

## **Effect of Altitude on Energy Exchange Characteristics of Some Alpine Medicinal Crops from Central Himalayas**

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*With 5 tables*

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### **Abstract**

To explore the conservation and cultivation of endangered alpine medicinal crops at comparatively lower altitudes, a study on variations in morphological parameters and energy exchange characteristics was conducted on five herbaceous medicinal crops from the alpine of Central Himalayas. Plants of same age were selected from the alpine medicinal crop nursery, Tungnath (3600 m), and were planted at the nurseries at 2100 and 550 m altitudes. After well acclimatization at lower altitudes, plants were examined for morphological and energy exchange studies during their active growth period. The energy balance sheet of these plant species indicates that most of the energy absorbed by the leaves dissipates by re-radiation, transpiration and thermal conductance across leaf surfaces. All species maintained leaf temperature below the surrounding air temperature at all altitudes and therefore gained energy by convection of heat as well as by boundary layer thermal conduction. Leaf-to-air temperature difference, gain of energy by convection of heat and boundary layer thermal conduction was maximum at an altitude of 2100 m in all the species. Boundary layer thermal conductivity, boundary layer thickness, thermal conductivity of the leaf and therefore, total energy absorbed by the leaves of these species increase significantly with decreasing altitude. Leaf thickness significantly decreases with decreasing altitude, which in turn enhances total energy absorption ( $r = -0.975$ ,  $P < 0.005$ ) of the leaves in all the species. The results indicate that all these species absorb higher amount of energy at lower altitudes, which indicates their adaptability to warm temperatures at low altitudes (up to 550 m). Therefore, these species can be cultivated at relatively lower altitudes. However, a proper agronomic methodology needs to be developed for better yields.

**Key words:** alpine medicinal crops — altitudinal gradient — energy exchange

### **Introduction**

In recent years, ecological disturbances and over exploitation of natural resources have resulted in

considerable decline in biodiversity in the Himalayas. In particular, various herbs of medicinal and economic value, growing at the high reaches of Central Himalayas, are under immense pressure due to unscientific and uncontrolled extraction, and increasing grazing pressure (Lata 1997). While several studies describe the taxonomic features, the chemical nature of active constituents and ethnobotanical attributes of Himalayan medicinal plant species (Jain 1991, Rastogi and Mehrotra 1991), studies on domestication and cultivation of these important plants are lacking. Although (in the 2000–3600 m elevation zone of Central Himalayas) rainfed cultivation of some medicinal crops are in practice by rural settlers (Maikhuri et al. 1998), many of them have already been declared threatened, rare or endangered in the red data book Nayar and Sastri 1987, 1988, 1990). Strategies are being developed for the conservation and cultivation of the Himalayan herbs at comparatively lower altitudes. Morphological and physiological information about the response of plants to contrasting environments found along with the altitudinal gradient is a prerequisite for any applied research whose objective is to extend the limits of cultivation of alpine medicinal cash crops and to assess the potential possibilities of selecting and breeding desirable high-yielding plants in the mountain terrain of the Himalayas. As the ability of species to acclimatize and adapt to contrasting environments is directly/indirectly associated with the ability to absorb the energy from microclimate, which in turn effects biochemical and physiological processes of the leaf and consequently the physiology and productivity of the whole plant (Raschke 1960, Gates 1975, Taylor 1975, Campbell 1977, Lange et al. 1981, Jones 1983, Korner et al. 1983,

Fitter and Hay 1987, Jarvis et al. 1988, Purohit and Dhyani 1988, Stoutjesdijk and Barkman 1992, Chandra 1993, 2000, 2003, Sharma and Dhyani 1993, Chandra and Dhyani 1997, Mishra et al. 1999, Karim et al. 2000), this study was undertaken to find out the changes in energy exchange characteristics in five alpine medicinal crops in their natural habitat (3600 m) and at comparatively lower altitudes (2100 and 550 m). It is expected that the present study will provide valuable information about the mechanism and physiological adjustment to lower altitudes in alpine herbs.

## Materials and Methods

### Plant material

Uniform seedlings of five alpine species (*Aconitum balfourii*, *Nardostachys jatamansi*, *Picrorhiza kurrooa*, *Podophyllum hexandrum* and *Rheum emodi*) were collected at an altitude of 3600 m in the Central Himalayas. These were transplanted in polythene bags of equal volume containing natural alpine soil at the alpine field station, Tungnath. After 15 days, 30 bags of each species were transplanted at three different experimental stations – at alpine garden Tungnath (3600 m), experimental field station Potiwas (2100 m) and field nursery (550 m) of High Altitude Plant Physiology Research Centre (Srinagar, UP, India). Energy exchange and morphological parameters were recorded during the summer of the next year, after acclimatization of these species at different altitudes for a complete life cycle. As leaf emergence and active growth period of alpine plants occurs little earlier at lower altitudes, recordings of data were first made on the plants at lowest altitude (550 m) and then at increasing altitudes (2100 and 3600 m respectively). At all altitudes, observations were recorded on randomly selected top three fully mature healthy leaves of 50–60 day-old plants of each species in 15 plants separately and then repeated twice on same leaves in 30-day intervals. Mean values were used in computation. At 8:00, 12:00 and 16:00 h both surfaces of the leaves were observed using a portable study state porometer (model LI-1600; LI-Cor Ltd, Lincoln, NE, USA) with Quantum sensor (Model LI-190s-1) attached to it, parallel with the leaf surface. Seven parameters [relative humidity (%), photosynthetically active radiation (PAR) ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ), diffusion resistance ( $\text{s cm}^{-1}$ ), rate of transpiration ( $\text{g cm}^{-2} \text{s}^{-1}$ ), air temperature ( $^{\circ}\text{C}$ ), leaf temperature ( $^{\circ}\text{C}$ ) and flow rate ( $\text{cm}^3 \text{s}^{-1}$ ) were recorded simultaneously. The leaf areas were measured with the help of an area meter (model LI-3000; LI-Cor). The free hand sections were used to measure the thickness of the leaves with the help of a microscope and the average values of 20 cross-sections were used in computation.

### Computation of energy exchange parameters

Energy exchange parameters were monitored and calculated by following Purohit and Dhyani (1988):

$$Q_a = Q_r + Q_t \pm Q_c \pm Q_g^{la} + Q_g^l \quad (1)$$

where  $Q_r$  is the energy lost by re-radiation,  $Q_t$  is the energy lost by transpiration,  $Q_c$  is the energy lost (+)/gained (–) by the convection of heat,  $Q_g^{la}$  is the energy lost (+)/gained (–) by boundary layer thermal conduction and  $Q_g^l$  is the energy lost by thermal conduction across leaf surfaces. Different parameters of this equation were calculated as follows.

#### Energy lost by re-radiation

Energy lost by re-radiation ( $Q_r$ ,  $\text{W m}^{-2}$ ) was calculated by the following equation (Gates 1980).

$$Q_r = \varepsilon \sigma (T_1)^4 \quad (2)$$

where  $\varepsilon$  is the emissivity of the leaf (0.98),  $\sigma$  is the Stefan-Boltzman coefficient ( $5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ ) and  $T_1$  is the temperature of leaf in  $^{\circ}\text{K}$ .

#### Energy lost by transpiration

Energy lost by transpiration ( $Q_t$ ,  $\text{W m}^{-2}$ ) was calculated by following formula (Gates 1980, Nobel 1983):

$$Q_t = T_r X H_{\text{vap}} \quad (3)$$

where  $T_r$  is the transpiration rate ( $\text{kg m}^{-2} \text{ s}^{-1}$ ) and  $H_{\text{vap}}$  is the heat of vaporization of water ( $\text{J K}^{-1} \text{ g}^{-1}$ ) at the temperature of leaf.

#### Energy lost by convection

Energy lost by convection ( $Q_c$ ,  $\text{W m}^{-2}$ ) of heat was calculated by the following equation (Gates 1965, Knoerr and Gay 1965):

$$Q_c = h_c (T_1 - T_a) \quad (4)$$

where  $h_c = 0.00586 (dt/D)^{1/4}$ , is the convection coefficient in  $\text{W m}^{-2} \text{ }^{\circ}\text{C}$ ,  $T_1$  and  $T_a$  are the temperatures of leaf and air respectively in  $^{\circ}\text{C}$ . ( $dt$ ) and  $D$  is the characteristic dimension of the leaf, i.e. leaf width.

#### Energy lost/gained by the boundary layer thermal conduction

Energy lost/gained by the boundary layer thermal conduction ( $Q_g^{la}$ ,  $\text{W m}^{-2}$ ) was calculated by following the fundamental equation of heat conduction through any conductor (Slavik 1974) (leaf in this case):

$$Q = \frac{KA(T_1 - T_2)t}{d}$$

where  $Q$  is the total amount of heat flow (J),  $K$  is the thermal conductivity of the medium ( $\text{W m}^{-1} \text{ }^{\circ}\text{C}^{-1}$ ),  $A$  is the area of the surface ( $\text{m}^2$ ),  $T_1$  is the temperature of the first surface,  $T_2$  is the temperature of the second surface,  $t$  is the time for heat flow (s) and  $d$  is the distance between the surfaces of the conductor (m).

For heat flux density ( $Q_{fd}$ ) the same equation can be written as:

$$Q_{fd} = \frac{Q}{At} = \frac{T_1 - T_2}{r} (\text{W m}^{-2})$$

where  $r = d/K$  ( $\text{W}^{-1} \text{ m}^2 \text{ }^{\circ}\text{C}$ ) is the thermal resistance of the conductor.

In case of heat flow by conduction between leaf and laminar boundary layer ( $Q_g^{la}$ ) of uniform thickness ( $d^a$ ), equation  $Q_g^{la}$  may be expressed as (Nobel 1983):

$$Q_g^{la} = \frac{dt^{la}}{r_h^{la}} \quad (5)$$

where  $dt^{la}$  is the temperature difference between the leaf surface and the boundary layer in  $^{\circ}\text{C}$  and  $r_h^{la}$  is the boundary layer thermal resistance in  $\text{W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$ .

Boundary layer thermal resistance was calculated as:

$$r_h^{la} = \frac{d^a}{K^a}$$

where  $d^a$  is the boundary layer thickness and  $k^a$  is the thermal conductivity coefficient of air in  $\text{W m}^{-1} \text{ }^{\circ}\text{C}^{-1}$  at different temperatures.

#### *Energy lost by conduction across leaf surfaces*

Energy lost by conduction across leaf surfaces ( $Q_g^l$ ,  $\text{W m}^{-2}$ ) was calculated by assuming two surfaces of the leaf at different temperatures. Each surface of the leaf attains its own local temperature and therefore, there must be a net flow of heat from hot surface to cold surface of the leaf (Dhyani et al. 1986, Purohit and Dhyani 1988). In such cases equation (5) can be expressed for a leaf as:

$$Q_g^l = \frac{dt^l}{r_h^l} \quad (6)$$

where  $dt^l$  is the temperature difference between the two surfaces of a leaf ( $^{\circ}\text{C}$ ) and  $r_h^l$  is the leaf thermal resistance in  $\text{W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$ .

Leaf thermal resistance can be calculated as

$$r_h^l = \frac{d^l}{k_h^l}$$

where  $d^l$  is the thickness of the leaf and  $k_h^l$  is the thermal conductivity of the leaf in  $\text{W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$  (Monteith 1981).

#### **Statistical analysis**

Pearson's correlation and regression analysis were performed to assess the relationship between studied traits using SYSTAT software package (SYSTAT Inc., Evanston, IL).

#### **Results and Discussion**

The average values of the environmental parameters at different altitudes during the period of observation are given in Table 1. While relative humidity and wind velocity decreased with decreasing altitude, ambient air temperature increased progressively. PAR was at its highest at higher altitudes and decreased with decreasing altitudes. Similar results were reported by Caldwell (1980) (Southern Alps, New Zealand) and Dhyani et al. (1986) (Central Himalayas, India).

The leaf dimensions (length, width, area and thickness) of different alpine herbs at different altitudes are given in Table 2. Leaf length, width and area increased significantly with decreasing altitudes. Similar results on leaf morphological parameters have also been reported by Korner et al. (1989) on some herbaceous perennial species from the Central Alps. However, in the present study leaf length increased more rapidly than width, which finally affects the total leaf area. The thickness of the leaf decreased with a decrease in the altitude.

The average values of boundary layer thickness, thermal conductivity of air, boundary layer thermal conductance, leaf-to-air temperature difference, thermal conductivity of the leaf, thermal conductance and upper-to-lower leaf surface temperature difference are shown in Table 3. While the boundary layer thickness ( $\text{LSD} = 0.05$ ,  $P < 0.05$ ) around the leaves and thermal conductivity of air ( $\text{LSD} = 0.16$ ,  $P < 0.05$ ) increased, boundary layer thermal conductance ( $\text{LSD} = 23.85$ ,  $P < 0.05$ ) decreased with decreasing altitude. Boundary layer thermal conductance was positively affected by increase in leaf thickening. Furthermore, boundary layer thermal conductance was more dependent on leaf boundary layer thickness than on the conductivity of air. All these species maintained leaf temperatures below the surrounding air temperature at all altitudes, thereby gaining energy by

Table 1: Average day time (8:00 a.m. to 6:00 p.m., 2-h intervals) relative humidity, photosynthetically active radiation (PAR), air temperature and wind velocity ( $\pm$ S.D.) on the days of observations at different altitudes in Garhwal Himalaya

Altitude (m)	Relative humidity (%)	PAR ( $\mu\text{mol m}^{-2} \text{ s}^{-1}$ )	Air temperature ( $^{\circ}\text{C}$ )	Wind velocity $\times 10^{-2}$ ( $\text{cm s}^{-1}$ )
3600	60.2 $\pm$ 8.2	1884.6 $\pm$ 211.1	8.9 $\pm$ 0.7	307.2 $\pm$ 13.2
2100	54.9 $\pm$ 7.2	1548.2 $\pm$ 192.2	17.6 $\pm$ 2.1	111.4 $\pm$ 8.9
550	52.5 $\pm$ 6.8	813.7 $\pm$ 72.8	37.4 $\pm$ 4.3	20.0 $\pm$ 5.2

Table 2: Average values of leaf length (cm  $\pm$  S.D.), leaf width (cm  $\pm$  S.D.), leaf area (cm<sup>2</sup>  $\pm$  S.D.) and leaf thickness ( $\mu$ m  $\pm$  S.D.) in the species at different altitudes of Central Himalayas

	Species	Altitude (m)			LSD, P < 0.05
		3600	2100	550	
Leaf length (cm)	<i>Aconitum balfourii</i>	4.7 $\pm$ 0.2	5.1 $\pm$ 0.5	6.3 $\pm$ 0.4	1.00
	<i>Nardostachys jatamansi</i>	5.1 $\pm$ 0.5	5.7 $\pm$ 0.4	6.4 $\pm$ 0.4	0.96
	<i>Picrorhiza kurrooa</i>	4.0 $\pm$ 0.6	4.6 $\pm$ 0.6	5.8 $\pm$ 0.6	0.55
	<i>Podophyllum hexandrum</i>	10.9 $\pm$ 0.6	11.7 $\pm$ 1.2	13.0 $\pm$ 0.9	1.71
	<i>Rheum emodi</i>	19.4 $\pm$ 1.0	21.9 $\pm$ 2.1	24.2 $\pm$ 2.3	3.09
	LSD, P < 0.05	1.33	2.46	0.42	
Leaf width (cm)	<i>Aconitum balfourii</i>	2.0 $\pm$ 0.2	2.1 $\pm$ 0.6	2.5 $\pm$ 0.3	0.84
	<i>Nardostachys jatamansi</i>	1.0 $\pm$ 0.2	1.1 $\pm$ 0.3	1.3 $\pm$ 0.5	0.55
	<i>Picrorhiza kurrooa</i>	3.1 $\pm$ 0.5	3.2 $\pm$ 0.5	3.4 $\pm$ 0.6	1.00
	<i>Podophyllum hexandrum</i>	9.5 $\pm$ 0.7	10.7 $\pm$ 0.8	11.0 $\pm$ 0.8	1.41
	<i>Rheum emodi</i>	17.1 $\pm$ 0.9	18.5 $\pm$ 1.4	20.8 $\pm$ 1.7	2.08
	LSD, P < 0.05	1.09	1.74	0.28	
Leaf area (cm <sup>2</sup> )	<i>Aconitum balfourii</i>	20.4 $\pm$ 4.1	26.8 $\pm$ 2.1	28.6 $\pm$ 1.5	6.13
	<i>Nardostachys jatamansi</i>	9.7 $\pm$ 2.5	10.6 $\pm$ 1.2	12.5 $\pm$ 1.1	3.66
	<i>Picrorhiza kurrooa</i>	11.2 $\pm$ 2.3	16.4 $\pm$ 1.7	18.9 $\pm$ 1.4	3.75
	<i>Podophyllum hexandrum</i>	64.2 $\pm$ 5.1	67.6 $\pm$ 4.5	71.9 $\pm$ 7.7	8.89
	<i>Rheum emodi</i>	79.6 $\pm$ 6.2	97.4 $\pm$ 6.1	119.0 $\pm$ 7.2	11.36
	LSD, P < 0.05	1.09	1.74	0.28	
Leaf thickness ( $\mu$ m)	<i>Aconitum balfourii</i>	402 $\pm$ 15	398 $\pm$ 11	392 $\pm$ 12	25.1
	<i>Nardostachys jatamansi</i>	318 $\pm$ 14	284 $\pm$ 12	280 $\pm$ 17	24.2
	<i>Picrorhiza kurrooa</i>	326 $\pm$ 11	287 $\pm$ 14	284 $\pm$ 14	23.7
	<i>Podophyllum hexandrum</i>	411 $\pm$ 13	396 $\pm$ 10	378 $\pm$ 13	21.8
	<i>Rheum emodi</i>	454 $\pm$ 12	421 $\pm$ 12	410 $\pm$ 19	34.5
	LSD, P < 0.05	27.9	25.9	37.1	

convection of heat as well as by boundary layer thermal conduction, which indicates that these species are able to survive much better in considerably higher air temperature at lower altitudes than alpine. The difference between leaf and air temperatures (LSD = 0.14, P < 0.05) was at its maximum at middle altitudes (2100 m) followed by lower altitudes (550 m) and alpine (3600 m). However, this difference was not as marked as reported earlier (Larcher and Wagner 1976, Korner and Cochrane 1983).

The temperature of the leaves was found to be significantly higher in the upper, than at the lower, surface at all altitudes. The average values were in the ranges of 0.20–0.41 °C, which can be considered fairly higher in comparison with a 0.1 °C difference causing considerable change in the thermal gradient, heterogeneity and heat transfer in the leaves (Perrier 1971). However, the temperature difference between the upper and lower surfaces of the leaves decreased progressively (LSD = 0.08, P < 0.05) with decreasing altitude. Leaf thermal conductivity (LSD = 6.11, P < 0.05) and their conductance

increased (LSD = 2.31, P < 0.05) with decreasing altitude in all the species. Similar results were also reported by Dhyani et al. (1986) in some other Himalayan trees and shrubs. These differences may be indicative of the catabolic changes within the plant, reflecting the adaptive and survival potential of the plant species to the altitude. However, more work is needed in this direction.

Energy budget of these species is illustrated in Table 4, which shows that total energy absorbed by the leaf was lost by re-radiation, transpiration and thermal conductance across leaf surfaces. All these parameters increased significantly with the decrease in altitude. Rawat and Purohit (1991) reported higher photosynthesis in seed-grown (not transplanted) plants of *P. hexandrum* at 550 m altitudes in comparison with its natural population at 3600 m in the Himalayas. Singh and Purohit (1997) reported a higher rate of photosynthesis and better growth in temperate populations of *P. hexandrum* in comparison with an alpine population in the Central Himalayas. These results are in agreement with the results of the present study,

Table 3: Average values of boundary layer thickness, thermal conductivity of air, boundary layer thermal conductance, difference between leaf and air temperature, thermal conductivity of leaves, leaf thermal conductance and temperature differences between leaf surfaces at different altitudes in Garhwal Himalayas

Altitude	Boundary layer thickness $\times 10^{-2}$ (m)	Thermal conductivity of air $\times 10^{-2}$ ( $\text{W m}^{-1} \text{ } ^\circ\text{C}^{-1}$ )	Boundary layer thermal conductance ( $\text{W m}^{-1} \text{ } ^\circ\text{C}^{-1}$ )	Leaf-to-air temperature difference ( $^\circ\text{C}$ )	Thermal conductivity of leaves $\times 10^{-2}$ ( $\text{W m}^{-1} \text{ } ^\circ\text{C}^{-1}$ )	Leaf thermal conductance ( $\text{W m}^{-1} \text{ } ^\circ\text{C}^{-1}$ )	Upper-to-lower leaf surface temperature difference ( $^\circ\text{C}$ )
3600	$0.03 \pm 0.01$	$1.80 \pm 0.05$	$86.75 \pm 28.2$	$-0.12 \pm 0.02$	$3.42 \pm 0.30$	$1.50 \pm 0.24$	$0.41 \pm 0.01$
2100	$0.09 \pm 0.04$	$2.12 \pm 0.03$	$36.52 \pm 14.2$	$-0.72 \pm 0.06$	$6.23 \pm 0.70$	$4.24 \pm 1.17$	$0.31 \pm 0.06$
550	$0.10 \pm 0.05$	$2.76 \pm 0.04$	$24.74 \pm 11.3$	$-0.04 \pm 0.01$	$11.12 \pm 1.10$	$8.72 \pm 1.31$	$0.20 \pm 0.03$
LSD, $P < 0.05$	0.05	0.16	23.85	0.14	6.11	2.31	0.08

which reflects the higher adaptability potential of these alpine species at lower altitude. Energy gained by convection of heat and air-to-leaf thermal conduction was at its maximum at middle altitude in comparison with other two altitudes. The leaf and air temperature differences as well as the temperature differences across the leaf surfaces influence the heat conduction from leaf to air and also across leaf surfaces. At higher temperature difference, more conduction of heat was observed. However, the conductance of heat/energy lost in conduction and across leaf surfaces was dependent more on thermal conductivity of the air (around leaf) and conductivity of the leaf, respectively. The leaves gained energy by convection of heat as well as the boundary layer thermal conduction, which is basically due to lower leaf temperature than that of the surrounding air at all altitudes. This seems to be the characteristic feature of alpine plants. The lower leaf temperature and the negative convection as well as conduction energy flow seems to help these plant species to survive under considerable high air thermal load by cooling the surrounding air. These species, therefore, can grow better at lower altitudes in warmer and drier environments. Similar advantages of lower leaf temperature, compared with the surrounding air and negative conventional energy flow, have been reported by Dhyani and Purohit (1983, 1984) and Dhyani et al. (1986) in some mountain species.

The correlation coefficients between different traits of energy budget and changing altitudes are given in Table 5, which indicates a highly significant role of leaf width in determining the boundary layer thermal conductance ( $r = 0.99$ ,  $P < 0.005$ ; not shown in correlation table) which in turn has a significant positive role in the total energy balance of the plants ( $r = -0.95$ ,  $P < 0.005$ ). Moreover, a highly significant, negative correlation between thermal conductivity of air around leaf and boundary layer thermal conduction from air to leaf ( $Q_{lg}^{la}$ ) ( $r = -0.86$ ,  $P < 0.01$ ) was observed, which indicates a flow of heat energy from air to leaf. A highly positive correlation was also observed between total energy absorbed and boundary layer thickness ( $r = 0.94$ ,  $P < 0.005$ ), which was highly influenced ( $r = 0.83$ ,  $P < 0.005$ ) by the thermal conductivity of the air around. However, thermal conductance across leaf surfaces was highly affected by thermal conductivity of leaves ( $r = 1.00$ ,  $P < 0.005$ ), which in turn has a significant positive effect on total energy balance ( $r = 0.98$ ,  $P < 0.005$ ). Thermal conductivity, conductance across leaf

Table 4: Average values of leaf energy exchange parameters at different altitudes in Garhwal Himalayas

Altitude (m)	$Q_r$	$Q_t$	$Q_c$	$Q_g^{la}$	$Q_g^l$	$Q_a$
3600	359.5 ± 25.2	4.2 ± 0.3	-0.4 ± 0.1	-8.9 ± 0.3	0.4 ± 0.1	344.8 ± 21.7
2576	389.3 ± 19.8	8.3 ± 0.2	-1.5 ± 0.3	-13.7 ± 0.2	1.0 ± 0.1	396.3 ± 17.5
550	452.6 ± 24.3	13.7 ± 1.5	-0.2 ± 0.1	-2.3 ± 0.1	1.8 ± 0.3	438.7 ± 19.1
LSD, $P < 0.05$	53.27	2.07	0.35	0.44	0.42	48.66

$Q_r$ , energy loss by radiation;  $Q_t$ , energy lost by re-radiation;  $Q_c$ , energy lost (+)/gained (-) by convection of heat;  $Q_g^{la}$ , energy lost and gained by boundary layer thermal conduction;  $Q_g^l$ , energy loss by conduction across leaf surfaces;  $Q_a$ , total energy absorbed by the leaf.

Table 5: Correlation among boundary layer thermal conductivity, boundary layer thermal conduction, boundary layer thickness, thermal conductivity of the leaf, leaf thermal conduction, leaf thickness and energy absorbed along with altitude

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1) Altitude							
(2) Thermal conductivity of air	-0.984***						
(3) Boundary layer thermal conduction	0.938***	-0.861**					
(4) Boundary layer thickness	-0.914***	0.836**	-0.999***				
(5) Leaf thermal conductivity	-0.989***	0.999***	-0.878***	0.855**			
(6) Leaf thermal conduction	-0.992***	0.999***	-0.886***	0.863**	1.000***		
(7) Leaf thickness	0.959***	0.892***	0.998***	-0.994***	-0.908***	-0.914***	
(8) Total energy absorbed by leaf	-0.998***	0.970***	-0.959***	0.944***	0.978***	0.981***	-0.975***

Significant at \*\*\*0.005 and \*\*0.01.

surfaces and therefore total energy balance significantly increased with decreasing altitude. A significant positive correlation was observed between altitude and leaf thickness ( $r = 0.95$ ,  $P < 0.005$ ). Thinner leaves (at lower elevation) have shown higher leaf thermal conductivity ( $r = -0.90$ ,  $P < 0.005$ ) and higher energy absorption potential ( $r = -0.97$ ,  $P < 0.005$ ). A highly significant positive correlation between leaf energy absorption and total plant biomass production has already been reported by Chandra (2003). In conclusion, the results of this study reveal that all these alpine medicinal crops have the potential of absorbing higher amounts of energy from warmer microclimate when transplanted at lower altitudes. Therefore, within the limits of the study, it can be concluded that these important medicinal crops can grow much better if cultivated at lower altitudes.

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