	13.537	9.205	200	100	133	10.00	0.6975	0.6405	0.7351	0.3333	0.0527	0.2948
09	18.30	63.00	1.40	2.37	400.00	658.33	784.00	15.629	9.846	200	100	133	13.34	0.7670	0.6405	0.8426	0.3333	0.0622	0.3464
10	19.30	58.00	1.20	2.93	400.00	813.89	784.00	16.580	9.616	200	100	133	16.07	0.8027	0.6405	0.8817	0.3333	0.0667	0.3666
11	20.30	48.00	2.30	3.09	400.00	858.33	784.00	17.580	8.438	200	100	133	21.10	0.8110	0.6405	0.9166	0.3333	0.0715	0.3751
12	21.40	43.00	2.70	3.27	400.00	908.33	784.00	18.740	8.058	200	100	133	24.65	0.8195	0.6405	0.9491	0.3333	0.0771	0.3818
13	21.60	41.00	3.30	3.08	400.00	855.56	784.00	18.958	7.773	200	100	133	25.81	0.8105	0.6405	0.9543	0.3333	0.0782	0.3792
14	21.40	38.00	4.00	2.78	400.00	772.22	784.00	18.740	7.121	200	100	133	26.81	0.7943	0.6405	0.9491	0.3333	0.0771	0.3733
15	21.00	45.00	4.40	2.05	400.00	569.44	784.00	18.311	8.240	200	100	133	23.24	0.7401	0.6405	0.9381	0.3333	0.0750	0.3530
16	21.70	48.00	3.70	1.60	400.00	444.44	784.00	19.067	9.152	200	100	133	22.88	0.6897	0.6405	0.9568	0.3333	0.0788	0.3355
17	19.60	60.00	4.00	1.03	400.00	286.11	784.00	16.874	10.125	200	100	133	15.58	0.5886	0.6405	0.8927	0.3333	0.0681	0.2857
18	18.30	68.00	4.10	0.37	400.00	102.78	784.00	15.629	10.628	200	100	133	11.54	0.3394	0.6405	0.8426	0.3333	0.0622	0.1544
19	17.50	72.00	3.10	0.02	400.00	5.56	784.00	14.902	10.730	1131	100	133	3.06	0.0270	0.6405	0.8086	0.3333	0.0589	−0.0407
20	16.90	76.00	2.70	0.00	400.00	0.00	784.00	14.377	10.926	1200	100	133	2.41	0.0000	0.6405	0.7818	0.3333	0.0565	−0.0565
21	16.00	77.00	2.10	0.00	400.00	0.00	784.00	13.619	10.487	1200	100	133	2.19	0.0000	0.6405	0.7399	0.3333	0.0531	−0.0531
22	15.00	81.00	2.60	0.00	400.00	0.00	784.00	12.817	10.382	1200	100	133	1.70	0.0000	0.6405	0.6914	0.3333	0.0495	−0.0495
23	14.90	82.00	2.20	0.00	400.00	0.00	784.00	12.739	10.446	1200	100	133	1.60	0.0000	0.6405	0.6864	0.3333	0.0492	−0.0492
24	14.80	83.00	2.50	0.00	400.00	0.00	784.00	12.662	10.509	1200	100	133	1.50	0.0000	0.6405	0.6815	0.3333	0.0488	−0.0488

Check the Pn_simulation.xlsx for details

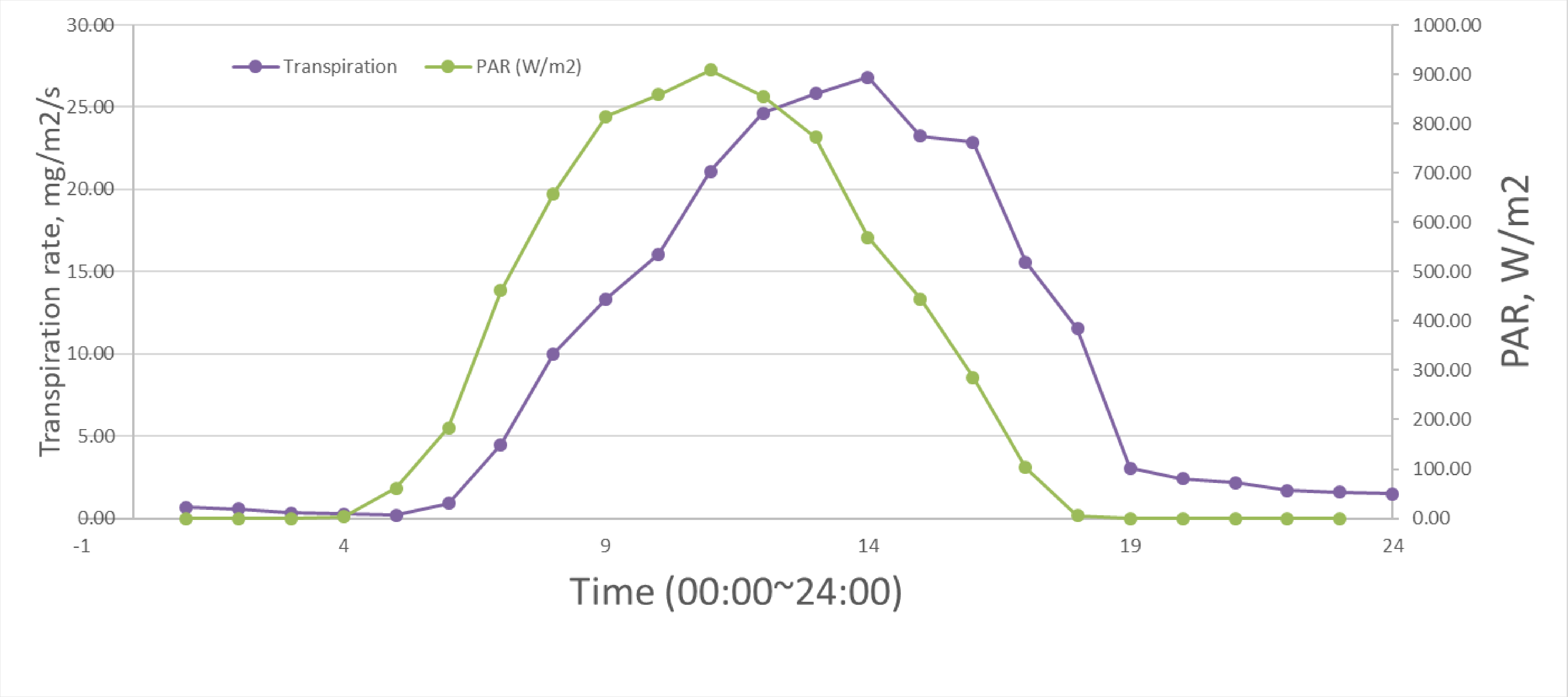
SUP



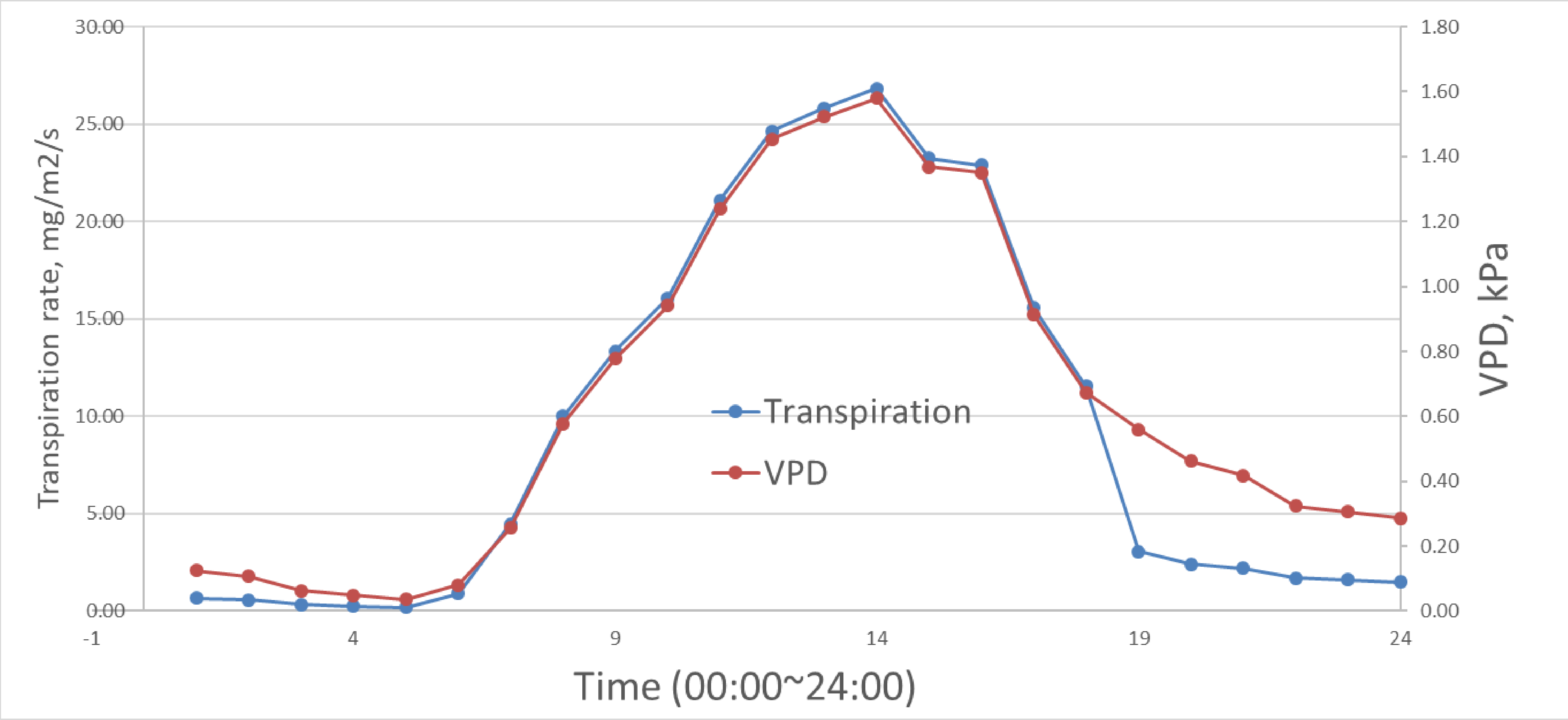
Tair
RH
PAR (W/m2)
Tair in deg.C and RH, %
120.00
100.00
80.00
60.00
40.00
20.00
0.00
1000.00
900.00
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
-1
4
9
14
19
24
Time (00:00 ~ 24:00



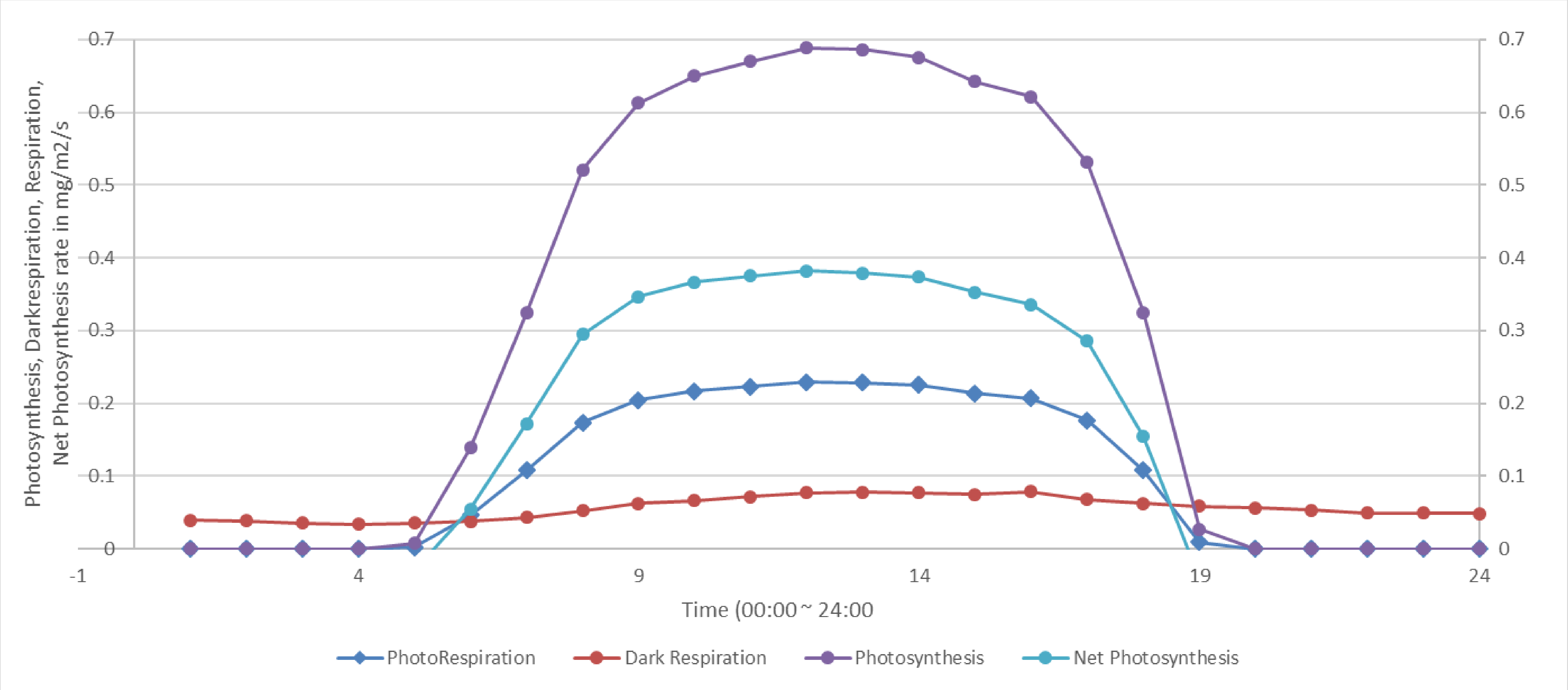
120
100
80
60
40
20
0
30
25
20
15
10
5
0
-1
4
9
14
19
24
RH, %
Tair, deg.C and Transpiration rate, mg/m2/s
Time (00:00 ~ 24:00)
RH
Tair
Transpiration



Transpiration
PAR (W/m2)
Transpiration rate, mg/m2/s
30.00
25.00
20.00
15.00
10.00
5.00
0.00
1000.00
900.00
800.00
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
PAR, W/m2
-1
4
9
14
19
24
Time (00:00~24:00)


Transpiration rate, mg/m2/s
30.00
25.00
20.00
15.00
10.00
5.00
0.00
VPD, kPa
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
-1
4
9
14
19
24
Time (00:00~24:00)
Transpiration
VPD

SUP



Photosynthesis, Darkrespiration, Respiration,
Net Photosynthesis rate in mg/m2/s
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-1
4
9
14
19
24
Time (00:00 ~ 24:00
PhotoRespiration
Dark Respiration
Photosynthesis
Net Photosynthesis

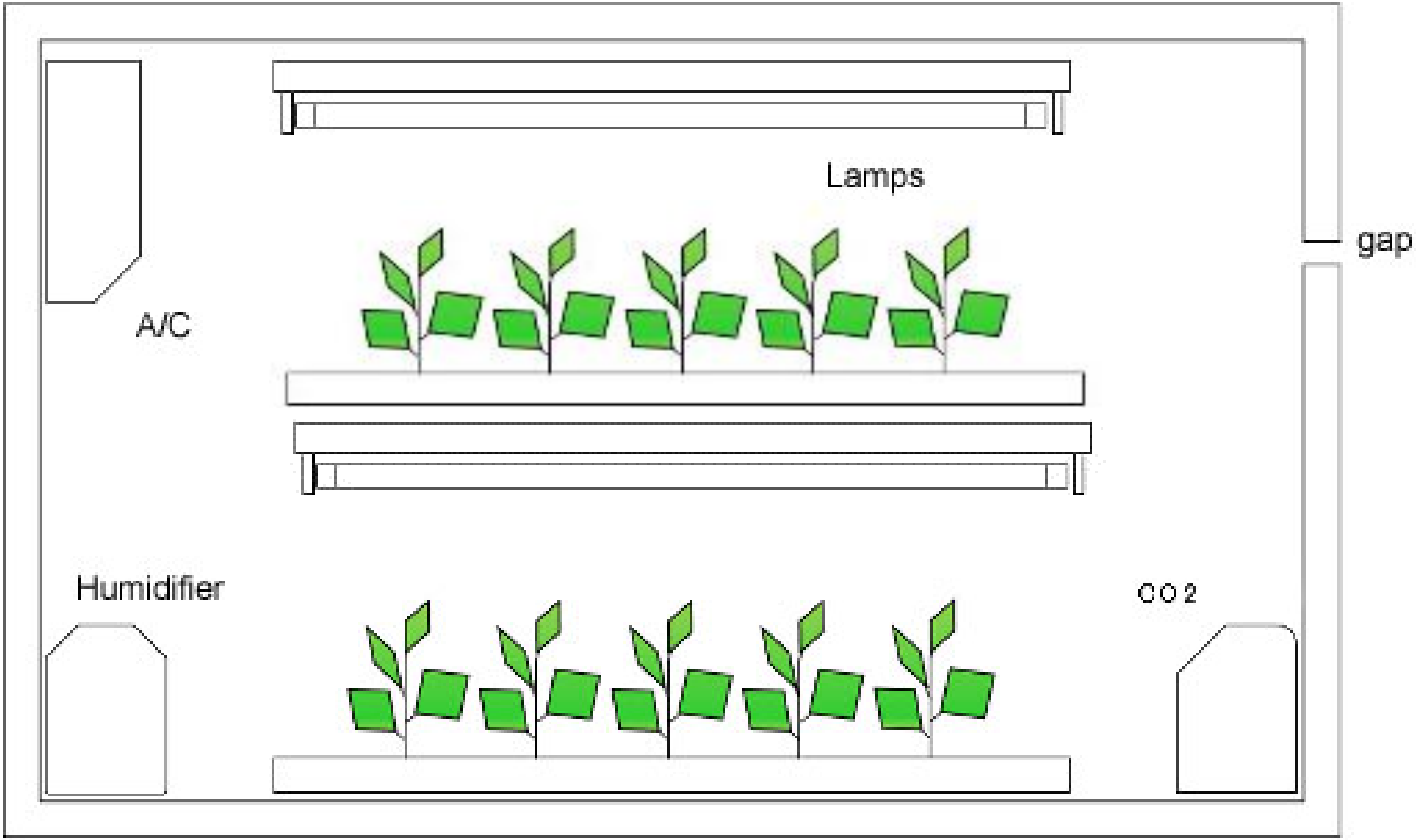
CHAPTER 17
ARTIFICIAL LIGHT TYPE PLANT FACTORIES

- Plant Factories with Artificial Light (PFAL) are facilities to grow plants in a closed space where plants have little influenced from the outside environment.
- No sunlight required in PFAL and walls covered by insulation.
- Almost air-tight (ACH < 0.01) to block air going in and block CO2 and cool air from going out.
- Need to supply light, CO2, water, nutrients, etc. in PFAL.
- Light source (mainly fluorescent lamps and LEDs) with high ratio of PAR to power consumption is desired
- PPFD of 200 to 300 $\mu mol/m^2/s$ or 40 to 70 W/m^2 of PAR is provided for leafy vegetables such as lettuce and spinach.

- In PFAL, CO_2 enrichment is required. CO_2 is supplied as liquefied CO_2, controlled with a solenoid valve while monitoring CO_2 concentration.
- PFALs normally much smaller than greenhouses, CO2 is not provided by burning gas or kerosene.
- Usually CO2 in PFALs is controlled at 1000 ppm (1.96 g/m3) ±20%.

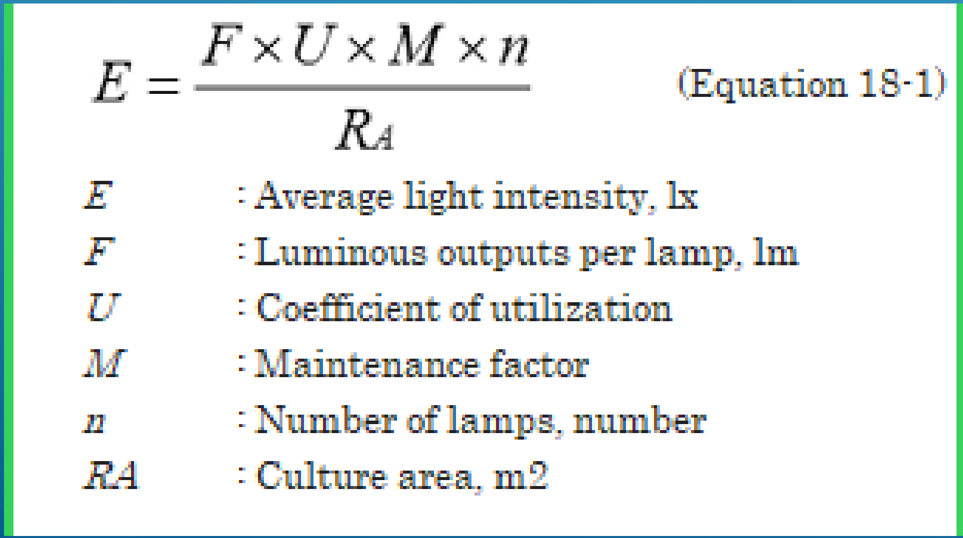
- In PFAL, most of the temperature (T) is through AC system. T needs to be controlled optimally for photosynthesis and plant growth.
- Normally T is kept constants with Light/Dark temperature difference.

- In PFAL, nutrient solution is provided in the rhizosphere through circulating system.
- The water with dissolved nutrients is absorbed by plants and then transpired from leaves to the air.
- Consequently, indoor relative humidity/water vapor density/absolute humidity/water vapor pressure goes up.
- Dehumidification (De-hum.) may be required. De-hum is performed with cooling, i.e. air conditioning.
- In PFALs, plants are grown on shelves in 5 to 10 layers to maximize production per unit floor area. There are culture solution flows on each shelf and the light sources above each shelf.


Lamps
gap
A/C
Humidifier
CO 2

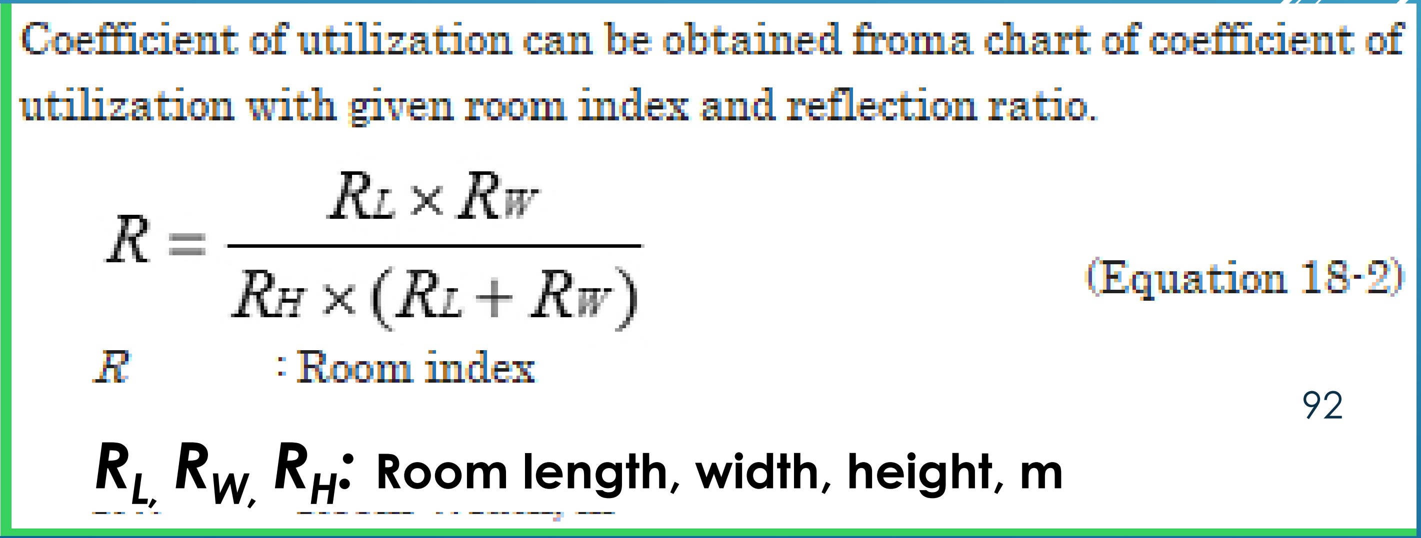
CHAPTER 18
LIGHTING AND IRRADIANCE

- It is always important to know what kind of lights will be used and how many of them are necessary.
- What are the light quality, duration and intensity required?
- Factors affecting light intensity on the surface of plants:
  1. Distance between lights and plants.
  2. Presence of light reflectors.
  3. Performance of light reflectors
  4. Surrounding environment, such as spacing among plants, color of walls or ceilings, distance of plants and walls, etc.
- An empirical equation is used in the area of architecture or lighting which calculate the light intensity with various light sources or room shapes.



$$E = \frac{F \times U \times M \times n}{R_A} \qquad \text{(Equation 18-1)}$$

E : Average light intensity, lx
F : Luminous outputs per lamp, lm
U : Coefficient of utilization
M : Maintenance factor
n : Number of lamps, number
RA : Culture area, m2



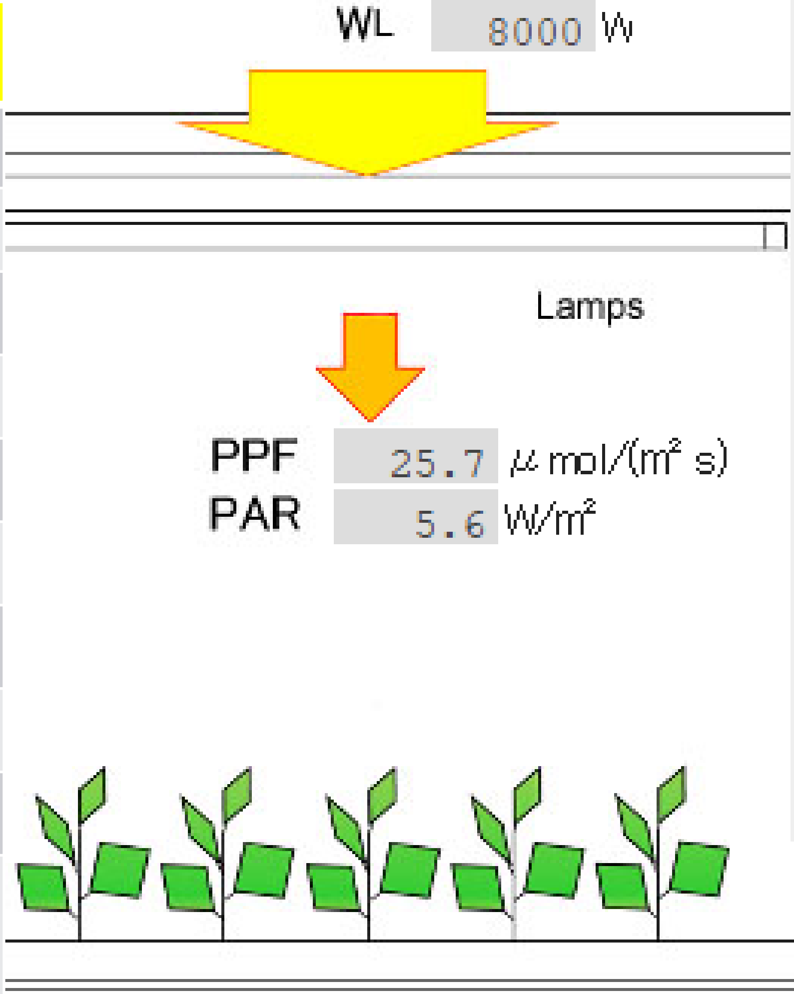
Coefficient of utilization can be obtained froma chart of coefficient of utilization with given room index and reflection ratio.

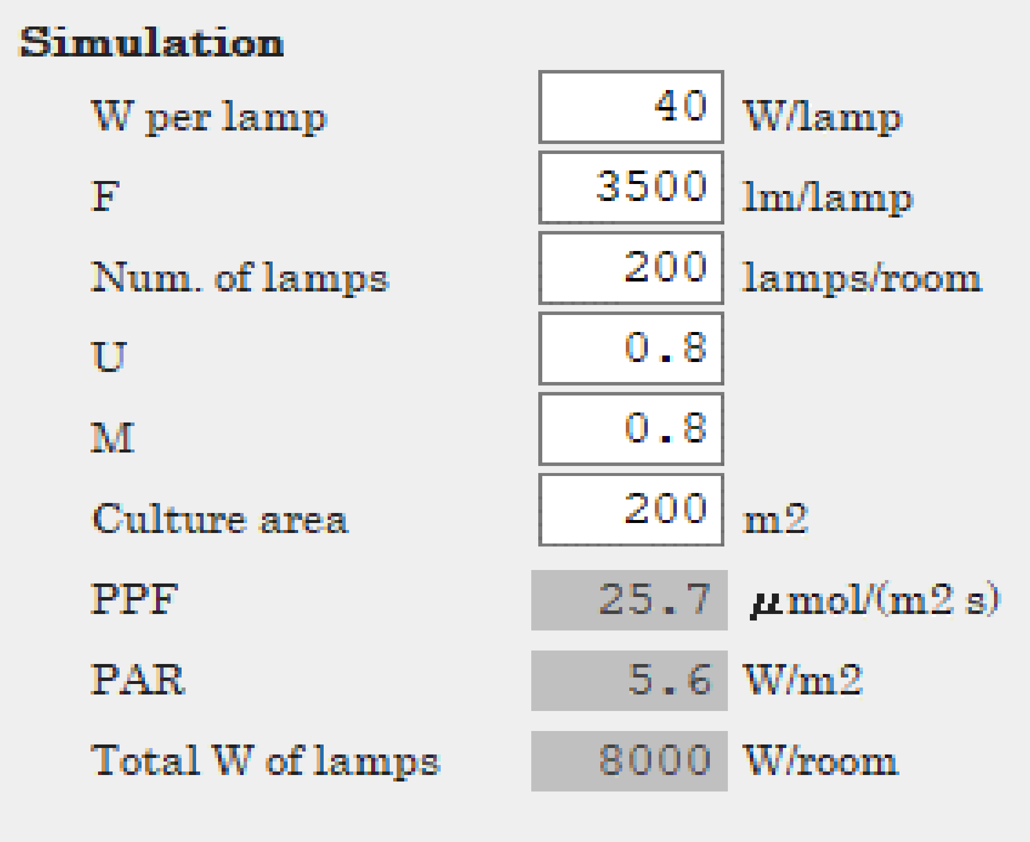
$$R = \frac{R_L \times R_W}{R_H \times (R_L + R_W)} \qquad \text{(Equation 18-2)}$$

R : Room index

R_L, R_W, R_H: Room length, width, height, m

2240 lux =	PPFD
Fluorescent lamp 5000K	30.22
Natural daylight	39.65
Halogen lamp 3000K	77.47
High CRI LED 6500K	38.6
High CRI LED 4000K	39.92
HPS 2000K	29.06
Red LED 650 nm	172.14
Blue LED 450 nm	258.84
Red+Blue LED	198.76
Red+Blue+White LED 450+650nm+3500K	57.54





Simulation

W per lamp	40	W/lamp
F	3500	lm/lamp
Num. of lamps	200	lamps/room
U	0.8	
M	0.8	
Culture area	200	m2
PPF	25.7	µmol/(m2 s)
PAR	5.6	W/m2
Total W of lamps	8000	W/room

WL (total W of lamps)= W/lamp*n

$= 40 * 200 = 8000$ W

$E = (F\ U\ M\ n)/R_A$

$= 3500*0.8*0.8*200/200$

$= 2240\ \text{lm/m}^2 = 2240$ lux

PPF = E/**87** = 25.7 $\mu\text{mol/m}^2/\text{s}$

PAR=PPF/**4.589** = 5.6 W/m^2

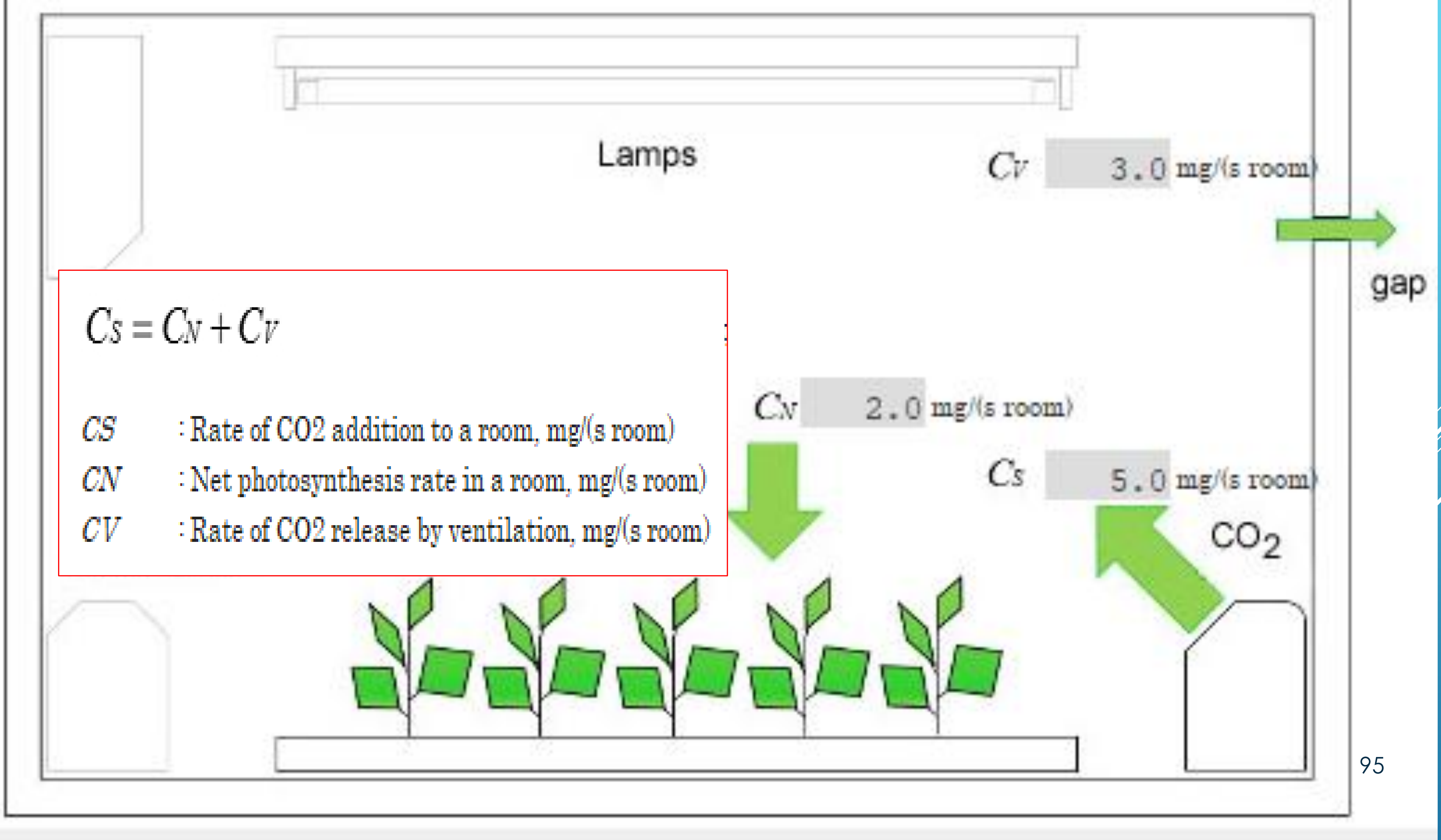
The coefficient of utilization (U): The % of light irradiated from light sources reaches the surface of plants. It is estimated 70% in efficient PAL.

The maintenance factor (M) accounts for deterioration of light sources by aging. A number of 60% for fluorescent lamps that have been used for a few year.

Fluorescent lamp only

assumed that 87 lx is equal to 1 µmol/(m2 s) or 0.218 W/m2.

CHAPTER 19
CO_2 BALANCE



$$C_S = C_N + C_V$$

CS : Rate of CO2 addition to a room, mg/(s room)
CN : Net photosynthesis rate in a room, mg/(s room)
CV : Rate of CO2 release by ventilation, mg/(s room)

Net Pn in a room (C_N) is calculated by multiplying the net Pn per leaf area (P_N, in mg/m^2/s) by total leaf area of plants in the room (L, m^2/room).

$$C_N = P_N * L$$

This is for the sake of simplicity, net Pn of a plant or a plant community is estimated using net Pn per leaf area.

$$C_N = P_N \times L \quad = P_N \times LA.plt \times Num.plt$$

P_N : Net photosynthesis rate per leave area, mg/(m2s)
L : Total leaf area in a room, m2/room

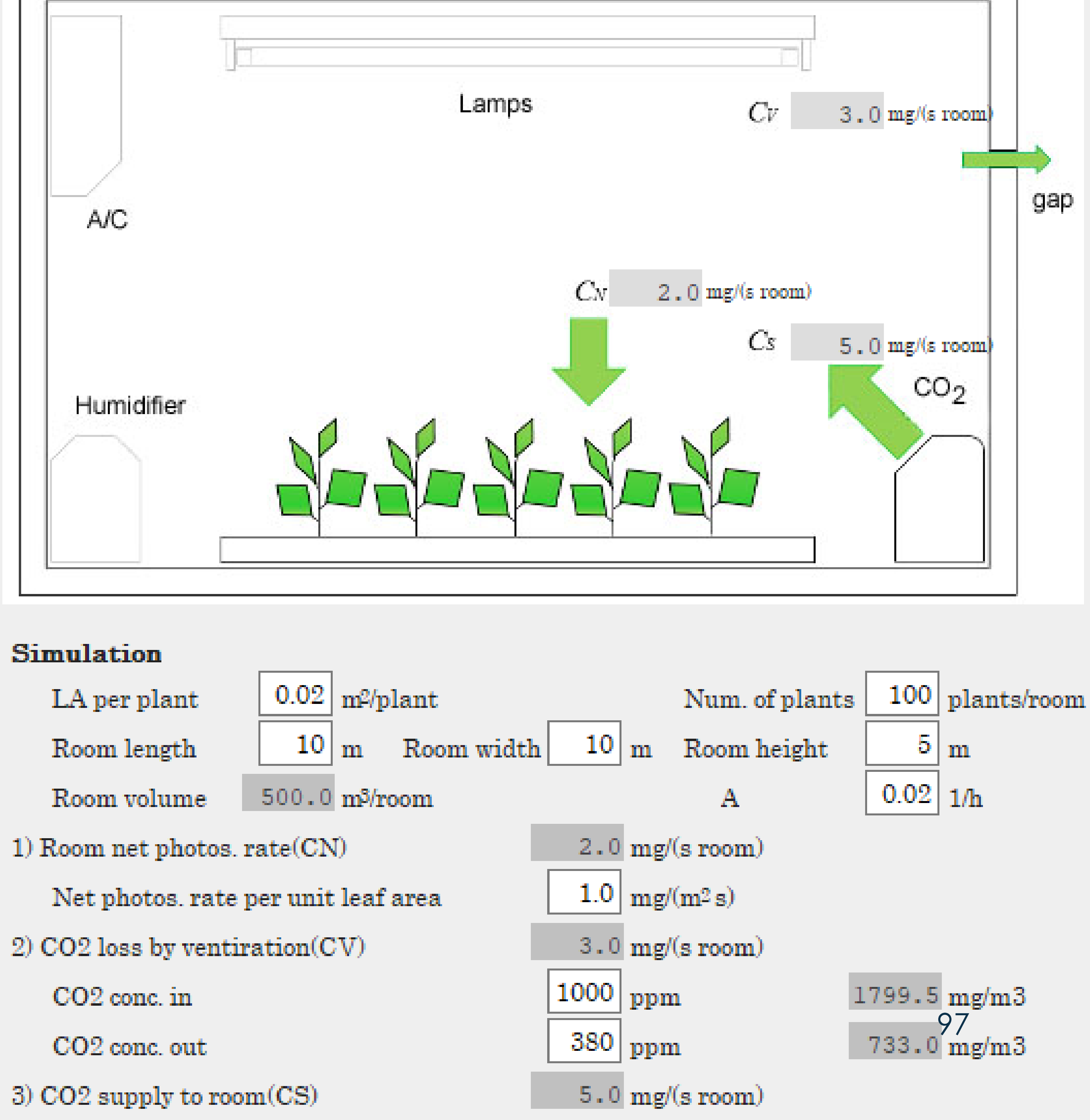
$$C_N = 1 * (0.02*100) = 2 \text{ mg/(s.room)}$$

$$C_V = A \times (\rho_{ca\,in} - \rho_{ca\,out}) \times V_r$$

A : Ventilation rate, 1/h
V_r : Interior Volume
ρ_{ca} in : Inside CO2 concentration, mg/m3
ρ_{ca} out : Outside CO2 concentration, mg/m3

$$C_v = 0.02*(1799.5-733)*500 / 3600 = 2.9625 \text{ mg/s}$$

$$C_s = C_v + C_N = 2 + 2.96 = 4.96 \text{ mg/s}$$

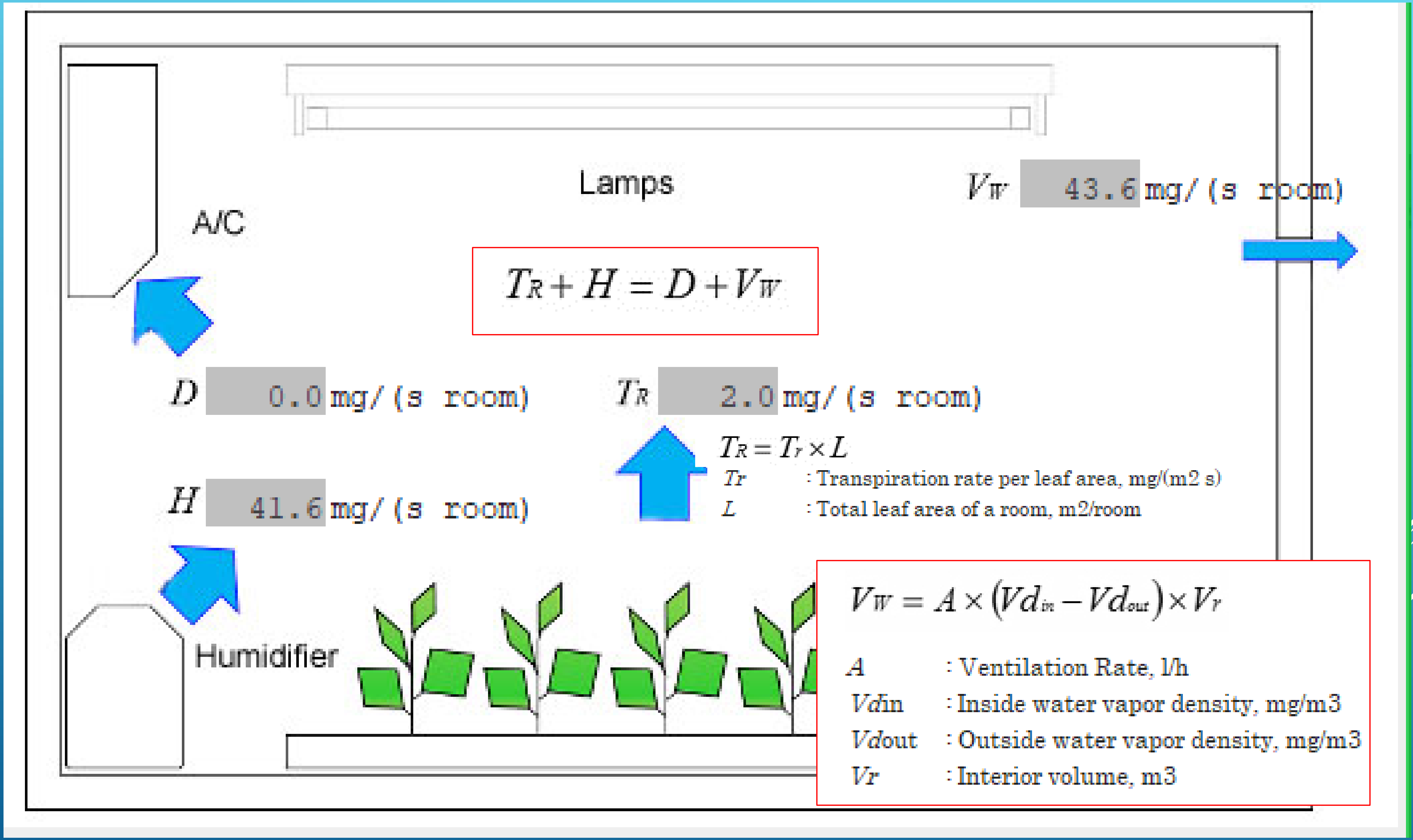


C_V 3.0 mg/(s room)
C_N 2.0 mg/(s room)
C_S 5.0 mg/(s room)

Simulation

LA per plant 0.02 m²/plant Num. of plants 100 plants/room
Room length 10 m Room width 10 m Room height 5 m
Room volume 500.0 m³/room A 0.02 1/h
1) Room net photos. rate(CN) 2.0 mg/(s room)
Net photos. rate per unit leaf area 1.0 mg/(m² s)
2) CO2 loss by ventiration(CV) 3.0 mg/(s room)
CO2 conc. in 1000 ppm 1799.5 mg/m3
CO2 conc. out 380 ppm 733.0 mg/m3
3) CO2 supply to room(CS) 5.0 mg/(s room)

CHAPTER 20
WATER BALANCE



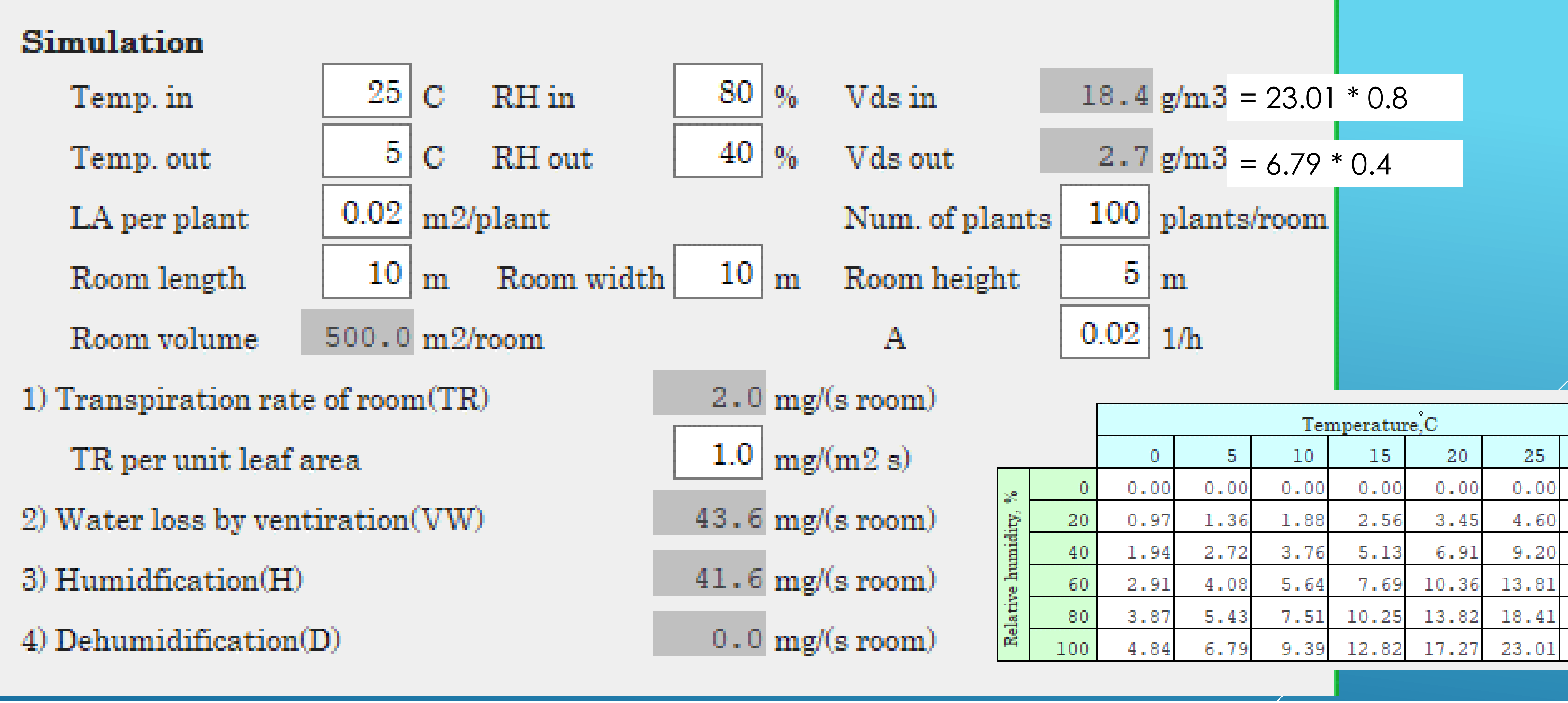
$$T_R + H = D + V_W$$

$$T_R = T_r \times L$$

T_r : Transpiration rate per leaf area, mg/(m2 s)
L : Total leaf area of a room, m2/room

$$V_W = A \times (Vd_{in} - Vd_{out}) \times V_r$$

A : Ventilation Rate, l/h
$Vdin$: Inside water vapor density, mg/m3
$Vdout$: Outside water vapor density, mg/m3
Vr : Interior volume, m3



Simulation

Temp. in	25	C	RH in	80	%	Vds in	18.4	g/m3	= 23.01 * 0.8
Temp. out	5	C	RH out	40	%	Vds out	2.7	g/m3	= 6.79 * 0.4
LA per plant	0.02	m2/plant				Num. of plants	100	plants/room	
Room length	10	m	Room width	10	m	Room height	5	m	
Room volume	500.0	m2/room				A	0.02	1/h	

1) Transpiration rate of room(TR)	2.0	mg/(s room)
TR per unit leaf area	1.0	mg/(m2 s)
2) Water loss by ventiration(VW)	43.6	mg/(s room)
3) Humidfication(H)	41.6	mg/(s room)
4) Dehumidification(D)	0.0	mg/(s room)

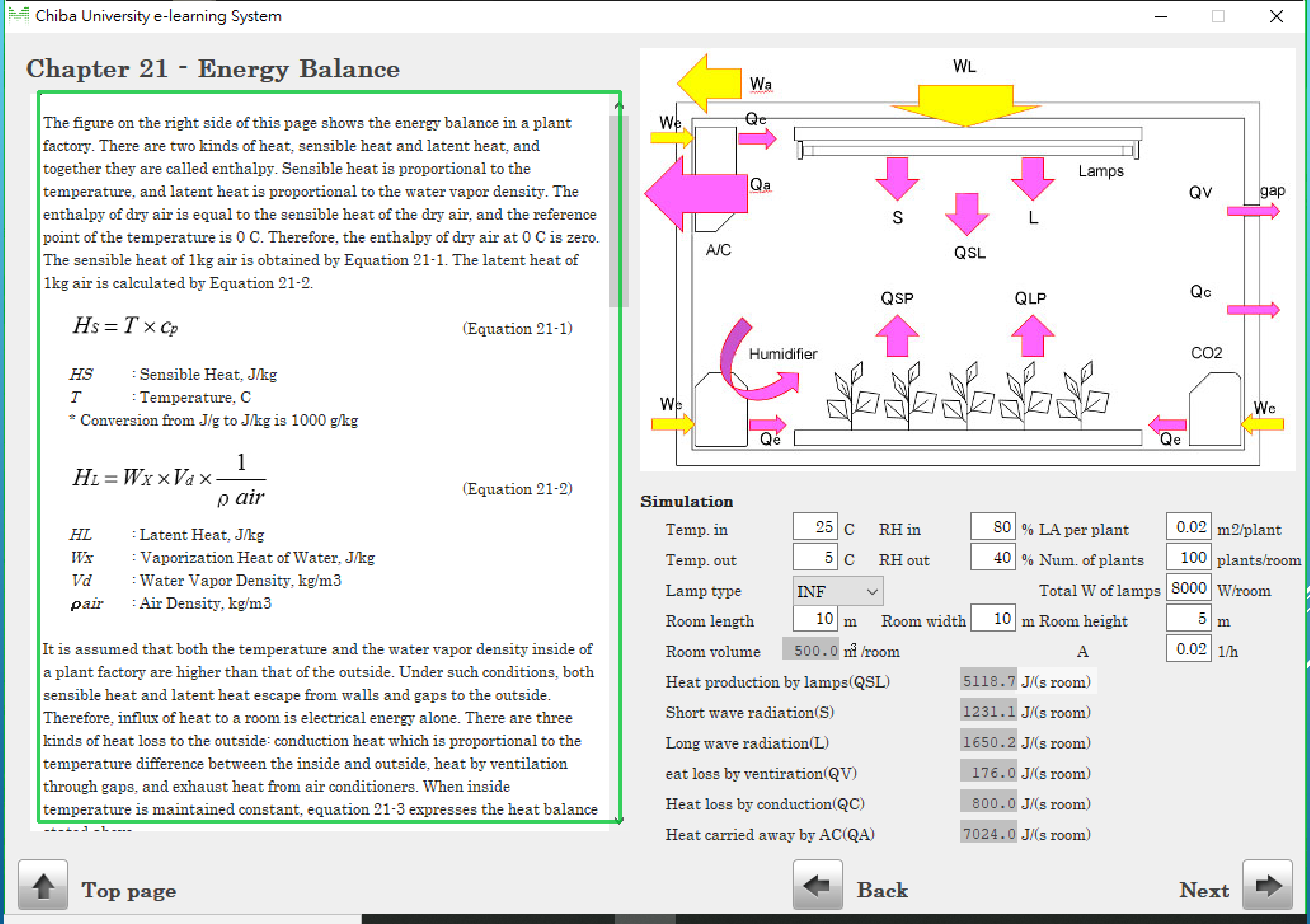
		Temperature, °C					
		0	5	10	15	20	25
Relative humidity, %	0	0.00	0.00	0.00	0.00	0.00	0.00
	20	0.97	1.36	1.88	2.56	3.45	4.60
	40	1.94	2.72	3.76	5.13	6.91	9.20
	60	2.91	4.08	5.64	7.69	10.36	13.81
	80	3.87	5.43	7.51	10.25	13.82	18.41
	100	4.84	6.79	9.39	12.82	17.27	23.01

$T_R = Tr * L = 1 * 2 = 2$ mg/(s.room)

$V_w = 0.02*(18.4-2.7)*500/3600 = 0.0436$ g/(s.room) = 43.6 mg/(s.room)

TR + H = D + Vw, 2 + H = D + 43.6, D=0 (no dehumidification), H = 43.6 – 2 = 41.6

CHAPTER 21
ENERGY BALANCE



Chapter 21 - Energy Balance

The figure on the right side of this page shows the energy balance in a plant factory. There are two kinds of heat, sensible heat and latent heat, and together they are called enthalpy. Sensible heat is proportional to the temperature, and latent heat is proportional to the water vapor density. The enthalpy of dry air is equal to the sensible heat of the dry air, and the reference point of the temperature is 0 C. Therefore, the enthalpy of dry air at 0 C is zero. The sensible heat of 1kg air is obtained by Equation 21-1. The latent heat of 1kg air is calculated by Equation 21-2.

$$H_S = T \times c_p \qquad \text{(Equation 21-1)}$$

HS : Sensible Heat, J/kg
T : Temperature, C
* Conversion from J/g to J/kg is 1000 g/kg

$$H_L = W_X \times V_d \times \frac{1}{\rho\ air} \qquad \text{(Equation 21-2)}$$

HL : Latent Heat, J/kg
Wx : Vaporization Heat of Water, J/kg
Vd : Water Vapor Density, kg/m3
ρair : Air Density, kg/m3

It is assumed that both the temperature and the water vapor density inside of a plant factory are higher than that of the outside. Under such conditions, both sensible heat and latent heat escape from walls and gaps to the outside. Therefore, influx of heat to a room is electrical energy alone. There are three kinds of heat loss to the outside: conduction heat which is proportional to the temperature difference between the inside and outside, heat by ventilation through gaps, and exhaust heat from air conditioners. When inside temperature is maintained constant, equation 21-3 expresses the heat balance

Simulation

Temp. in 25 C
RH in 80 %
LA per plant 0.02 m2/plant
Temp. out 5 C
RH out 40 %
Num. of plants 100 plants/room
Lamp type INF
Total W of lamps 8000 W/room
Room length 10 m
Room width 10 m
Room height 5 m
Room volume 500.0 ㎥ /room
A 0.02 1/h
Heat production by lamps(QSL) 5118.7 J/(s room)
Short wave radiation(S) 1231.1 J/(s room)
Long wave radiation(L) 1650.2 J/(s room)
eat loss by ventiration(QV) 176.0 J/(s room)
Heat loss by conduction(QC) 800.0 J/(s room)
Heat carried away by AC(QA) 7024.0 J/(s room)

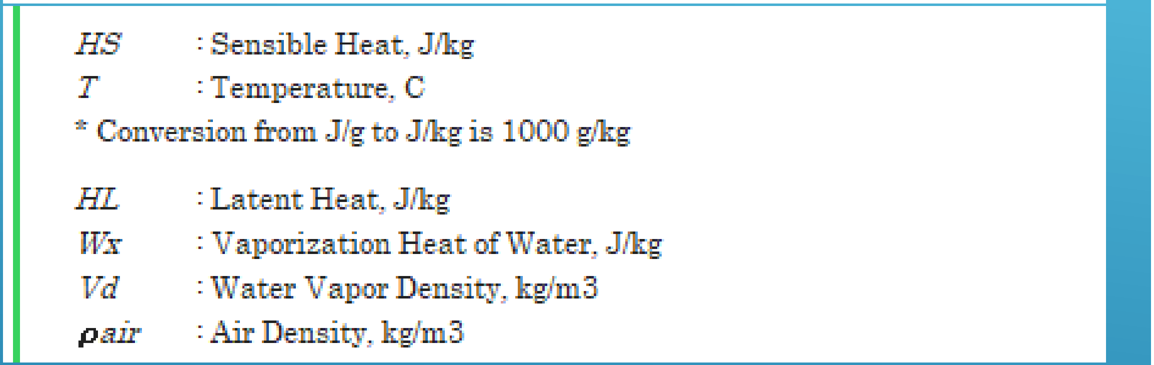
There are two kinds of heat, together they are called enthalpy:

1. Sensible heat of 1 kg air

$$H_s \text{ (in J/kg)} = T \times C_p$$

2. Latent heat of 1 kg air:

$$H_L \text{ (in J/kg)} = W_x \times V_d / \rho_{air} = W_x * AH$$



HS : Sensible Heat, J/kg
T : Temperature, C
* Conversion from J/g to J/kg is 1000 g/kg

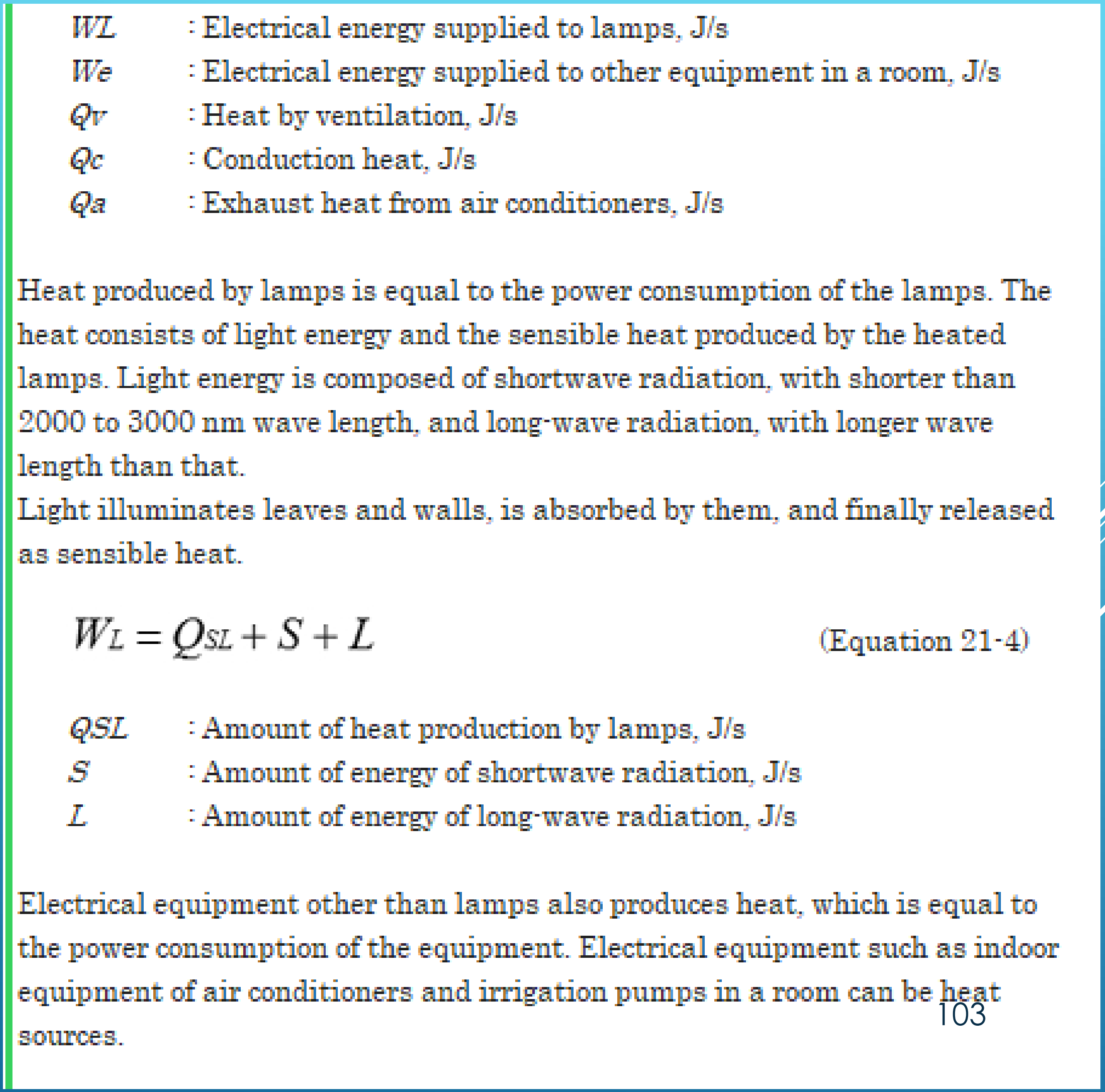
HL : Latent Heat, J/kg
Wx : Vaporization Heat of Water, J/kg
Vd : Water Vapor Density, kg/m3
ρair : Air Density, kg/m3

Assumed T and Vd in a PFAL are higher than outside, thus Hs and HL escape from walls and gaps to outside.

Influx of the heat to PFAL is electrical energy alone (W_L and W_e).

When indoor T keep constant, the heat balance can be expressed as follows:

$$W_L + W_e = Q_V + Q_c + Q_a$$



WL : Electrical energy supplied to lamps, J/s
We : Electrical energy supplied to other equipment in a room, J/s
Qv : Heat by ventilation, J/s
Qc : Conduction heat, J/s
Qa : Exhaust heat from air conditioners, J/s

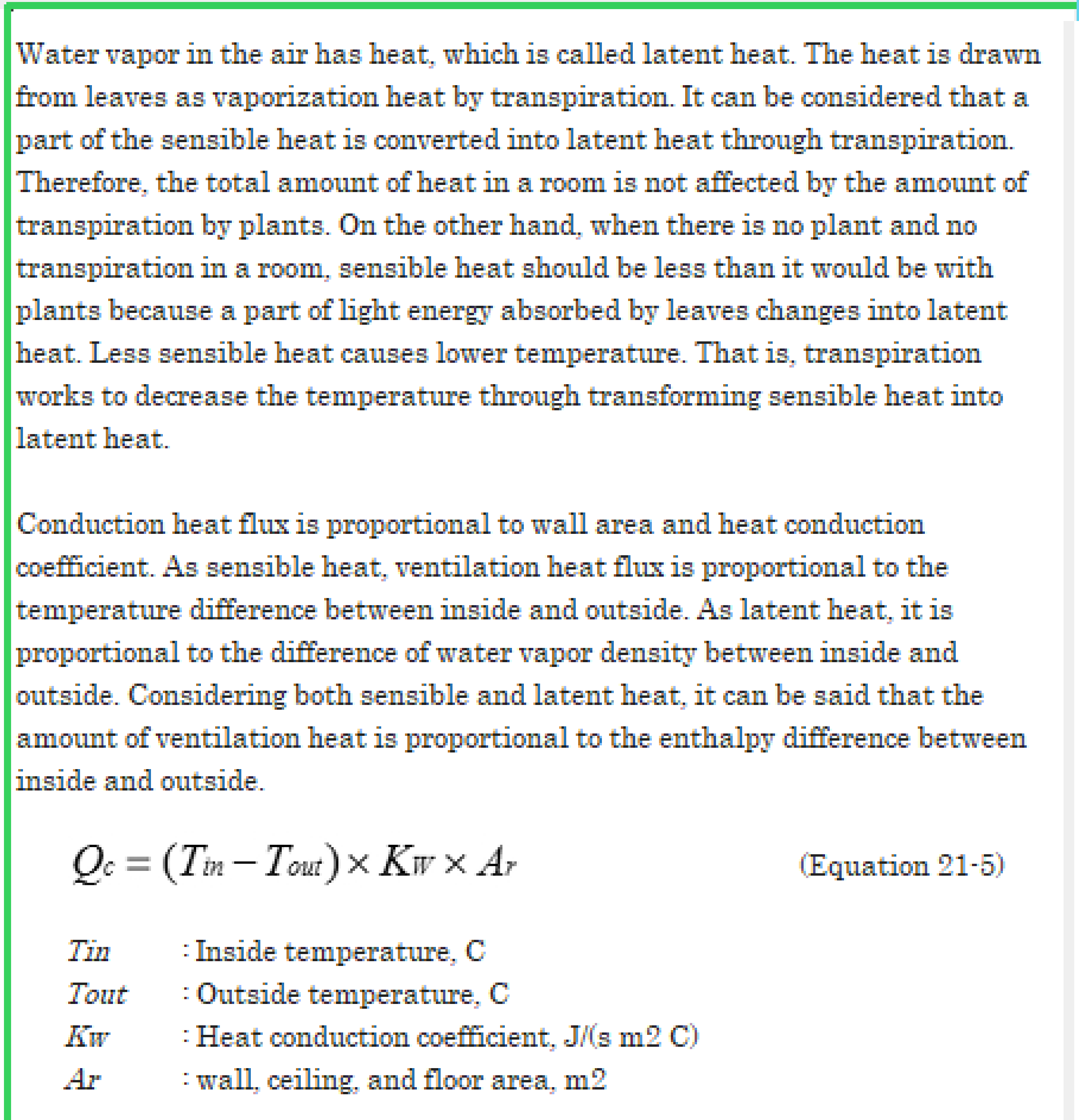
Heat produced by lamps is equal to the power consumption of the lamps. The heat consists of light energy and the sensible heat produced by the heated lamps. Light energy is composed of shortwave radiation, with shorter than 2000 to 3000 nm wave length, and long-wave radiation, with longer wave length than that.

Light illuminates leaves and walls, is absorbed by them, and finally released as sensible heat.

$$W_L = Q_{SL} + S + L \qquad \text{(Equation 21-4)}$$

QSL : Amount of heat production by lamps, J/s
S : Amount of energy of shortwave radiation, J/s
L : Amount of energy of long-wave radiation, J/s

Electrical equipment other than lamps also produces heat, which is equal to the power consumption of the equipment. Electrical equipment such as indoor equipment of air conditioners and irrigation pumps in a room can be heat sources.

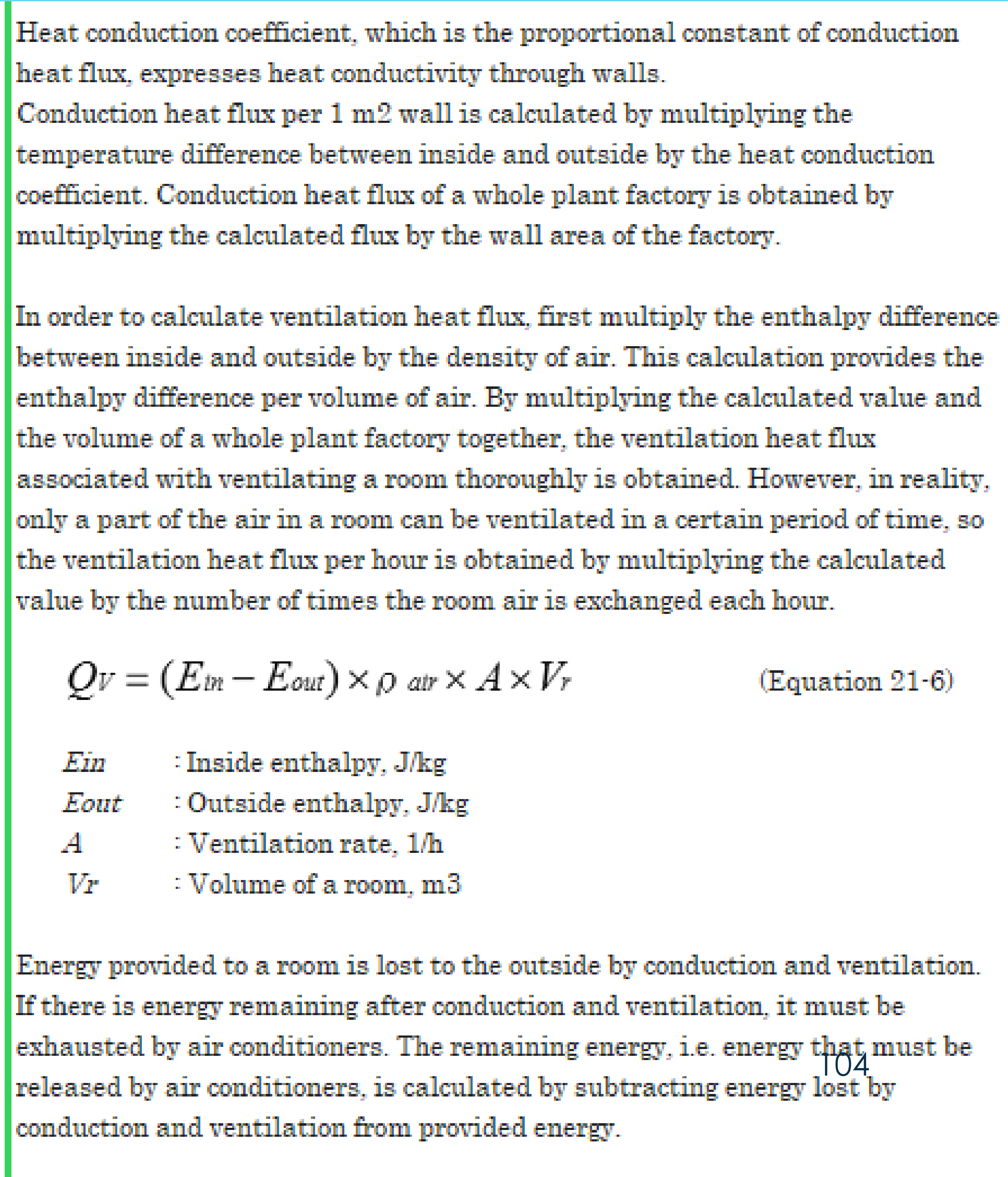


Water vapor in the air has heat, which is called latent heat. The heat is drawn from leaves as vaporization heat by transpiration. It can be considered that a part of the sensible heat is converted into latent heat through transpiration. Therefore, the total amount of heat in a room is not affected by the amount of transpiration by plants. On the other hand, when there is no plant and no transpiration in a room, sensible heat should be less than it would be with plants because a part of light energy absorbed by leaves changes into latent heat. Less sensible heat causes lower temperature. That is, transpiration works to decrease the temperature through transforming sensible heat into latent heat.

Conduction heat flux is proportional to wall area and heat conduction coefficient. As sensible heat, ventilation heat flux is proportional to the temperature difference between inside and outside. As latent heat, it is proportional to the difference of water vapor density between inside and outside. Considering both sensible and latent heat, it can be said that the amount of ventilation heat is proportional to the enthalpy difference between inside and outside.

$$Q_c = (T_{in} - T_{out}) \times K_W \times A_r \qquad \text{(Equation 21-5)}$$

Tin : Inside temperature, C
$Tout$: Outside temperature, C
Kw : Heat conduction coefficient, J/(s m2 C)
Ar : wall, ceiling, and floor area, m2



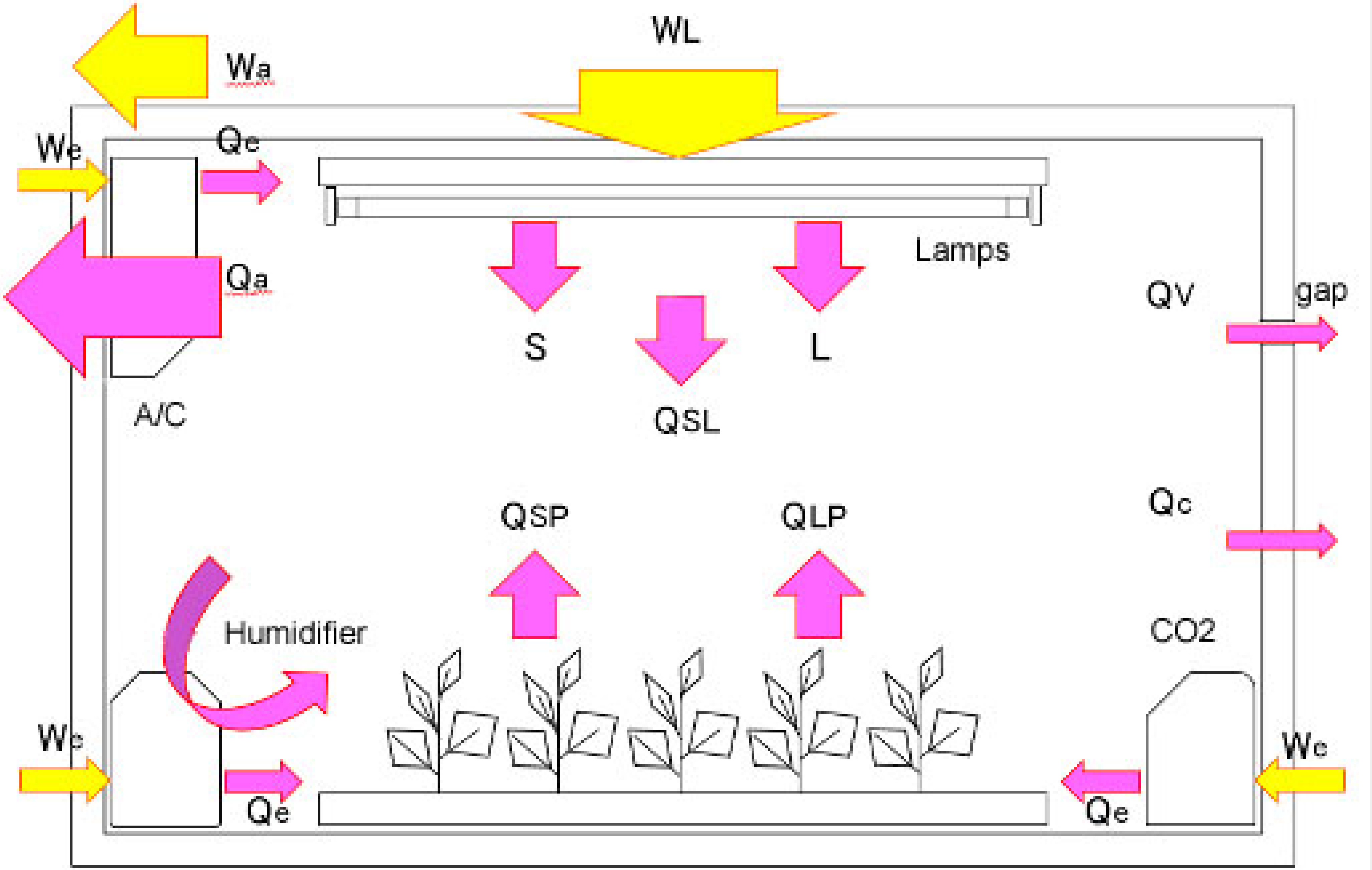
Heat conduction coefficient, which is the proportional constant of conduction heat flux, expresses heat conductivity through walls.
Conduction heat flux per 1 m2 wall is calculated by multiplying the temperature difference between inside and outside by the heat conduction coefficient. Conduction heat flux of a whole plant factory is obtained by multiplying the calculated flux by the wall area of the factory.

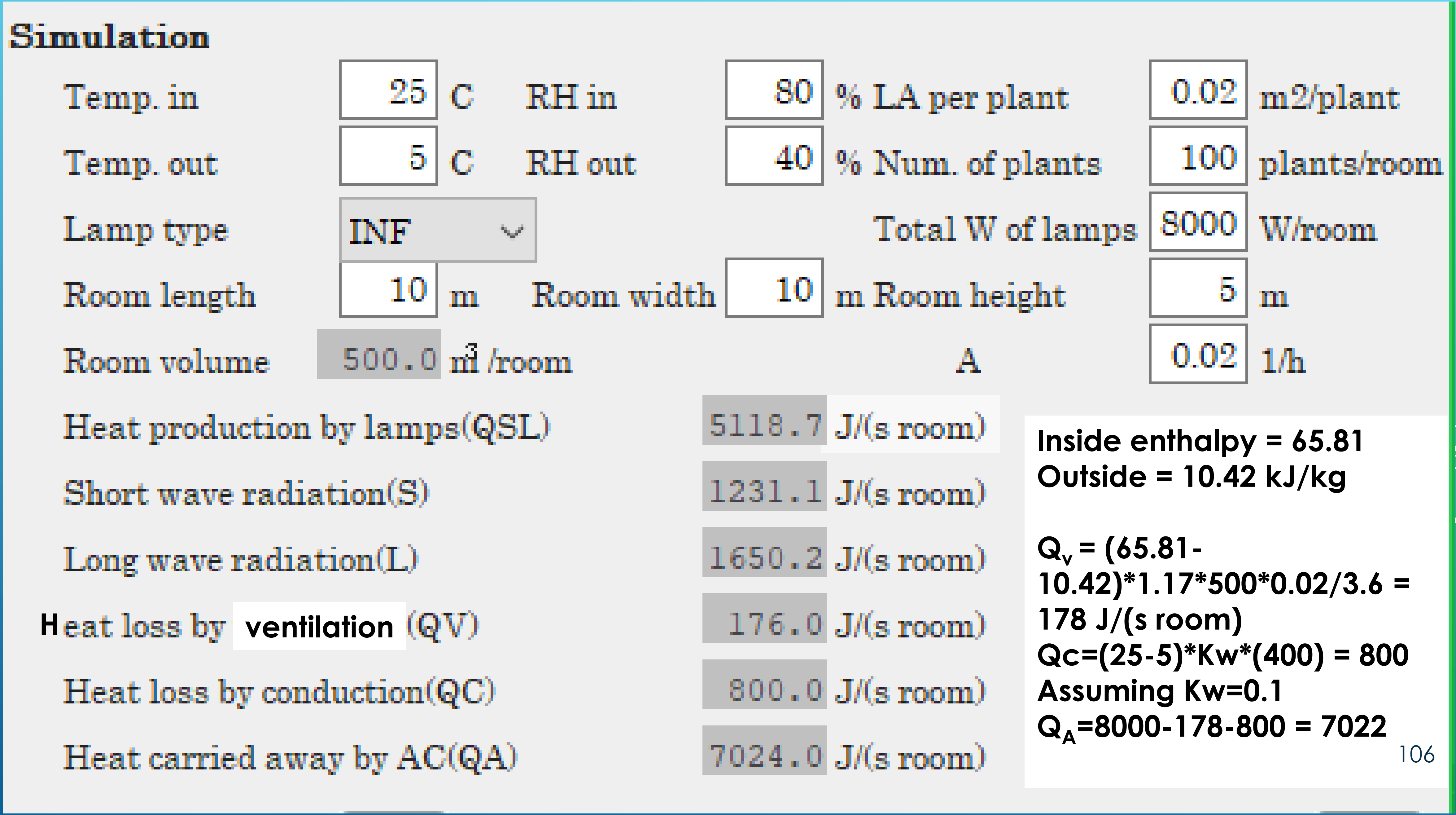
In order to calculate ventilation heat flux, first multiply the enthalpy difference between inside and outside by the density of air. This calculation provides the enthalpy difference per volume of air. By multiplying the calculated value and the volume of a whole plant factory together, the ventilation heat flux associated with ventilating a room thoroughly is obtained. However, in reality, only a part of the air in a room can be ventilated in a certain period of time, so the ventilation heat flux per hour is obtained by multiplying the calculated value by the number of times the room air is exchanged each hour.

$$Q_V = (E_{in} - E_{out}) \times \rho_{air} \times A \times V_r \qquad \text{(Equation 21-6)}$$

Ein : Inside enthalpy, J/kg
$Eout$: Outside enthalpy, J/kg
A : Ventilation rate, 1/h
Vr : Volume of a room, m3

Energy provided to a room is lost to the outside by conduction and ventilation. If there is energy remaining after conduction and ventilation, it must be exhausted by air conditioners. The remaining energy, i.e. energy that must be released by air conditioners, is calculated by subtracting energy lost by conduction and ventilation from provided energy.


Wa
WL
We
Qe
Qa
A/C
Lamps
S
L
QSL
QV
gap
Qc
QSP
QLP
Humidifier
CO2
Wb
Qe
Qe
Wc



Simulation

Temp. in 25 C

RH in 80 %

LA per plant 0.02 m2/plant

Temp. out 5 C

RH out 40 %

Num. of plants 100 plants/room

Lamp type INF

Total W of lamps 8000 W/room

Room length 10 m

Room width 10 m

Room height 5 m

Room volume 500.0 m^3 /room

A 0.02 1/h

Heat production by lamps(QSL) 5118.7 J/(s room)

Short wave radiation(S) 1231.1 J/(s room)

Long wave radiation(L) 1650.2 J/(s room)

Heat loss by ventilation (QV) 176.0 J/(s room)

Heat loss by conduction(QC) 800.0 J/(s room)

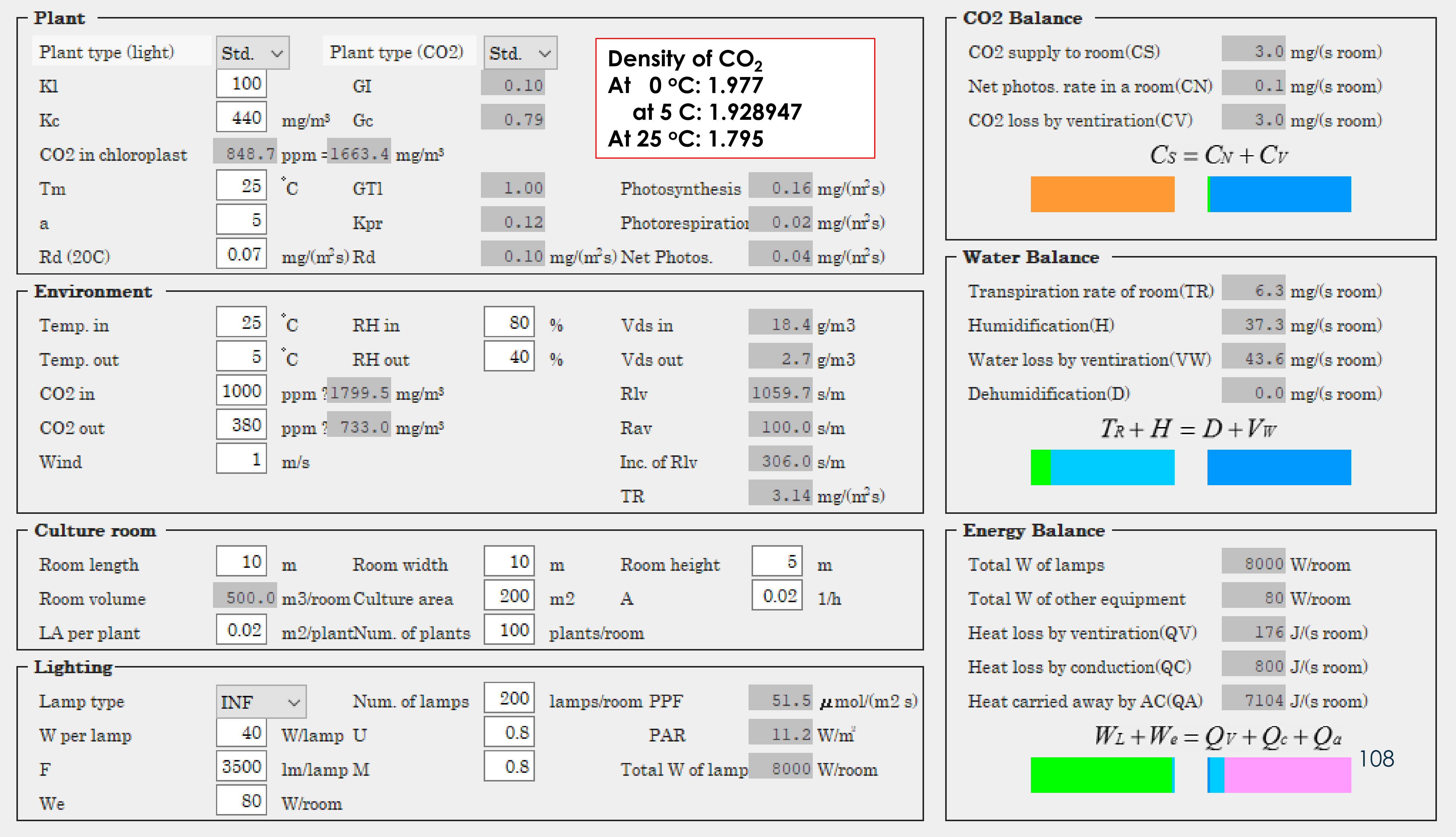
Heat carried away by AC(QA) 7024.0 J/(s room)

Inside enthalpy = 65.81
Outside = 10.42 kJ/kg

Q_v = (65.81-10.42)*1.17*500*0.02/3.6 = 178 J/(s room)
Qc=(25-5)*Kw*(400) = 800
Assuming Kw=0.1
Q_A=8000-178-800 = 7022

CHAPTER 22

SIMULATION OF A PLANT FACTORY



Plant

Plant type (light)	Std.		Plant type (CO2)	Std.				
Kl	100		GI	0.10				
Kc	440	mg/m³	Gc	0.79				
CO2 in chloroplast	848.7	ppm = 1663.4 mg/m³						
Tm	25	°C	GT1	1.00		Photosynthesis	0.16	mg/(m²s)
a	5		Kpr	0.12		Photorespiratio	0.02	mg/(m²s)
Rd (20C)	0.07	mg/(m²s)	Rd	0.10	mg/(m²s)	Net Photos.	0.04	mg/(m²s)

Density of CO_2
At 0 °C: 1.977
at 5 C: 1.928947
At 25 °C: 1.795

Environment

Temp. in	25	°C	RH in	80	%	Vds in	18.4	g/m3
Temp. out	5	°C	RH out	40	%	Vds out	2.7	g/m3
CO2 in	1000	ppm ? 1799.5 mg/m³				Rlv	1059.7	s/m
CO2 out	380	ppm ? 733.0 mg/m³				Rav	100.0	s/m
Wind	1	m/s				Inc. of Rlv	306.0	s/m
						TR	3.14	mg/(m²s)

Culture room

Room length	10	m	Room width	10	m	Room height	5	m
Room volume	500.0	m3/room	Culture area	200	m2	A	0.02	1/h
LA per plant	0.02	m2/plant	Num. of plants	100	plants/room			

Lighting

Lamp type	INF		Num. of lamps	200	lamps/room	PPF	51.5	μmol/(m2 s)
W per lamp	40	W/lamp	U	0.8		PAR	11.2	W/m²
F	3500	lm/lamp	M	0.8		Total W of lamp	8000	W/room
We	80	W/room						

CO2 Balance

CO2 supply to room(CS)	3.0	mg/(s room)
Net photos. rate in a room(CN)	0.1	mg/(s room)
CO2 loss by ventiration(CV)	3.0	mg/(s room)

$$C_S = C_N + C_V$$

Water Balance

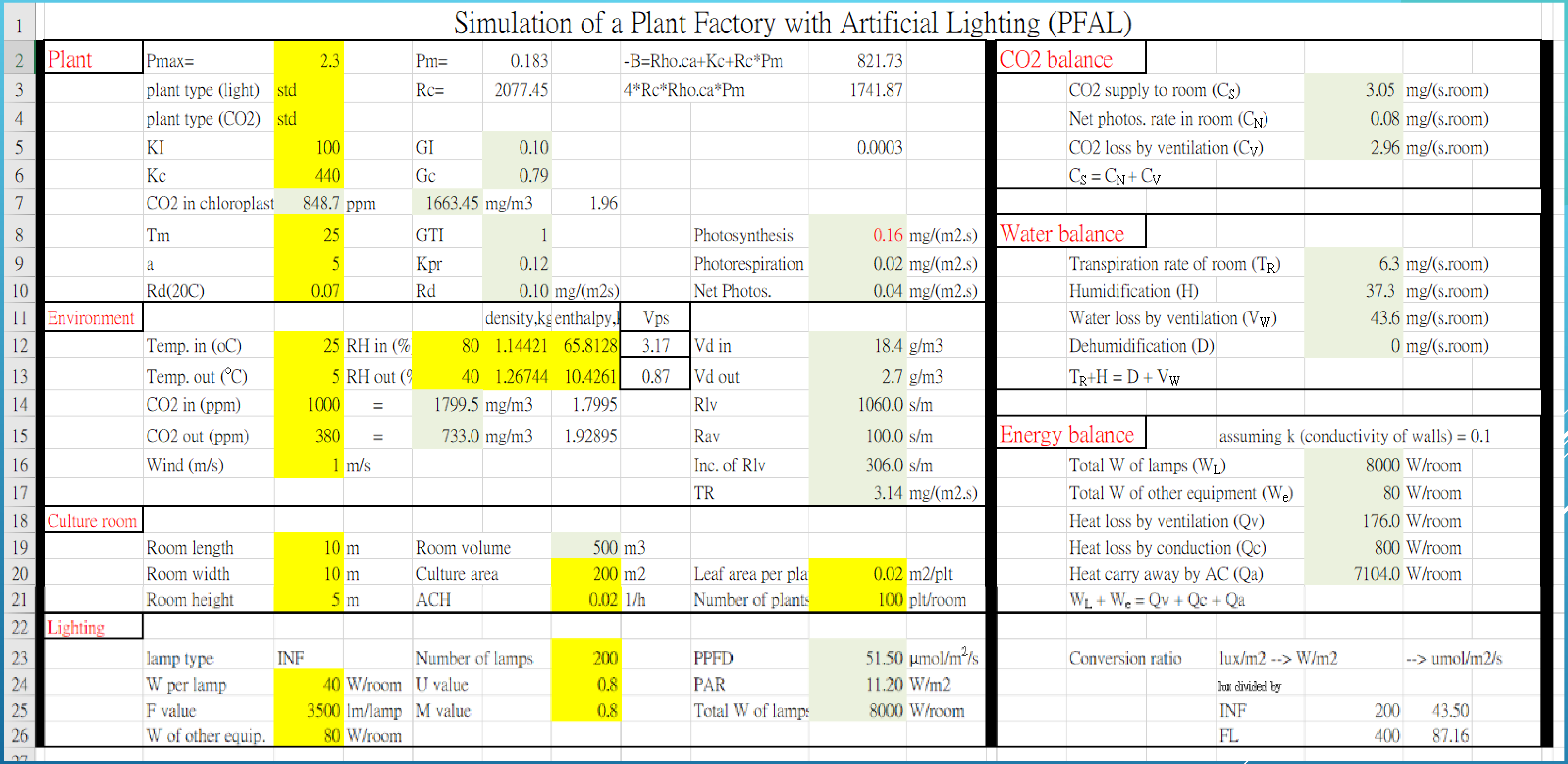
Transpiration rate of room(TR)	6.3	mg/(s room)
Humidification(H)	37.3	mg/(s room)
Water loss by ventiration(VW)	43.6	mg/(s room)
Dehumidification(D)	0.0	mg/(s room)

$$T_R + H = D + V_W$$

Energy Balance

Total W of lamps	8000	W/room
Total W of other equipment	80	W/room
Heat loss by ventiration(QV)	176	J/(s room)
Heat loss by conduction(QC)	800	J/(s room)
Heat carried away by AC(QA)	7104	J/(s room)

$$W_L + W_e = Q_V + Q_c + Q_a$$



Simulation of a Plant Factory with Artificial Lighting (PFAL)

2	Plant	Pmax=	2.3		Pm=	0.183		-B=Rho.ca+Kc+Rc*Pm		821.73	
3		plant type (light)	std		Rc=	2077.45		4*Rc*Rho.ca*Pm		1741.87	
4		plant type (CO2)	std								
5		KI	100		GI	0.10				0.0003	
6		Kc	440		Gc	0.79					
7		CO2 in chloroplast	848.7	ppm	1663.45	mg/m3	1.96				
8		Tm	25		GTI	1			Photosynthesis	0.16	mg/(m2.s)
9		a	5		Kpr	0.12			Photorespiration	0.02	mg/(m2.s)
10		Rd(20C)	0.07		Rd	0.10	mg/(m2s)		Net Photos.	0.04	mg/(m2.s)
11	Environment					density,kg	enthalpy,k	Vps			
12		Temp. in (oC)	25	RH in (%	80	1.14421	65.8128	3.17	Vd in	18.4	g/m3
13		Temp. out (°C)	5	RH out (%	40	1.26744	10.4261	0.87	Vd out	2.7	g/m3
14		CO2 in (ppm)	1000	=	1799.5	mg/m3	1.7995		Rlv	1060.0	s/m
15		CO2 out (ppm)	380	=	733.0	mg/m3	1.92895		Rav	100.0	s/m
16		Wind (m/s)	1	m/s					Inc. of Rlv	306.0	s/m
17									TR	3.14	mg/(m2.s)
18	Culture room										
19		Room length	10	m	Room volume		500	m3			
20		Room width	10	m	Culture area		200	m2	Leaf area per pla	0.02	m2/plt
21		Room height	5	m	ACH		0.02	1/h	Number of plants	100	plt/room
22	Lighting										
23		lamp type	INF		Number of lamps		200		PPFD	51.50	μmol/m^2/s
24		W per lamp	40	W/room	U value		0.8		PAR	11.20	W/m2
25		F value	3500	lm/lamp	M value		0.8		Total W of lamps	8000	W/room
26		W of other equip.	80	W/room							

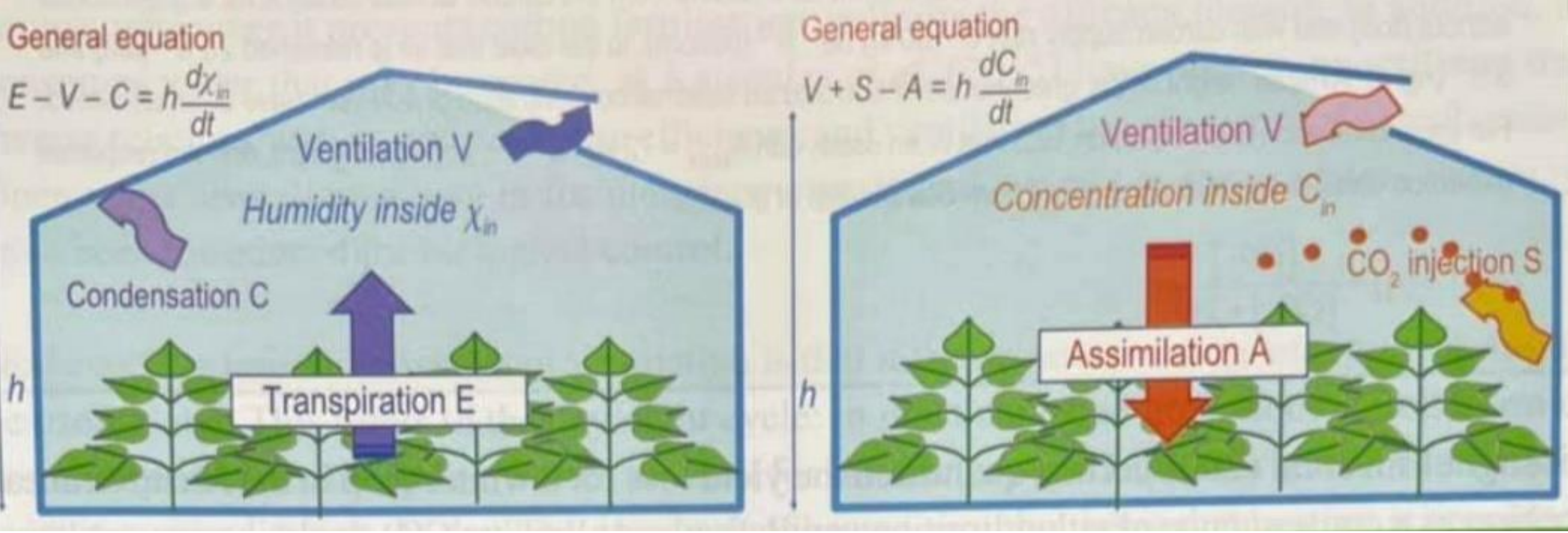
2	CO2 balance					
3		CO2 supply to room (C_S)			3.05	mg/(s.room)
4		Net photos. rate in room (C_N)			0.08	mg/(s.room)
5		CO2 loss by ventilation (C_V)			2.96	mg/(s.room)
6		$C_S = C_N + C_V$				
8	Water balance					
9		Transpiration rate of room (T_R)			6.3	mg/(s.room)
10		Humidification (H)			37.3	mg/(s.room)
11		Water loss by ventilation (V_W)			43.6	mg/(s.room)
12		Dehumidification (D)			0	mg/(s.room)
13		$T_R + H = D + V_W$				
15	Energy balance			assuming k (conductivity of walls) = 0.1		
16		Total W of lamps (W_L)			8000	W/room
17		Total W of other equipment (W_e)			80	W/room
18		Heat loss by ventilation (Qv)			176.0	W/room
19		Heat loss by conduction (Qc)			800	W/room
20		Heat carry away by AC (Qa)			7104.0	W/room
21		$W_L + W_e = Qv + Qc + Qa$				
23		Conversion ratio		lux/m2 --> W/m2		--> umol/m2/s
24				lux divided by		
25				INF	200	43.50
26				FL	400	87.16

Check the Pn_simulation.xlsx for details

THE END

SUP

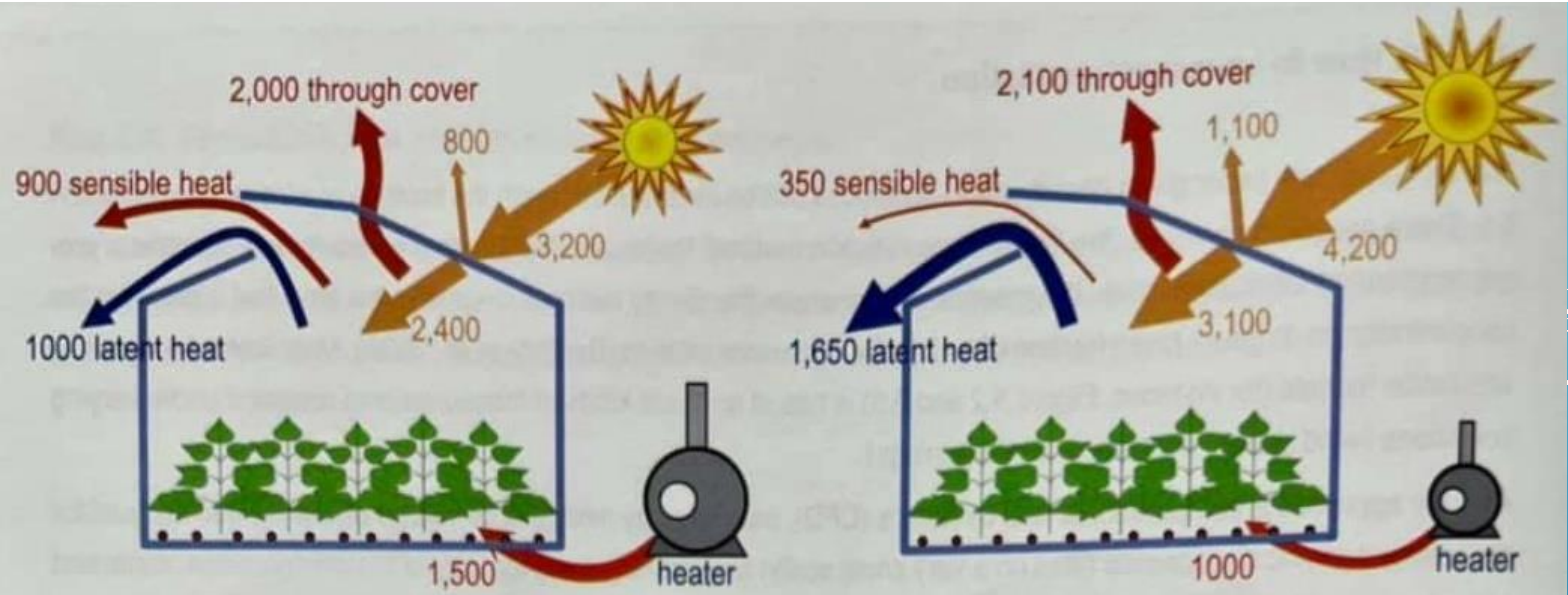
Transpiration / Assimilation Rate



Left: water vapor balance, ventilation (V) and condensation (C) can remove water vapor generated by transpiration (E).
Right: carbon dioxide balance, CO_2 assimilated (A) is added from outside by ventilation (V) and by injection/enrichment (S).
E-V-C=0 and V+S-A=0 when at steady state.

SUP

Energy budget (MJ m^{-2} y^{-1})



reasonably insulated glasshouse in the Netherlands

plastic greenhouse in Central Italy

$$Qi_{sun}+Qi_{heater} = Q_S + Q_L$$

SUP

- (left) RH in The Netherlands is low, thus latent heat (Q_L) occupied 1000/1900 = 52.63%, sensible heat (Qs) occupied 900/1900 (47.37%).
- (right) RH in central Spain is high, thus Qs only occupied 350/2000 (17.5%), most of the energy entering GH turns into QL, 1650/2000 (82.5%), for the evapotranspiration (evaporation of free water and transpiration from plants in GH).
- Weather of Taiwan is similar to the south of Spain. RH is high in GH, if without heating, the RH will be quite high especially during the night.