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Analysis of life cycle of plants from point of energy balance

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Abstract — The paper has chosen it subject as a novel example: thermodynamics of an ecosystem, namely the photosynthesis.

It presents the photon-electron based approach to the photosynthesis from point of view of bioengineering. Reactions of photosynthesis occur in the chloroplast, so it is a solar cell and 'sugar factory', while mitochondria are a 'powerhouse'. Clearly,despite of essentially limitless power flowing from the sun to the earth, plants can store only a small fraction (approx. 2.2 % or less) of that energy, and the fraction sets up an upper limit to the energy available to all other organisms in the ecosystem

Entropy flow and entropy production: calculation of entropy production of photosynthesis.

Keywords — photosynthesis , plants., thermal- and bioengineering, thermodynamics

1 INTRODUCTION

The original energy source for virtually all living things is the sun, and light energy is converted by plants to chemical energy and stored in the bonds of carbohydrate molecules. Plant cells can then use the energy from these molecular storehouses to fuel their activities, and animals, fungi, and many kind of microorganisms can obtain their energy indirectly by consuming plant matter or other plant eaters as food.

Ecosystem: a community of organisms interacting with a particular environment. Photosynthesis: the reciprocal of aerobic respiration. Phenomenologicaly the photosynthesis uses CO_2 and H_2O , generates O_2 and traps and stores solar energy in the chemical bonds of sugar molecules.

During the growing season (June-September) in an experimental forest was monitored energy flow and material cycling through a lot of specific experiments About 15 % of the sun's radiant energy striking the forestland immediately reflects back into the atmosphere as light. Another large fraction (41%) warms the ground and the photosynthesizing plants and eventually radiates back to the atmosphere as heat. Still an amount of incoming energy (41.8%) is used to evaporate water from the soil and cells of plant leaves, a combined process called evapotranspiration.

Thermodynamic approach to ecosystems is another way of the presentation of the photosynthesis: the energy balance and entropy production of photosynthesis. Entropy flow and entropy production: calculation of entropy production of photosynthesis.

2 ENERGY INTER-CONVERSIONS AND THE LAWS OF THERMODYNAMICS IN THE PLANTS

The first law states that energy can be changed from one form to another but is neither created nor destroyed. Here, nuclear energy from atomic fusions taking place in the sun is converted to light, to chemical energy in the plant's tissues, and to mechanical energy in the animal's tissues. Some of the light is reflected as the green light we see as the plant's colour. and a small amount is absorbed as light and is converted by the plant to chemical energy; but during this process, still more heat is lost (Fig. 1.).

The second law of thermodynamics states that all such inter-conversions are inefficient to some degree. Thus, with each inter-conversion in the chain, some energy is lost as heat, diffuses away, and becomes more disorganized

There is no doubt that this cascade of energy conversion: sun - plants – organic molecules – life processes within cells , satisfies the second law, because it takes place spontaneously and heat is lost at every step. But within the cell, there is a delicate balance between order-producing activities such as maintenance, repair, and protein synthesis, and activities that mainly generate heat. A living cell, in a real sense, is a temporary repository of order purchased at the cost of constant flow energy. If that energy flow impeded, order quickly fades, disorder reigns, and the cell dies. The impediment can be lack of food or an injury or aging of the cellular constituents that maintain order (such as the nucleus and ribosomes).

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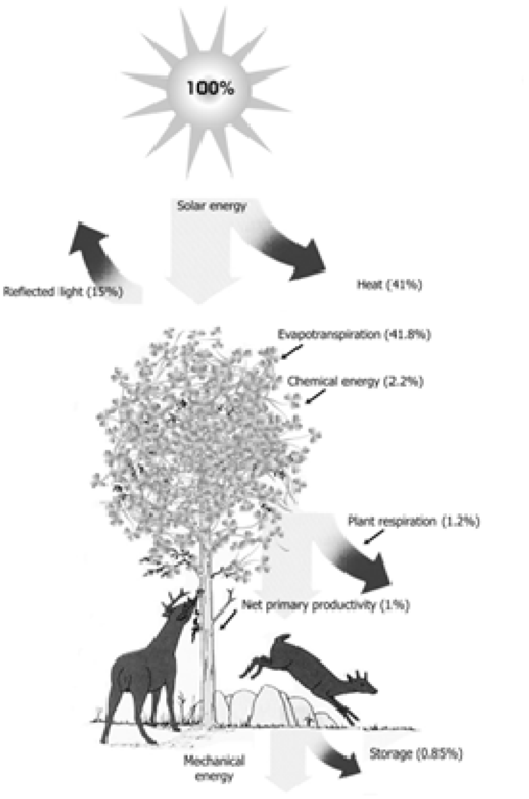

Fig.1. *Energy interconversion and the laws of thermodynamics*

3 AN OVERVIEW OF PHOTOSYNTHESIS

There is a spectacular symmetry to the metabolic processes of respiration and photosynthesis that is revealed by their nearly opposite overall equations. When oxygen is present, aerobic respiration in mitochondria (power for cell) allows cells to break down glucose into carbon-dioxid and water to release chemical energy:

$C_6H_{12}O_6$+$6O_2$ ***results*** $6CO_2$+ $6H_2O$ + chemical energy.

In photosynthesis, nearly the reverse take place in the chloroplast. Light energy trapped, transformed, and then used to convert carbon-dioxide and water into glucose and oxygen:

$6CO_2$+ $6H_2O$ +light energy ***results*** $C_6H_{12}O_6$ + $6O_2$

In the first equation, chemical energy is released from glucose, the products have less energy stored in their chemical bonds than do the reactants. In the second equation, solar energy is stored in chemical bonds of glucose; thus, the products contain more energy than the reactants. Clearly, living things must have both a means a source of energy as well as means of releasing it, and for green plants and most other autotrophs, the direct energy source in sunlight

During photosynthesis sunlight drives the oxidation of water and the reduction of carbon-dioxide. Another way of saying that is that light energy is used to remove electrons in a high energy state from water and then add them to CO2 , thus capturing their energy

This all sounds simple enough, but what does it really mean? The answer recalls the definitions of oxidation and reduction: the respective loss and gain electrons and hydrogen ions. When sunlight strikes green chlorophyll or other coloured pigments in the chloroplast of a leaf, let us say , some of the solar energy becomes trapped as a boosts electron in the pigment molecules to higher energy level. Then before the electrons drop back to their original energy levels, they pass down an electron transport chain much like the one in the mithocondrial membrane, and trapped solar energy is converted to chemical energy. As energy is released from the light-boosted electrons bit by bit, it is stored in the chemical bonds of the high-energy carriers ATP (adenosin triphosphate) and NADH (nikotinamid adenine dinucleotid phosphate). (ATP and its lower-energy partner ADP are the carriers that link metabolic energy exchange in the cell). These events make up the first phase, or so called light-dependent reaction, of photosynthesis. The reactions are driven by light energy and can take place only when light is available. The above mentioned high-energy carriers ATP and NADPH then supply the energy needed for second phase of photosynthesis, the light-independent or dark reaction, during which the bond energy in the carriers is released and stored in the bonds of glucose molecules. The dark reaction can take place in darkness, but they do not require darkness; they simply do not require the presence of light. During the dark reactions, energy from the carrier molecules convers CO_2 molecules to compounds containing carbon and hydrogen, such as glucose, $C_6H_{12}O_6$ .These compounds can be used in glycolysis within the plant cell, or can be used to build cellulose or starch. The hydrogen are atoms donated by H_2Omolecules, which are split and oxidized during water and the reduction ofCO2 and the major consequences are twofold: a.) during the light reactions, solar energy is converted to and stored as chemical energy in the bonds of ATP and NADPH molecules; and during the dark reactions, this chemical bond energy is released and stored in a more stable form the bonds of sugars and other nutrients

3.1 The chloroplast : solar cell and sugar factory

Reactions of photosynthesis occur in the chloroplast (Fig. 2.). Each leaf cell may contain 40-50 chloroplast, and each square millimetre of leaf surface more than 500,000 of the organelles. Chloroplast are analogous to mitochondria, both

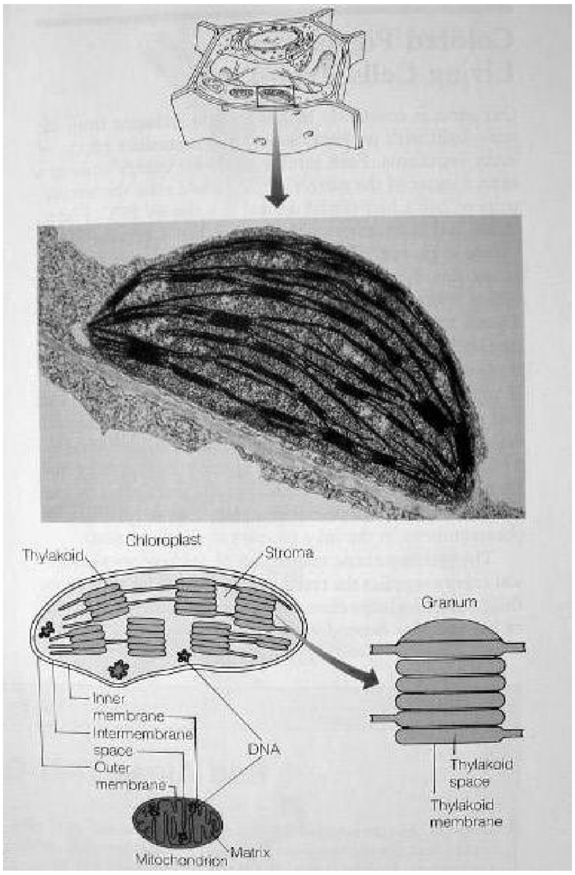

Fig.2. *Chloroplast structure: chloroplast are membrane-bound organelles with outer and inner membranes and an inter-membrane space between them, as well as a third set of membranes forming stacks of disc-like sacs called thylakoids. Each thylakoid has its own membrane and internal space, plus a stroma, or matrix surrounding the thylakoid stacks. The chloroplast form a tomato leaf shown here is magnified 25,000 times. (DNA: deoxyribonucleic acid, contains genetic information.)*

have their own DNA (deoxyribonucleic acid), however, while mitochondria are 'powerhouse' that generate ATP, chloroplast are more a combination of solar cell and sugar factory that captures sunlight and generates glucose and other carbohydrates. The light dependent reactions of photosynthesis take place in thylakoid membrane. Chlorophyll and other coloured pigments are embedded in his membrane, along with electron transport protein.

4 PIGMENT COMPLEES: ENERGY CAPTURE IN THE REACTION CENTRE

Leaves literally have antennae: embedded in the thykaloid membrane of each chloroplast in every photosynthetic cell are so-called antenna complexes. These are clusters of 200-300 chlorophyll, carotenoid, and other pigment molecules. The pigment molecules are arranged around a central chlorophyll 'a' ,the reaction centre (Fig. 3.). The molecule absorbs slightly lower energy than the other pigments; thus, when the other pigment molecules are struck by photons of light, they pass the energy they absorb in the form of electrons) from one molecule to the next until the electrons are finally transferred to the reaction centre that actually participates in photosynthesis. Somewhat like table tennis balls bouncing off a hard surface, the electrons bounce from pigment to pigment within the antenna complex at high speeds; each electron transfer takes only 10^{-12} second. Two kind of chlorophyll 'a' molecules function as reaction centres: one is called P700 and the other P680, according to the wavelengths in nm . The former absorbs wavelengths around 700 nm, the latter around 680 nm. Each kind of chlorophyll is associated in the thilakoid membrane with its own set of pigments and with both an electron acceptor and an electron donor in a photosystem. P700 at the centre of photosystem I and P600 at the centre of photosystem II . The actual conversion of the light energy to chemical energy takes place within the photosystems, and each photosystem play a different but crucial role in photosynthesis. A short overview of what happens, as shown in Fig. 4.

Photosystem II receives light energy funnelled down through the antenna complex to P680 (see step 1. in Fig.3.). A pair of reaction centre's own electrons is then ejected with high energy (step 2.).This energetic pair is quickly transferred to an special electron acceptor molecule (step 3.), thus trapping the light energy as chemical energy. To replace the missing electrons, another electron pair is passed from water (step 4.), the actual electron donor, to take place of the electrons ejected from P680. (A water molecule is split during this passage form 2H+ and O (step 5.); this is called photolysis,

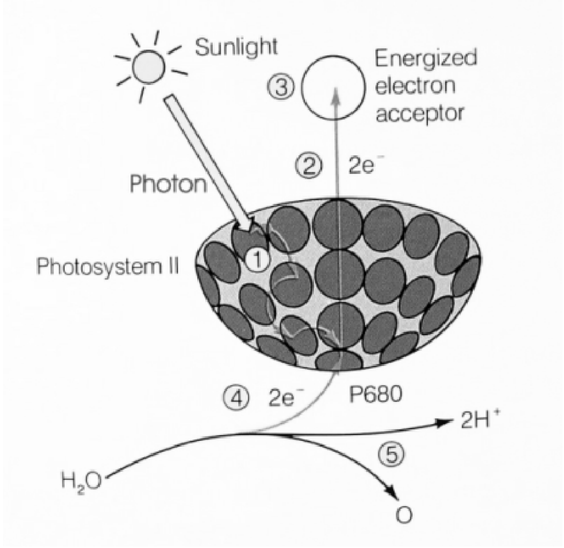

Fig.3 *'Antenna complex': a cluster of pigment molecules. In the chloroplast inside a plant's photosynthetic cells, the thylakoid membranes contain antenna complexes, cluster of light-absorbing pigment molecules. These complexes channel the energy from impinging photons of light to a central chlorophyll molecule, the reaction center.*

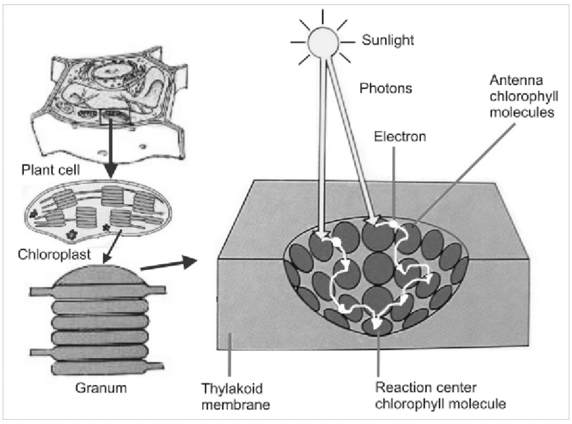

***Fig. 4** Conversion of light energy in 'photosystem II.': the reaction center chlorophyll is called P680 because it absorbs wavelengths of visible light around 680 nm. When light energy is funneled to P680 from the 'antenna complex' pigments, a pair of electrons is boosted from the reaction center molecule and accepted by an electron acceptor. A water molecule is simultaneously spit via the process of photolysis), and an electron pair replaces the electrons lost from P680.*

the splitting of water by light.) During this sequence, light energy has successfully been converted to chemical energy by means of oxidation-reduction. The remaining steps of photosynthesis merely shuffle about this chemical energy trapped in the electron acceptor, eventually storing it in the bonds of carbohydrate molecules.

5 ENERGY FLOW THROUGH ECOSYSTEMS

Tropic levels and food webs describe the general routes of energy flow and material cycling in ecosystems. Whether an organism is a producer or a consumer, it needs energy for movement, for active transport of nutrients and ions, and for synthesis of proteins, nucleic acids, and other large molecules for growth and repair. Producers obtain their energy directly from the environment in the form of light (in most ecosystems) or organic molecules (in deep-sea vents and few other ecosystems). Consumers, however, can get their energy only from producers. Hence, the activities of producers in a community set a limit for the amount of energy that can be captured and channelled throughout the entire ecosystem. Ecologists have closely studied the hardwood forest ecosystem to precisely measure available energy and how it is spent.

5.1 Experimental study: energy budget for an ecosystem

About 15 per cent of the sun's radiant energy striking the forestland immediately reflects back into the atmosphere as light (Table 1A-b.). Another large fraction (41 per cent) warms the ground and the photosynthesizing plants and eventually radiates back to the atmosphere as heat (Table 1A-c.). Still an amount of the incoming energy (41.8 per cent) is used to evaporate water from the soil and cells of plant leaves, a combined process called

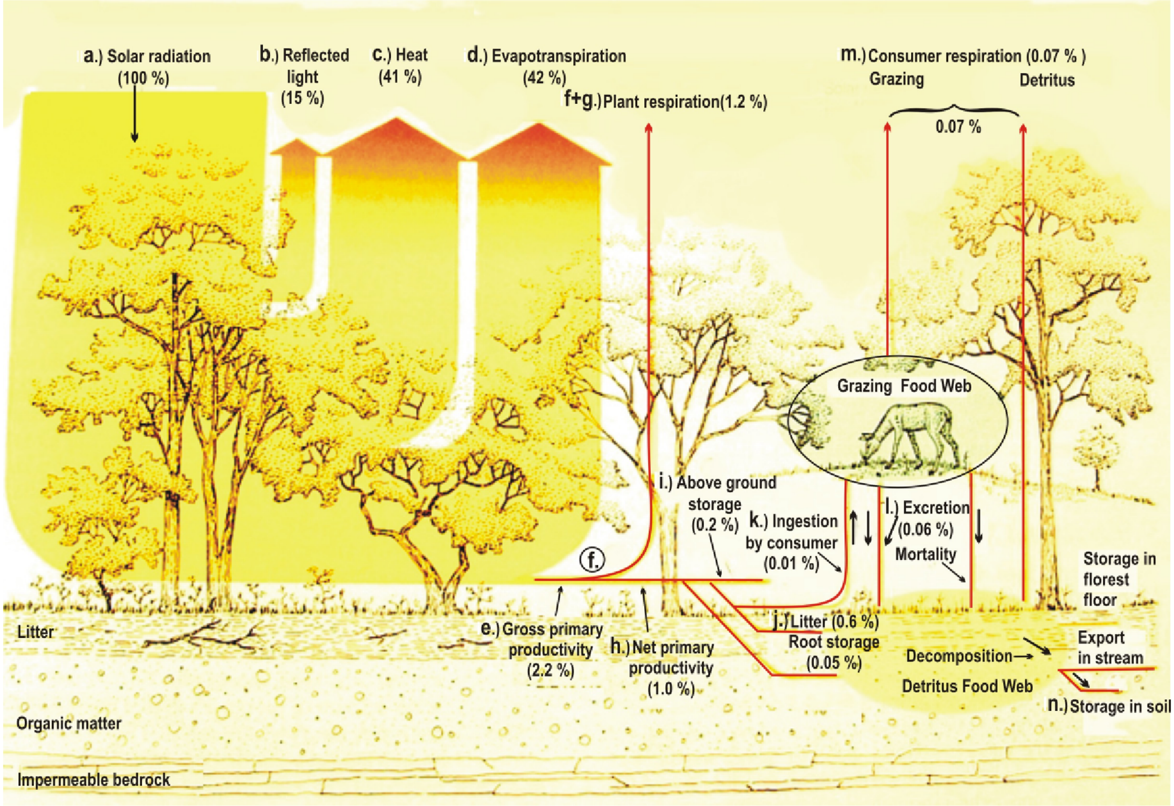

Fig.5 Energy flow through hardwood forest ecosystem

evapotranspiration (Table 1A-d.).

Table 1. Energy budget for an hardwood forest ecosystem

Table 1.A Energy balance of a hardwood forest: the flow of the energy through an ecosystem (marked from 'b.' to 'j.').

Item	Fraction	Percent, %
k.	Ingestion by consumer	- 0.01
l.	Excretion, mortality	- 0.06 (= - 0.07)
m.	Consumer respiration: grazing & detritus	- 0.07
n.	Export in stream, storage in soil (decomposition, detritus food web)	- 0.01 (= - 0.08)
Sum	**Energy lost by organisms**	**(k.-n.)= - 0.15**

Table 1. B As sunlight strikes the forest, light and heat are returned to the environment, and a small fraction of original energy is fixed in organisms and their waste products (marked from 'k.' to 'n').

Item	Fraction	Percent, %	
a.	Solar radiation	+ 100.0	
b.	Reflected light	- 15.00	
c.	Heat	- 41.00	
d.	Evapotranspiration	- 41.80	(= - 97.8)
e.	Gross primary productivity	+ 2.20	
f.	Plant respiration	- 1.20	
g.	Net primary productivity	+ 1.00	
h.	Above-ground storage	- 0.20	
i.	Litter	- 0.60	
j.	Root storage	- 0.05	(= -0.85)
Sum	**Energy fixed in organisms**	**(g.-j.) = +0.15**	

Clearly, over 82.8 per cent of the solar energy that reaches the hardwood forest flows through as heat and other 15 per cent as light - for a total of 97.8 per cent that returns rapidly to the physical environment. The 2.2 per cent or so remaining is the amount of energy that producers convert by photosynthesis to chemical energy in the form of sugars and other organic compounds. Ecologist call this small fraction an ecosystem's gross primary productivity (Table 1A-e.), and ultimately, it limits an ecosystem's structure, including how many birch trees will grow and how many chipmunks will thrive.

Not all the chemical energy that a plant initially traps will be stored in newly formed leaves, and fruits. Plant cells themselves use a little more than half of this energy to fuel their own cellular respiration, eventually losing it as heat (Table 1A-f.). The small amount of energy remaining after respiration is called the net primary productivity, the amount of chemical energy that is actually stored in new cells, leaves, roots, stems, flower and fruits (Table 1A-g.).

Of all the energy impinging on the ecosystem, only the net primary productivity is available to consumers. During a growing season, plants retain some of the net primary productivity in permanent organ (new stems and roots, for example (Table 1A-h.), but most becomes litter on the forest floor (Table 1A-i.). In fact, nearly twice as much energy is stored in litter and decomposing humus as in the majestic banks of leaves overhead in a forest. Most of the energy contained in the litter fuels the detritus food web (Table 1A-i.). Only a small fraction of the energy stored aboveground in the forest enters the grazing food web (Table 1A-j.), and some of that enters the detritus food web owing to the excretion and mortality of consumers from the grazing food web (Table 1B-k.).

The information in Table 1. allows ecologists to formulate general principles about the energy budget of a hardwood or similar. First, even in a lush, leafy green forest, plants or other producers convert only a small fraction (approx. 2 per cent or less) of the solar energy that enters the ecosystem into stored chemical energy. Second, animal ingest an even smaller amount (in the case, 0.01 percent of the energy) in the grazing food web. Finally, as energy flows through the tropic levels of the ecosystem, metabolic activities (mostly respiration) release it back to the air, where it ultimately returns to space as heat.

6 INCREASE OF ENTROPY IN A BIOLOGIC SYSTEM

6.1 Entropy production of the green leaf's photosynthesis

The entropy change of leaf (dS) relating the biomass growth at the initial state in an open system

$$dS = d_aS + d_iS \qquad (6.1)$$

where

d_aS - the net absorbed light energy,
d_iS - the thermal dissipation of the leaf.

We have the equation 6.1 in the form of energy

$$E_{bm} = (E_l - E') - E_i \qquad (6.2)$$

where

E_{bm} - the energy change relating to the biomass' growth,
E_l - the sunlight's energy striking the leaf,
E' - the thermal loss due to the photosynthesis
E_i - thermal dissipation (irreversibility) due metabolic process

The entropy production per unit time (d_iS / dt) is the entropy flow rate (Eq.6.3)

For calculation of values of ($d_i S / dt$) and dE_i / dt (thermal dissipation) we have to choose an indirect way for deduction.

The way is based on the calculation of the total metabolic heat that is back to the physical environment

$$(d_i S/ dt) = dE_i / dt \qquad (6.3)$$

To provide for the flow rate of entropy we can deduce from the analysis of the irreversible heat transfer system

$$(d_i S/ dt)_q = q \cdot (\Delta T \, . \, T^{-2}) \qquad (6.4)$$

where

q - the heat flow rate per unit area between the leaf and the environment ($J.cm^{-2} . min^{-1}$) ,

ΔT - temperature difference between the leaf and the environment (deg) ,

T - mean temperature of the leaf and the environment (K)

We have for the evapotranspiration between the leaf and the environment

$$(d_iS / dt)_{T,q} = r . e^{\cdot} (\Delta x. T^{-1}) \qquad (6.5)$$

where

r - the heat of vaporisation of water (J/g)

e - the mass flow rate per unit area of evapotranspiration ($g.cm^{-2}.min^{-1}$),

Δx - the relative humidity difference between the leaf and environment ($g. deg^{-1}$).

Substituting the Equations 6.4 and 6.5 to the Eq.6.1 we deduce Eq.6.6.

$$d_iS= q^{\cdot} (\Delta T.T^{-2}) + r. e^{\cdot} (\Delta x.T^{-1}) \qquad (6.6)$$

Multiplying the Eq.6.6. by T , we can get the dissipation function

$$\beta= T (d_iS.T^{-1}) \qquad (6.7)$$

6.2 An example of calculation of photosynthesis efficiency

Different experiences show that $\beta=E_i$ and can be calculated by this way the efficiency of the photosynthesis (see Table 1.).

The mean productivity of the biomass by leaves during a year: $E_{bm}= 1809$ $J.cm^2year$.

The entropy production in the same period: $d_iS/dt=1.37$ $J.cm^2year.K$.

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$(E_l-E') = E_{bm}+ Ei = 1809+390.45= 2139.45$ $J.cm^2year$.

The total yearly sunshine radiation $(E_l)=223.9$ $kJ.cm^2year$

Efficiency of photosyntesis : $\eta_{ph} = (E_{bm} + E_i)/(E_l)= 2.139/223.9=0.0098 \sim 0.1$ % (see Table 1.)

7 CONCLUSIONS

The paper gives a general thermodynamic method for thermal evaluation and comparison of efficiency of different kind of plants. It presents the photon-electron based approach to the photosynthesis from point of view of bioengineering. This is a suitable way for better understanding how the light energy is converted by plant to chemical energy and stored in the bonds of carbohydrate molecules. It is basically very important because the original energy source for virtually all living things is the sun. The possibility of calculation of the efficacity of plants helps for biologists to select and develop some plants using the sunshine in a higher level..

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