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Manuscript title: Photosynthesis As a Thermodynamic Cycle
Short Title: Photosynthesis

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ABSTRACT

Thermodynamics of photosynthesis has been a subject of interest to the scientific community; it is, therefore, addressed in this paper. This work reveals that traditional thermodynamic relationships may be used to calculate and project photosynthesis. Solar energy is required for the chemical reaction of green matter production. When the size of the green matter expands, less solar energy is received by the surroundings and more chemical energy is stored in plants and vegetation. If everything else is the same, the increase in the chemical energy produced is equal to the decrease in the heat of the biosphere and vice versa. Photosynthesis expansion is thus equivalent to heat transfer from the biosphere to the green matter. Plants surrounding air may be assumed as a heat reservoir at air dry bulb temperature, T_{db}. The colder air enclosed by the space of the green matter may be assumed as a cold reservoir at air wet bulb temperature, T_{wb}, and photosynthesis may be represented by a Carnot engine cycle. The thermal efficiency of the cycle is equal to $1-(T_{wb}/T_{db})^{0.5}$. If everything else is the same, the difference, T_{db}-T_{wb}, is a limiting factor of terrestrial photosynthesis. Based on this understanding, equations to predict growth of the green matter and tree diameter are derived and validated based on observations. Other findings include photosynthesis global average thermal efficiency is between 0.61% and 0.72%, and seasonal greening is nearly 0.80%. Neglecting deforestation, surface greening trend with climate change is between 0.23% and 0.28% annually.

Keywords: Photosynthesis, Exponential Growth Rate, Carnot Cycle, Seasonal Variation, Climate Change

INTRODUCTION

The living matter of the early biosphere lacked chlorophyll and relied on chemosynthesis or equal processes for photosynthesis did not exist [1]. The biosphere could have provided energy for life at that time. Even in the absence of photosynthesis, solar energy must have been necessary for energy exchange between surroundings and the living matter. Solar energy during the day provides a positive temperature gradient between surroundings and living matter. Energy thus flowed from the surroundings to the living matter and life multiplied. The same is the case for photosynthesis. An increase in the size of the green matter requires more solar energy, and the surroundings of the green matter receive less solar energy. The increase in the chemical energy of the green matter is equal to the decrease in the energy of the surroundings. Photosynthesis can thus be treated as a thermodynamic process, where energy transfers from the biosphere to plants and vegetation.

The main thermodynamic requirements for present plants and vegetation and early primitive life are in fact the same. First, there has to be a source of energy supply, typically referred to as a heat reservoir. Second, there must be a temperature difference between the heat reservoir and a heat sink, typically referred to as a cold reservoir. Finally, a medium of heat transfer must exist, which transfers heat between the reservoirs. The biosphere is a heat reservoir, and it is available for all living things. Plants, through evapotranspiration, reverse osmosis, water in plants' tissues, and soil moisture can make a cold reservoir out of the air present in the space they occupy. Air is available and it is the medium of heat transfer; therefore, all main components of Carnot thermodynamic cycle are available at the disposal of the green matter. Consequently, photosynthesis may be treated as a thermodynamic cycle and calculated using traditional thermodynamic relationships. Based on seasonal variations data available, the calculated thermal efficiency of the seasonal photosynthesis thermodynamic cycle is found to agree closely with the observed one. The equations are then applied to the climate and the calculated trend of surface greening is found to be in agreement as well. Also, equations to predict plants exponential growth rate and tree trunk diameter have been derived and compared with observations. They are found to be consistent with the natural trend. These findings may be useful for scientists and researchers in climate, agriculture, ecology, and other fields. In addition, the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report [2] reveals increasing trend of incorporating biosphere and carbon cycle components in climate models. Surface greening, deforestation, and other photosynthesis related components are therefore important for climatologists and meteorologists.

Because of the broadness and multidisciplinary nature of this work, a section "Symbols and Abbreviations" is appended to the end of this paper. The intended meanings of parameters and symbols are explained in this section.

BACKGROUND INFORMATION

Reference [3] discusses a long history of controversies relative to photosynthesis thermodynamics and provides references for further reading on the subject. Photosynthesis as a Carnot cycle as described in the introduction section does not appear to be part of the current knowledge. Publications [1, 4] summarize the current state of photosynthesis understanding, environmental constrains, photorespiration, efficiency and its variability on the surface of the earth. Photosynthesis is not addressed as the Carnot cycle described in Introduction. Based on these literatures "Anything that influences energy gain by photosynthesis has the potential to affect the survival, growth, and reproduction of organisms. The rates of photosynthesis are greatly impacted by water availability and temperature." Photosynthesis main features involve conversion of carbon dioxide and water in the presence of chlorophyll and light into glucose, which is the basic constituent of cellulose, carbohydrates, sugars, and others. This chemical reaction requires energy to realize, and solar radiation provides this energy. A reduction in the temperature of the environment decreases the efficiency of photosynthesis [5]. Our basic observations are in agreement as well: photosynthesis grows in size during the warming season and contracts during the cooling season. Plants growth follows Liebig's law, or the law of the minimum. The law states that plants growth is controlled not by the resources available, but by the scarcest resource, or limiting factor. For the green matter on the surface, water, carbon dioxide, nutrients, and light are the main natural limiting resources of photosynthesis. The difference between air dry bulb and wet bulb temperatures does not appear to be mentioned as a limiting factor in the literature of photosynthesis available at this time.

Terrestrial greening is observed at the global level with this warming trend [6, 7]. Also, at the regional level [8] noted greening of summits of the Alps, even though the height of the Alps has not changed. These are sample publications revealing a correlation between climate heat addition to the biosphere and surface greening, and that photosynthesis may potentially be treated as a thermodynamic transformation. When vegetation and plants expand in size, more solar energy is stored as a chemical energy in plants' tissues. As a result, less solar energy is exchanged with the surroundings. The biosphere, therefore, cools down. The decrease in the heat of the biosphere is equal to the energy stored as chemical energy in plants components. Photosynthesis expansion in size is equivalent to heat transfer from the biosphere to the green matter. Plants oxidation and decay is the opposite process of photosynthesis; the chemical energy returns back to the biosphere as heat.

If the space enclosing a mass of green matter on land is mentally imagined, the surroundings are atmospheric air. The temperature of this space is maintained by evapotranspiration, plant tissues' water, and soil moisture closely equal to the wet bulb temperature of the enclosed air. This air may be assumed as a heat sink or cold reservoir. The surrounding warm air, at dry bulb temperature, may be considered as a heat reservoir. Therefore, the heat can be imagined to flow from the surrounding warmer air to the green matter. In the presence of light, a small fraction of this heat is converted by chlorophyll into chemicals such as glucose, carbohydrates, and sugars. The balance of the heat available is rejected to the cold reservoir. This colder air at the wet bulb temperature being heavier than the warmer air then exits the space, gains heat, and returns back as warm air to the green matter, and the cycle repeats. The process may be treated as a thermodynamic cycle, and basic thermodynamics may be used to analyze photosynthesis. For instance, if the air wet bulb temperature approaches the air dry bulb temperature, cycle thermal efficiency approaches zero and photosynthesis is inhibited. Thermodynamic understanding and relationships may be used to estimate the observed photosynthesis expansion with latitude and altitude as well as plants and vegetation growth rates.

In Fig. 1 an idealized Carnot heat engine of photosynthesis is schematically illustrated on the entropy (S)-temperature (T) diagram. The surrounding warm air of plants and vegetation is the heat reservoir having average temperature, T_{db}, that is equal to air dry bulb temperature. The air in the space enclosed by plants is the cold reservoir having average temperature, T_{wb}, nearly equal to the air wet bulb temperature. The solar energy absorbed by the surrounding air during the day maintains a positive temperature difference, T_{db}-T_{wb}. This transformation is represented by the isothermal expansion of the surrounding air between points 1 and 2 at the temperature T_{db}, during which an amount of heat equal to Q_h is absorbed. The air then adiabatically expands and cools from point 2 at air dry bulb temperature to point 3 at air wet bulb temperature, and the chemical energy of photosynthesis, $W_{chemical}$, is produced. This energy increases the size of the green matter. At the air wet bulb temperature, T_{wb}, the air is isothermally compressed from point 3 to point 4 and the heat Q_c is rejected. The compression is in the form of air cooling and density increase by evapotranspiration. The rejected heat Q_c finds its way to the atmosphere by latent heat transfer of water vapor. Finally, the cold air being heavier than the warm air above it, exits the space enclosed by plants to the warmer surroundings. It then gains heat and adiabatically compressed from point 4 to point 1, and the cycle repeats. At average conditions, $Q_h=Q_c+W_{chemical}$. Plants decay, combustion, or oxidation is a thermodynamic process having the reversed cycle. In this case, all arrows of the cycle of Fig. 1 reverse directions. The chemical energy produced by photosynthesis, $W_{chemical}$, now combusts, oxidizes, and decays, and the heat released returns to the surroundings. The biosphere gains this heat. At the completion of a full seasonal photosynthesis-green matter-decay cycle, the net change in the chemical energy of the green matter and heat of the biosphere is negligible.

Also, similar discussion may apply to aquatic photosynthesis; however, the thermal efficiency formula will be different than that of terrestrial photosynthesis. The thermodynamic parameters such as heat and cold reservoirs as well as medium of heat transfer exist. In this case, it is water instead of air, and similar conclusions may be obtained. The related thermodynamics is important but will not be addressed in this work.

THEORY AND ANALYSIS

Thermodynamic equations of photosynthesis

The following equations may be used to calculate thermodynamic parameters of seasonal photosynthesis:

$$\text{Carnot cycle efficiency} = 1-(Q_c/Q_h) \quad (1)$$

$$\text{Thermal efficiency } \eta = 1-(T_{wb}/T_{db})^{0.5} \quad (2)$$

$$W_{chemical} = Q_h \times \eta \quad (3)$$

$$dQ_s = 2 \times dT_s \times \Gamma \times C_{pa}/W_s \quad (4)$$

Where

Q_c	=Heat sink lost to the cold reservoir, J.
Q_h	=Heat supplied by the heat reservoir, J.
η	=Thermal efficiency of photosynthesis, dimensionless.
T_{wb}	=Air wet bulb temperature, °K.
T_{db}	=Air dry bulb temperature, °K.
$W_{chemical}$	=Seasonal chemical energy of photosynthesis, J.
dQ_s	=Seasonal heat exchanged with the biosphere, J.
dT_s	=Seasonal variation of sea water temperature, 0.6 °K.
Γ	=Average seasonal precipitation rate, 1.22×10^{17} kg.
C_{pa}	=Specific heat of air, 1 000 J kg^{-1} $°K^{-1}$.
W_s	=World average water vapor mixing ratio at saturation, 0.01 kg water per kg dry air.

Equations (1), (2), and (3) are basic thermodynamic relationships [9]. Derivation of Eq. (4) is a straight forward application of the mass and heat balance of surface air and water vapor, bearing in mind that surface evaporation and precipitation are equal and that surface heating is only one-half of the total seasonal heat exchanged with the surface. The other half melts ice masses. Average seasonal precipitation is calculated based on 953 mm of precipitation annually [10]. Sea seasonal temperature variation of 0.6 °K is obtained from [11].

Chemical equations of photosynthesis

The chemical equations of photosynthesis and green matter decay may be used to cross-check calculations obtained by the thermodynamic equations. The following are suggested related equations:

$$6CO_2(g)+6H_2O(l) \xrightarrow{\text{Light/Chlorophyll}} C_6H_{12}O_6(s)+6O_2(g) \quad (5)$$

$$C+O_2 ===> CO_2 \quad (6)$$

In equation (5), photosynthesis process is shown to produce glucose for simplicity. In realty, photosynthesis is more complex, and products of this chemical reaction are not limited to glucose but include other plants basic constituents. Photosynthesis is a non-spontaneous chemical reaction and requires solar energy. This energy is equal to $W_{chemical}$ produced by the thermodynamic engine cycle of Fig. 1. Equation (6) on the other hand is the reverse process, or plant decay, combustion, and oxidization, and the chemical energy released, $-W_{chemical}$, returns back to the biosphere as heat. The following equations are valid for two consecutive photosynthesis states, 1 and 2, in the proximity of each other:

$$K_1=[C_6H_{12}O_6]_1 [O_2]_1^6/[H_2O]_1^6[CO_2]_1^6 \quad (7)$$
$$K_2=[C_6H_{12}O_6]_2 [O_2]_2^6/[H_2O]_2^6[CO_2]_2^6 \quad (8)$$
$$[O_2]_2^6/[O_2]_1^6=[CO_2]_2^6/[CO_2]_1^6 \quad (9)$$
$$([O_2]_2-[O_2]_1)/[O_2]_1=([CO_2]_2-[CO_2]_1)/[CO_2]_1 \quad (10)$$

Where the brackets indicate concentration of the chemical specie of the chemical reaction. The parameters, K_1 and K_2, are constants of equilibrium of the reaction for states 1 and 2 respectively. They may be assumed to be equal for small variation in temperature, which is the case. Because glucose and water are in pure phases, solid and liquid respectively, their concentration may be assumed to be equal to unity. On these bases, equations (9) and (10) are derived. Since the states, 1 and 2, are in the proximity of each other, then Eq. (10) may be simplified

$$dn_{O2}/n_{O2}=dn_{CO2}/n_{CO2} \quad (11)$$

Where n_i is the number of moles of the i-th specie. From Eq. (5), oxygen is a product of the reaction. Therefore, dn_G/n_G is equal to the left hand side of Eq. (11), where n_G is the number of moles of glucose produced. The percent change in surface greening may be obtained

$$\%\ Greening=100 \times dn_G/n_G=100 \times dn_{O2}/n_{O2}=100 \times dn_{CO2}/n_{CO2} \quad (12)$$

The concentration of carbon dioxide in the atmosphere is typically provided in parts per million by volume (ppmv) at the end of the year or period of time. Equations (12) may be transformed

$$\%\ Greening=100 \times (dppmv/2)/ppmv \quad (13)$$

The division of variation in the concentration of carbon dioxide, dppmv, by two in Eq. (13) is required in order to obtain average concentration change. The term, ppmv, is average concentration of carbon dioxide in parts per million by volume for the period of time in consideration. Also the reverse process, or carbon combustion, Eq. (6), may be calculated: When the green matter decay and combust, carbon dioxide is released into the atmosphere. It interacts with climate elements such as air and water vapor, and an exchange of energy of formation between surface and atmosphere occurs. Assuming that the heat of carbon combustion is equal to

3.27×10^7 J kg^{-1}, the seasonal energy produced by carbon decay, oxidization, and combustion may be calculated

$$-W_{chemical}=-8.20 \times 10^6 \times \Delta C \quad (14)$$

Where

$-W_{chemical}$ =Seasonal heat of decay, oxidization, and combustion of the green matter, J.
ΔC = Seasonal increase in the content of carbon in the atmosphere, kg.

If, n_G, is now assumed to be equal to the number of moles of the green matter instead of glucose, then dn_G/n_G is equal to surface greening ratio. It can be demonstrated that this ratio is equal to the thermal efficiency of photosynthesis. The thermal efficiency is negligible at the beginning of the warming season and increases with time. It generally reaches a maximum value towards the end of the warming season when air temperature assumes maximum value and relative humidity minimum value. Also, the efficiency is variable during the day. In the morning, air temperature is minimum and relative humidity is maximum. The wet and dry bulb temperatures are closest to each other and the area of the square enclosed by the Carnot cycle, Fig. 1, is minimum. So is the work produced for it is proportional to the area. The area increases and approaches maximum value daily in the afternoon and annually towards the end of the dry and hot season. Therefore, plants growth is proportional to the maximum value of photosynthesis thermal efficiency, and the following may apply:

$$dn_G/n_G=\eta_{max} \quad (15)$$

$$\int_{n_{G0}}^{n_G} dn_G/n_G=\int_{t0}^{t}\eta_{max}\, dt \quad (16)$$

Where the zero prefix stands for initial condition, t is plant age in years, and η_{max} is the maximum value of seasonal thermal efficiency. Integration of Eq. (16) yields

$$n_G= n_{G0}\ \mathrm{Exp}\ [\eta_{max}\ (t-t_0)] \quad (17)$$

For a single tree, geometric and elastic similarity may be assumed and $n_G/d\approx$constant. Where, d, is tree trunk diameter. Accordingly, Eq. (17) gives

$$d=d_0\ \mathrm{Exp}\ [\eta_{max}\ (t-t_0)] \quad (18)$$

VALIDATION

The climate record contains a good seasonal variation information and data, which may be used for analysis. From [12], terrestrial photosynthesis appears to exercise considerable influence on the trend of seasonal photosynthesis. The content of carbon dioxide in the atmosphere decreases during plants growth season of the northern hemisphere and increases in autumn and winter of this hemisphere. Apparently, land area of northern hemisphere, being greater than that of the southern hemisphere, dictates trends of seasonal photosynthesis. Because the hydrosphere is greater in the southern hemisphere, aquatic photosynthesis is expected to have opposite sign of seasonal trend of terrestrial photosynthesis. However, they do not appear to cancel out based on the data available, and aquatic photosynthesis may be neglected for the purpose of this validation.

Using Eq. (4), the heat exchanged with the surface during the warming season is equal to dQ_s=1.46 x 10^{22} J. This seasonal heat is the heat supply of the heat reservoir, Q_h. Seasonal variation of carbon dioxide is provided by [12]. For the year 2011, carbon dioxide concentration in the atmosphere increased by nearly five (5) parts per million by volume (ppmv) in about six months. For atmospheric air mass of 5.18 x 10^{18} kg and air molecular weight of 28.8, ΔC=1.08 x 10^{13} kg. Equation (14) may be used to calculate photosynthesis seasonal heat requirement, and -$W_{chemical}$ is equal to -8.85 x 10^{19} J. From Eq. (3), the observed global average thermal efficiency of seasonal photosynthesis is equal to 8.85 x 10^{19}/1.46 x 10^{22}=0.0061. or 0.61%. The related world average meteorological parameters are available. For example, land air temperature is nearly 288.06 °K [13], and average land relative humidity is 60% [14]. These can be used to calculate the thermal efficiency of photosynthesis. At average air dry bulb temperature, T_{db}, of 288.06 and 60% relative humidity, the psychometric chart gives a world average wet bulb temperature of about T_{wb}=283.91 °K. Equation (2) yields global average thermal efficiency η=0.0072, or 0.72%

Publication [12] provides for 2011 an average carbon dioxide content in the atmosphere of 391.67 ppmv and five (5) ppmv for seasonal carbon dioxide variation. Using Eq. (13) and 5 for dppmv, the theoretical seasonal surface greening is equal to 0.64%. This value may be compared with the observed seasonal surface greening: The report [6] indicates that primary forests cover approximately 30% of the land and average carbon content is nearly 74 tons per hectare. Using 3.27 x 10^7 J kg^{-1} for carbon heat of combustion, then present stock of forests energy is 1.11 x 10^{22} J. Consequently, the observed seasonal surface greening percent is equal to 100 x 8.85 x 10^{19}/1.11 x 10^{22}=0.80%.

The world average relative humidity is declining by 0.11% to 0.22% per decade [14], which implies that the difference between dry and wet bulb temperatures is increasing. Based on these data, psychometric relationships suggest that the world average air wet bulb temperature is increasing by 0.001% annually, and air dry bulb temperature is increasing by nearly 0.004% annually. When these are accounted for in the thermal efficiency, Eq. (2), surface greening trend is nearly 0.28% annually. This value may be compared with the chemical equations: For 2011, the annual increase in the content of carbon dioxide in the atmosphere is 1.79 ppmv based on [12]. The chemical equation, Eq. (13), gives surface greening trend of 0.23% annually. Results of these calculations are summarized in Table 1 for comparison and discussion.

Table 2 is prepared to validate Eq. (18). The observed diameter and age of sugar maple trees are obtained from a study by [15]. Research location is in the Bowl Research Natural Area, on the Southern Edge of the White Mountain National Forest. For this location, the period of time July/August observes the hottest and driest climates. Average high temperature approaches 299.6 °K and average relative humidity is about 50%. The psychometric chart gives wet bulb temperature of 292.3 °K. Therefore, η_{max}=0.012 may be used for this research location, and tree age or trunk diameter obtained. They are tabulated in Table 2.

DISCUSSION AND CONCLUSIONS

Where the Author resides at this time in Kodiak, Alaska, U.S.A., the difference between air dry and wet bulb temperatures appears to be a photosynthesis limiting factor. Kodiak is an island in the Pacific Ocean located at 57.7900 °N and 152.4072 °W. At this location, photosynthesis appears to be very sensitive to slight variation in climatic conditions. Annual average temperature is 4.70 °C, relative humidity is 80%, and precipitation is 1 980 mm, all measured by weather stations located at about sea level. At this level, tall spruce trees and vegetation growth are reasonably sustained. Near Island, Holiday Island, and smaller islands located nearby south are covered to the maximum extent with tall spruce trees, including poor soil and rock floors. The islands are several meters above sea level. This scenario applies to the low lands of Kodiak Island as well as slightly elevated land in directions facing sunrise. Moving up the mountains, vegetation and tree growth is dramatically reduced. For land located higher than 610 meters above sea level, land is practically void of vegetation, in spite of the fact that soil, rain, carbon dioxide, and sun light availability are about the same as in lower elevations. Apparently, at higher elevations photosynthesis is inhibited for reasons other than sunlight, carbon dioxide, or precipitation. Examination of the psychometric conditions of the island reveals that annual average specific humidity is 0.0042 kg water per kg dry air. At 610 meter above sea level, air expansion causes its sea level temperature to decreases by nearly 4.0 °C, and air wet bulb temperature thus approaches air dry bulb temperature. The driving force of heat for photosynthesis is minimal and may be inhibited as discussed under the background section. As a result, substantial vegetation growth may not be sustainable at high elevations.

The above discussion and the background section reveal that if everything else is the same, there appears to be a correlation between heat availability in the biosphere and photosynthesis. Heat availability is a necessary condition but insufficient, temperature difference between surroundings and green matter is required as well. Therefore, the difference between dry bulb and wet bulb air temperatures, T_{db}-T_{wb}, is a limiting factor of photosynthesis. If this temperature difference is large, heat flows and drives photosynthesis. If, however, the wet bulb temperature approaches the dry bulb temperature, the thermal efficiency decreases and photosynthesis is reduced dramatically and may be arrested altogether. This is the scenario encountered most of the year at high mountain peaks and high latitudes. At these locations, heat supply to fuel photosynthesis is unavailable and vegetation growth is minimal to none.

Table 1 is prepared by considering seasonal photosynthesis as a thermodynamic process as described in the background section. Temperature gradient, T_{db}-T_{wb}, transfers heat from the heat reservoir to the cold reservoir. Not all of the seasonal heat to the biosphere is converted into chemical energy; only 0.72% is converted into green matter as the calculations reveal. The majority of the heat sinks into the clod reservoir. The observed converted energy into green matter of nearly 0.61% is in agreement with the calculated 0.72%. Seasonal surface greening is 0.72%, calculated using thermodynamics, and the chemical relationships yielded 0.64%. The two values cross-check each other reasonably, and they are within 20% of the observed seasonal greening of 0.80%. Neglecting deforestation, the derived thermodynamic and chemical equations yielded annual surface greening trend of 0.28% and 0.23% respectively with climate change. They are in good agreement.

Equation (17) reveals that η_{max} is equal to the exponential growth rate of the green matter, Cain et al. (2014). For wild ginger growing in a maple forest located in eastern Ontario, Canada, this reference reveals that the estimates maximum geometric growth rate to be nearly 1.01. Consequently, the observed maximum exponential growth rate for wild ginger is 0.01. This value may be compared with the value of η_{max} calculated for the field of research. For this field, eastern

Ontario, Canada, July/August observes maximum thermal efficiency. The average air dry bulb temperature is T_{db}≈298.2 °K and average relative humidity is nearly 65%. The air wet bulb temperature is T_{wb}=290.9 °K, and field thermal efficiency η_{max} is about 0.01, which is in agreement with the observed maximum exponential growth rate.

From Table 2, the observed and calculated age of sugar maple tree are within 3%. Therefore, Eq. (18) may be used to project trunk diameter at breast height of old trees grown naturally without humans' care. For young trees, diameter at breast height may not be representative and caution must be exercised; diameters at locations of geometric similarity are recommended instead. Humans' care of trees and vegetation on the other hand may render the difference between air dry and wet bulb temperatures as a non-limiting factor of photosynthesis.

Based on these agreements between calculations and observations, it is reasonable to conclude that photosynthesis is a thermodynamic cycle and may be calculated as such. The thermal efficiency of the cycle is expressed by Eq. (2), and the difference between air dry and wet bulb temperatures is a limiting factor of terrestrial photosynthesis. The derived equations and conclusions are valid for other applications such climate and growth of the green matter. Photosynthesis size and trend may be calculated and projected for the ongoing warming trend at the regional and global levels, which could be of interest for researchers and society.

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TABLES

Table 1. Calculated and observed world average climate parameters. The calculated values were obtained using thermodynamic and chemical equations.

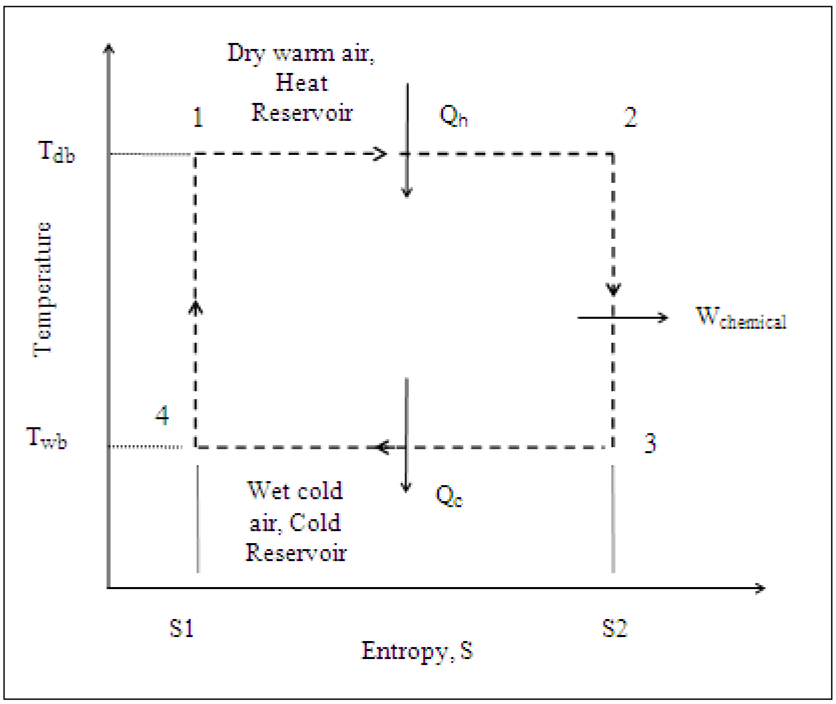
Description	Thermodynamic Equations	Chemical Equations	Observed
Seasonal heat of photosynthesis, J	-	-	8.85E+19
Total seasonal heat exchanged, J	-	-	1.46E+22
Forests inventory, J	-	-	1.11E+22
Efficiency of photosynthesis	0.72%	-	0.61%
Seasonal surface greening percent	0.72%	0.64%	0.80%
Surface greening trend%	0.28%	0.23%	-

Table 2. Calculated and observed trunk diameter of naturally grown old sugar maple trees measured at breast height, obtained from [15]. The calculated tree age is computed by Eq. (18).

Sugar maple diameter mm	Observed age Years	Calculated age Years
210	80	80
260	100	97.8
300	112.5	109.7
400	130	133.7

FIGURE CAPTIONS

Fig. 1. A schematic representation of photosynthesis as an ideal Carnot thermodynamic engine. Q_h=heat supply at the temperature of the heat reservoir, vegetation surrounding warm air; Q_c=heat rejected to the wet cold air enclosed by the green matter; $W_{chemical}$=chemical energy produced by photosynthesis thermodynamic cycle; T_{db}=air dry bulb temperature, °K; and T_{wb}=air wet bulb temperature, °K.



SYMBOLS AND ABREVIATIONS

C	Carbon stock in the terrestrial green matter, kg
ΔC	Seasonal variation of terrestrial carbon stock, kg
$C_6H_{12}O_6$	Glucose
d	Tree trunk diameter measured at breast height, mm
dppmv	Variation in the concentration of carbon dioxide in the atmosphere in parts per million by volume
% Greening	Percent change in the mass or number of moles of terrestrial plants and vegetation, dimensionless
K	Constant of equilibrium of the photosynthesis chemical reaction, dimensionless
mol	Molar concentration
n	Number of moles
η	Thermal efficiency of photosynthesis thermodynamic cycle, equals to the ratio between variation in the chemical energy of the green matter and heat added to the biosphere, dimensionless
η_{max}	Maximum value assumed by the thermal efficiency of photosynthesis in a complete seasonal cycle, dimensionless
$\eta\%$	Efficiency of photosynthesis %, equals to η x 100
n_{CO2}	Number of moles of carbon dioxide in the atmosphere, mol
n_G	Number of moles of glucose or green matter, mol
dn_G/n_G	Surface greening ratio, dimensionless. It is equal to the ratio between variation in the number of moles of the green matter divided by the initial number of moles
n_{O2}	Number of moles of oxygen in the atmosphere, mol
ppmv	Concentration of carbon dioxide in the atmosphere in parts per million by volume, measured at the end of the year or period of time
Γ	Precipitation, mm water, equivalent to kg water per m^2.
t	Tree age, years
T_{db}	Air dry bulb temperature measured by placing a thermometer in shaded air space, °K
T_{wb}	Air wet bulb temperature measured by placing a thermometer in a shaded air space and covering thermometer bulb with a wetted cloth in equilibrium with the surrounding air, °K
$W_{chemical}$	Energy converted to green matter by photosynthesis, J
$-W_{chemical}$	Energy of decay, combustion, and oxidization of the green matter, J.
[x]	Concentration of specie x