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Theoretical Guidelines to Estimate Plant Transpiration

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Abstract-Knowledge of photosynthesis water requirement is important for agriculture. The world population is increasing and water and land resources are limited. Food and energy prices have had increasing trends and will continue in the future. Agriculture is a central industry for both, and thermodynamic understanding of photosynthesis may help in improving agricultural practices and water management. Green matter transpiration is an integral part of photosynthesis thermodynamics; it represents the minimum amount of water required for green matter. This work reveals that the mass transpiration ratio may be estimated by analyzing photosynthesis as a thermodynamic cycle. Its value varies with air temperature, humidity, and elevation and is equal to 0.40 x $(1-\eta)/\eta$, where η is photosynthesis efficiency considered as a thermodynamic heat engine. Because surface temperature has been increasing, the transpiration ratio of terrestrial photosynthesis has decreased. For an equal amount of transpiration water available, green matter may produce more biomass. Between 1979 and 2012, photosynthesis productivity increased by 2.22 % per decade, which is equal to surface greening.

Keywords: Photosynthesis; Transpiration Ratio; Biomass; Thermodynamics; Carnot cycle

SYMBOLS AND ABBREVIATIONS

C_p	Specific heat of air mixture, kJ kg^{-1} °C^{-1}
$C_6H_{12}O_6$	Glucose
CO_2	Carbon dioxide
C_v	Specific heat of air mixture at constant volume, kJ kg^{-1} °C^{-1}
d	A symbol that denotes an infinitesimal variation
d^{-1}	Per day
e	Natural logarithm base, equal to 2.7183
ha	Hectare
h_V	Latent heat of water evaporation, J kg^{-1}
ΔH_{CO2}	Enthalpy of carbon combustion, kJ mol^{-1}
ΔH_v	Enthalpy of water evaporation, kJ mol^{-1}
H_2O	Water
g	Gas phase
k	Thousand
Ln	Natural logarithm
l	Liquid phase
Mg	Mega grams (one million grams)
m_T	Mass of plant transpiration, kg
m_{CO2}	Mass of carbon dioxide, kg
M_{H2O}	Molecular weight of water, kg kmol^{-1}
M_{CO2}	Molecular weight of carbon dioxide, kg kmol^{-1}
mol	Molar concentration
$m_{Glucose}$	Mass of glucose, kg
μ	Chemical potential, kJ mol^{-1}
m_{H2O}	Mass of transpiration water, kg
n	Number of moles
η	Actual efficiency of photosynthesis , dimensionless
η_C	Theoretical efficiency of photosynthesis as a Carnot heat engine, dimensionless
η_T	Thermal efficiency of photosynthesis, dimensionless
n_{CO2}	Number of moles of carbon dioxide in the atmosphere, mol
n_{H2O}	Number of moles of water vapor in the atmosphere, mol
O_2	Oxygen
P	Pressure of atmospheric air, kPa
Q_T	Heat rejected by the cold reservoir as latent heat of transpiration, kJ
Q_s	Heat provided by the surrounding air as a heat reservoir, kJ
R	Gas-law constant
RH	Relative humidity
s	Solid phase
S	Entropy kJ °K^{-1}.
t	Plant age in years or time in days
T_{db}	Air dry bulb temperature measured by placing a thermometer in shaded air space
T_{wb}	Air wet bulb temperature, measured by placing a thermometer in a shaded air space and covering thermometer bulb with a wet cloth at equilibrium with the surrounding air
T_R	Transpiration ratio, kg water per kg biomass
T_A	Actual or field transpiration ratio, kg water per kg biomass
v	Vapor phase
v	Air mixture specific volume, m^3 kg^{-1}
w	Air humidity, kg water per kg dry air
W	Work produced by Carnot heat engine cycle, kJ

INTRODUCTION

Food and energy are basic requirements for the world population. They have been as such throughout history and will continue to be in the future. The world population is projected to be at least 10.3 billion by the turn of the century [1, 2], and per capita energy consumption has had an increasing trend [3]. Food and energy will thus continue to be lucrative businesses, and agriculture provides both. The cost of biomass energy has remained competitive, and there appears to be a demand for it. Deforestation and farming of the cleared land have provided food for the world population. Clearly, there will come a time when the global market dictates the ratio between size of land used for food production and that for energy. Therefore, land size for farming is expected to be limited. Also, water availability will be limited as well. Rainfall is nearly 953 mm annually [4], and it is not projected to change significantly. These place limits on the amount of food and biomass energy produced by the world. Therefore, optimizing agriculture production will be a basic necessity, and calculation of the theoretical ratio between transpiration and biomass may provide guidelines for more efficient farming.

Many methods are presently available for estimating water requirements for agriculture. They are theoretical, empirical, or measured in the field. The Food and Agriculture Organization (FAO) publication authored by [5] discusses methods of calculating evaporation and evapotranspiration. Evapotranspiration is the sum of soil evaporation and plant transpiration. Soil evaporation is estimated using Bowen ratio energy balance instruments and micro-lysimeter methodologies for a wheat field [6]. Actual measurement of evapotranspiration may be obtained by using potable evapotranspiration chambers [7]. Many methodologies are available such as aerodynamic, water balance, eddy covariance, remote sensing, and others [8]. These publications discuss a mere partial list of methods used to calculate or measure evapotranspiration, soil evaporation, and transpiration. Separating plant transpiration from the total evapotranspiration stream is a major task and requires considerable resources, and obtaining mass ratio between transpiration and biomass produced is equally expensive and has a large margin of errors [9]. The ratio is meaningful and useful in agricultural feasibility study, planning, as well as management of existing operations. The theoretical determination of the ratio on the other hand is inexpensive, and the ratio may be calculated for crops as well as forests and other plantations. This work provides thermodynamic methodologies to obtain theoretical values of the mass ratio between transpiration and biomass produced for any climatic conditions.

Unlike soil evaporation, terrestrial transpiration exists where green matter exists, and there is a correlation between transpiration and biomass. The objective of this manuscript is to determine the theoretical mass ratio between transpiration water and biomass produced using traditional thermodynamics. A general and simplified formula to calculate the ratio is then derived. Sample calculations are provided, and comparisons with observations available are discussed. Because of the interdisciplinary nature of this work, a section entitled "Symbols and abbreviations" is included. The intended meanings of symbols used are explained in this section.

BACKGROUND INFORMATION

Plant growth follows Liebig's law, or the law of the minimum. The law states that plant growth is controlled not by the resources available, but by the scarcest resource, or limiting factor. The limiting factors are numerous and include but are not limited to water, sunlight, carbon dioxide, nutrients, pests, weed, climate conditions, human care, and others. For the objectives of this work, water and climate conditions are the limiting factors considered. Climate is changing and water consumption for non-agricultural use is increasing with population growth. These factors are important for biomass energy and food of the future.

The conclusion of publication [10] is that, if everything else is the same, air dry and wet bulb temperatures are limiting factors of photosynthesis. As will be demonstrated in this work, their values may be used to calculate plant transpiration and its variability with climate conditions. Thermodynamic methodologies are used to estimate plant transpiration. Photosynthesis as a thermodynamic cycle and thermodynamics of the carbon cycle [10, 11] are fundamental requirements for the theoretical work presented in this manuscript. The thermodynamic methodology is equivalent to the radiative model of photosynthesis: An increase in the size of green matter converts solar energy into chemical energy in the form of plant constituents. As a result, green matter gains chemical energy and the surroundings lose solar energy. This chemical/radiative process is equivalent to heat transfer from the surroundings to the green matter, and thermodynamic representation of photosynthesis as a heat engine as shown in Fig. 1 is thus possible. The related theoretical Carnot heat engine cycle is discussed in detail by [10]. The surroundings supply heat dQ_s at air dry bulb temperature T_{db} to green matter. Some of the heat, dQ_T, is lost by green matter at the colder air wet bulb temperature T_{wb} by transpiration. This heat finds its way to the atmosphere. The difference, dQ_s-dQ_T, is equal to the chemical energy produced by photosynthesis, dW. The ratio between transpiration and biomass produced may therefore be calculated. For actual thermodynamic transformation of photosynthesis, Fig. 1, the area enclosed by transformations 1 through 4 is not a square as is the case for a Carnot heat engine cycle, it is a parallelogram. The area enclosed by the parallelogram is equal to dW. In a natural world without humans, dQ_s is equal to the heat supplied by sea water, and dQ_T is equal to total transpiration of terrestrial photosynthesis. The difference, dQ_s-dQ_T, is equal to terrestrial green matter produced. Based on this theoretical understanding of photosynthesis, the thermodynamic model is parameterized in the theory section. Observed biomass and transpiration ratio are reconstructed from experiments and compared with theoretically calculated values. They are found to be in agreement. Accordingly, transpiration ratio for different climate conditions and production trends of terrestrial photosynthesis are estimated.

DATA AND METHOD

This work is intended to provide a theoretical approach to calculating mass ratio between plant transpiration and biomass produced. The methodology examines photosynthesis as a chemical reaction and thermodynamic cycle simultaneously. Typical thermodynamic analysis for each thermodynamic transformation of Fig. 1 is applied, and the efficiency and transpiration ratio of photosynthesis are determined. To compare the theoretical values of transpiration ratio with field data, many publications have been examined for alignment with the objectives of this theoretical work. Most of the literature available at this time appears to address plant transpiration as an integral part of evapotranspiration. Although there is an impressive number of field experiments on this subject, the experiments are not aligned with the objectives of this manuscript. For instance, soil evaporation is not relevant for comparison and validation, nor would transpiration measurement alone suffice. It is the simultaneous field measurement of biomass and transpiration that is needed, which is a major undertaking as discussed in Introduction. However, small-scale experiments may be useful. Transpiration of a three- year old apricot tree, having approximate crown size and height of 1.5 m and 2 m respectively, was measured in a greenhouse [12]. Soil water evaporation was eliminated, and the measured total water supplied was equal to tree transpiration. The measured transpiration ranged between 5 and 7 liters per day. The recorded daily temperatures were between 20 °C and 24 °C. Biomass was not provided, but it may be estimated from the given dimensions of the tree. Equation (4) of [13], may be used to estimate the aboveground mass of the tree, $Ln(BM)=1.738+0.965\ Ln\ (ca)+1.058\ Ln\ (H)+1.384\ Ln\ (\rho)$. Where

BM is biomass, kg; ca is crown area, 1.77 m^2; and H is tree height, 2 m. For wood density, ρ in g cm^{-3}, the estimate by [13] was 0.530, which is nearly equal to that estimated by [14] of 0.539 Mg M^{-3}. Therefore, biomass BM=8.52 kg. Root biomass may add 25% of the above ground biomass [15], and the total tree biomass was thus nearly equal to 10.65 kg. As Table 1 shows, typical photosynthesis efficiency at 20 °C and 24 °C is about 1.1%. Consequently, daily growth of apricot trees during transpiration measurement was approximately 0.12 kg d^{-1}. The observed mass transpiration ratio was therefore between 42.69 to 58.33 kg water of transpiration per kg of biomass produced.

A comprehensive study was conducted in 2010 by [16] on corn fields in Nebraska, U.S.A., which may be used for comparison. Results of the research relative to Fully Irrigated Treatment (FIT) and rain fed are used. They are tabulated in Table 1 of [16]. Corn biomass at the end of the growing season is provided in the paper as well as evapotranspiration. Biomass data is then used to reconstruct crop growth during the growing season, and the mass ratio between transpiration and biomass calculated. The rest of the data required for analysis of photosynthesis as a heat engine cycle are available in typical textbooks or engineering handbooks of thermodynamics. Thermodynamics is summarized in general and for the particular case of ideal gases, which is applicable to surface air [17, 18, 19]. Of interest is air entropy change with isothermal and adiabatic transformations that are an integral part of the photosynthesis thermodynamic cycle. The related thermodynamic equations are used to calculate entropy change and the area enclosed by the parallelogram of Fig. 1. The physical properties of air water mixture are obtained from [20]. The relevant physical properties are specific heat of air, 1.006 kJ kg^{-1} $°K^{-1}$; specific heat of water vapor, 4.19 kJ kg^{-1} $°K^{-1}$; and gas-law constant, 0.289, kJ kg $°K^{-1}$. Air psychometry related relationships are described in [21]. This reference provides equations of the physical properties of air/water mixture with climate parameters such as air dry and wet bulb temperatures, relative humidity, and altitude. They are used in this work.

THEORY AND ANALYSIS

The chemical reaction of terrestrial photosynthesis and its interaction with the biosphere may be summarized based on [11] as follows:

$$6CO_2(g) + 6H_2O(l) \xrightarrow{\text{Light/Chlorophyll}} C_6H_{12}O_6(s) + 6O_2(g) \quad (1)$$

$H_2O(l)$ =====> $H_2O(v)$ (2)

In Eq. (1) carbon dioxide, CO_2, and soil water, H_2O, are converted into solid glucose, $C_6H_{12}O_6$, and oxygen, O_2, in the presence of sunlight and chlorophyll. It is a non-spontaneous reaction and requires heat, dQ_s, shown in Fig. 1. Simultaneously, evapotranspiration occurs, Eq. (2). Water from the soil is evaporated by plant transpiration. Just like other organisms, green matter too must reject excess heat, otherwise it will not survive. The latent heat of transpiration water is equal to dQ_T of Fig. 1. Variation in the content of water vapor and carbon dioxide in the atmosphere are correlated by Eq. (8) of [11] as follows:

$$dn_{H2O}\ \mu_{H2O} = -\ dn_{CO2}\ \mu_{CO2} \quad (3)$$

Where

dn_{H2O} =Variation in the number of moles of water vapor, mol.

μ_{H2O} =Chemical potential of water vapor, 43.97 kJ mol^{-1}.

dn_{CO2} =Variation in the number of moles of carbon dioxide, mol.

μ_{CO2} =Chemical potential of carbon dioxide, -393.14 kJ mol^{-1}.

and

$$dn_{H2O} = 8.94\ dn_{CO2} \quad (4)$$

Equation (4) is the same as Eq. (9) of [11]. Variation in masses of water vapor and carbon dioxide may be obtained from Eq. (4) as follows:

$$dm_T = 8.94\ dm_{CO2}\ M_{H2O}/M_{CO2} \quad (5)$$

$$dm_T = 8.94\ dm_{CO2} \times (18/44) \quad (6)$$

$$dm_T/dm_{CO2} = 3.657 \quad (7)$$

Where

dm_T =Variation in mass of transpiration water of terrestrial photosynthesis, kg.
dm_{CO2} =Variation in mass of carbon dioxide in the atmosphere, kg.
M_{H2O} =Molecular weight of water, 18 kg kmol^{-1}.
M_{CO2} =Molecular weight of carbon dioxide, 44 kg kmol^{-1}.

Based on the Periodic Table of Elements, the atomic mass of carbon, C, Oxygen, O, and hydrogen, H, are 12, 16, and 1 respectively. From the mass balance of Eq. (1), it takes 264 kg of carbon dioxide, CO_2, to produce 180 kg of glucoses, $C_6H_{12}O_6$. Nearly 1.467 kg of CO2 are required to produce 1 kg of solid glucose. Or, $dm_{CO2}/dm_{Glucose}$=1.467, where $dm_{Glucose}$ is equal to variation in the mass of solid glucose. This ratio and Eq. (7) give $dm_T/dm_{Glucose}=dm_T/dm_{CO2}$ x $dm_{CO2}/dm_{Glucose}$=3.657 x 1.467. Therefore, $dm_T/dm_{Glucose}$=5.36. This mass ratio between transpiration and biomass is set by nature; it is equal to the minimum ratio to which terrestrial photosynthesis can approach. The ratio is typically referred to as the transpiration ratio [22], and will be indicated as such hereafter. The transpiration ratio of terrestrial photosynthesis may, at best, approach the value of 5.36.

Referring to Fig. 1, green matter may be assumed as a thermodynamic system. The surrounding air at air dry bulb temperature is the heat reservoir, and the colder air enclosed by green matter space is the cold reservoir at air wet bulb temperature. Air is the medium of heat transfer; it circulates between the heat and cold reservoirs. Heat supply dQ_s is equal to the thermal capacity of air multiplied by the difference in temperature between the reservoirs. For one (1) kg of air mixture, the following equations may apply:

Isothermal expansion, transformation 1-2

$$dS_{1\text{-}2}=dQ_s/T_{db}=C_p\,(T_{db}-T_{wb})/T_{wb} \tag{8}$$

Where
$dS_{1\text{-}2}$=Entropy change between point 1 and point 2, kJ °K^{-1}.
dQ_s =Heat supply by the heat reservoir, kJ.
C_p =Specific heat of air mixture, kJ kg^{-1} °K^{-1}.
T_{db} =Air dry bulb temperature, °K.
T_{wb} =Air wet bulb temperature, °K.

Adiabatic expansion, transformation 2-3

$dS_{2\text{-}3}$=Ln(T_{wb}/T_{db})-R Ln(P_3/P_2) (9)

P_3 =P_2 x $(T_{wb}/T_{db})^{[k/(k-1)]}$ (10)

k =C_p/C_v (11)

C_v =C_p-R (12)

Where

$dS_{2\text{-}3}$=Entropy change between point 2 and point 3, kJ °K^{-1}.

P_3 =Air pressure of point 3, kPa.

P_2 =Air pressure of point 2, kPa.

C_v =Air specific heat at constant volume, kJ kg^{-1} °K^{-1}.

R =Gas-law constant, kJ kg^{-1} °K^{-1}.

Isothermal compression, transformation 3-4

$dS_{3\text{-}4}$=P_3 (v_4-v_3)/T_{wb} (13)

Where

$dS_{3\text{-}4}$ =Entropy change between point 3 and point 4, kJ °K^{-1}.

v_4 =Air specific volume at point 4, M^3 kg^{-1}.

v_3 =Air specific volume at point 3, M^3 kg^{-1}.

Adiabatic compression, transformation 4 to 1

$dS_{4\text{-}1}$=Ln(T_{db}/T_{wb})-R Ln(P_1/P_4) (14)

Where

P_4 =Air pressure of point 4, kPa.

The work produced, dW, by the thermodynamic cycle is equal to the area enclosed by transformations 1-2, 2-3, 3-4, 4-1. This area is equal to the chemical energy produced as biomass. The actual area is not necessarily an exact square as is the case for the theoretical Carnot cycle, it has a slight positive offset (transformation 1-2) and a slight negative offset (transformation 3-4) as shown in Fig 1. These offsets may be assumed to enclose small triangles. The total area may reasonably be estimated as follows:

$$dW = 1/2 \times (dS_{1\text{-}2} - dS_{3\text{-}4} + dS_{2\text{-}3} + dS_{4\text{-}1}) \times (T_{db} - T_{wb}) \quad (15)$$

$$dQ_T = dQ_s - dW \quad (16)$$

$$T_R = (dQ_T/dW) \times M_{H2O}/M_{CO2} \quad (17)$$

Efficiency of the thermodynamic cycle, $\eta = dW/dQ_s$ (18)

Carnot cycle theoretical efficiency $\eta_c = 1-(T_{wb}/T_{db})$ (19)

Thermal efficiency $\eta_T = 1-(T_{wb}/T_{db})^{0.5}$ (20)

$$T_R = [(1-\eta)/\eta] \times M_{H2O}/M_{CO2} \quad (21)$$

Where

T_R=Transpiration ratio of photosynthesis, kg of transpiration water per kg of biomass produced

Equations (16), (18), (19), and (20) may be found in typical thermodynamic references, for example [18]. Equation (17) converts the ratio between latent heat of transpiration water and biomass energy into the mass transpiration ratio in analogy with Eq. (5). Equation (21) is derived from Eq. (16), (17), and (18).

SAMPLE CALCULATIONS

As discussed in the data section, the experiment of [12] yielded values of transpiration ratio between 42.69 and 58.33. The experiment was conducted in a greenhouse at a temperature between 20 °C and 24 °C. Assuming that atmospheric pressure is at sea level and average global relative humidity is equal to 61.52%, the psychometric chart [21] gives air humidity of nearly 0.01 kg water per kg dry air. Also, the chart gives air wet bulb temperature at saturation of approximately 17.11 °C. Therefore, the following calculations may be performed:

Transformation 1-2 Data: P=100 kpa; T_{db}=22°C; Relative humidity=61.52%; Humidity=0.01 kg water per kg dry air.

Transformation 3-4 Data: T_{wb}= 17.11 °C; relative humidity is at about saturation; Humidity=0.012 kg water per kg dry air

Transformation 1-2

$C_p=1.038$ kJ kg^{-1} °k^{-1}; $dQ_s=C_p\ (T_{db}-T_{wb})=1.038 \times (22-17.11)=5.07$ kJ

$dS_{1\text{-}2}=dQ_s/T_{db}=5.07/295.16=0.0172$ kJ °K^{-1}

Transformation 2-3

$C_v=C_p-R=1.038-0.289=0.749$ kJ kg^{-1} °k^{-1}; $k=C_p/C_v=1.038/0.749=1.386$

$P_3=P_2 \times (T_{wb}/T_{db})^{[k/(k-1)]}=100 \times (290.27/295.16)^{[1.386/(1.386-1)]}=94.18$ kpa

$dS_{2\text{-}3}=Ln(T_{wb}/T_{db})-R\ Ln(P_3/P_2)=Ln(290.27/295.16)-0.289\ Ln(94.18/100)=0.000626$ kJ °K^{-1}

Transformation 3-4

$v_1=0.852$ kg m^{-3}; $v_2=0.903$ kg m^{-3}; $v_3=0.943$ kg m^{-3}; $v_4=0.891$ kg m^{-3}

$dS_{3\text{-}4}=P3\ (v_4-v_3)/T_{wb}=94.18\ (0.891-0.943)/(290.27)=-0.0168$ kJ °K^{-1}

Transformation 4-1

$dS_{4\text{-}1}=Ln(T_{db}/T_{wb})-R\ Ln(P_1/P_4)= Ln(295.16/290.27)-0.289\ Ln(100/94.18)=-0.000626$ kJ °K^{-1}

$dW=1/2 \times (dS_{1\text{-}2}-dS_{3\text{-}4}+ dS_{2\text{-}3}+ dS_{4\text{-}1}) \times (T_{db}-T_{wb})=1/2 \times (0.0172+0.0168+0.000626-0.00626)$
$\times (22-17.11)=0.083$ J

$dQ_T= dQ_s-dW=5.07-0.083=4.99$ J

$T_R=(4.99/0.083) \times (18/44)=24.56$

Efficiency of photosynthesis $\eta=dW/dQ_s=0.083/5.07=0.0164$

Carnot cycle theoretical efficiency, η_C =1-290.27/295.16=0.0166

Thermal efficiency, η_T =1-(290.27/295.16)$^{0.5}$=0.0083

T_R =[(1-η_c)/η_c] x M_{H2O}/M_{CO2}=0.4 (1-0.0166)/0.0166 =23.70

As the sample calculations show, for temperature values of heat and cold reservoirs located on the wet bulb temperature of the psychometric chart, the calculated efficiency is about equal to the Carnot cycle theoretical efficiency of Eq. (19). The efficiency assumes maximum value when the temperature of the cold reservoir approached air wet bulb temperature at saturation because it is the lowest air temperature possible. This may be the case in conditions of calm days, ample irrigation water, and fully developed plant canopy. However, in practice these conditions may not be satisfied. For instance on a windy day or early in the growing season, plant canopy is not fully developed, and approaching saturation would be difficult. The data provided by [12] are insufficient to determine how far from saturation was the air enclosed by tree canopy in the experiment. However, based on experiment description, it was likely away from saturation, and the actual value of photosynthesis efficiency may be less than the maximum. Most likely photosynthesis efficiency approached the calculated thermal efficiency of 0.0083. Transpiration ratio may thus be equal to T_R=0.4 x (1-0.0083)/0.0083=47.79. This value of transpiration ratio falls well within the observed value between 42.69 and 58.33.

Results of the study conducted by [16] may be compared with those calculated by thermodynamics. The relevant data for this work are dates of corn planting, emergence, and maturity/harvest; biomass produced; and air temperature, humidity, and field elevation. Planting day was April 28; plant emergence day was May 15, and harvest day was October 7. Site elevation is 552 m, and air temperature and relative humidity are given in figures 1 (c) and (e) of [16]. For simplicity, the median value of the month is considered as the monthly average value of air temperature and relative humidity. Because corn harvest was made on October 7, climate conditions of the month of September are used for these seven days of early October. Table 1 of [16] details results of the study. Data relative to Fully Irrigation Treatment (FIT) and rain fed scenarios are considered for discussion. At maturity, the table reveals that the total biomass above ground measured 28.6 Mega grams per hectare (Mg ha^{-1}), the observed average evapotranspiration was 3.9 mm per day, and the cumulative evapotranspiration was 634 mm. To account for root biomass, 7% of the observed biomass above ground is added based on researches conducted by [23]. Referring to equation 17 of [10], biomass as a function of photosynthesis efficiency follows:

$$m_G=m_{G0}\, e^{\eta_{max}(t-t0)} \quad (22)$$

Where

m_G =Mass of green matter at age t, kg.

m_{G0}=Mass of green matter at age t_0, kg.

η_{max}=Maximum efficiency of seasonal photosynthesis thermodynamic cycle, dimensionless.

Equation (22) may be used to estimate biomass and its variation during the growing season by knowing final biomass at maturity m_G. From Eq. (22), average monthly biomass may be obtained $m_{G0}=m_G/[e^{\eta(t-t0)}]$, and the average daily growth in biomass is equal to $dm_G= m_{G0}\, e^{\eta}-m_{G0}=m_{G0}\,[e^{\eta}-1]$, where η is equal to daily average efficiency of photosynthesis. The age, t, now is in days. Lines 1 and 2 of Table 1 are monthly average temperature and relative humidity. At 552 m of site elevation above sea level, monthly average air humidity is tabulated in line 4. Therefore, lines 1 and 4 are data for transformation 1-2 of Fig.1. The psychometric chart gives air wet bulb temperature and humidity at saturation, lines 5 and 6. They are thermodynamic parameters for the cold reservoir, transformation 3-4. Accordingly, photosynthesis efficiency is calculated and presented in line 9. Transpiration ratio is calculated in a similar manner to the sample calculations above and tabulated in line 10. Monthly biomass is then reconstructed by using Eq. (22) and it is presented in line 8. Cumulative transpiration ratio is then obtained by multiplying monthly biomass inventory by the transpiration ratio, which is shown in line 11. Lines 12 through 16 reconstruct transpiration and plant growth for the rain fed scenario. For this scenario, above ground biomass obtained at maturity was 23.9 Mg ha^{-1} and 7% of this biomass is added to account for root biomass. Rain fed biomass inventory is calculated by using Eq. (22). Biomass of May for FIT is assumed to be the same for both scenarios. To converge the calculations to the final biomass of rain fed scenario of 25.57 Mg ha^{-1}, the calculated photosynthesis efficiency of FIT, line 9, had to be multiplied by a factor of 0.87, and the obtained rain fed efficiency is shown in line 14. Transpiration ratio and cumulative transpiration are then calculated in the same way as that for FIT crop and presented in lines 15 and 16.

Example: From Table 1, the total biomass at maturity of Fully Irrigation Treatment crop in October 7 was nearly 30.60 Mg ha^{-1}, and the calculated photosynthesis theoretical efficiency for September is 0.011. Average corn biomass for September is thus equal to $30.60/[e^{0.011 \times 7}]=28.33$ Mg ha^{-1}. Average daily increase in biomass for September, dm_G, is equal to$=28.33[e^{0.011}-1]=0.31$ Mg ha^{-1}. Similarly, the average corn biomass for August may be obtained from the calculated biomass of September, $m_G=28.33/[e^{0.011 \times 30}]=20.37$ Mg ha^{-1}. The procedure is then repeated for the months of July, June, and May, line 8 of Table 1. It is reasonable to assume that for May, both corn crops, fully irrigated and rain fed, had the same biomass inventory before any irrigation, which is equal to 7.56 Mg ha^{-1}. Using biomass of May as a starting inventory for the rain fed crop, biomass growth during the season may be determined following the same methodology. For June, biomass $m_G=7.56 \times e^{(0.011 \times 0.87 \times 31)} =10.17$ Mg ha^{-1}, line 13. And the procedure may be repeated for the succeeding months of July, August, September, and October. The calculated monthly biomasses are illustrated in Fig. 2, and transpiration versus biomass produced for FIT scenario is plotted in Fig. 3.

Greening of the surface including arid and semiarid areas has been observed [24, 25]. The process with which surface greening occurs is an ongoing research subject. Surface greening may be explained based on this work. The Intergovernmental Panel on Climate Change report [26] provides sea surface temperature and surface air temperature trends for the present surface warming. Analysis of the data provided suggests that for the period of time between 1979 and 2012, sea surface temperature rise and terrestrial air temperature rise were nearly equal to 0.0725 °C and 0.165°C per decade respectively. It is reasonable to assume that sea air is at saturation with sea water, and sea air temperature rise is thus equal to sea water temperature rise. Because this air is at the saturation curve of the psychometric chart, air wet bulb temperature had a trend of nearly 0.0725°C per decade as well. At average surface temperature of 14.5 °C and relative humidity of nearly 61.52%, air wet bulb temperature is equal to 10.50 °C. Therefore, $\eta_C=1-(10.5+273.16)/(14.5+273.16)= 0.0139$, Eq. (19). The initial value of transpiration ratio, $T_{R0}=0.4 \times (1-0.0139)/0.0139=28.37$, Eq. (21). For dry bulb temperature rise of 0.165 °C and wet bulb temperature rise of 0.0725 °C per decade, $\eta_C=1- (10.573+273.16)/(14.665+273.16)= 0.0142$, and the transpiration ratio after a decade is equal to $T_R=$ $0.4 \times (1-0.142)/0.142=27.74$. The transpiration ratio decreased by 2.22% in ten years. For the same amount of transpiration water available, green matter sustained more biomass, and productivity of terrestrial photosynthesis increased by 2.22% per decade in the period of time between 1979 and 2012. Also, this increase is equal to surface greening.

DISCUSSION AND CONCLUSIONS

The medium of heat transfer of photosynthesis considered as a thermodynamic cycle is surface air that resembles an ideal gas. Friction losses during air expansion and compression are negligible, and a theoretical Carnot heat engine representation of photosynthesis is potentially possible. As expected, sample calculations show that equations (1) through (18) yield about the same value of efficiency as the theoretical Carnot thermodynamic cycle, Eq. (19). Photosynthesis efficiency of fully irrigated corn field was nearly equal to the maximum theoretical efficiency of the Carnot cycle, η_C. Temperature of the air enclosed by corn plants was coldest because it approached air wet bulb temperature at saturation. The area enclosed by the thermodynamic transformations of Fig. 1 assumed maximum value, and the thermodynamic cycle was most efficient. Its efficiency approached the theoretical efficiency of Carnot cycle. The theoretical transpiration ratio assumed a minimum value that is equal to $T_R= [(1-\eta_c)/\eta_c] \times M_{H2O}/M_{CO2}=0.4 \times [(1-\eta_c)/\eta_c]$. However, in practical agricultural applications, wind, water shortage, undeveloped plant canopy, and other reasons may decrease the efficiency of photosynthesis considerably. The actual efficiency of photosynthesis in the field, η, is less than maximum, and actual transpiration ratio $T_A=[(1-\eta)/\eta] \times M_{H2O}/M_{CO2}=0.4 \times [(1-\eta)/\eta]$.

It is unknown how far away from saturation the air enclosed by the corn field of research was because air wet bulb temperatures are not provided by [16]. However, for Fully Irrigation Treatment (FIT), approach to saturation may be the case. This yielded a minimum total transpiration, 109 mm, line 11 of Table 1, whereas rain fed transpiration was 125.29 mm, line 16. The fully irrigated corn crop required less transpiration water than the rain fed crop by 13%, yet biomass produced was nearly 20% greater than the rain fed crop, lines 8 and 13. Transpiration ratio for the corn fields varied between 35.62 and 45.78 kg water per kg of biomass produced as lines 10 and 15 of Table 1 show. This calculated value is within 22% of the observed range of 42.69 to 58.33 during an experiment on apricot trees as discussed in the data section. These results indicate that if green matter is subjected to nearly the same climatic conditions of air dry and wet bulb temperatures, it would require about an equal amount of transpiration water per unit of biomass produced. As figure 2 illustrates, biomass grows exponentially during the growing season; however, the relationship between transpiration and biomass produced is linear, Fig. 3. These theoretical findings are generally expected based on empirical conclusions [16]. Analysis of the researched corn fields reveals that the photosynthesis efficiency of the rain fed field was less than that of the fully irrigated field, and thus used more transpiration water per unit of biomass produced. This is likely to be the case for most crops that rely on rainfall. For parts of the world where rainfall is less than that of the researched corn fields, say 250 mm annually or less, photosynthesis efficiency is likely to be much less, and may approach the thermal efficiency of photosynthesis, η_T.

A general rule may be provided based on this work: if the measured field temperatures of the heat and cold reservoirs are aligned with the wet bulb temperature of the psychometric chart, the Carnot cycle theoretical efficiency, η_C, Eq. (19), may be used to calculate photosynthesis efficiency and transpiration ratio without running the calculations. Transpiration ratio assumes minimum value when the space enclosed by green matter approaches air wet bulb temperature at saturation. For all other cases, the thermal efficiency of photosynthesis, η_T, Eq. (20), may be used to estimate photosynthesis efficiency and plant transpiration ratio if running the calculations is not possible.

It should be noted that the transpiration ratio is correlated with climate conditions. The value of the ratio depends on air dry bulb temperature, air humidity, and elevation. For equal values of air dry bulb temperature and humidity, air wet bulb temperature decreases with elevation. Therefore, the transpiration ratio decreases with elevation. For comparison, tables 2 and 3 present values of theoretical transpiration ratio at sea level and 1 000 m above sea level for different values of air temperature and humidity. Moving along one column of the table from top to bottom, the transpiration ratio varies in a typical day. Early in the morning, the transpiration ratio is high; however, photosynthesis efficiency is small to negligible because air dry and wet bulb temperatures are close to each other. Plant transpiration and growth are negligible. As the surface gains solar heat during the day, air dry and wet bulb temperatures depart from each other. The value of the transpiration ratio decreases and the efficiency of photosynthesis increases. Green matter grows, and transpiration increases as a result. Moving diagonally along the table from top left to bottom right, the transpiration ratio varies in a typical season. Photosynthesis efficiency approaches maximum values and the transpiration ratio approaches minimum values. The tables show that the lowest value of mass transpiration ratio may only approach the theoretical minimum value of 5.36 calculated in the theory section. These theoretical understandings of photosynthesis apply to all green matter species, regardless of size or geographic location. Green matter provides food for non-green living matter, and photosynthesis as a thermodynamic cycle may be utilized to analyze the effects of changes in climate on ecosystems. The application section reveals a decreasing trend of transpiration ratio with surface temperature rise, and global and regional greening of the surface is thus expected.

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This article does not contain any studies involving animals or human participants as objects of research. The authors declare that they have no conflict of interest.

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TABLES

Table 1. Theoretical calculations of corn fields growth parameters and transpiration. Climate conditions and biomass at maturity for Fully Irrigation Treatment (FIT) and rain fed scenarios are obtained from [16] for the year 2010.

Line	Description\Month	May	June	July	August	September	October
1	Air temperature, Tdb °C	17.00	22.00	24.50	24.00	17.00	17.00
2	Air relative humidity %	75.00	74.00	71.00	69.00	72.00	72.00
3	Altitude, m	552.00	552.00	552.00	552.00	552.00	552.00
4	Humidity of point 1 of cycle, kg water/kg dry air	0.010	0.013	0.016	0.015	0.010	0.010
5	Humidity of point 4 of cycle, kg water/kg dry air	0.011	0.014	0.017	0.016	0.010	0.010
6	Air wet bulb temperature, Twb °C	14.11	18.72	21.28	20.78	13.78	13.78
7	Number of days after plant emergence	15.00	46.00	76.00	107.00	137.00	144.00
8	Fully Irrigated Treatment (FIT) biomass, Mg per hectare	7.56	10.48	14.56	20.37	28.31	30.60
9	FIT photosynthesis efficiency	0.010	0.011	0.011	0.011	0.011	0.011
10	FIT, transpiration ratio, kg water/kg biomass	39.78	35.62	36.55	36.49	35.62	35.62
11	FIT cumulative transpiration, mm	30.07	37.32	53.22	74.33	100.85	109.00
12	Percent of observed evapotranspiration	23.36%	20.80%	17.95%	17.81%	18.88%	19.41%
13	Rain fed biomass, Mg per hectare	7.56	10.04	13.37	17.91	23.85	25.52
14	Rain fed efficiency of photosynthesis	0.009	0.010	0.009	0.009	0.010	0.010
15	Rain fed transpiration ratio, kg water/ kg biomass	45.78	41.00	42.07	42.00	41.00	41.00
16	Rain fed cumulative transpiration, mm	34.56	42.90	61.17	85.44	115.92	125.29
17	Percent of observed evapotranspiration	29.09%	25.91%	22.36%	22.18%	23.50%	24.17%

Table 2. Values of the theoretical transpiration ratio, T_R, in kg water per kg biomass at sea level. Air dry bulb temperature, T_{db}, and air wet bulb temperature, T_{wb}, are in degrees centigrade.

Air temperature	Humidity ratio, kg water per kg dry air											
Tdb	0.006			0.010			0.014			0.018		
	T_{wb}	RH%	T_R	T_{wb}	RH%	T_R	T_{wb}	RH%	T_R	T_{wb}	RH%	T_R
12	9.22	69.87	40.66	--	--	--	--	--	--	--	--	--
14	10.11	61.40	29.14	--	--	--	--	--	--	--	--	--
16	11.00	53.98	22.73	14.94	89.40	109.18	--	--	--	--	--	--
18	11.83	47.58	18.49	15.67	78.79	49.51	--	--	--	--	--	--
20	12.67	42.00	15.59	16.39	69.56	32.07	19.67	96.77	351.39	--	--	--
22	13.50	37.15	13.49	17.11	61.52	23.75	20.28	85.58	68.15	--	--	--
24	14.28	32.90	11.83	17.78	54.49	18.70	20.89	75.81	37.81	23.61	96.86	305.25
26	15.06	29.19	10.53	18.50	48.35	15.56	21.50	67.26	26.19	24.17	85.94	64.87
28	15.78	29.54	9.46	19.11	42.97	13.15	22.06	59.77	19.86	24.67	76.37	35.74
30	16.50	23.09	8.58	19.78	38.24	11.46	22.67	53.20	16.14	25.22	67.97	24.98
32	17.22	20.58	7.86	20.39	34.09	10.11	23.22	47.42	13.51	25.72	60.59	19.04
34	17.89	18.38	7.23	21.00	30.43	9.05	23.78	42.34	11.62	26.22	54.09	15.40
36	18.56	16.43	6.69	21.61	27.21	8.19	24.28	37.85	10.15	26.72	48.36	12.93

Table 3. Values of the theoretical transpiration ratio, T_R, in kg water per kg biomass at 1 000 m above sea level. Air dry bulb temperature, T_{db}, and air wet bulb temperature, T_{wb}, are in degrees centigrade.

Air temperature	Humidity, kg water per kg dry air											
T_{db}	0.006			0.010			0.014			0.018		
	T_{wb}	RH%	T_R	T_{wb}	RH%	T_R	T_{wb}	RH%	T_R	T_{wb}	RH%	T_R
12	8.00	61.97	28.12	--	--	--	--	--	--	--	--	--
14	8.83	54.42	21.83	12.94	90.13	108.42	--	--	--	--	--	--
16	9.67	47.88	17.86	13.67	79.30	49.17	--	--	--	--	--	--
18	10.44	42.20	15.01	14.33	69.89	31.36	17.67	97.22	348.99	--	--	--
20	11.17	37.26	12.88	15.00	61.70	23.05	18.28	85.84	67.69	--	--	--
22	11.89	32.95	11.28	15.61	54.57	18.08	18.83	75.91	36.88	21.61	96.99	303.19
24	12.61	29.19	10.04	16.22	48.34	14.88	19.39	67.24	25.38	22.11	85.92	62.53
26	13.33	25.90	9.05	16.83	43.89	12.65	19.89	59.66	19.18	22.61	76.23	34.91
28	14.00	23.01	8.20	17.44	38.11	11.01	20.44	53.02	15.54	23.06	67.74	23.96
30	14.67	20.48	7.51	18.00	33.92	9.71	20.94	47.19	12.99	23.56	60.29	18.42
32	15.33	18.26	6.92	18.61	30.24	8.72	21.44	42.07	11.16	24.00	53.75	14.86
34	15.94	16.30	6.40	19.17	26.99	7.88	21.94	37.55	9.79	24.44	47.98	12.46
36	16.56	14.57	5.96	19.67	24.13	7.17	22.44	33.57	8.72	24.89	42.90	10.73

FIGURE CAPTIONS

Fig. 1. A schematic representation of photosynthesis as a thermodynamic heat engine cycle on the entropy, S, versus temperature, T, diagram. dQ_s=heat supply from the surrounding air of green matter at air dry bulb temperature; dQ_T=heat rejected by green matter as latent heat of transpiration water at air wet bulb temperature; dW=chemical energy produced by photosynthesis thermodynamic cycle as biomass; T_{db}=air dry bulb temperature, °K; and T_{wb}=air wet bulb temperature, °K. The figure is created by Microsoft Word.

Fig. 2. Plant biomass versus time. The plots are relative to corn fields researched by [16] in the year 2010 for Fully Irrigation Treatment (FIT) and rain fed scenarios. The figure is created by Microsoft Excel.

Fig. 3. Plant transpiration versus biomass produced. The plot is relative to a corn field researched by [16] in the year 2010 for Fully Irrigation Treatment (FIT). The figure is created by Microsoft Excel.

Fig. 1

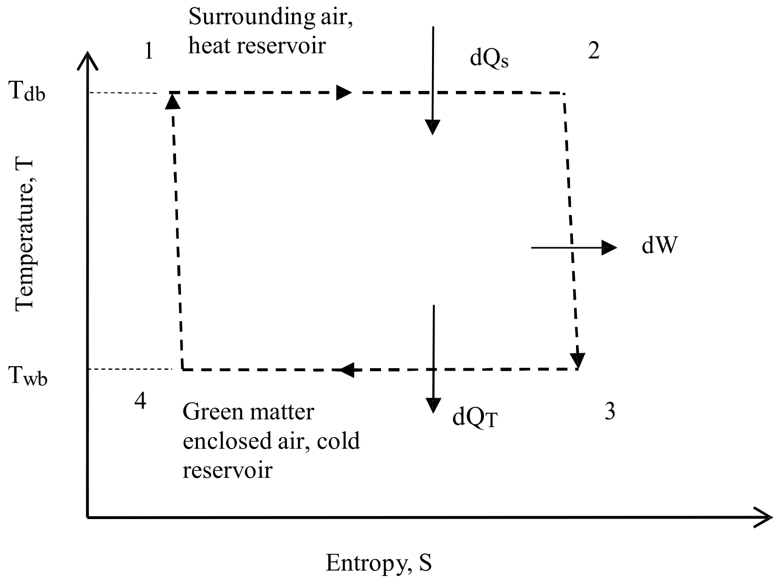

Surrounding air,
heat reservoir
1
2
dQs
Tdb
Temperature, T
dW
Twb
4
Green matter
enclosed air, cold
reservoir
dQT
3
Entropy, S

Fig. 2

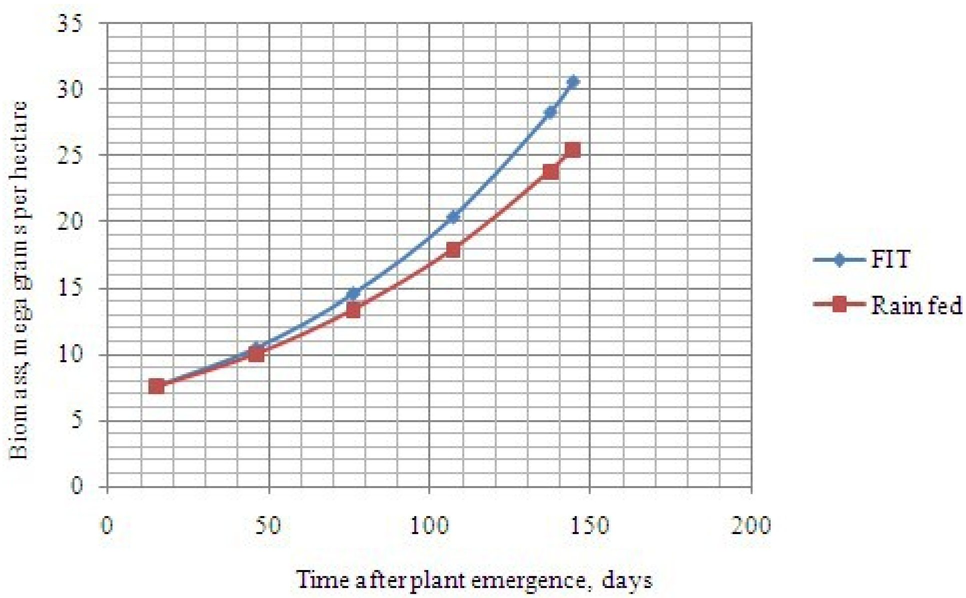
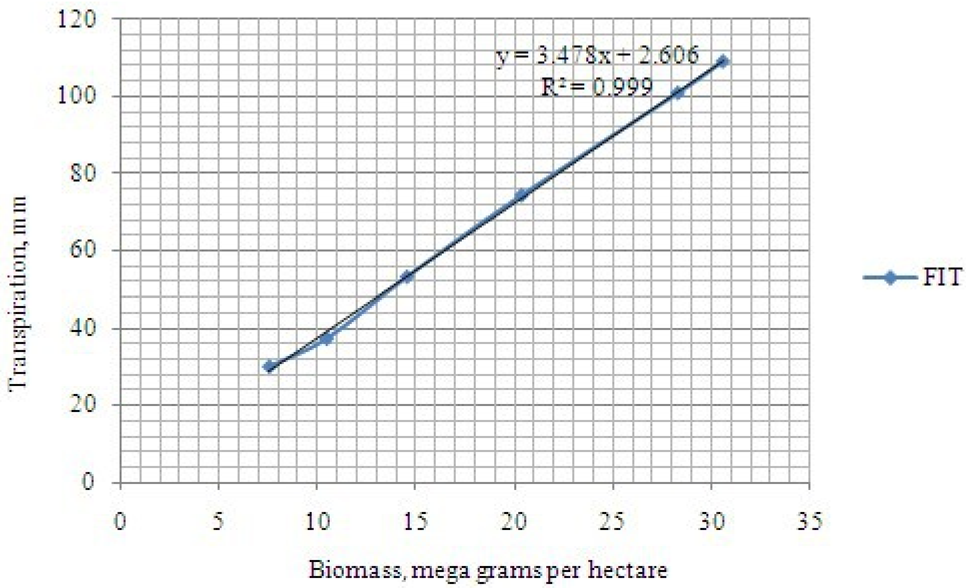

Biomass, mega grams per hectare
35
30
25
20
15
10
5
0
0
50
100
150
200
Time after plant emergence, days
FIT
Rain fed

Fig. 3


120
100
80
60
40
20
0
0
5
10
15
20
25
30
35
y = 3.478x + 2.606
R² = 0.999
Transpiration, mm
Biomass, mega grams per hectare
FIT