



# Conversion factors and general equations applied in agricultural and forest meteorology

Mariana Gonçalves dos Reis<sup>1(\*)</sup> and Aristides Ribeiro<sup>1</sup>

<sup>1</sup>Universidade Federal de Viçosa, Departamento de Engenharia Agrícola. Campus Universitário, CEP 36570-900 Viçosa, Minas Gerais, Brasil. E-mails: [mariana.reis@ufv.br](mailto:mariana.reis@ufv.br) and [ribeiro@ufv.br](mailto:ribeiro@ufv.br).

(\*)Corresponding author.

## ARTICLE INFO

### Article history:

Received 16 August 2019

Accepted 11 March 2020

### Index terms:

solar radiation

evapotranspiration

canopy conductance

trace gases

resource use efficiency

carbon balance

## ABSTRACT

Scientific communication in agricultural and forest meteorology requires a correct conversion of units and the adequate use of equations. In general, most of conversion and equations are found separately in a specific book, paper or document. Thus, here we propose a single document with conversion units of solar radiation, evapotranspiration, resource use efficiency, carbon balance, ecophysiology, trace gases and water; and general equations: Penman-Monteith, canopy conductance, decoupling factor and Bowen ratio. This document has a lot of value for teaching, for scientists and as a quick reference.

© 2020 SBAgrom. All rights reserved.

## Introduction

The knowledge of the interactions between the ecosystem and atmosphere play an important role in the agricultural and forest meteorology studies (Allen et al., 1998). Hence, a lot of data from field is required to understanding all these system interactions. The correct use of all factors and equations is the key of the agricultural and forest meteorology applications and results (Nobel, 2009).

In general, most of conversion factors and equations are found separately in a specific book, paper or document.

Thus, here we propose a single document with conversion units of solar radiation, evapotranspiration, resource use efficiency, carbon balance, ecophysiology, trace gases and water; and general equations: Penman-Monteith, canopy conductance, decoupling factor and Bowen ratio.

The idealization and preparation of this document is coming from the demand on the part of students and researchers to convert units and equations according to constants, values and time. We expect that this document can be support all members of the agrometeorological community, such as professors, scientists and professionals.

**List of abbreviations and symbols**

**Constant and values**

**Solar radiation**

$R_s$  ( $W\ m^{-2}$ )  $\leftrightarrow$   $R_s$  ( $kJ\ m^{-2}\ time^{-1}$ )  
 $R_s$  ( $W\ m^{-2}$ )  $\leftrightarrow$   $R_s$  ( $MJ\ m^{-2}\ time^{-1}$ )  
 $R_s$  ( $W\ m^{-2}$ )  $\leftrightarrow$  PAR ( $\mu mol\ m^{-2}\ s^{-1}$ )  
 PAR ( $\mu mol\ m^{-2}\ s^{-1}$ )  $\leftrightarrow$  PAR ( $mol\ m^{-2}\ time^{-1}$ )

**Evapotranspiration**

LE ( $W\ m^{-2}$ )  $\rightarrow$  ET ( $mm\ time^{-1}$ )  
 $R_s$  ( $MJ\ m^{-2}\ time^{-1}$ )  $\rightarrow$  ET ( $mm\ time^{-1}$ )

**General equations**

Evapotranspiration - Penman-Monteith (1965)  
 Evapotranspiration - Penman-Monteith (FAO 56)  
 Canopy Conductance (inversion of Penman-Monteith equation)  
 Canopy Conductance (inversion of Penman-Monteith equation) – Simplified  
 Decoupling Factor ( $\Omega$ )  
 Bowen Ratio ( $\beta$ )

**Resource use efficiency**

WUE  $\rightarrow$  Water-use efficiency (GPP/ET)  
 $WUE_i$   $\rightarrow$  Intrinsic water-use efficiency (GPP/ $g_c$ )  
 CUE  $\rightarrow$  Carbon-use efficiency (NPP/GPP)  
 LUE  $\rightarrow$  Light-use efficiency (GPP/PAR)  
 RUE  $\rightarrow$  Rain-use efficiency (GPP/PPT)

**Carbon balance**

$CO_2$  ( $\mu mol\ m^{-2}\ s^{-1}$ )  $\rightarrow$  C ( $g\ m^{-2}\ time^{-1}$ )  
 C ( $g\ m^{-2}\ yr^{-1}$ )  $\rightarrow$  C ( $t\ ha^{-1}\ yr^{-1}$ )  
 $CO_2$  storage (ppm  $\rightarrow$   $\mu mol\ m^{-2}\ s^{-1}$ )

**Ecophysiology conversion units**

Assimilation rate (A)  
 A ( $\mu mol\ CO_2\ m^{-2}\ s^{-1}$ )  $\rightarrow$  A ( $mg\ CO_2\ m^{-2}\ s^{-1}$ )

Transpiration rate (E)  
 $E$  ( $mmol\ H_2O\ m^{-2}\ s^{-1}$ )  $\rightarrow$   $E$  ( $mg\ H_2O\ m^{-2}\ s^{-1}$ )  
 $E$  ( $mmol\ H_2O\ m^{-2}\ s^{-1}$ )  $\rightarrow$   $E$  ( $W\ m^{-2}$ )

Stomatal conductance ( $g_s$ )  
 $g_s$  ( $mol\ m^{-2}\ s^{-1}$ )  $\leftrightarrow$   $g_s$  ( $m\ s^{-1}$ )  
 $g_s$  ( $mol\ m^{-2}\ s^{-1}$ )  $\leftrightarrow$   $g_s$  ( $cm\ s^{-1}$ )  
 $g_s$  ( $mol\ m^{-2}\ s^{-1}$ )  $\leftrightarrow$   $g_s$  ( $mm\ s^{-1}$ )

**General conversion units for trace gases and water**

$CO_2$  ( $mmol\ m^{-3}$   $\leftrightarrow$   $mg\ m^{-3}$ )  
 $H_2O$  ( $mmol\ m^{-3}$   $\leftrightarrow$   $g\ m^{-3}$ )  
 $CH_4$  ( $mmol\ m^{-3}$   $\leftrightarrow$   $mg\ m^{-3}$ )  
 $NO_2$  ( $mmol\ m^{-3}$   $\leftrightarrow$   $mg\ m^{-3}$ )  
 $O_3$  ( $mmol\ m^{-3}$   $\leftrightarrow$   $mg\ m^{-3}$ )

**Acknowledgments**

**References**

## LIST OF ABBREVIATIONS AND SYMBOLS

A	Assimilation Rate	Pa	Pascal
°C	Degree Celsius	PAR	Photosynthetically Active Radiation
C	Carbon	ppm	Parts Per Million
c	CO <sub>2</sub> Concentration	PPT	Precipitation
cal	Calorie	R	Universal Gas Law Constant
CH <sub>4</sub>	Methane	$r_a$	Aerodynamic Resistance
CO <sub>2</sub>	Carbon Dioxide	$r_c$	Canopy Resistance
$c_p$	Air Specific Heat	$R_d$	Universal Gas Constant Specific for Dry Air
CUE	Carbon-use efficiency	$R_s$	Solar Radiation
dz	Height of the Profile	RH	Relative Humidity
E	Transpiration Rate	$r_l$	Stomatal resistance of the Well-Illuminated Leaf
$e_a$	Actual Vapor Pressure	$R_n$	Net Radiation
$e_s$	Saturation Vapor Pressure	$r_s$	Surface Resistance
ET <sub>o</sub>	Evapotranspiration	RUE	Rain-use efficiency
FAO	Food and Agriculture Organization of the United Nations	$R_w$	Universal Gas Constant Specific for Water Vapor
g	Gram	s	Second
G	Soil Heat Flux	Sc	Storage Flux
$g_a$	Aerodynamic Conductance	T	Air Temperature
$g_c$	Canopy Conductance	t	Ton
GPP	Gross Primary Production	t	Time
$g_s$	Stomatal Conductance	$T_{kv}$	Virtual Temperature
h	Crop Height	$u_2$	Wind Speed at 2 m height
H	Sensible Heat Flux	$u_z$	Wind Speed at z m above ground surface
H <sub>2</sub> O	Water	V	Volume of the Gas
ha	Hectare	VPD	Vapor Pressure Deficit
hm	Maximum Measurement Height	W	Watt
J	Joule	WUE	Water-use efficiency
K	Kelvin	WUE <sub>i</sub>	Intrinsic water-use efficiency
k	Kilo	yr	Year
$k_e$	Turbulent Transfer Coefficient for Water;	z	Elevation; Height Above Sea Level
$k_H$	Turbulent Transfer Coefficient for Heat;	$z_m$	Height of Wind Measurements
L	Liter	$z_h$	Height of Humidity Measurements
LAI	Leaf Area Index	d	Zero Plane Displacement Height
LAI <sub>active</sub>	Active Leaf Area Index	$z_{om}$	Roughness Length Governing Momentum Transfer
LE	Latent Heat Flux	$z_{oh}$	Roughness Length Governing Transfer of Heat and Vapor k von Karman's constant
LUE	Light-use efficiency	$u_z$	Wind Speed at Height z
M	Mega	$\beta$	Bowen Ratio
m	Meter	$\gamma$	Psychrometric Constant
min	Minute	$\Delta$	Slope Vapor Pressure
mm	Millimeter	$\varepsilon$	Ratio Molecular Weight of Water Vapor/Dry Air
n	Number of Moles	$\lambda$	Latent Heat of Vaporization for Water
NO <sub>2</sub>	Nitrogen Dioxide	$\rho_a$	Air density
NPP	Net Primary Production	$\Omega$	Decoupling Factor
O <sub>3</sub>	Ozone		
P	Atmospheric Pressure		

## CONSTANTS AND VALUES

1 minute = 60 seconds	1 mm H <sub>2</sub> O = 1 kg m <sup>-2</sup> H <sub>2</sub> O = 1 L m <sup>-2</sup> H <sub>2</sub> O
30 minutes = 1800 seconds	1 W = J s <sup>-1</sup>
60 minutes (1 hour) = 3600 seconds	1 cal = 4.184 J
24 hours (1 day) = 86400 seconds	$\lambda$ (J kg <sup>-1</sup> ) = 10 <sup>3</sup> (2500 - 2.37T), T = °C
1 mol H <sub>2</sub> O = 18 g H <sub>2</sub> O	$\lambda$ (J kg <sup>-1</sup> ) = 10 <sup>3</sup> (3147 - 2.37T), T = K
1 mol CO <sub>2</sub> = 44 g CO <sub>2</sub>	$\lambda$ (cal g <sup>-1</sup> ) = 10 <sup>3</sup> (597 - 0.564T), T = °C
1 mol CO <sub>2</sub> = 12 g Carbon	$\lambda$ = 2.45 (MJ kg <sup>-1</sup> ), T = 20 °C;
1 mol CH <sub>4</sub> = 16 g CH <sub>4</sub>	1 W m <sup>-2</sup> of total solar radiation ~ 2.02 $\mu$ mol m <sup>-2</sup> s <sup>-1</sup>
1 mol NO <sub>2</sub> = 46 g NO <sub>2</sub>	photons of PAR
1 mol O <sub>3</sub> = 48 g O <sub>3</sub>	Pa = J m <sup>-3</sup>
1 g = 10 <sup>-6</sup> t	J = L / 10 <sup>3</sup> (2500 - 2.37T)
1 kg = 10 <sup>3</sup> g	1 MJ m <sup>2</sup> day <sup>-1</sup> = 0.408 mm day <sup>-1</sup>
1 kJ = 10 <sup>3</sup> J	R = 8.314510 J K <sup>-1</sup> mol <sup>-1</sup> or m <sup>3</sup> Pa K <sup>-1</sup> mol <sup>-1</sup>
1 M = 10 <sup>6</sup>	R <sub>d</sub> = 287.058 J kg <sup>-1</sup> K <sup>-1</sup>
1 ha = 10000 m <sup>2</sup>	R <sub>w</sub> = 461.495 J kg <sup>-1</sup> K <sup>-1</sup>
1 K = °C + 273.16	$\epsilon$ = 0.622;
1 kg H <sub>2</sub> O = 1 L H <sub>2</sub> O = 10 <sup>-3</sup> m <sup>3</sup> H <sub>2</sub> O	c <sub>p</sub> = 1.013 x 10 <sup>3</sup> (MJ kg <sup>-1</sup> °C <sup>-1</sup> );
1 mm H <sub>2</sub> O = 10 <sup>-3</sup> m <sup>3</sup> H <sub>2</sub> O m <sup>-2</sup> area	k = 0.41

### Solar radiation

**Conversion factor for solar radiation: (W m<sup>-2</sup>) to (kJ m<sup>-2</sup> time<sup>-1</sup>)**

$$\frac{W}{m^2} \rightarrow \frac{kJ}{m^2 \cdot time} \quad (1)$$

$$\frac{W}{m^2} \rightarrow \frac{J}{m^2 \cdot s} \rightarrow 10^{-3} \frac{kJ}{m^2 \cdot s} \quad (2)$$

Conversion of W m<sup>-2</sup> to kJ m<sup>-2</sup> considering the time of 30 min (1800 s):

$$\frac{W}{m^2} \rightarrow 10^{-3} \frac{kJ}{m^2 \cdot \frac{1}{1800}} \rightarrow 1800 * 10^{-3} \frac{kJ}{m^2 \cdot 30min} \rightarrow 1.8 \frac{kJ}{m^2 \cdot 30min} \quad (3)$$

Conversion of W m<sup>-2</sup> to kJ m<sup>-2</sup> considering the time of 1 hour (3600 s):

$$\frac{W}{m^2} \rightarrow 10^{-3} \frac{kJ}{m^2 \cdot \frac{1}{3600}} \rightarrow 3600 * 10^{-3} \frac{kJ}{m^2 \cdot hour} \rightarrow 3.6 \frac{kJ}{m^2 \cdot hour} \quad (4)$$

Conversion of W m<sup>-2</sup> to kJ m<sup>-2</sup> considering the time of 1 day (86400 s):

$$\frac{W}{m^2} \rightarrow 10^{-3} \frac{kJ}{m^2 \cdot \frac{1}{86400}} \rightarrow 86400 * 10^{-3} \frac{kJ}{m^2 \cdot day} \rightarrow 86.4 \frac{kJ}{m^2 \cdot day} \quad (5)$$

**Examples:**

$$700 \frac{W}{m^2} \rightarrow 700 * 1.8 \frac{kJ}{m^2 \cdot 30min} \rightarrow 1260 \frac{kJ}{m^2 \cdot 30min} \quad (6)$$

$$700 \frac{W}{m^2} \rightarrow 700 * 3.6 \frac{kJ}{m^2 \cdot hour} \rightarrow 2520 \frac{kJ}{m^2 \cdot hour} \quad (7)$$

$$300 \frac{W}{m^2} \rightarrow 300 * 86.4 \frac{kJ}{m^2 \cdot day} \rightarrow 25920 \frac{kJ}{m^2 \cdot day} \quad (8)$$

**Conversion factor for solar radiation: (W m<sup>-2</sup>) to (MJ m<sup>-2</sup> time<sup>-1</sup>)**

$$\frac{W}{m^2} \rightarrow \frac{MJ}{m^2 \cdot time} \quad (9)$$

$$\frac{W}{m^2} \rightarrow \frac{J}{m^2 \cdot s} \rightarrow 10^{-6} \frac{MJ}{m^2 \cdot s} \quad (10)$$

Conversion of W m<sup>-2</sup> to MJ m<sup>-2</sup> considering the time of 30 min (1800 s):

$$\frac{W}{m^2} \rightarrow 10^{-6} \frac{MJ}{m^2 \cdot \frac{1}{1800}} \rightarrow 1800 * 10^{-6} \frac{MJ}{m^2 \cdot 30min} \rightarrow 0.0018 \frac{MJ}{m^2 \cdot 30min} \quad (11)$$

Conversion of W m<sup>-2</sup> to MJ m<sup>-2</sup> considering the time of 1 hour (3600 s):

$$\frac{W}{m^2} \rightarrow 10^{-6} \frac{MJ}{m^2 \cdot \frac{1}{3600}} \rightarrow 3600 * 10^{-6} \frac{MJ}{m^2 \cdot hour} \rightarrow 0.0036 \frac{MJ}{m^2 \cdot hour} \quad (12)$$

Conversion of W m<sup>-2</sup> to MJ m<sup>-2</sup> considering the time of 1 day (86400 s):

$$\frac{W}{m^2} \rightarrow 10^{-6} \frac{MJ}{m^2 \cdot \frac{1}{86400}} \rightarrow 86400 * 10^{-6} \frac{MJ}{m^2 \cdot day} \rightarrow 0.0864 \frac{MJ}{m^2 \cdot day} \quad (13)$$

**Examples:**

$$700 \frac{W}{m^2} \rightarrow 700 * 0.0018 \frac{MJ}{m^2 \cdot 30min} \rightarrow 1.26 \frac{MJ}{m^2 \cdot 30min} \quad (14)$$

$$700 \frac{W}{m^2} \rightarrow 700 * 0.0036 \frac{MJ}{m^2 \cdot hour} \rightarrow 2.52 \frac{MJ}{m^2 \cdot hour} \quad (15)$$

$$300 \frac{W}{m^2} \rightarrow 300 * 0.0864 \frac{MJ}{m^2 \cdot day} \rightarrow 25.92 \frac{MJ}{m^2 \cdot day} \quad (16)$$

Conversion factor for solar radiation: (kJ m<sup>-2</sup> time<sup>-1</sup>) to (W m<sup>-2</sup>)

$$\frac{kJ}{m^2 \cdot time} \rightarrow \frac{W}{m^2} \quad (17)$$

$$\frac{kJ}{m^2 \cdot s} \rightarrow 10^3 \frac{J}{m^2 \cdot s} \rightarrow 10^3 \frac{W}{m^2} \quad (18)$$

Conversion of kJ m<sup>-2</sup> to W m<sup>-2</sup> considering the time of 30 min (1800 s):

$$\frac{kJ}{m^2 \cdot time} \rightarrow \frac{kJ}{m^2 \cdot 30min} \rightarrow \frac{1}{1800} * 10^3 \frac{W}{m^2} \rightarrow 0.5556 \frac{W}{m^2} \quad (19)$$

Conversion of kJ m<sup>-2</sup> to W m<sup>-2</sup> considering the time of 1 hour (3600 s):

$$\frac{kJ}{m^2 \cdot time} \rightarrow \frac{kJ}{m^2 \cdot hour} \rightarrow \frac{1}{3600} * 10^3 \frac{W}{m^2} \rightarrow 0.2778 \frac{W}{m^2} \quad (20)$$

Conversion of kJ m<sup>-2</sup> to W m<sup>-2</sup> considering the time of 1 day (86400 s):

$$\frac{kJ}{m^2 \cdot time} \rightarrow \frac{kJ}{m^2 \cdot day} \rightarrow \frac{1}{86400} * 10^3 \frac{W}{m^2} \rightarrow 0.01157 \frac{W}{m^2} \quad (21)$$

Examples:

$$1260 \frac{kJ}{m^2 \cdot 30min} \rightarrow 1260 * 0.5556 \frac{W}{m^2} \rightarrow 700 \frac{W}{m^2} \quad (22)$$

$$2520 \frac{kJ}{m^2 \cdot hour} \rightarrow 2520 * 0.2778 \frac{W}{m^2} \rightarrow 700 \frac{W}{m^2} \quad (23)$$

$$25920 \frac{kJ}{m^2 \cdot day} \rightarrow 25920 * 0.01157 \frac{W}{m^2} \rightarrow 300 \frac{W}{m^2} \quad (24)$$

Conversion factor for solar radiation: (MJ m<sup>-2</sup> time<sup>-1</sup>) to (W m<sup>-2</sup>)

$$\frac{MJ}{m^2 \cdot time} \rightarrow \frac{W}{m^2} \quad (25)$$

$$\frac{MJ}{m^2 \cdot s} \rightarrow 10^6 \frac{J}{m^2 \cdot s} \rightarrow 10^6 \frac{W}{m^2} \quad (26)$$

Conversion of MJ m<sup>-2</sup> to W m<sup>-2</sup> considering the time of 30 min (1800 s):

$$\frac{MJ}{m^2 \cdot time} \rightarrow \frac{MJ}{m^2 \cdot 30min} \rightarrow \frac{1}{1800} * 10^6 \frac{W}{m^2} \rightarrow 555.56 \frac{W}{m^2} \quad (27)$$

Conversion of MJ m<sup>-2</sup> to W m<sup>-2</sup> considering the time of 1 hour (3600 s):

$$\frac{MJ}{m^2 \cdot time} \rightarrow \frac{MJ}{m^2 \cdot hour} \rightarrow \frac{1}{3600} * 10^6 \frac{W}{m^2} \rightarrow 277.78 \frac{W}{m^2} \quad (28)$$

Conversion of MJ m<sup>-2</sup> to W m<sup>-2</sup> considering the time of 1 day (86400 s):

$$\frac{MJ}{m^2 \cdot time} \rightarrow \frac{MJ}{m^2 \cdot day} \rightarrow \frac{1}{86400} * 10^6 \frac{W}{m^2} \rightarrow 11.57 \frac{W}{m^2} \quad (29)$$

**Examples:**

$$1.26 \frac{MJ}{m^2 \cdot 30min} \rightarrow 555.56 * 1.26 \frac{W}{m^2} \rightarrow 700 \frac{W}{m^2} \quad (30)$$

$$2.52 \frac{MJ}{m^2 \cdot hour} \rightarrow 277.78 * 2.52 \frac{W}{m^2} \rightarrow 700 \frac{W}{m^2} \quad (31)$$

$$25.92 \frac{MJ}{m^2 \cdot day} \rightarrow 11.57 * 25.92 \frac{W}{m^2} \rightarrow 300 \frac{W}{m^2} \quad (32)$$

**Conversion factor for solar radiation: R<sub>s</sub> (W m<sup>-2</sup>) to PAR (μmol m<sup>-2</sup> s<sup>-1</sup>)**

$$R_s - \frac{W}{m^2} \rightarrow PAR - \frac{\mu mol}{m^2 \cdot s} \quad (33)$$

$$1 \frac{W}{m^2} \rightarrow 2.02 \frac{\mu mol}{m^2 \cdot s} \quad (34)$$

**Examples:**

$$500 \frac{W}{m^2} \rightarrow 500 * 2.02 \frac{\mu mol}{m^2 \cdot s} \rightarrow 1010 \frac{\mu mol}{m^2 \cdot s} \quad (35)$$

$$800 \frac{W}{m^2} \rightarrow 800 * 2.02 \frac{\mu mol}{m^2 \cdot s} \rightarrow 1616 \frac{\mu mol}{m^2 \cdot s} \quad (36)$$

The approximation 1 W m<sup>-2</sup> ≈ 4.57 μmol m<sup>-2</sup> s<sup>-1</sup> (Thimijan & Heins, 1983) is assuming that the W m<sup>-2</sup> is for photosynthetically active radiation (PAR) from 4.0 to 7.0 μm. But, in general pyranometers measure total solar radiation and only ~ 45% of the energy of solar radiation is actually in the 4.0 to 7.0 μm range. Thus, the conversion of solar radiation (R<sub>s</sub>) to photosynthetically active radiation (PAR) is about ~ 2.02, rather than 4.57.

The photosynthetically active radiation (PAR) depends of the light color (spectrum, clouds, etc). Here, the ~ 2.02 conversion factor is described in Mavi & Tupper (2004), but there are many others conversion factors for different region around the world described in Foken (2008).

**Conversion factor for solar radiation: PAR (μmol m<sup>-2</sup> s<sup>-1</sup>) to R<sub>s</sub> (W m<sup>-2</sup>)**

$$PAR - \frac{\mu mol}{m^2 \cdot s} \rightarrow R_s - \frac{W}{m^2} \quad (37)$$

$$1 \frac{\mu\text{mol}}{\text{m}^2 \cdot \text{s}} \rightarrow \frac{1}{2.02} \frac{\text{W}}{\text{m}^2} \quad (38)$$

Examples:

$$1010 \frac{\mu\text{mol}}{\text{m}^2 \cdot \text{s}} \rightarrow 1010 * \frac{1}{2.02} \frac{\text{W}}{\text{m}^2} \rightarrow 500 \frac{\text{W}}{\text{m}^2} \quad (39)$$

$$1616 \frac{\mu\text{mol}}{\text{m}^2 \cdot \text{s}} \rightarrow 1616 * \frac{1}{2.02} \frac{\text{W}}{\text{m}^2} \rightarrow 800 \frac{\text{W}}{\text{m}^2} \quad (40)$$

Conversion factor for solar radiation: PAR ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) to PAR ( $\text{mol m}^{-2} \text{time}^{-1}$ )

$$\frac{\mu\text{mol}}{\text{m}^2 \cdot \text{s}} \rightarrow \frac{\text{mol}}{\text{m}^2 \cdot \text{time}} \quad (41)$$

$$\frac{\mu\text{mol}}{\text{m}^2 \cdot \text{s}} \rightarrow 10^{-6} \frac{\text{mol}}{\text{m}^2 \cdot \text{time}} \quad (42)$$

Conversion of  $\mu\text{mol m}^{-2} \text{s}^{-1}$  to  $\text{mol m}^{-2}$  considering the time of 30 min (1800 s):

$$\frac{\mu\text{mol}}{\text{m}^2 \cdot \text{s}} \rightarrow 10^{-6} \frac{\text{mol}}{\text{m}^2 \cdot \frac{1}{1800}} \rightarrow 1800 * 10^{-6} \frac{\text{mol}}{\text{m}^2 \cdot 30\text{min}} \rightarrow 0.0018 \frac{\text{mol}}{\text{m}^2 \cdot 30\text{min}} \quad (43)$$

Conversion of  $\mu\text{mol m}^{-2} \text{s}^{-1}$  to  $\text{mol m}^{-2}$  considering the time of 1 hour (3600 s):

$$\frac{\mu\text{mol}}{\text{m}^2 \cdot \text{s}} \rightarrow 10^{-6} \frac{\text{mol}}{\text{m}^2 \cdot \frac{1}{3600}} \rightarrow 3600 * 10^{-6} \frac{\text{mol}}{\text{m}^2 \cdot \text{hour}} \rightarrow 0.0036 \frac{\text{mol}}{\text{m}^2 \cdot \text{hour}} \quad (44)$$

Conversion of  $\mu\text{mol m}^{-2} \text{s}^{-1}$  to  $\text{mol m}^{-2}$  considering the time of 1 day (86400 s):

$$\frac{\mu\text{mol}}{\text{m}^2 \cdot \text{s}} \rightarrow 10^{-6} \frac{\text{mol}}{\text{m}^2 \cdot \frac{1}{86400}} \rightarrow 86400 * 10^{-6} \frac{\text{mol}}{\text{m}^2 \cdot \text{day}} \rightarrow 0.0864 \frac{\text{mol}}{\text{m}^2 \cdot \text{day}} \quad (45)$$

Examples:

$$1500 \frac{\mu\text{mol}}{\text{m}^2 \cdot \text{s}} \rightarrow 1500 * 0.0018 \frac{\text{mol}}{\text{m}^2 \cdot 30\text{min}} \rightarrow 2.7 \frac{\text{mol}}{\text{m}^2 \cdot 30\text{min}} \quad (46)$$

$$1500 \frac{\mu\text{mol}}{\text{m}^2 \cdot \text{s}} \rightarrow 1500 * 0.0036 \frac{\text{mol}}{\text{m}^2 \cdot \text{hour}} \rightarrow 5.4 \frac{\text{mol}}{\text{m}^2 \cdot \text{hour}} \quad (47)$$

$$500 \frac{\mu\text{mol}}{\text{m}^2 \cdot \text{s}} \rightarrow 500 * 0.0864 \frac{\text{mol}}{\text{m}^2 \cdot \text{day}} \rightarrow 43.2 \frac{\text{mol}}{\text{m}^2 \cdot \text{day}} \quad (48)$$

Conversion factor for solar radiation: PAR ( $\text{mol m}^{-2} \text{time}^{-1}$ ) to PAR ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )

$$\frac{\text{mol}}{\text{m}^2 \cdot \text{time}} \rightarrow \frac{\mu\text{mol}}{\text{m}^2 \cdot \text{s}} \quad (49)$$



$$\frac{\text{mol}}{\text{m}^2 \cdot \text{time}} \rightarrow 10^6 \frac{\mu\text{mol}}{\text{m}^2 \cdot \text{time}} \quad (50)$$

Conversion of mol m<sup>-2</sup> s<sup>-1</sup> to μmol m<sup>-2</sup> considering the time of 30 min (1800 s):

$$\frac{\text{mol}}{\text{m}^2 \cdot \text{time}} \rightarrow \frac{\text{mol}}{\text{m}^2 \cdot 30\text{min}} \rightarrow \frac{1}{1800} * 10^6 \frac{\mu\text{mol}}{\text{m}^2 \cdot \text{s}} \rightarrow 555.56 \frac{\mu\text{mol}}{\text{m}^2 \cdot \text{s}} \quad (51)$$

Conversion of mol m<sup>-2</sup> s<sup>-1</sup> to μmol m<sup>-2</sup> considering the time of 1 hour (3600 s):

$$\frac{\text{mol}}{\text{m}^2 \cdot \text{time}} \rightarrow \frac{\text{mol}}{\text{m}^2 \cdot \text{hour}} \rightarrow \frac{1}{3600} * 10^6 \frac{\mu\text{mol}}{\text{m}^2 \cdot \text{s}} \rightarrow 277.78 \frac{\mu\text{mol}}{\text{m}^2 \cdot \text{s}} \quad (52)$$

Conversion of mol m<sup>-2</sup> s<sup>-1</sup> to μmol m<sup>-2</sup> considering the time of 1 day (86400 s):

$$\frac{\text{mol}}{\text{m}^2 \cdot \text{time}} \rightarrow \frac{\text{mol}}{\text{m}^2 \cdot \text{day}} \rightarrow \frac{1}{86400} * 10^6 \frac{\mu\text{mol}}{\text{m}^2 \cdot \text{s}} \rightarrow 11.57 \frac{\mu\text{mol}}{\text{m}^2 \cdot \text{s}} \quad (53)$$

**Examples:**

$$2.7 \frac{\text{mol}}{\text{m}^2 \cdot 30\text{min}} \rightarrow 2.7 * 555.56 \frac{\mu\text{mol}}{\text{m}^2 \cdot \text{s}} \rightarrow 1500 \frac{\mu\text{mol}}{\text{m}^2 \cdot \text{s}} \quad (54)$$

$$5.4 \frac{\text{mol}}{\text{m}^2 \cdot \text{hour}} \rightarrow 5.4 * 277.78 \frac{\text{mol}}{\text{m}^2 \cdot \text{s}} \rightarrow 1500 \frac{\mu\text{mol}}{\text{m}^2 \cdot \text{s}} \quad (55)$$

$$43.2 \frac{\text{mol}}{\text{m}^2 \cdot \text{day}} \rightarrow 43.2 * 11.57 \frac{\mu\text{mol}}{\text{m}^2 \cdot \text{s}} \rightarrow 500 \frac{\mu\text{mol}}{\text{m}^2 \cdot \text{s}} \quad (56)$$

## Evapotranspiration

**Conversion factor for evapotranspiration: LE (W m<sup>-2</sup>) to ET (mm time<sup>-1</sup>)**

$$LE = ET \cdot \lambda \rightarrow ET = \frac{LE}{\lambda} \quad (57)$$

Conversion value of LE to ET considering the time of 30 minutes (1800 seconds), and:

Equation (58)

$\lambda$  (J kg<sup>-1</sup>) = 10<sup>3</sup>(3147.5 - 2.37T), T = Air Temperature in K (Kelvin) (Aubinet et al., 2012):

$$ET \left( \frac{\text{mm}}{30\text{min}} \right) = \frac{1800}{10^3(3147.5 - 2.37T)} LE \rightarrow \frac{1.8}{(3147.5 - 2.37T)} LE \quad (58)$$

Equation (59)

$\lambda$  (J kg<sup>-1</sup>) = 10<sup>3</sup>(2500 - 2.37T), T = Air Temperature in °C (Celsius) (Pereira et al., 2013):

$$ET \left( \frac{\text{mm}}{30\text{min}} \right) = \frac{1800}{10^3(2500 - 2.37T)} LE \rightarrow \frac{1.8}{(2500 - 2.37T)} LE \quad (59)$$

Equation (59)

$\lambda$  (cal g<sup>-1</sup>) = 10<sup>3</sup>(597 - 0.564T), T = Air Temperature in °C (Celsius), 1 cal = 4.184 J:

$$ET \left( \frac{mm}{30min} \right) = \frac{\frac{1.8}{4.184}}{\left( \frac{2500}{4.184} - \frac{2.37}{4.184} T \right)} LE \rightarrow \frac{0.43}{(597 - 0.564T)} LE \quad (60)$$

**Conversion factor for evapotranspiration: LE (W m<sup>-2</sup>) to ET (mm time<sup>-1</sup>)**

$$LE = ET \cdot \lambda \rightarrow ET = \frac{LE}{\lambda} \quad (61)$$

$$ET \left( \frac{mm}{time} \right) = \frac{LE}{\lambda} = \frac{\left( \frac{W}{m^2} \right)}{\left( \frac{J}{kg} \right)} \rightarrow \frac{\left( \frac{J}{m^2 \cdot s} \right)}{\left( \frac{J}{kg} \right)} \rightarrow \left( \frac{J}{m^2 \cdot s} \right) * \frac{kg}{J} \rightarrow \frac{kg}{m^2 \cdot s} \rightarrow \frac{mm}{s} \quad (62)$$

$$ET \left( \frac{mm}{30min} \right) = \frac{mm}{\frac{1}{1800}} \rightarrow 1800 \frac{mm}{30min} \rightarrow 1800 \frac{LE}{\lambda} \rightarrow 1800 \left( \frac{LE}{10^3(3147.5 - 2.37T)} \right) \quad (63)$$

**Examples:**

Considering:

. LE (latent heat flux) = 500 W m<sup>-2</sup>

. T (air temperature) = 25 °C

$$ET \left( \frac{mm}{30min} \right) = \frac{1.8}{(3147.5 - 2.37 \cdot (25 + 273.16))} * 500 \rightarrow 0.3687 \frac{mm}{30min} \quad (64)$$

$$ET \left( \frac{mm}{30min} \right) = \frac{1.8}{(2500 - 2.37 \cdot (25))} * 500 \rightarrow 0.3687 \frac{mm}{30min} \quad (65)$$

$$ET \left( \frac{mm}{30min} \right) = \frac{0.43}{(597 - 0.564 \cdot (25))} * 500 \rightarrow 0.3688 \frac{mm}{30min} \quad (66)$$

**Conversion factor for evapotranspiration: R<sub>s</sub> (MJ m<sup>-2</sup> time<sup>-1</sup>) to ET (mm time<sup>-1</sup>)**

$$R_s - \frac{MJ}{m^2 \cdot time} \rightarrow ET - \frac{mm}{time} \quad (67)$$

Considering:

1 mm = 1 L m<sup>-2</sup>

1 L H<sub>2</sub>O = 1 kg H<sub>2</sub>O

To evaporate 1 L H<sub>2</sub>O is necessary 10<sup>3</sup>(2500 - 2.37T) J

J = L/10<sup>3</sup>(2500 - 2.37T)

$$\frac{MJ}{m^2 \cdot time} \rightarrow 10^6 \frac{J}{m^2 \cdot time} \quad (68)$$

$$10^6 \frac{L}{10^3(2500 - 2.37T).m^2.time} \rightarrow \frac{1mm}{(2.5 - 0.00237T).time} \rightarrow \frac{1}{(2.5 - 0.00237T)} \frac{mm}{time} \quad (69)$$

**Example:**

Considering:

. T (air temperature) = 25 °C

. Energy to evaporate = 12 MJ m<sup>-2</sup> day<sup>-1</sup>

$$ET \left( \frac{mm}{day} \right) = \frac{12}{(2.5 - 0.00237 * (25))} \rightarrow ET = 4.91 \frac{mm}{day} \quad (70)$$

**General equations**

Evapotranspiration - Penman-Monteith (1965)

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma(1 + \frac{r_s}{r_a})} = \frac{\Delta(R_n - G) + \rho_a c_p \frac{VPD}{r_a}}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \quad (71)$$

Where:

λ is latent heat of vaporization of water (MJ kg<sup>-1</sup>);

ET is evapotranspiration (mm day<sup>-1</sup>);

R<sub>n</sub> is net radiation at the crop surface (MJ m<sup>-2</sup> day<sup>-1</sup>);

G is soil heat flux (MJ m<sup>-2</sup> day<sup>-1</sup>);

ρ<sub>a</sub> is mean air density at constant pressure (kg m<sup>-3</sup>);

c<sub>p</sub> is air specific heat at constant pressure (MJ kg<sup>-1</sup> °C<sup>-1</sup>);

e<sub>s</sub> is saturation vapor pressure (kPa);

e<sub>a</sub> is actual vapor pressure (kPa);

(e<sub>s</sub> - e<sub>a</sub>) is saturation vapor pressure deficit (kPa);

VPD is vapor pressure deficit (kPa);

Δ is slope vapor pressure curve (kPa °C<sup>-1</sup>);

γ is psychrometric constant (kPa °C<sup>-1</sup>);

r<sub>s</sub> is surface resistance (s m<sup>-1</sup>);

r<sub>a</sub> is aerodynamic resistance (s m<sup>-1</sup>).

The Penman-Monteith is a combined method that included the energy balance and mass transfer. The meteorological variables, solar radiation, air temperature, relative humidity and wind speed, are used to compute the evapotranspiration (Allen et al., 1998).

**Evapotranspiration - Penman-Monteith (FAO 56)**

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 VPD}{\Delta + \gamma(1 + 0.34u_2)} \quad (72)$$

Where:

ET<sub>0</sub> is reference evapotranspiration (mm day<sup>-1</sup>);

R<sub>n</sub> is net radiation at the crop surface (MJ m<sup>-2</sup> day<sup>-1</sup>);

G is soil heat flux density (MJ m<sup>-2</sup> day<sup>-1</sup>);

T is mean daily air temperature at 2 m height ( $m s^{-1}$ );  
 $u_2$  is wind speed at 2 m height ( $m s^{-1}$ );  
 $e_s$  is saturation vapor pressure (kPa);  
 $e_a$  is actual vapor pressure (kPa);  
 $e_s - e_a$  is saturation vapor pressure deficit (kPa);  
VPD is vapor pressure deficit (kPa);  
 $\Delta$  is slope vapor pressure curve ( $kPa \text{ } ^\circ C^{-1}$ );  
 $\gamma$  is psychrometric constant ( $kPa \text{ } ^\circ C^{-1}$ ).

The FAO Penman-Monteith method provides the evapotranspiration of the reference surface ( $ET_0$ ). This method is defined according to the following definition for the reference surface: "A hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of  $70 s m^{-1}$  and an albedo of 0.23" (Allen et al., 1998).

### Evapotranspiration-Parameters

The evapotranspiration parameters are described in Allen et al. (1998).

#### Saturation Vapor Pressure ( $e_s$ )

$$e_s = 0.6108 \exp\left(\frac{17.27T}{T+237.3}\right) \quad (73)$$

Where:

$e_s$  is saturation vapor pressure (kPa);  
T is mean air temperature ( $^\circ C$ ).

#### Actual Vapor Pressure ( $e_a$ )

$$e_a = \frac{e_s * RH}{100} \quad (74)$$

Where:

$e_a$  is actual vapor pressure (kPa);  
 $e_s$  is saturation vapor pressure (kPa);  
RH is relative humidity (%).

#### Relative Humidity (RH)

$$RH = \frac{e_a}{e_s} * 100 \quad (75)$$

Where:

RH is relative humidity (%);  
 $e_a$  is actual vapor pressure (kPa);  
 $e_s$  is saturation vapor pressure (kPa).

#### Vapor Pressure Deficit (VPD)

$$VPD = e_s - e_a \quad (76)$$

Where:

VPD is vapor pressure deficit (kPa);  
 $e_s$  is saturation vapor pressure (kPa);  
 $e_a$  is actual vapor pressure (kPa).

### Latent Heat of Vaporization ( $\lambda$ )

$$\lambda = \frac{10^3(2500 - 2.37T)}{10^6} \quad (77)$$

Where:

$\lambda$  is latent heat of vaporization (MJ kg<sup>-1</sup>);

T is mean air temperature (°C).

“As  $\lambda$  varies only slightly over normal temperature ranges a single value of 2.45 MJ kg<sup>-1</sup> is taken in the simplification of the FAO Penman-Monteith equation. This is the latent heat flux for an air temperature of about 20 °C” (Allen et al., 1998).

### Slope of saturation vapor pressure curve ( $\Delta$ )

$$\Delta = \frac{4098[0.6108 \exp(\frac{17.27T}{T+237.3})]}{(T + 237.3)^2} \quad (78)$$

Where:

$\Delta$  is slope of saturation vapor pressure curve at air temperature T (kPa °C<sup>-1</sup>);

T is mean air temperature (°C).

### Psychrometric Constant ( $\gamma$ ):

$$\gamma = \frac{c_p P}{\epsilon \lambda} \quad (79)$$

Where:

$\gamma$  is psychrometric constant (kPa °C<sup>-1</sup>);

P is atmospheric pressure (kPa);

$\lambda$  is latent heat of vaporization (MJ kg<sup>-1</sup>);

$c_p$  is air specific heat at constant pressure, 1.013 x 10<sup>-3</sup> (MJ kg<sup>-1</sup> °C<sup>-1</sup>);

$\epsilon$  ratio molecular weight of water vapor/dry air, ( $\epsilon = 0.622$ ).

### Atmospheric Pressure (P):

$$P = 101.3 \left( \frac{293 - 0,0065z}{293} \right)^{5.26} \quad (80)$$

Where:

P is atmospheric pressure (kPa);

z is elevation above sea level (m).

### Wind Profile Relationship ( $u_z$ )

$$u_z = u_2 \frac{4.87}{\ln(67.8z - 5.42)} \quad (81)$$

Where:

$u_2$  is wind speed at 2 m above ground surface (m s<sup>-1</sup>);

$u_z$  is measured wind speed at z m above ground surface (m s<sup>-1</sup>);

z is height of measurement above ground surface (m).

### Air Density ( $\rho_a$ )

$$\rho_a = \frac{P}{T_{kv} R_d} \quad (82)$$

Where:

$\rho_a$  is air density ( $\text{kg m}^{-3}$ );

P is atmospheric pressure (kPa);

$T_{kv}$  is virtual temperature (K);

$R_d$  is universal gas constant specific for dry air =  $0.287 \text{ kJ kg}^{-1} \text{ K}^{-1}$ .

### Virtual Temperature ( $T_{kv}$ )

$$T_{kv} = 1.01(T + 273) \quad (83)$$

Where:

$T_{kv}$  is virtual temperature (K);

T is mean air temperature ( $^{\circ}\text{C}$ ).

### Surface resistance ( $r_s$ ):

$$r_s = \frac{r_l}{LAI_{active}} \quad (84)$$

Where:

$r_s$  is surface resistance ( $\text{s m}^{-1}$ );

$r_l$  is stomatal resistance of the well-illuminated leaf ( $\text{s m}^{-1}$ );

$LAI_{active}$  is active (sunlit) leaf area index ( $\text{m}^2$  (leaf area)  $\text{m}^{-2}$  (soil surface)).

### Leaf Area Index Active ( $LAI_{active}$ )

$$LAI_{active} = 0.5LAI \quad (85)$$

Where:

$LAI_{active}^*$  is active (sunlit) leaf area index ( $\text{m}^2$  (leaf area)  $\text{m}^{-2}$  (soil surface));

LAI is leaf area index ( $\text{m}^2 \text{ m}^{-2}$ ).

\*The  $LAI_{active}$  is also depends on the leaf angle distribution (extinction coefficient).

### Aerodynamic resistance ( $r_a$ )

$$r_a = \frac{\ln \left[ \frac{z_m - d}{z_{om}} \right] \cdot \ln \left[ \frac{z_h - d}{z_{oh}} \right]}{k^2 \cdot u_z} \quad (86)$$

Where:

$r_a$  is aerodynamic resistance ( $\text{s m}^{-1}$ );

$z_m$  is height of wind measurements (m);

$z_h$  is height of humidity measurements (m);

d is zero plane displacement height (m);

$z_{om}$  is roughness length governing momentum transfer (m);

$z_{oh}$  is roughness length governing transfer of heat and vapor (m);

k is von Karman's constant, 0.41 (dimensionless);

$u_z$  is wind speed at height z ( $\text{m s}^{-1}$ ).

### Zero Plane Displacement Height (d)

$$d = \frac{2}{3}h \quad (87)$$

Where:

d\* is zero plane displacement height (m);

h is crop height (m).

\*The d is also depends on canopy structure and openness.

### Roughness Length (z)

$$z_{om} = 0.123h \quad (88)$$

$$z_{oh} = 0.1z_{om} \quad (89)$$

Where:

h is crop height (m);

z<sub>om</sub> is roughness length governing momentum transfer (m);

z<sub>oh</sub> is roughness length governing transfer of heat and vapor (m).

### Canopy conductance (inversion of Penman-Monteith)

Canopy conductance ( $g_c$ , m s<sup>-1</sup>) was calculated by inverting the Penman-Monteith equation (Monteith, 1965):

$$\lambda ET = \frac{\Delta(Rn - G) + \rho_a c_p \frac{VPD}{r_a}}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \quad (90)$$

Considering:

$$r_a = \frac{1}{g_a} \rightarrow g_a = \frac{1}{r_a} \quad (91)$$

$$r_s = r_c = \frac{1}{g_c} \rightarrow g_c = \frac{1}{r_c} \quad (92)$$

$$\frac{r_s}{r_a} = \frac{r_c}{r_a} = \frac{\frac{1}{g_c}}{\frac{1}{g_a}} \rightarrow \frac{1}{g_c} \cdot \frac{g_a}{1} \rightarrow \frac{g_a}{g_c} \quad (93)$$

“The surface resistance ( $r_s$ ) describes the resistance of vapor flow through stomata openings, total leaf area and soil surface” (Allen et al., 1998). Thus, here we are considering the approach of surface resistance ( $r_s$ ) ~ canopy resistance ( $r_c$ ).

Then:

$$\lambda ET = \frac{\Delta(Rn - G) + \rho_a c_p VPD g_a}{\Delta + \gamma(1 + \frac{g_a}{g_c})} \quad (94)$$

$$\lambda ET\Delta + \lambda ET\gamma + \lambda ET\gamma \frac{g_a}{g_c} = \Delta(Rn - G) + \rho_a c_p VPD g_a \quad (95)$$

$$\lambda ET(\Delta + \gamma) + \lambda ET\gamma \frac{g_a}{g_c} = \Delta(Rn - G) + \rho_a c_p VPD g_a \quad (96)$$

$$\lambda ET\gamma \frac{g_a}{g_c} = \Delta(Rn - G) + \rho_a c_p VPD g_a - \lambda ET(\Delta + \gamma) \quad (97)$$

$$g_c = \frac{\lambda ET\gamma g_a}{\Delta(Rn - G) + \rho_a c_p VPD g_a - \lambda ET(\Delta + \gamma)} \quad (98)$$

### Canopy conductance (inversion of Penman-Monteith) – Simplified

Canopy conductance ( $g_c$ ,  $m s^{-1}$ ) was calculated by inverting the Penman-Monteith equation (Monteith, 1965). It can be expressed in its simplest form as follows:

First Equation (Noormets et al., 2010):

$$g_c = \frac{PETR_w}{\rho_a VPD R_d} \quad (99)$$

$$g_c = \frac{kPa * \frac{kg}{m^2.s} * \frac{J}{kg.K}}{\frac{kg}{m^3} * kPa * \frac{J}{kg.K}} \rightarrow \frac{kPa * \frac{1}{m^2.s} * \frac{J}{1.K}}{\frac{1}{m^3} * kPa * \frac{J}{1.K}} \rightarrow \frac{kPa * J}{m^2.s * K} * \frac{m^3 * K}{kPa * J} \rightarrow \frac{m}{s} \quad (100)$$

Where:

$g_c$  is canopy conductance ( $m s^{-1}$ );

P is atmospheric pressure (kPa);

ET is evapotranspiration ( $kg m^{-2} s^{-1}$ );

$R_w$  is universal gas constant specific for water vapor ( $461.495 J kg^{-1} K^{-1}$ );

$\rho_a$  is air density ( $kg m^{-3}$ );

VPD is vapor pressure deficit (kPa);

$R_d$  is universal gas constant specific for dry air ( $287.058 J kg^{-1} K^{-1}$ ).

Second Equation (Mallick et al., 2013):

$$g_c = \frac{\gamma LE}{\rho_a c_p VPD} \quad (101)$$

$$g_c = \frac{\frac{kPa}{^\circ C} * \frac{W}{m^2}}{\frac{kg}{m^3} * \frac{J}{kg.^\circ C} * kPa} \rightarrow \frac{\frac{kPa}{^\circ C} * \frac{J}{m^2.s}}{\frac{1}{m^3} * \frac{J}{1.^\circ C} * kPa} \rightarrow \frac{kPa * J}{^\circ C * m^2.s} * \frac{m^3 * ^\circ C}{J * kPa} \rightarrow \frac{m}{s} \quad (102)$$

Where:

$g_c$  is canopy conductance ( $m s^{-1}$ );

$\gamma$  is psychrometric constant ( $kPa ^\circ C^{-1}$ );

LE is latent heat flux ( $W m^{-2}$ );

$\rho_a$  is air density ( $kg m^{-3}$ );



$c_p$  is specific heat at constant pressure,  $1.013 \times 10^3 \text{ (MJ kg}^{-1} \text{ }^\circ\text{C}^{-1}) = 1013 \text{ (J kg}^{-1} \text{ }^\circ\text{C}^{-1})$ ;  
VPD is vapor pressure deficit (kPa).

Considerations:

$$\frac{R_w}{R_d} = \frac{1}{\varepsilon} \quad (103)$$

$$g_c = \frac{PETR_w}{\rho_a VPD R_d} = \frac{\gamma LE}{\rho_a c_p VPD} \quad (104)$$

So, these two canopy conductance simplified equations are similarity.

### Decoupling Factor ( $\Omega$ )

The dimensionless decoupling factor ( $\Omega$ ) was calculated according to Jarvis & McNaughton (1986):

$$\Omega = \frac{\frac{\Delta}{\gamma} + 1}{\frac{\Delta}{\gamma} + 1 + \frac{g_a}{g_c}} \quad (105)$$

$$\Omega = \frac{\frac{\frac{kPa}{^\circ C}}{\frac{kPa}{^\circ C}} + 1}{\frac{\frac{kPa}{^\circ C}}{\frac{kPa}{^\circ C}} + 1 + \frac{\frac{m}{s}}{\frac{m}{s}}} \rightarrow \text{dimensionless} \quad (106)$$

Where:

- $\Omega$  is decoupling factor (dimensionless);
- $\Delta$  is slope vapor pressure curve ( $\text{kPa } ^\circ\text{C}^{-1}$ );
- $\gamma$  is psychrometric constant ( $\text{kPa } ^\circ\text{C}^{-1}$ );
- $g_a$  is aerodynamic conductance ( $\text{m s}^{-1}$ );
- $g_c$  is canopy conductance ( $\text{m s}^{-1}$ ).

The decoupling factor ranges from zero to one.

### Bowen Ratio ( $\beta$ )

The Bowen ratio ( $\beta$ ) is calculated by the ratio of sensible heat flux (H) and latent heat flux (LE) (Perez et al., 1999):

$$\beta = \frac{H}{LE} \quad (107)$$

Where:

- $\beta$  is Bowen ration (dimensionless);
- H is sensible heat flux ( $\text{W m}^{-2}$ );
- LE is latent heat flux ( $\text{W m}^{-2}$ ).

Considering the simplified energy balance equation:

$$R_n = LE + H + G \quad (108)$$

Where:

$R_n$  is net radiation ( $W m^{-2}$ );

LE is latent heat flux ( $W m^{-2}$ );

H is sensible heat flux ( $W m^{-2}$ );

G is soil heat flux ( $W m^{-2}$ ).

The H and LE can be expression according to energy balance equation:

$$\lambda LE = \frac{R_n - G}{1 + \beta} \quad (109)$$

$$H = \frac{\beta}{1 + \beta} (R_n - G) \quad (110)$$

Considering T and VPD in two levels:

Measurements of the air temperature and vapor pressure gradients between two levels (1 and 2) within the surface layer,  $\beta$  can be obtained by following equation (Perez et al. 1999):

$$\beta = \gamma \frac{\delta T}{\delta e} \quad (111)$$

Considering:

$$\lambda LE = \frac{-\rho_a c_p}{\gamma} k_e \frac{\delta e}{\delta z} \quad (112)$$

$$H = -\rho_a c_p k_H \frac{\delta T}{\delta z} \quad (113)$$

$$\beta = \frac{-\rho_a c_p k_H \frac{\delta T}{\delta z}}{\frac{-\rho_a c_p}{\gamma} k_e \frac{\delta e}{\delta z}} \quad (114)$$

Assuming  $k_H = k_e$

$$\beta = \frac{-\rho_a c_p k_H \frac{\delta T}{\delta z}}{\frac{-\rho_a c_p}{\gamma} k_e \frac{\delta e}{\delta z}} \rightarrow \gamma \frac{\delta T}{\delta z} \frac{\delta z}{\delta e} \rightarrow \gamma \frac{\delta T}{\delta e} \rightarrow \gamma \frac{(T_2 - T_1)}{(e_{a1} - e_{a2})} \quad (115)$$

Where:

$k_H$  is turbulent transfer coefficient for heat;

$k_e$  is turbulent transfer coefficient for water;

$T_1$  is air temperature level 1 ( $^{\circ}C$ );

$T_2$  is air temperature level 2 ( $^{\circ}C$ );

$e_{a1}$  is air vapor pressure level 1 (kPa);

$e_{a2}$  is air vapor pressure level 2 (kPa).

## RESOURCE USE EFFICIENCY

WUE – Water-use efficiency (GPP/ET)

$$WUE = \frac{GPP}{ET} = \frac{gC}{kg.H_2O} \quad (116)$$

$$WUE = \frac{GPP}{ET} = \frac{gC}{L.H_2O} \quad (117)$$

Considering:

$$GPP = g C m^{-2} time^{-1}$$

$$ET = mm time^{-1}$$

$$1 mm = 1 L m^{-2}$$

$$1 L H_2O = 1 kg H_2O$$

$$WUE = \frac{GPP}{ET} \rightarrow \frac{\frac{gC}{\frac{mm}{time}}}{\frac{mm}{time}} \rightarrow \frac{\frac{gC}{\frac{L.H_2O}{m^2.time}}}{\frac{m^2.time}{m^2.time}} \rightarrow \frac{gC}{m^2.time} * \frac{m^2.time}{L.H_2O} \rightarrow \frac{gC}{kg.H_2O} \quad (118)$$

$$WUE = \frac{GPP}{ET} \rightarrow \frac{\frac{gC}{\frac{mm}{time}}}{\frac{mm}{time}} \rightarrow \frac{\frac{gC}{\frac{L.H_2O}{m^2.time}}}{\frac{m^2.time}{m^2.time}} \rightarrow \frac{gC}{m^2.time} * \frac{m^2.time}{L.H_2O} \rightarrow \frac{gC}{L.H_2O} \quad (119)$$

### Examples:

Considering the time of 1 hour:

$$GPP = 1.5 g C m^{-2} hour^{-1}$$

$$ET = 0.5 mm hour^{-1}$$

$$WUE = \frac{GPP}{ET} \rightarrow \frac{1.5}{0.5} \rightarrow 3 \frac{gC}{kg.H_2O} \quad (120)$$

$$WUE = \frac{GPP}{ET} \rightarrow \frac{1.5}{0.5} \rightarrow 3 \frac{gC}{L.H_2O} \quad (121)$$

WUE<sub>i</sub> – Intrinsic water-use efficiency (GPP/g<sub>c</sub>)

$$WUE_i = \frac{GPP}{g_c} = \frac{gC}{kg.H_2O} \quad (122)$$

$$WUE_i = \frac{GPP}{g_c} = \frac{gC}{L.H_2O} \quad (123)$$

Considering:

$$GPP = g C m^{-2} time^{-1}$$

$$g_c = m time^{-1}$$

$$1 kg H_2O = 1 L H_2O 10^{-3} m^3 H_2O$$

$$WUE_i = \frac{GPP}{g_c} \rightarrow \frac{\frac{gC}{m^2 \cdot time}}{\frac{m}{time}} \rightarrow \frac{gC}{m^2 \cdot time} * \frac{time}{m \cdot H_2O} \rightarrow \frac{gC}{m^3 \cdot H_2O} \rightarrow 10^3 \frac{gC}{kg \cdot H_2O} \quad (124)$$

$$WUE_i = \frac{GPP}{g_c} \rightarrow \frac{\frac{gC}{m^2 \cdot time}}{\frac{m}{time}} \rightarrow \frac{gC}{m^2 \cdot time} * \frac{time}{m \cdot H_2O} \rightarrow \frac{gC}{m^3 \cdot H_2O} \rightarrow 10^3 \frac{gC}{L \cdot H_2O} \quad (125)$$

### Examples:

Considering the time of 1 hour:

$$GPP = 1.5 \text{ g C m}^{-2} \text{ hour}^{-1}$$

$$g_c = 0.01 \text{ m s}^{-1} \rightarrow 36 \text{ m hour}^{-1}$$

$$WUE_i = \frac{GPP}{g_c} \rightarrow \frac{1.5}{36} \rightarrow 0.0416 * 10^3 \frac{gC}{kg \cdot H_2O} \rightarrow 41.6 \frac{gC}{kg \cdot H_2O} \quad (126)$$

$$WUE_i = \frac{GPP}{g_c} \rightarrow \frac{1.5}{36} \rightarrow 0.0416 * 10^3 \frac{gC}{L \cdot H_2O} \rightarrow 41.6 \frac{gC}{L \cdot H_2O} \quad (127)$$

### CUE - Carbon-use efficiency (NPP/GPP)

$$CUE = \frac{NPP}{GPP} \quad (128)$$

Considering:

$$GPP = g \text{ C m}^{-2} \text{ time}^{-1}$$

$$NPP = g \text{ C m}^{-2} \text{ time}^{-1}$$

$$CUE = \frac{NPP}{GPP} \rightarrow \frac{\frac{gC}{m^2 \cdot time}}{\frac{gC}{m^2 \cdot time}} \rightarrow \frac{gC}{m^2 \cdot time} * \frac{m^2 \cdot time}{gC} \rightarrow \text{dimensionless} \quad (129)$$

### Example:

Considering the time of 1 hour:

$$GPP = 1.5 \text{ g C m}^{-2} \text{ hour}^{-1}$$

$$NPP = 1.2 \text{ g C m}^{-2} \text{ hour}^{-1}$$

$$CUE = \frac{NPP}{GPP} \rightarrow \frac{1.2}{1.5} \rightarrow 0.8 \quad (130)$$

### LUE - Light-use efficiency (GPP/PAR)

$$LUE = \frac{GPP}{PAR} \rightarrow \frac{gC}{molphotons} \quad (131)$$

$$LUE = \frac{GPP}{PAR} \rightarrow \frac{molC}{molphotons} \quad (132)$$

Considering:

$$GPP = mol\ m^{-2}\ time^{-1}\ CO_2$$

$$PAR = mol\ m^{-2}\ time^{-1}\ photons$$

$$1\ mol\ CO_2 = 12\ g\ C$$

$$LUE = \frac{GPP}{PAR} \rightarrow \frac{\frac{mol}{m^2 \cdot time} CO_2}{\frac{mol}{m^2 \cdot time} photons} \rightarrow \frac{mol}{m^2 \cdot time} CO_2 * \frac{mol}{m^2 \cdot time} photons \quad (133)$$

$$\rightarrow \frac{molCO_2}{molphotons} \rightarrow 12 \cdot \frac{gC}{molphotons} \quad (134)$$

$$LUE = \frac{GPP}{PAR} \rightarrow \frac{\frac{mol}{m^2 \cdot time} CO_2}{\frac{mol}{m^2 \cdot time} photons} \rightarrow \frac{mol}{m^2 \cdot time} CO_2 * \frac{mol}{m^2 \cdot time} photons \rightarrow \frac{molCO_2}{molphotons} \quad (135)$$

#### Examples:

Considering the time of 1 hour:

$$GPP = 0.15\ mol\ m^{-2}\ time^{-1}\ CO_2$$

$$PAR = 100\ mol\ m^{-2}\ time^{-1}\ photons$$

$$LUE = \frac{GPP}{PAR} \rightarrow \frac{0.15}{100} * 12 \rightarrow 0.018 \frac{gC}{molphotons} \quad (136)$$

$$LUE = \frac{GPP}{PAR} \rightarrow \frac{1.5}{100} \rightarrow 0.0015 \frac{molCO_2}{molphotons} \quad (137)$$

#### RUE - Rain-use efficiency (GPP/PPT)

$$RUE = \frac{GPP}{PPT} \rightarrow \frac{gC}{kg \cdot H_2O} \quad (138)$$

$$RUE = \frac{GPP}{PPT} \rightarrow \frac{gC}{L \cdot H_2O} \quad (139)$$

Considering:

$$GPP = g\ C\ m^{-2}\ time^{-1}$$

$$ET = mm\ time^{-1}$$

$$1\ mm = 1\ L\ m^{-2}$$

$$1\ L\ H_2O = 1\ kg\ H_2O$$

$$RUE = \frac{GPP}{PPT} \rightarrow \frac{\frac{gC}{m^2 \cdot time}}{\frac{mm}{time}} \rightarrow \frac{\frac{gC}{m^2 \cdot time}}{\frac{L.H_2O}{m^2 \cdot time}} \rightarrow \frac{gC}{m^2 \cdot time} * \frac{m^2 \cdot time}{L.H_2O} \rightarrow \frac{gC}{kg.H_2O} \quad (140)$$

$$RUE = \frac{GPP}{PTT} \rightarrow \frac{\frac{gC}{m^2 \cdot time}}{\frac{mm}{time}} \rightarrow \frac{\frac{gC}{m^2 \cdot time}}{\frac{L.H_2O}{m^2 \cdot time}} \rightarrow \frac{gC}{m^2 \cdot time} * \frac{m^2 \cdot time}{L.H_2O} \rightarrow \frac{gC}{L.H_2O} \quad (141)$$

### Examples:

Considering the time of 1 hour:

GPP = 1.5 g C m<sup>-2</sup> hour<sup>-1</sup>

PPT = 5 mm hour<sup>-1</sup>

$$RUE = \frac{GPP}{PPT} \rightarrow \frac{1.5}{5} \rightarrow 0,3 \frac{gC}{kg.H_2O} \quad (142)$$

$$RUE = \frac{GPP}{PTT} \rightarrow \frac{1.5}{5} \rightarrow 0,3 \frac{gC}{L.H_2O} \quad (143)$$

### CARBON BALANCE

Conversion factor for carbon balance: (μmol CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup>) to (g C m<sup>-2</sup> time<sup>-1</sup>)

$$\frac{\mu mol CO_2}{m^2 \cdot s} \rightarrow \frac{gC}{m^2} \quad (144)$$

Conversion value of CO<sub>2</sub> considering the interval of 30 minutes (1800 seconds):

$$\frac{\mu mol CO_2}{m^2 \cdot s} \rightarrow \frac{10^{-6} mol CO_2}{m^2 \cdot \frac{1}{1800}} \rightarrow \frac{10^{-6} * 12 gC}{m^2 \cdot \frac{1}{1800}} \rightarrow 10^{-6} * 12 * 1800 \frac{gC}{m^2} \rightarrow 0.0216 \frac{gC}{m^2} \quad (145)$$

Example:

$$10 \frac{\mu mol CO_2}{m^2 \cdot s} \rightarrow 10 * 0.0216 \frac{gC}{m^2} \rightarrow 0.216 \frac{gC}{m^2} \quad (146)$$

Conversion annual value of CO<sub>2</sub> (g m<sup>-2</sup> yr<sup>-1</sup> C) to (t ha<sup>-1</sup> yr<sup>-1</sup> C), 1 ha = 10000 m<sup>2</sup>:

$$\frac{gC}{m^2 \cdot year} \rightarrow \frac{tC}{ha \cdot year} \quad (147)$$

$$\frac{gC}{m^2 \cdot year} \rightarrow 10^{-6} \frac{tC}{\frac{1}{10000} \cdot year} \rightarrow \frac{1}{10^{-4}} * 10^{-6} \frac{tC}{ha \cdot year} \rightarrow 10^{-2} \frac{tC}{ha \cdot year} \quad (148)$$

### Examples:

If the ecosystem was a carbon source:

$$800 \frac{gC}{m^2 \cdot year} \rightarrow 800 \cdot 10^{-2} \frac{tC}{ha \cdot year} \rightarrow 8 \frac{tC}{ha \cdot year} \quad (149)$$

If the ecosystem was a carbon sink:

$$-800 \frac{gC}{m^2 \cdot year} \rightarrow -800 \cdot 10^{-2} \frac{tC}{ha \cdot year} \rightarrow -8 \frac{tC}{ha \cdot year} \quad (150)$$

### CO<sub>2</sub> storage

The CO<sub>2</sub> storage is deduced from CO<sub>2</sub> concentration (c) profile as describe in Aubinet et al. (2001):

$$Sc = \frac{Pa}{RT} \int_0^{hm} \frac{dc(z)}{dt} dz \quad (151)$$

$$Sc = \frac{Pa}{\frac{J}{K \cdot mol} \cdot K} * \frac{\mu mol}{mol} * \frac{m}{s} \rightarrow \frac{J}{m^3} * \frac{\mu mol}{J} * \frac{m}{s} \rightarrow \frac{\mu mol}{m^2 \cdot s} \quad (152)$$

Where:

Sc is storage flux ( $\mu mol m^{-2} s^{-1}$ );

Pa is atmospheric pressure (Pa);

R is universal gas law constant ( $J mol^{-1} K^{-1}$ );

T is air temperature (K);

hm is maximum measurement height (m);

c is CO<sub>2</sub> concentration (ppm or  $\mu mol mol^{-1}$ );

t is time (s);

z is height above ground surface (m);

dc/dt refers to the temporal change in CO<sub>2</sub> concentration over a period of time;

dz is the height of the profile.

### ECOPHYSIOLOGY CONVERSION UNITS

Assimilation rate (A) - ( $\mu mol CO_2 m^{-2} s^{-1} \rightarrow mg CO_2 m^{-2} s^{-1}$ )

$$\frac{\mu mol CO_2}{m^2 \cdot s} \rightarrow \frac{mg CO_2}{m^2 \cdot s} \quad (153)$$

$$\frac{\mu mol CO_2}{m^2 \cdot s} \rightarrow 10^{-6} \frac{mol CO_2}{m^2 \cdot s} \rightarrow 44 * 10^{-6} \frac{g CO_2}{m^2} \rightarrow 44 * 10^{-6} * 10^3 \frac{mg CO_2}{m^2} \rightarrow 0.044 \frac{mg CO_2}{m^2 \cdot s} \quad (154)$$

Example:

$$20 \frac{\mu mol CO_2}{m^2 \cdot s} \rightarrow 20 * 0.044 \frac{mg CO_2}{m^2 \cdot s} \rightarrow 0.88 \frac{mg CO_2}{m^2 \cdot s} \quad (155)$$

Transpiration rate (E) - ( $\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1} \rightarrow \text{mg H}_2\text{O m}^{-2} \text{ s}^{-1}$ )

$$\frac{\text{mmolH}_2\text{O}}{\text{m}^2.\text{s}} \rightarrow \frac{\text{mgH}_2\text{O}}{\text{m}^2.\text{s}} \quad (156)$$

$$\frac{\text{mmolH}_2\text{O}}{\text{m}^2.\text{s}} \rightarrow 18 \frac{\text{mgH}_2\text{O}}{\text{m}^2.\text{s}} \quad (157)$$

**Example:**

$$5 \frac{\text{mmolH}_2\text{O}}{\text{m}^2.\text{s}} \rightarrow 5 * 18 \frac{\text{mgH}_2\text{O}}{\text{m}^2.\text{s}} \rightarrow 90 \frac{\text{mgH}_2\text{O}}{\text{m}^2.\text{s}} \quad (158)$$

Transpiration rate (E) - ( $\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1} \rightarrow \text{W m}^{-2}$ )

$$\frac{\text{mmolH}_2\text{O}}{\text{m}^2.\text{s}} \rightarrow \frac{\text{W}}{\text{m}^2} \quad (159)$$

$$\frac{\text{mmolH}_2\text{O}}{\text{m}^2.\text{s}} \rightarrow 10^{-3} \frac{\text{molH}_2\text{O}}{\text{m}^2.\text{s}} \rightarrow 10^{-3} * 18 \frac{\text{gH}_2\text{O}}{\text{m}^2.\text{s}} \rightarrow 10^{-3} * 18 * 2450 \frac{\text{J}}{\text{m}^2.\text{s}} \rightarrow 44.1 \frac{\text{W}}{\text{m}^2} \quad (160)$$

**Example:**

Considering:

. 1 mol H<sub>2</sub>O = 18 g H<sub>2</sub>O

. To evaporate 1 g H<sub>2</sub>O is necessary ~ 2450 J

$$5 \frac{\text{mmolH}_2\text{O}}{\text{m}^2.\text{s}} \rightarrow 5 * 44.1 \frac{\text{W}}{\text{m}^2} \rightarrow 220.5 \frac{\text{W}}{\text{m}^2} \quad (161)$$

Stomatal Conductance (g<sub>s</sub>) - ( $\text{mol m}^{-2} \text{ s}^{-1} \leftrightarrow \text{m s}^{-1}$ )

$$g_s \left( \frac{\text{mol}}{\text{m}^2 \text{ s}} \right) \leftrightarrow g_s \left( \frac{\text{m}}{\text{s}} \right) \quad (162)$$

Simplified or approximation conversion

Through the stomata there are input and output of many gases, including: CO<sub>2</sub>, O<sub>2</sub>, water vapor and other gases. Thus, considering air temperature of 0 °C and atmospheric pressure of 101 325 Pa the molar density of gases is 44.6 mol m<sup>-3</sup>. Considering the ideal gas equation (Nobel 2009):

$$PV = nRT \quad (163)$$



$$\frac{n}{V} = \frac{P}{RT} \quad (164)$$

$$\frac{mol}{m^3} = \frac{P}{RT} \quad (165)$$

$$\frac{n}{V} = \frac{101325}{8,314510 * (273,16 + 0)} \rightarrow \frac{101325}{2271,1915516} \rightarrow 44,6 \frac{mol}{m^3} \quad (166)$$

Then:

$$\frac{mol}{m^3} = \frac{P}{RT} = \frac{g_s \left( \frac{mol}{m^2 s} \right)}{g_s \left( \frac{m}{s} \right)} \quad (167)$$

$$\frac{g_s \left( \frac{mol}{m^2 s} \right)}{g_s \left( \frac{m}{s} \right)} = \frac{P}{RT} \quad (168)$$

$$\frac{g_s \left( \frac{mol}{m^2 s} \right)}{g_s \left( \frac{m}{s} \right)} = 44,6 \frac{mol}{m^3} \quad (169)$$

$$g_s \left( \frac{mol}{m^2 s} \right) = g_s \left( \frac{m}{s} \right) * 44,6 \frac{mol}{m^3} \quad (170)$$

$$g_s \left( \frac{m}{s} \right) = g_s \left( \frac{mol}{m^2 s} \right) * \frac{1}{44,6} \frac{m^3}{mol} \quad (171)$$

### Examples:

(1) Stomatal conductance = 0.8 mol m<sup>-2</sup> s<sup>-1</sup>

$$g_s \left( \frac{m}{s} \right) = g_s \left( \frac{mol}{m^2 \cdot s} \right) * \frac{1}{44,6} \frac{m^3}{mol} \quad (172)$$

$$g_s \left( \frac{m}{s} \right) = 0,8 * \frac{1}{44,6} = 0,018 \quad (173)$$

$$g_s \left( \frac{cm}{s} \right) = 0,8 * \frac{1}{44,6} = 0,018 * 100 = 1,8 \quad (174)$$

$$g_s \left( \frac{mm}{s} \right) = 0,8 * \frac{1}{44,6} = 0,018 * 1000 = 18 \quad (175)$$

(2) Stomatal conductance = 0.015 m s<sup>-1</sup>

$$g_s \left( \frac{mol}{m^2 \cdot s} \right) = g_s \left( \frac{m}{s} \right) * 44,6 \frac{mol}{m^3} \quad (176)$$

$$g_s \left( \frac{\text{mol}}{\text{m}^2 \cdot \text{s}} \right) = 0,015 * 44,6 = 0,669 \quad (177)$$

(3) Stomatal conductance = 1.5 cm s<sup>-1</sup>

$$g_s \left( \frac{\text{mol}}{\text{m}^2 \cdot \text{s}} \right) = g_s \left( \frac{\text{m}}{\text{s}} \right) * \frac{1}{100} * 44,6 \frac{\text{mol}}{\text{m}^3} \quad (178)$$

$$g_s \left( \frac{\text{mol}}{\text{m}^2 \cdot \text{s}} \right) = 1,5 * \frac{1}{100} * 44,6 = 0,669 \quad (179)$$

(4) Stomatal conductance = 15 mm s<sup>-1</sup>

$$g_s \left( \frac{\text{mol}}{\text{m}^2 \cdot \text{s}} \right) = g_s \left( \frac{\text{m}}{\text{s}} \right) * \frac{1}{1000} * 44,6 \frac{\text{mol}}{\text{m}^3} \quad (180)$$

$$g_s \left( \frac{\text{mol}}{\text{m}^2 \cdot \text{s}} \right) = 15 * \frac{1}{1000} * 44,6 = 0,669 \quad (181)$$

#### Stomatal Conductance (g<sub>s</sub>) - (mol m<sup>-2</sup> s<sup>-1</sup> ↔ m s<sup>-1</sup>)

To calculate the stomatal conductance in metric dimensions, with other air temperature and atmospheric pressure conditions the ideal gas law comes in handy (Nobel, 2009):

$$PV = nRT \quad (182)$$

$$\frac{n}{V} = \frac{P}{RT} \quad (183)$$

$$\frac{\text{mol}}{\text{m}^3} = \frac{P}{RT} \quad (184)$$

$$\frac{\text{mol}}{\text{m}^3} = \frac{P}{RT} \rightarrow \frac{\text{Pa}}{\frac{\text{J}}{\text{mol} \cdot \text{K}} * \text{K}} \rightarrow \frac{\text{Pa}}{\frac{\text{J}}{\text{mol}}} \rightarrow \text{Pa} * \frac{\text{mol}}{\text{J}} \rightarrow \frac{\text{J}}{\text{m}^3} * \frac{\text{mol}}{\text{J}} \rightarrow \frac{\text{mol}}{\text{m}^3} \quad (185)$$

Where:

P is atmospheric pressure (Pa);

R is universal gas law constant (J mol<sup>-1</sup> K<sup>-1</sup>);

T is air temperature (K).

Considering:

$$\frac{\text{mol}}{\text{m}^3} = \frac{g_s \left( \frac{\text{mol}}{\text{m}^2 \cdot \text{s}} \right)}{g_s \left( \frac{\text{m}}{\text{s}} \right)} \rightarrow \frac{\text{mol}}{\text{m}^2 \cdot \text{s}} * \frac{\text{s}}{\text{m}} \rightarrow \frac{\text{mol}}{\text{m}^3} \quad (186)$$

Then:

$$\frac{g_s \left( \frac{\text{mol}}{\text{m}^2 \cdot \text{s}} \right)}{g_s \left( \frac{\text{m}}{\text{s}} \right)} = \frac{P}{RT} \quad (187)$$

$$g_s \left( \frac{\text{mol}}{\text{m}^2 \cdot \text{s}} \right) = g_s \left( \frac{\text{m}}{\text{s}} \right) * \frac{P}{RT} \quad (188)$$

$$g_s \left( \frac{\text{m}}{\text{s}} \right) = g_s \left( \frac{\text{mol}}{\text{m}^2 \cdot \text{s}} \right) * \frac{RT}{P} \quad (189)$$

Stomatal Conductance ( $g_s$ ) - ( $\text{mol m}^{-2} \text{s}^{-1} \leftrightarrow \text{cm s}^{-1}$ )

$$g_s \left( \frac{\text{mol}}{\text{m}^2 \cdot \text{s}} \right) = g_s \left( \frac{\text{cm}}{\text{s}} \right) * \frac{1}{100} * \frac{P}{RT} \quad (190)$$

$$g_s \left( \frac{\text{cm}}{\text{s}} \right) = g_s \left( \frac{\text{mol}}{\text{m}^2 \cdot \text{s}} \right) * 100 * \frac{RT}{P} \quad (191)$$

Stomatal Conductance ( $g_s$ ) - ( $\text{mol m}^{-2} \text{s}^{-1} \leftrightarrow \text{mm s}^{-1}$ )

$$g_s \left( \frac{\text{mol}}{\text{m}^2 \cdot \text{s}} \right) = g_s \left( \frac{\text{mm}}{\text{s}} \right) * \frac{1}{1000} * \frac{P}{RT} \quad (192)$$

$$g_s \left( \frac{\text{mm}}{\text{s}} \right) = g_s \left( \frac{\text{mol}}{\text{m}^2 \cdot \text{s}} \right) * 1000 * \frac{RT}{P} \quad (193)$$

**Example:**

Considering:

- . Air temperature (T) = 25 °C;
- . Atmospheric pressure (P) = 101 325 Pa;
- . Universal gas law constant (R) = 8.314510 J mol<sup>-1</sup> K<sup>-1</sup>.

$$g_s \left( \frac{\text{mol}}{\text{m}^2 \cdot \text{s}} \right) = g_s \left( \frac{\text{m}}{\text{s}} \right) * \frac{P}{RT} \quad (194)$$

$$g_s \left( \frac{\text{mol}}{\text{m}^2 \cdot \text{s}} \right) = g_s \left( \frac{\text{m}}{\text{s}} \right) * \frac{101325}{8,314510 * (273,16 + 25)} \quad (195)$$

$$g_s \left( \frac{\text{mol}}{\text{m}^2 \cdot \text{s}} \right) = g_s \left( \frac{\text{m}}{\text{s}} \right) * \frac{101325}{2479,0543016} \quad (196)$$

$$g_s \left( \frac{\text{mol}}{\text{m}^2 \cdot \text{s}} \right) = g_s \left( \frac{\text{m}}{\text{s}} \right) * 40,87 \quad (197)$$

$$g_s \left( \frac{\text{m}}{\text{s}} \right) = g_s \left( \frac{\text{mol}}{\text{m}^2 \cdot \text{s}} \right) * \frac{RT}{P} \quad (198)$$

$$g_s \left( \frac{m}{s} \right) = g_s \left( \frac{mol}{m^2 \cdot s} \right) * \frac{8.314510 * (273.16 + 25)}{101325} \quad (199)$$

$$g_s \left( \frac{m}{s} \right) = g_s \left( \frac{mol}{m^2 \cdot s} \right) * \frac{2479.0543016}{101325} \quad (200)$$

$$g_s \left( \frac{m}{s} \right) = g_s \left( \frac{mol}{m^2 \cdot s} \right) * 0.0245 \quad (201)$$

#### GENERAL CONVERSION UNITS FOR TRACE GASES AND WATER

##### Conversion factor for CO<sub>2</sub> variable: molar to mass density

$$\frac{mmol}{m^3} CO_2 \rightarrow \frac{mg}{m^3} CO_2 \quad (202)$$

$$\frac{mmol}{m^3} CO_2 \rightarrow 44 \frac{mg}{m^3} CO_2 \quad (203)$$

##### Example:

$$15 \frac{mmol}{m^3} CO_2 \rightarrow 15 * 44 \frac{mg}{m^3} CO_2 \rightarrow 660 \frac{mg}{m^3} CO_2 \quad (204)$$

##### Conversion factor for CO<sub>2</sub> variable: mass to molar density

$$\frac{mg}{m^3} CO_2 \rightarrow \frac{mmol}{m^3} CO_2 \quad (205)$$

$$\frac{mg}{m^3} CO_2 \rightarrow \frac{1}{44} \frac{mmol}{m^3} CO_2 \rightarrow 0.0227 \frac{mmol}{m^3} \quad (206)$$

##### Example:

$$660 \frac{mg}{m^3} CO_2 \rightarrow 660 * 0.0227 \frac{mmol}{m^3} CO_2 \rightarrow 15 \frac{mmol}{m^3} CO_2 \quad (207)$$

##### Conversion factor for H<sub>2</sub>O variable: molar to mass density

$$\frac{mmol}{m^3} H_2O \rightarrow \frac{g}{m^3} H_2O \quad (208)$$

$$\frac{mmol}{m^3} H_2O \rightarrow \frac{18}{1000} \frac{g}{m^3} H_2O \rightarrow 0.018 \frac{g}{m^3} H_2O \quad (209)$$

##### Example:

$$1000 \frac{mmol}{m^3} H_2O \rightarrow 1000 * 0.018 \frac{g}{m^3} H_2O \rightarrow 18 \frac{g}{m^3} H_2O \quad (210)$$

Conversion factor for H<sub>2</sub>O variable: mass to molar density

$$\frac{g}{m^3} H_2O \rightarrow \frac{mmol}{m^3} H_2O \quad (211)$$

$$\frac{g}{m^3} H_2O \rightarrow \frac{1000 \text{ mmol}}{18 \text{ m}^3} H_2O \rightarrow 55.55 \frac{mmol}{m^3} H_2O \quad (212)$$

Example:

$$18 \frac{g}{m^3} H_2O \rightarrow 18 * 55.55 \frac{mmol}{m^3} H_2O \rightarrow 1000 \frac{mmol}{m^3} H_2O \quad (213)$$

Conversion factor for CH<sub>4</sub> variable: molar to mass density

$$\frac{mmol}{m^3} CH_4 \rightarrow \frac{mg}{m^3} CH_4 \quad (214)$$

$$\frac{mmol}{m^3} CH_4 \rightarrow 16 \frac{mg}{m^3} CH_4 \quad (215)$$

Example:

$$0.15 \frac{mmol}{m^3} CH_4 \rightarrow 0.15 * 16 \frac{mg}{m^3} CH_4 \rightarrow 2.4 \frac{mg}{m^3} CH_4 \quad (216)$$

Conversion factor for CH<sub>4</sub> variable: mass to molar density

$$\frac{mg}{m^3} CH_4 \rightarrow \frac{mmol}{m^3} CH_4 \quad (217)$$

$$\frac{mg}{m^3} CH_4 \rightarrow \frac{1 \text{ mmol}}{16 \text{ m}^3} CH_4 \rightarrow 0.0625 \frac{mmol}{m^3} CH_4 \quad (218)$$

Example:

$$2.4 \frac{mg}{m^3} CH_4 \rightarrow 2.4 * 0.0625 \frac{mmol}{m^3} CH_4 \rightarrow 0.15 \frac{mmol}{m^3} CH_4 \quad (219)$$

Conversion factor for NO<sub>2</sub> variable: molar to mass density

$$\frac{mmol}{m^3} NO_2 \rightarrow \frac{mg}{m^3} NO_2 \quad (220)$$

$$\frac{mmol}{m^3} NO_2 \rightarrow 46 \frac{mg}{m^3} NO_2 \quad (221)$$

Example:

$$0.0250 \frac{mmol}{m^3} NO_2 \rightarrow 0.0250 * 46 \frac{mg}{m^3} NO_2 \rightarrow 1.15 \frac{mg}{m^3} NO_2 \quad (222)$$

### Conversion factor for NO<sub>2</sub> variable: mass to molar density

$$\frac{mg}{m^3} NO_2 \rightarrow \frac{mmol}{m^3} NO_2 \quad (223)$$

$$\frac{mg}{m^3} NO_2 \rightarrow \frac{1}{46} \frac{mmol}{m^3} NO_2 \rightarrow 0.02174 \frac{mmol}{m^3} NO_2 \quad (224)$$

**Example:**

$$1.15 \frac{mg}{m^3} NO_2 \rightarrow 1.15 * 0.02174 \frac{mmol}{m^3} NO_2 \rightarrow 0.0250 \frac{mmol}{m^3} NO_2 \quad (225)$$

### Conversion factor for O<sub>3</sub> variable: molar to mass density

$$\frac{mmol}{m^3} O_3 \rightarrow \frac{mg}{m^3} O_3 \quad (226)$$

$$\frac{mmol}{m^3} O_3 \rightarrow 48 \frac{mg}{m^3} O_3 \quad (227)$$

**Example:**

$$0.015 \frac{mmol}{m^3} O_3 \rightarrow 0.015 * 48 \frac{mg}{m^3} O_3 \rightarrow 0.72 \frac{mg}{m^3} O_3 \quad (228)$$

### Conversion factor for O<sub>3</sub> variable: mass to molar density

$$\frac{mg}{m^3} O_3 \rightarrow \frac{mmol}{m^3} O_3 \quad (229)$$

$$\frac{mg}{m^3} O_3 \rightarrow \frac{1}{48} \frac{mmol}{m^3} O_3 \rightarrow 0.02083 \frac{mmol}{m^3} O_3 \quad (230)$$

**Example:**

$$0.72 \frac{mg}{m^3} O_3 \rightarrow 0.72 * 0.02083 \frac{mmol}{m^3} O_3 \rightarrow 0.015 \frac{mmol}{m^3} O_3 \quad (231)$$

### Acknowledgements

Thanks for the financially supported by the National Council for Scientific and Technological Development (CNPq, process 140635/2014-9), Coordination for Improvement of Higher level education (CAPES-PDSE, process 88881.135370/2016-01), and Foundation for Research Assistance of the Minas Gerais State (FAPEMIG). We also thank Dr. Thieres George Freire da Silva (UFRPE) for encourage us to publish this work, and Dr. Bart Kruijt (Wageningen University & Research) for comments and suggestions which helped improve this work.

### References

ALLEN, R. G.; PEREIRA, L. S.; RAES, D.; SMITH, M. Crop evapotranspiration - Guidelines for computing crop water requirements - **FAO Irrigation and drainage paper 56**. FAO, Rome, 300(9), D05109, 1998.

- AUBINET, M.; CHERMANNE, B.; VANDENHAUTE, M.; LONGDOZ, B.; YERNAUX, M.; LAITAT, E. Long term carbon dioxide exchange above a mixed forest in the Belgian Ardennes. **Agricultural and Forest Meteorology**, 108 (4), 293–315, 2001.
- AUBINET, M.; VESALA, T.; PAPAIE, D. Eddy covariance: a practical guide to measurement and data analysis. **Springer Science & Business Media**, 2012.
- FOKEN, T. **Micrometeorology**. Springer-Verlag Berlin Heidelberg, 306 p, 2008.
- JARVIS, P. G.; MCNAUGHTON, K. G. Stomatal control of transpiration: scaling up from leaf to region. **Advances in Ecological Research**, 15: 1-49, 1986.
- MALLICK, K.; JARVIS, A.; FISHER, J. B.; TU, K. P.; BOEGH, E.; NIYOGI, D. Latent heat flux and canopy conductance based on Penman–Monteith, Priestley–Taylor Equation, and Bouchet’s complementary hypothesis. **Journal of Hydrometeorology**, 14(2), 419–442, 2013.
- MAVI, H. S.; TUPPER, G. J. **Agrometeorology: principles and applications of climate studies in agriculture**. CRC Press, 381p, 2004.
- MONTEITH, J. L. Evaporation and environment. **Symposia of the Society for Experimental Biology**, v. 19, p. 205–234, 1965.
- NOBEL, P. S. **Physicochemical and Environmental Plant Physiology**. 4.ed. Burlington, MA: Academic Press, 604 p, 2009.
- NOORMETS, A.; GAVAZZI, M. J.; MCNULTY, S. G.; DOMEK, J. C.; SUN, G.; KING, J. S.; CHEN, J. Response of carbon fluxes to drought in a coastal plain loblolly pine forest. **Global Change Biology**, v. 16, p. 272–287, 2010.
- PEREIRA, A. R.; SEDIYAMA, G. C.; VILLA NOVA, N. A. Evapotranspiração. **Fundag**, Campinas, 323p, 2013.
- PEREZ, P. J.; CASTELLVI, F.; IBAÑEZ, M.; ROSELL, J. I. Assessment of reliability of Bowen ratio method for partitioning fluxes. **Agricultural and Forest Meteorology**, 97(3), 141–150, 1999.
- THIMIJJAN, R. W.; HEINS, R. D. Photometric, radiometric and quantum light units of measure: a review of procedures for interconversion. **HortScience**, 18(6), 818–22, 1983.

CITATION

REIS, M. G.; RIBEIRO, A. Conversion factors and general equations applied in agricultural and forest meteorology. **Agrometeoros**, Passo Fundo, v.27, n.2, p.227-258, dez 2019.



# Fatores de conversão e equações gerais aplicadas em meteorologia agrícola e florestal

Mariana Gonçalves dos Reis<sup>1(✉)</sup> e Aristides Ribeiro<sup>1</sup>

<sup>1</sup>Universidade Federal de Viçosa, Departamento de Engenharia Agrícola, Campus Universitário, CEP 36570-900 Viçosa, Minas Gerais, Brasil. E-mails: [mariana.reis@ufv.br](mailto:mariana.reis@ufv.br) e [ribeiro@ufv.br](mailto:ribeiro@ufv.br).

(✉) Autor para correspondência.

## INFORMAÇÕES

### História do artigo:

Recebido em 16 de agosto de 2019

Aceito em 11 de março de 2020

### Termos para indexação:

radiação solar

evapotranspiração

condutância do dossel

gases traços

uso eficiente dos recursos

balanço de carbono

## RESUMO

A comunicação científica em meteorologia agrícola e florestal exige uma conversão correta de unidades e o uso adequado de equações. Em geral, a maioria das conversões e equações são encontradas separadamente em um livro, artigo ou documento específico. Assim, propomos aqui um único documento com unidades de conversão de radiação solar, evapotranspiração, eficiência no uso de recursos, balanço de carbono, ecofisiologia, gases traços e água; e equações gerais: Penman-Monteith, condutância do dossel, fator de desacoplamento e razão de Bowen. Este documento tem muito valor para o ensino, para os cientistas e como uma referência rápida.

© 2020 SBAgro. Todos os direitos reservados.

## REFERENCIAÇÃO

REIS, M. G.; RIBEIRO, A. Conversion factors and general equations applied in agricultural and forest meteorology. *Agrometeoros*, Passo Fundo, v.27, n.2, p.227-258, dez 2019.