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ENERGY EXCHANGE CHARACTERISTICS AS AN INDICATOR OF BIOMASS PRODUCTION POTENTIAL IN TREE SPECIES

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ABSTRACT. - A study on variation in energy exchange characteristics and their relation with total leave dry weight was conducted in sixteen Himalayan tree species grown under identical natural environmental conditions at 550 m altitude in Central Himalayas. The study revealed a highly positive correlation in all the species between the total energy absorbed by their leaves and leaf dry weight, which is directly correlated with total plant biomass. Therefore, the possibility of using leaf energy exchange characteristics as a means of predicting the biomass production potential is proposed.

KEY WORDS. - Energy exchange characteristics, leaf dry weight, biomass production potential.

INTRODUCTION

The use of renewable energy sources is becoming increasingly necessary, if we are to achieve the changes required to address the impacts of global climatic changes. Biomass has acquired considerable importance as a potential renewable source of energy (CHUM & OVEREN 2001, HIROYUKI 2001, KAYGUSUZ 2002, MCKENDRY 2002, SHIRO 2002). It is an important contributor to the world economy. Agriculture and forest product industries provide food, feed, fiber, and a wide range of necessary products like shelter, packaging, clothing, and communications. Biomass is also a source of a large variety of chemicals and materials, and of electricity and fuels. The screening of plant species is under way to identify the most promising energy source for biomass production. However, the methodologies involved are either destructive sampling involving the whole harvest of the plant, or they are time consuming (e.g., growth studies). There is a need to elaborate methods offering instant results from measurement in intact systems. Therefore, an attempt has been made to find out if the energy exchange characteristics of the leaves can be used to predict the biomass production potential of a species.

MATERIAL AND METHODS

PLANT MATERIAL AND EXPERIMENTAL SETUP

Seeds of different species were collected from their natural habitats in the Central Himalayas and were sown in styrofoam seedling trays (Table 1). Sixty days old, the uniform seedlings were transplanted in earthen pots (30 cm diameter and 30 cm height) containing a 1:1:1 mixture of farmyard manure, sand and soil. Three sets (fifteen pots in each set) of each species were kept under natural environmental conditions at the experimental garden of High Altitude Plant Physiology Research Center at Srinagar Garhwal, (located between

30°-31° North and 78°-78°48' East at an elevation of 550 m above mean sea level) UP, India. Pots were irrigated twice a day to maintain soil moisture (23-25%). After nine months acclimatization of the seedlings, five plants of each species from each set were used for the observations on leaf energy exchange and dry weights during the month of April. The experiment was repeated two more times on the rest of the plants during the following months (i.e., in May and June) (Fig.1).

TABLE 1

Description of natural habitats of different central Himalayan tree species used for study

Tree Species	Habitat
Aesculus indica Colebr.	Temperate/deciduous
Bauhinia purpurea Linn.	Tropical/evergreen
Bauhinia retusa Roxb.	Tropical/evergreen
Betula utilis Don	Temperate/deciduous
Boehmeria rugulosa Wedd.	Tropical/evergreen
Celtis australis L.	Tropical/deciduous
Dalbergia sissoo Roxb.	Tropical/deciduous
Eugenia jambolana Lam.	Tropical/evergreen
Ficus cunia Buch.-Ham.	Tropical/evergreen
F. glomerata Roxb.	Tropical/evergreen
F. racemosa Roxb.	Tropical/deciduous
Olea glandulifera Wall. ex Don	Tropical/evergreen
Ogeinia dalbergioides Benth.	Tropical/deciduous
Prunus cerasoides Don	Tropical/deciduous
Sapium sebiferum Roxb.	Tropical/deciduous
Toona ciliata Roem.	Tropical/deciduous

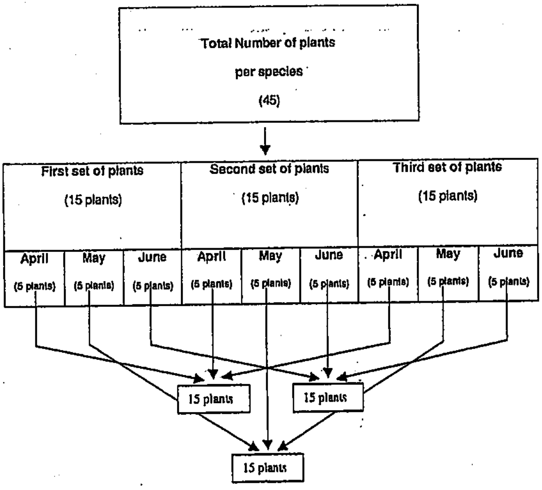

FIG. 1. — Experimental setup for sixteen Himalayan tree species used for the study.

RECORDING OF ENERGY EXCHANGE PARAMETERS

After nine months of acclimatization of the seedlings, intact leaves were mounted in the cuvette of a Portable Steady state Porometer (Li-Cor Ltd., U.S.A. ; Model, LI-1600) with Quantum sensor (Model Li-190s-1) attached to it, parallel with the leaf surface. Rate of transpiration (μg cm^{-2} sec^{-1}), air temperature (°C) and leaf temperature (°C) were recorded simultaneously using the porometer. Observations were made on the upper and lower surfaces of ten fully developed healthy leaves of each plant of each species from top to bottom during morning hours. On the basis of these observations leaf to air surface temperature difference (dT) and upper to lower leaf surface difference (dT_l) were calculated.

LEAF WEIGHT MEASUREMENT

After the energy exchange parameters were recorded in all ten leaves of a particular plant, all the leaves were properly marked and were harvested for dry weight measurement. After harvesting the leaves, the fresh weight of the individual leaves was measured and the dry weight was recorded after drying the leaves at 80°C for 48 hours. Percent leaf dry weight content was calculated following EVANS (1972).

COMPUTATION OF ENERGY EXCHANGE PARAMETERS

Energy exchange parameters (W m^{-2}) were monitored and calculated by the following equation (PUROHIT & DHYANI 1988) :

$$Q_n = Q_r + Q_l + Q_c + Q_{gla} + Q_{gl} \qquad (1)$$

where Q_r is the energy lost by the re-radiation, Q_l the energy lost by transpiration, Q_c is the energy lost or gained by the convection of heat, Q_{gla} is the energy lost or gained by boundary layer thermal conduction and Q_{gl} is the energy lost by thermal conduction across leaf surfaces. The different parameters of this equation were calculated as follows :

Energy lost by re-radiation (Q_r, W m^{-2}) was calculated by the following equation (GATES 1980) :

$$Q_r = \varepsilon \, \sigma \, (T_l)^4 \qquad (2)$$

where ε is the emmissivity constant for the green leaf (0.98, GATES 1980), σ is the Stefan-Boltzman coefficient (5.67 X 108 W m^{-2} K^{-4}) and T_l is the leaf temperature in °K.

Energy lost by transpiration (Q_l, W m^{-2}) was calculated by the following formula (GATES 1980, NOBEL 1983) :

$$Q_t = Tr \times H_{vap} \quad (3)$$

where Tr is the transpiration rate (kg m^{-2} sec^{-1}) and H_{vap} is the heat of vaporization of water (J kg^{-1}) at the temperature of leaf.

Energy lost by convection (Q_c, W m^{-2}) of heat was calculated by the following equation (GATES & JANKE 1966, KNOERR & GAY 1965) :

$$Q_c = h_c\,(T_l - T_a) = h_c\,(dT) \quad (4)$$

where $h_c = 0.00586\,(dT/D)^{1/4}$, is the convection coefficient in W m^{-2} °C, T_l and T_a are the temperatures of leaf and air respectively in °C (dT) and D is the characteristic dimension of the leaf (i.e., leaf width).

Energy lost or gained by the boundary layer thermal conduction (Q_{gla}, W m^{-2}) was calculated by the following equation (DHYANI *et al.* 1986) :

$$Q_{gla} = \frac{dT_{la}}{rh_{la}} \quad (5)$$

where dT_{la} is the temperature difference between the leaf surface and the boundary layer in °C and rh_{la} is the boundary layer thermal resistance in W m^{-2} °C^{-1}.

Boundary layer thermal resistance was calculated as :

$$rh_{la} = \frac{d_a}{k_a}$$

where d_a is the boundary layer thickness (0.13 cm for broad leaved plants, DHYANI *et al.* 1986) and k_a is the thermal conductivity coefficient of air in W m^{-1} °C^{-1} at the temperature of the air.

Energy lost by conduction across leaf surfaces (Q_{gl}, W m^{-2}) was calculated by the following equation (DHYANI *et al.* 1986) :

$$Q_{gl} = \frac{dT_l}{rh_l} \quad (6)$$

where dT_l is the temperature difference between the two surfaces of a leaf (°C) and rh_l is the leaf thermal resistance in W m^{-2} °C^{-1}.

Leaf thermal resistance can be calculated as :

$$rh_l = \frac{d_l}{kh_l}$$

where d_l is the thickness of the leaf and kh_l is the thermal conductivity of the leaf in W m^{-2} °C^{-1} (MONTEITH 1981). Pearson's correlation and regression analyses were performed to assess the relation between studied traits, using the SYSTAT software package (SYSTAT Inc., Evanston, IL).

RESULTS AND DISCUSSION

A description of the natural habitats of the different Central Himalayan tree species used in this study is given in Table 1. The average values and variations in environmental temperature at the experimental site during the months of observations are given in Table 2. Air temperature ranged from 22.08 °C to 38.40 °C with minimum around morning hours in April and maximum around noon hours in May.

Diurnal variation in leaf temperature (T_l), leaf to air temperature difference (dT), upper to lower leaf surface temperature difference (dT_l) and transpiration (Tr) of different species are shown in Table 3. Leaf temperature is considered as an important factor to determine the energy budget of a leaf and the extent of variations has been reported to be species dependent (LANGE 1965, PUROHIT *et al.* 1983, YARWOOD 1961). It was interesting to note that all the studied species maintained their leaf temperature below the temperature of the surrounding air throughout the day during the months of April, May and June, which reflects the adaptation potential of these species to a warmer environment. Average leaf temperature ranged from 29.54 °C (*Toona ciliata*) to 32.46 °C

TABLE 2

Variations in air temperature, T_a (°C) at the experimental site during the experimental period

	Solar time (hours)				
	6:00	9:00	12:00	15:00	18:00
April	22.08 ± 0.98	24.80 ± 0.55	31.54 ± 0.83	30.39 ± 0.47	28.91 ± 0.85
May	27.28 ± 0.31	37.28 ± 0.91	38.40 ± 3.35	37.40 ± 0.48	32.38 ± 1.03
June	28.16 ± 0.46	36.24 ± 0.73	37.93 ± 0.66	35.00 ± 0.58	31.90 ± 0.78

TABLE 3

Variation in leaf temperature (T_l)*, leaf to air temperature difference* (dT)*, upper to lower leaf surface temperature difference* (dT_l) *and leaf surface transpiration rate* (Tr) *in different central Himalaya tree species used for study. Each value in the table is the mean of three months (April, May and June)*

Tree species (°C)	T_l (°C)	dT (°C)	dT_l (°C)	Tr (µg cm^{-2} sec^{-1})
Aesculus indica Colebr.	32.29	-0.72	0.59	2.64
Bauhinia purpurea Linn.	31.64	-0.59	0.57	1.98
Bauhinia retusa Roxb.	32.06	-0.64	0.43	2.49
Betula utilis Don	32.46	-0.74	0.63	2.70
Boehmeria rugulosa Wedd.	30.55	-0.46	0.39	1.75
Celtis australis L.	31.81	-0.62	0.55	2.39
Dalbergia sissoo Roxb.	29.65	-0.42	0.42	1.55
Eugenia jambolana Lam.	32.28	-0.68	0.58	2.58
Ficus cunia Buch.-Ham.	31.02	-0.51	0.42	1.89
F. glomerata Roxb.	30.00	-0.45	0.38	1.73
F. racemosa Roxb.	31.79	-0.61	0.54	2.12
Olea glandulifera Wall.ex Don	31.73	-0.57	0.42	2.04
Ogeinia dalbergioides Benth.	31.76	-0.58	0.47	2.12
Prunus cerasoides Don	29.89	-0.43	0.37	1.59
Sapium sebiferum Roxb.	30.56	-0.49	0.41	1.76
Toona ciliata Roem.	29.54	-0.41	0.35	1.54

(*Betula utilis*). A positive correlation was observed between leaf to air temperature difference (dT) and rate of transpiration (Tr). Species showing higher dT also showed higher rate of transpiration. Leaf to air temperature difference (dT) and Tr were observed to be highest in *Aesculus indica* (-0.72 and 2.64, respectively) and lowest in *Toona cilliata* (-0.41 and 1.54, respectively). DHYANI *et al.* (1986) have also reported -0.04 °C to –0.7 °C in leaf to air temperature difference in some Himalayan trees and herbs at different altitudes. However, these differences observed in Himalayan species are not as sharp as those reported earlier by other workers in other parts of the world (LARCHER & WAGNER 1976). The difference could be due to the differences in original habitats of the plants or different genetic background of the species in those areas.

Since leaf length, width, area and thickness are influenced to a great extent by the environment in which a plant grows (KÖRNER & COCHRANE 1983), the temperature of the lower and upper leaf surface varies considerably. Consequently, the conduction energy across the two leaf surfaces has a significant effect on the status of the internal energy budget, which affects the metabolic activity and finally also the survival and productivity of the leaf. Higher temperature difference between the two leaf surfaces causes higher energy flow, which provides more energy for metabolic activities inside the leaf. In the present study, the temperature difference between upper to lower leaf surfaces ranged between 0.35 °C (*Toona cilliata*) to 0.63 °C (*Betula utilis*), which can be considered fairly large as compared to a 0.1 °C difference causing considerable change in the thermal gradient, heterogeneity and heat transfer in leaves as reported earlier by PERRIER (1971).

A plant in its natural environment receives energy from the sun in the form of radiation and also as thermal infrared radiation from the surrounding surface, as well as from atmosphere. The major loss of heat energy from leaf is through re-radiation, convection and latent heat exchange through transpiration (CHANDRA 1992). Under conditions of low incident radiation, leaves can gain energy through convection, if leaf temperature is lower than the surrounding air temperature, or through latent heat condensation if leaf temperature falls below the dew-point temperature. Changes in energy storage and in flow of heat energy inside the leaf from one surface to the other (i.e., conduction, which includes metabolic balances inside the leaf) are considered minor components in the leaf energy balance. Since they usually represent less than 5% of the combined convective latent heat loss, these terms have been neglected in most of the energy balance computations (GATES & SCHMERL 1975). These authors assumed both surfaces of plant leaf at the same temperature and therefore considered negligible amount of heat energy flow through conduction of heat inside the leaf. However, NOBEL (1983) reported considerable differences in the leaf temperature across the leaf sufaces in the leaves of some succulent plants. Significant differences in leaf temperature across the leaf surfaces (0.05 - 0.70 °C) in some mountain plants species were also reported by PUROHIT & DHYANI (1988). These authors reported a significant relationship between conduction and metabolic energy and the total heat energy absorption potential of plants. Therefore, they modified the theoretical model of leaf energy balance and incorporated an additional parameter of energy flow (which includes all the metabolic process inside the leaf) across the leaf surfaces in theoretical model of GATES (1980). Subsequently, PUROHIT & DHYANI (1988) assessed the significance of conduction energy in terms of adaptation and survival potential of tropical broadleaved mountain plant species. However, these authors did not describe significant relationship between energy exchange characteristics and biomass production potential of the leaf. In the present study an effort was made to correlate energy exchange characteristics with biomass production potential in Himalayan tree species. Average values of leaf energy exchange parameters of sixteen Himalayan tree species are shown in Table 4, which shows that total energy absorbed by the leaves was lost by re-radiation, transpiration and thermal conductance across leaf surfaces. In all the species it was observed that leaves gained energy by convection of heat as well as by boundary layer thermal conduction, which is basically due to lower leaf temperature than that of the surrounding air. The lower leaf temperature and the negative convection as well as conduction energy will help these plant species to survive under considerable air thermal load by cooling down the surrounding air and by reducing the sur-

TABLE 4

Average values of energy exchange parameters and percent leaf dry weight in different tree species of Central Himalayas grown at 550 m altitude.
Q_r, *energy lost by re-radiation;* Q_t, *energy lost by transpiration;* Q_c, *energy gained (-) by convection of heat;* Q_{gla}, *energy gained (-) by boundary layer thermal conduction;* Q_{gl}, *energy lost by thermal conduction across two leaf surfaces;* Q_a, *total leaf energy absorption; LDW, leaf dry weight*

Tree species	Q_r	Q_t	Q_c	Q_{gla}	Q_{gl}	Q_n	LDW(%)
Aesculus indica Colebr.	564.55	16.74	-1.03	-3.24	2.32	579.34	54.12
Bauhinia purpurea Linn.	481.29	13.47	-0.92	-2.62	1.23	492.45	48.74
Bauhinia retusa Roxb.	550.25	15.94	-2.13	-3.46	2.13	562.73	52.86
Betula utilis Don	569.03	18.72	-2.42	-4.98	2.47	582.82	64.21
Boehmeria rugulosa Wedd.	463.45	10.24	-0.98	-4.61	1.36	469.46	47.12
Celtis australis L.	540.14	16.32	-2.31	-5.12	2.34	551.37	52.34
Dalbergia sissoo Roxb.	420.97	13.82	-0.89	-2.63	0.98	432.25	43.96
Eugenia jambolana Lam.	553.89	15.27	-1.45	-1.89	1.42	567.24	53.21
Ficus cunia Buch.-Ham.	479.26	14.64	-1.82	-2.13	1.31	491.26	48.32
F. glomerata Roxb.	448.72	15.28	-1.76	-1.68	2.16	462.72	44.76
F. racemosa Roxb.	530.20	15.86	-2.32	-2.74	1.64	542.64	51.28
Olea glandulifera Wall.ex Don	504.44	16.24	-1.98	-4.36	1.93	516.27	50.94
Ogeinia dalbergioides Benth.	518.96	16.67	-2.21	-3.98	1.87	531.31	50.97
Prunus cerasoides Don	427.16	14.63	-1.16	-3.23	0.96	438.36	44.12
Sapium sebiferum Roxb.	478.47	15.46	-1.37	-3.41	1.13	490.28	48.12
Toona ciliata Roem.	401.62	13.18	-0.98	-2.98	1.41	412.25	38.97

face evaporation under their canopies and maintain relatively higher soil moisture content. Similar advantages of lower leaf temperature as compared to the surrounding air have been reported earlier by DHYANI & PUROHIT (1983, 1984) and by DHYANI *et al.* (1986).

Plant survival, growth and productivity have been reported to be intimately coupled with the aerial environment through processes such as heat energy exchange, loss of water vapour in transpiration and uptake of carbon dioxide in photosynthesis (FITTER & HAY 1987, JARVIS *et al.* 1988, STOUTJESDIJK & BARKMAN 1992, HIKOSAKA 1996, KOSTNER *et. al.* 2002). The water vapour exchange rate affects the energy budget and the temperature of a leaf and, consequently, the physiology of the whole plant (GATES & SCHMERL 1975, CHANDRA & DHYANI 1997, BERTAMINI & NEDUNCHEZHIAN 2002, HIEKE *et al.* 2002). This water vapour exchange rate is influenced by the leaf temperature, which in turn is determined by the energy absorbed, air temperature, wind and leaf diffusion resistance (HALL & BJORKMAN 1975). Most of these parameters have been found to be correlated with the leaf dimension (TAYLOR 1975). However, there is inadequate information concerning the magnitude of changes in leaf energy exchange characteristics in relation to biomass production potential. The most important aspect of this experiment was to explore the possibilities of using the described and calculated energy exchange parameters as indicators of biomass production potential of a particular species. Average values of percent leaf dry weight of the different species are shown in Table 5. Species that absorbed more energy (Q_a) than others exhibited a higher leaf dry weight. A highly significant positive correlation ($r = 0.826$, $P < 0.01$) was observed between total energy absorbed by the leaves of different species and their leaf dry weights. The regression equation worked out on the basis of this relationship and the regression line, taking dry weight as the dependent variable and energy absorbed by leaves as the independent variable, are shown in Fig. 2. A highly significant positive correlation ($r = 0.779$, $P < 0.005$) between percent leaf dry weight and total plant biomass has already been reported by THAPLIYAL *et al.* (1986). Those species that absorbed more energy than others may be potential species for biomass production. These results open the possibility for using energy exchange characteristics of leaves to assess the biomass production potential of the species in an intact system.

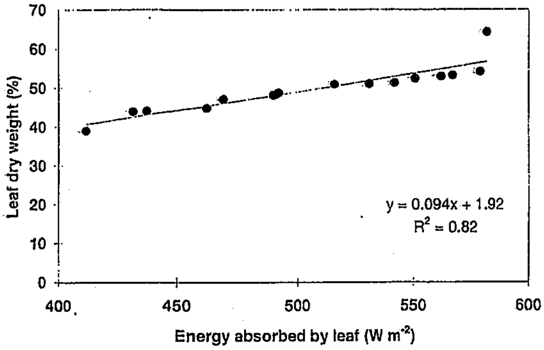

FIG. 2. — Relationship between energy absorbed by leaf and percent leaf dry weight.

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