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Energy Content and Photosynthetic Efficiency of *Quercus mongolica* Stands in Korea

Ki-Cheol Kwon[1]* and Don Koo Lee[2]

[1]*Korea Forest Research Institute, Seoul 130-712, Korea*
[2]*Dept. of Forest Sciences, Seoul National University, Seoul 151-921, Korea*

Abstract : This study was conducted to examine the energy content and photosynthetic efficiency of *Quercus mongolica* stands in Korea. Study sites were located in Mt. Joongwang, Gangwon-do (1,000 m and 800 m above sea level), Mt. Baekwoon, Jeollanam-do (800 m a.s.l.), Mt. Halla, Jeju-do (1,000 m a.s.l.), Mt. Taehwa, Gyeonggi-do (350 m a.s.l.), and Mt. Wolak, Chungcheongbuk-do (300 m a.s.l.). Total energy content and annual energy accumulation in *Q. mongolica* stands were 2,916-6,435 GJ/ha and 284-441 GJ/ha, respectively. Lower latitude (N.L.) stands of *Q. mongolica* showed higher energy contents than higher latitude stands, but *Quercus* stands in Mt. Baekwoon had higher annual energy accumulation than those in Mt. Halla located at a lower latitude. During the growing season, the photosynthetic efficiency of 60 to 70-year-old *Q. mongolica* stands ranged from 1.19 to 1.34% while that of 35-year-old stands did from 1.87 to 1.95%. There were no significant differences in photosynthetic efficiency among the latitudes because solar radiation was higher in low latitudes.

Key words **:** *energy content, latitude, photosynthetic efficiency,* Quercus mongolica, *stand age*

Introduction

Throughout the process of photosynthesis, plants transfer and store solar energy to chemical energy into its components (Smith and Smith, 2001). A large portion of organic energy in plants is consumed during respiration, and the remaining energy is accumulated in stem, branch, foliage, seed, and other plant components. The energy accumulated in plants is used by human beings and animals as energy resources.

Forest has the highest vegetation biomass production among various ecosystems (Lee, 1984). Biomass exploitation plays an important role in the production of energy from renewable sources in the forest. A comprehensive approach to biomass exploitation is required for regions where the use of biomass energy can reduce environmental pollution and enhance regional welfare.

Most simulation models and essays that consider the basic processes of photosynthesis and primary production start with solar energy or CO_2 as input and end with dry-matter weight produced as output (Kimmins, 1997). The importance of interpreting productivity in terms of energy has long been realized but the large amount of work necessary to convert dry-matter values into caloric values has in many cases discouraged further investigation of energy of productivity (Lieth, 1975).

The rate of primary production is of great interest to ecologists and forest managers (Kimmins, 1997). The accumulation efficiency with which solar energy enters the ecosystems is referred to as photosynthetic efficiency. Photosynthetic efficiencies have been calculated for a wide variety of ecosystems. The values are generally small (1 to 5%) and almost invariable in ecosystems that have a continuous plant community (Phillipson, 1966; Gates, 1971).

In the secondary forests of Korea, oaks and pines are the two common representatives. Oaks occupy 75% of the total natural broadleaved forests by area and comprise more than 27% of the total standing stock by volume (Lee *et al.*, 1990). *Quercus mongolica* is a deciduous oak species that grows broadly in Korea. But the photosynthetic efficiency and energy content of *Q. mongolica* were not yet investigated.

The purpose of this study was to investigate differences in photosynthetic efficiency and energy content of *Q. mongolica* stands with respect to latitudes and environmental factors.

Materials and Methods

1. Study site

The energy content and photosynthetic efficiency of *Q. mongolica* stands were studied at Mt. Joongwang

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*Corresponding author
E-mail: kkch30@yahoo.co.kr

Table 1. Physical characteristics of the study sites.

Sites	Plot no.	Altitude (m)	Topo.*	Aspect (°)	Slope (°)	Mean age (yr.)	SV** (%)	No/ha	No. of sample trees***	Sub-major species****
Mt. Joongwang (37°29'N, 128°32'E)	J-a	1,000	MS	SE15	27	70	93.2	1,250	6	-
	J-b	1,000	MS	SE40	20	70	89.7	1,175	-	FR
	J-c	1,050	MS	SE20	25	70	91.4	1,100	-	FR
	J-d	800	MS	SE60	25	60	88.5	1,200	5	PDS
	J-e	825	MS	SE80	23	60	87.4	1,275	-	PDS, MA
	J-f	890	R	SE85	25	60	86.8	1,325	-	FR
Mt. Baekwoon (35°15'N, 127°35'E)	B-a	810	US	SW40	35	70	80.8	1,525	9	CL, RS
	B-b	790	US	SW40	35	70	87.5	1,575	-	RS, SB
	B-c	820	US	SW30	38	70	85.8	1,500	-	RS, SB
Mt. Halla (33°21'N, 126°31'E)	H-a	1,040	MS	SW10	10	60	88.3	2,850	-	UD, AP, SB
	H-b	1,010	MS	SW25	10	60	72.6	3,500	-	UD, SB
	H-c	1,000	MS	SE10	10	60	81.9	2,800	5	APM, SB
Mt. Taehwa (37°19'N, 127°18'E)	T-a	350	MS	SW50	15	35	80.5	1,875	8	QV, CC
	T-b	340	MS	SW45	15	35	78.7	1,775	-	QV, CC
	T-c	380	MS	SW70	20	35	79.4	1.950	-	QV, PS
Mt. Wolak (36°51'N, 128°11'E)	W-a	300	LS	NE65	10	35	80.8	2,425	10	QV, SO
	W-b	320	LS	NE60	15	35	84.4	2,050	-	QV, SO
	W-c	275	LS-V	NE80	10	35	82.5	2,475	-	QV, SO

*Topography : R; Ridge, US; Upper slope, MS; Middle slope, LS; Lower slope, V; Valley

**SV : Synthetic Value of *Quercus mongolica*, SV = (Relative density + Relative coverage) / 2

***Sample trees collected for the measurement of biomass and energy content

****Sub-major species : AP; *Acer pseudosieboldianum*, APM; *A. pictum* subsp. *mono*, CC; *Castanea crenata*, CL; *Carpinus laxiflora*, FR; *Fraxinus rhynchophylla*, PDS; *Pinus densiflora*, PS; *Prunus sargentii* var. *sargentii*, QV; *Quercus variabilis*, RS; *Rhododendron schlippenbachii*, SB; *Sasa borealis*, SO; *Styrax obassia*, UD; *Ulmus davidiana*

Table 2. Soil characteristics of *Quercus mongolica* stands in the study sites.

Site		Soil moisture (%)	pH (1:5 H_2O)	Organic matter (%)	Total N (%)	CEC (cmol$_c$/kg)	Soil texture (USDA)
Mt. Joongwang	(1,000 m a.s.l.)	29.3	4.7	9.7	0.4	18.8	SCL
Mt. Joongwang	(800 m a.s.l.)	33.3	4.8	8.4	0.2	8.3	SL
Mt. Baekwoon	(800 m a.s.l.)	33.6	4.3	12.0	0.3	19.2	SCL
Mt. Halla	(1,000 m a.s.l.)	52.4	4.4	22.4	1.1	27.8	C
Mt. Taehwa	(350 m a.s.l.)	20.3	4.9	9.7	0.7	8.2	SL
Mt. Wolak	(300 m a.s.l.)	33.4	4.9	4.3	0.2	5.7	SCL

(1,000 m and 800 m above sea level), Pyeongchang-gun, Gangwon-do, Mt. Baekwoon (800 m a.s.l.), Gwangyang-si, Jeollanam-do, Mt. Halla (1,000 m a.s.l.), Jeju-do, Mt. Taehwa (350 m a.s.l.), Gwangju-si, Gyeonggi-do, and Mt. Wolak (300 m a.s.l.), Jecheon-si, Chungcheongbuk-do. These study sites are situated in national parks or national forests protected intensively. Physical characteristics of the study sites are given in Table 1.

2. Soil analysis

The soil samples of A-layer were air-dried in the shade, sifted with a 2 mm sieve and stored for analyzing its physical and chemical characteristics (Table 2). The dominant soils of *Q. mongolica* stands are acidic. The soil texture was sandy clay loam in Mt. Joongwang, Mt. Wolak and Mt. Baekwoon, sandy loam in Mt. Taehwa, and clay in Mt. Halla. The soil moisture and organic matter in Mt. Halla were higher than those in other areas because of a nearby large damp ground.

3. Measurement

Vegetation data were collected using the quadrat sampling method. The size of each quadrat was 400 m^2 (20 m × 20 m). Species type, diameter at breast height (DBH) and tree height were recorded for each tree in every quadrat. Three quadrats were used for survey at each site, and the total number of quadrats used was 18. Field survey in all of the sites was carried out in 2003

Table 3. Meteorological data in the study sites during the study period.

Sites	Altitude* (m)	WI (°C·month)	Precipitation (mm)	Solar radiation$_1$ (MJ/m^2)**	Solar radiation$_2$ (MJ/m^2)
Mt. Joongwang***	1,050	63.62	1,890.0	2,382.11	3,394.48
Mt. Baekwoon	450	87.67	1,887.2	2,674.04	4,586.10
Mt. Halla	5	134.55	2,100.6	2,823.50	5,826.50
Mt. Taehwa	100	88.00	1,806.5	1,951.45	3,389.83
Mt. Wolak	200	96.67	1,851.0	2,261.30	3,735.40

*Location of the automatic weather station

**Solar radiation$_1$ (Mar.-Aug. in 2002), Solar radiation$_2$ (Sep. 2002-Aug. 2003)

***The meteorological data of Mt. Joongwang collected in Sep. 2003 to Aug. 2004.

except for Mt. Joongwang done in 2004.

The whole components including roots of *Q. mongolica* trees with DBH ranging between 6-35 cm were harvested to develop equations for estimating energy contents. The number of trees harvested for estimating aboveground energy content in Mt. Joongwang (1,000 m a.s.l., southern aspect), Mt. Joongwang (800 m a.s.l., southern aspect), Mt. Baekwoon (800 m a.s.l., southern aspect), Mt. Halla (1,000 m a.s.l., southern aspect), Mt. Taehwa (350 m a.s.l., southern aspect), and Mt. Wolak (300 m a.s.l., northern aspect) were 6, 5, 9, 5, 8, and 10, respectively. The number of trees grown from seedlings for estimating root energy content was 18 for all of the study sites. All the selected trees at Mt. Joongwang were measured and weighted between late August and early September in 2004 and those at the other sites in 2003.

Foliage and woody tree components (branch, stem bark, stem wood, and root) were separated and weighted. Sapwood and heartwood volumes were measured using Smalian rule and transformed into dry matter by multiplying with its specific density. The density values ranged from 0.685-0.796 kg dm^{-3} for sapwood and 0.705-0.865 kg dm^{-3} for heartwood in each tree sample. Sub-samples of each tree were oven-dried for more than 48 hours at 80°C, of which dry matter coefficients resulted were used to calculate total dry matter. Then, dry matter values were calculated on a hectare basis. Other tree components like fine roots, acorns, coarse woody debris or understory species were not measured.

4. Energy content of biomass

Biomass energy content was analyzed twice in each tree component (leaves, branches, stem bark, stem wood, and roots). Sub-sampled portions of all tree components were dried at 90°C to a constant weight and the energy content was analyzed using the USA Oxygen Bomb Calorimeter (1241 PARR).

Allometric regressions of the energy content (J) of each tree component with DBH (cm) and tree height (m) for each study site were developed. Annual energy accumulation of aboveground components and roots was estimated from the difference of energy content between the year of harvest and its previous year in the sites. The equations resulted were used to estimate energy content at stand level of each site.

5. Photosynthetic efficiency

Photosynthetic efficiency is the total heat energy content of the stand divided by net incoming solar energy (Hellmers and Bonner, 1959). The solar energy is the total amount of radiation during the growing season (March to August) of *Q. mongolica* (Leak, 1970; Kwon, 2006).

Climatic data were obtained for the whole year during the study period from the automatic weather station (CR10X, Campbell Scientific, INC.) with radiation sensor(LI-COR, 1991) near the study sites (Table 3).

6. Statistical analysis

Correlation coefficient was used to measure the relationship between annual energy accumulation or photosynthetic efficiency and environmental factors. The environmental factors were warm index, precipitation, solar radiation, organic matter content in soil, soil moisture, and latitude. The calculation of warm index presumes a dry adiabatic (no heat exchange) lapse rate (rate of temperature change with altitude) of 0.005°C/meter.

The data of photosynthetic efficiency in *Q. mongolica* stands were tested for latitude as the main factor and for tree sampling quadrats as replications. The sampling sites used for analysis were Mt. Joongwang (1,000 m and 800 m a.s.l.), Mt. Baekwoon, and Mt. Halla in the southern aspect. These stands have similar mean age in upper layer and topographical factors but different latitudes.

The allometric regressions, correlation, and ANOVA were conducted using Statistical Analysis System program version 9.1.3 (SAS Inc.).

Results and Discussion

1. Energy content of *Quercus mongolica* stands

Allometric relations induced from the energy content of each aboveground component for the tree samples are

Table 4. Regression coefficients and R^2 when aboveground energy content of *Q. mongolica* was regressed on D^2H [$log Y=A+B log X$; Y, energy content (J); X, DBH (cn)^2×height (m)].

Parameter (Y)	A	B	R^2	Prob. level	A	B	R^2	Prob. level
	Mt. Joongwang (1,000m, S)				Mt. Joongwang (800m, S)			
Stem wood	5.464	1.034	0.99	<0.001	5.522	1.035	0.99	<0.001
Sapwood	5.743	0.847	0.96	<0.001	5.371	0.976	0.99	<0.001
Heartwood	4.657	1.189	0.99	<0.001	5.118	1.076	0.96	0.002
Stem bark	4.778	1.004	0.99	<0.001	5.328	0.855	0.98	<0.001
Live branches	4.430	1.154	0.97	<0.001	3.840	1.282	0.90	0.008
Leaves	4.737	0.791	0.98	<0.001	4.309	0.908	0.99	<0.001
	Mt. Baekwoon (800m, S)				Mt. Halla (1,000m, S)			
Stem wood	5.430	1.062	0.98	<0.001	5.216	1.109	0.98	<0.001
Sapwood	5.646	0.920	0.96	<0.001	5.648	0.878	0.92	<0.001
Heartwood	4.221	1.311	0.99	<0.001	3.586	1.505	0.98	<0.001
Stem bark	5.186	0.913	0.97	<0.001	4.490	1.083	0.98	<0.001
Live branches	4.637	1.144	0.97	<0.001	4.083	1.274	0.98	<0.001
Leaves	4.447	0.937	0.94	<0.001	5.200	0.696	0.93	0.004
	Mt. Taehwa (350m, S)				Mt. Wolak (300m, N)			
Stem wood	5.515	1.002	0.99	<0.001	5.818	0.922	0.93	<0.001
Sapwood	6.051	0.756	0.97	<0.001	5.970	0.800	0.91	<0.001
Heartwood	3.421	1.523	0.96	<0.001	4.765	1.127	0.93	<0.001
Stem bark	5.385	0.823	0.97	<0.001	5.810	0.708	0.93	<0.001
Live branches	3.573	1.427	0.99	<0.001	4.953	0.994	0.96	<0.001
Leaves	3.804	1.195	0.90	<0.001	4.655	0.946	0.98	<0.001

Table 5. The energy contents (GJ/ha) of *Q. mongolica* stands in the study sites.

Site	Sap-wood	Heart-wood	Bark	Live branch	Leaf	Above-ground total	Root	Total
Mt. Joongwang (1,000 m, S)	820.09	1,581.19	377.80	679.74	48.84	3,507.66	673.16	4,180.82
	(19.62)*	(37.82)	(9.04)	(16.26)	(1.17)	(83.90)	(16.10)	(100.00)
Mt. Joongwang (800 m, S)	1,196.75	1,654.35	363.43	569.05	55.68	3,839.26	720.71	4,559.97
	(26.24)	(36.28)	(7.97)	(12.48)	(1.22)	(84.19)	(15.81)	(100.00)
Mt. Baekwoon (800 m, S)	1,168.11	1,549.35	402.21	926.53	91.31	4,137.51	655.64	4,793.15
	(24.37)	(32.32)	(8.39)	(19.33)	(1.91)	(86.32)	(13.68)	(100.00)
Mt. Halla (1,000 m, S)	1,167.00	2,219.19	543.62	1,201.05	80.46	5,211.33	1,223.36	6,434.70
	(18.14)	(34.49)	(8.45)	(18.67)	(1.25)	(80.99)	(19.01)	(100.00)
Mt. Taehwa (350 m, S)	611.60	799.31	243.10	542.47	134.86	2,331.33	584.66	2,915.99
	(20.97)	(27.41)	(8.34)	(18.60)	(4.62)	(79.95)	(20.05)	(100.00)
Mt. Wolak (300 m, N)	1,003.54	982.89	339.33	503.95	168.20	2,997.91	798.28	3,796.19
	(26.44)	(25.89)	(8.94)	(13.28)	(4.43)	(78.97)	(21.03)	(100.00)

*The values in parenthesis indicate the percentage of each component to the total.

summarized in Table 4. Determination coefficients between D^2H and energy content of each components were high (more than 0.9). Because of the limited number of sample trees for below-ground biomass and energy content, it was not possible to develop the equations for each site. Allometric relation for root was developed as $log\ E_R = 5.713 + 0.841\ log\ D^2H$ (adj. $R^2 = 0.97$) for all study sites, where E_R is energy content (J) of root and D^2H is the value of multiplying the square value of DBH (cm) by tree height (m). The energy content was significantly related to the respective DBH and height in most of the equations.

Table 5 shows the mean energy content for each above- and below-ground biomass component on a hectare basis. The total energy content ranged between 2,916 and 6,435 GJ/ha, The lowest was the 35-year-old stand

Table 6. Annual net energy accumulation (GJ/ha/yr) of *Q. mongolica* stands in the study sites.

Site	Sapwood	Heartwood	Bark	Live branch	Leaf	Aboveground total	Root	Total
Mt. Joongwang (1,000 m, S)	38.69 (13.65)*	92.11 (32.48)	19.96 (7.04)	38.77 (13.67)	48.84 (17.23)	238.37 (84.07)	45.16 (15.93)	283.53 (100.00)
Mt. Joongwang (800 m, S)	56.42 (19.41)	85.28 (29.34)	15.10 (5.20)	32.80 (11.29)	55.68 (19.16)	245.28 (84.39)	45.36 (15.61)	290.64 (100.00)
Mt. Baekwoon (800 m, S)	57.37 (15.95)	91.56 (25.46)	19.33 (5.38)	52.03 (14.47)	91.31 (25.39)	311.61 (86.65)	47.99 (13.35)	359.60 (100.00)
Mt. Halla (1,000 m, S)	43.99 (12.66)	84.08 (24.21)	23.19 (6.68)	47.53 (13.68)	80.46 (23.16)	279.26 (80.39)	68.11 (19.61)	347.37 (100.00)
Mt. Taehwa (350 m, S)	31.14 (8.52)	70.44 (19.28)	13.26 (3.63)	45.77 (12.52)	134.86 (36.91)	295.47 (80.86)	69.96 (19.14)	365.43 (100.00)
Mt. Wolak (300 m, N)	57.30 (12.99)	83.20 (18.86)	16.80 (3.81)	30.53 (6.92)	168.20 (38.14)	356.03 (80.72)	85.02 (19.28)	441.04 (100.00)

*The values in parenthesis indicate the percentage of each component to the total.

in Mt. Taehwa whereas the highest was the 60-year-old stand in Mt. Halla. Among the tree components, stemwood accounted for the highest energy content and ranged from 48 to 63% of the total, followed by roots (14-21%), live branches (12-19%), stembark (8-9%), and foliage (1-5%). With increasing stand age, the ratio of the stem and live branches to the total energy content increased but those of roots and foliage decreased.

Study sites at Mt. Joongwang, Mt. Baekwoon, and Mt. Halla compared for the energy contents of *Q. mongolica* stands along the latitude were as follows. These sites had similar stand conditions such as stand age (60 to 70-year-old), altitude (800 m to 1,000 m a.s.l.), and slope aspect (southern aspect). Total energy contents for the sites in the southern aspect of Mt. Joongwang (1,000 m a.s.l.), Mt. Joongwang (800 m a.s.l.), Mt. Baekwoon, and Mt. Halla were 4,181 GJ/ha, 4,560 GJ/ha, 4,793 GJ/ha, and 6,435 GJ/ha, respectively, which shows an increasing trend with decreasing latitude (N.L.).

Meanwhile, the energy contents of the 35-year-old stands in the southern aspect of Mt. Taehwa and in the northern aspect of Mt. Wolak were 2,915 GJ/ha and 3,796 GJ/ha, respectively (Table 5). These values were smaller than those of 60 to 70-year-old *Q. mongolica* stands with more than 4,000 GJ/ha because the stands in Mt. Taehwa and Mt. Wolak were younger than other sites.

Table 6 shows the mean annual energy accumulation of *Q. mongolica* stands for each above- and belowground biomass compartment on a hectare basis. The annual energy accumulation ranged from 284 to 441 GJ/ha/yr. The lowest was the 70-year-old stand in Mt. Joongwang (1,000 m a.s.l.) whereas the highest was the 35-year-old stand in Mt. Wolak. Stemwood accounted for the highest annual energy accumulation (28 to 49% of the total), followed by foliage (17-38%), roots(13-20%), live branches (7-14%), and stembark (4-7%).

Annual energy accumulation for the 60 to 70-year-old stands in the southern aspect of Mt. Joongwang (1,000 m a.s.l.), Mt. Joongwang (800 m a.s.l.), Mt. Baekwoon, and Mt. Halla were 283 GJ/ha/yr, 290 GJ/ha/yr, 359 GJ/ha/yr, and 347 GJ/ha/yr, respectively. The stand in Mt. Baekwoon showed the highest energy accumulation and the lowest in Mt. Joongwang (1,000 m a.s.l.). The annual energy accumulation for the 35-year-old stands in the southern aspect of Mt. Taehwa and in the northern aspect of Mt. Wolak were 365 GJ/ha/yr and 441 GJ/ha/yr, respectively. These values were greater than those of 60 to 70-year-old *Q. mongolica* stands.

The annual energy accumulation of *Q. mongolica* stands were similar to that of 48-year-old *Pinus densiflora* stand with 393 GJ/ha/yr but smaller than that of 30-year-old *Larix kaempferi* stand in Mt. Wolak with 1,256 GJ/ha/yr and that of 36-year-old *Pinus rigida* stand in Mt. Taehwa with 932 GJ/ha/yr (Lee and Kwon, 2005).

2. Photosynthetic efficiency of *Q. mongolica* stands

Figure 1 shows the photosynthetic efficiency of *Q. mongolica* stands in the study sites. Photosynthetic efficiency for the 60 to 70-year-old stands in the southern aspect of Mt. Joongwang (1,000 m a.s.l.), Mt. Joongwang (800 m a.s.l.), Mt. Baekwoon, and Mt. Halla was 1.19%, 1.22%, 1.34%, and 1.23%, respectively. The photosynthetic efficiency of *Q. mongolica* stands by latitude of the study sites is shown in Table 7. There was not significantly different among latitudes. The reason was assumed due to higher solar radiation in low lati-

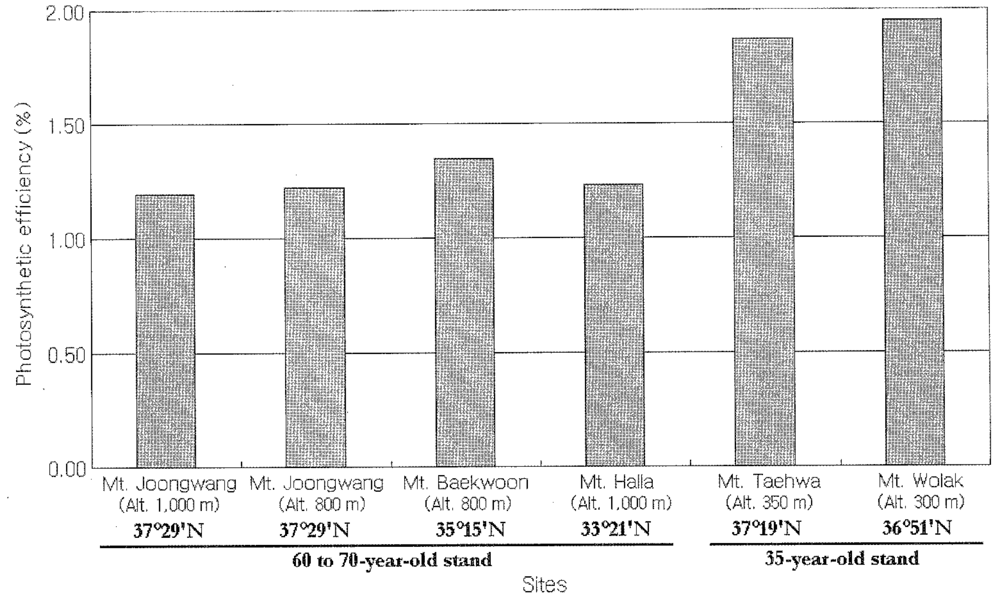

Figure 1. Photosynthetic efficiency of *Q. mongolica* stands.

tudes which thus increased annual energy accumulation of the stands.

The photosynthetic efficiencies for the 35-year-old stands in the southern aspect of Mt. Taehwa and in the northern aspect of Mt. Wolak were 1.87% and 1.95%, respectively (Figure 1). These values were higher than that of 60 to 70-year-old *Q. mongolica* stands with photosynthetic efficiency ranging between 1.19 and 1.34%. The percentage of energy in leaves to the total in 35-year-old *Q. mongolica* stands ranged from 36.91% (Mt. Taehwa) to 38.14% (Mt. Wolak) whereas that in 60 to 70-year-old stands ranged from 17.23% to 25.39%. It was assumed that differences in stand age and amount of leaves had mainly caused the variation of photosynthetic efficiencies of the stands in this study. Woody plants accumulate most of the biomass and energy into the photosynthetic organs (leaves) at young age, but did into the woody parts as trees grow older (Kozlowski *et al.*, 1991). Ovington and Heitkamp (1960), Satoo and Madgwick (1982), and Kimmins (1997) also reported that the photosynthetic efficiency of forest varied according to stand age and amount of leaves.

The photosynthetic efficiencies of *Q, mongolica* stands were similar to those of Scotch pine with 1.3% (Ovington, 1962) and those of the temperate forest with 0.5% to 1.7% (Kira, 1976) but smaller than those of sugar cane with 1.9% (Hellmers and Bonner, 1959) and those of the tropical rain forest with 3% (Ogawa *et al.*, 1961).

Table 7. ANOVA for photosynthetic efficiency of *Q. mongolica* stands by latitude.

Source	df	Mean Squares	Pr > F
Latitude	3	0.014	0.379
Residual	8	0.012	

Annual energy accumulation and photosynthetic efficiency varied depending on the environmental factors (Hocker, 1979; Kwon, 2006). In order to explain variation in annual energy accumulation and photosynthetic efficiency at stand level, correlations between annual energy accumulation or photosynthetic efficiency and environmental factors (warm index (WI), annual precipitation (Prec.), solar radiation during growing season ($Solar_1$) and annual solar radiation ($Solar_2$), soil organic matter (OM), and soil moisture (MO)) as well as latitude were compared. In Table 8, both of annual energy accumulation and photosynthetic efficiency of the stands in this study areas were significantly correlated to the warm index. The limiting factors of photosynthetic efficiency were temperature, precipitation, light intensity, species, age, amount of leaves, and/or stage of succession (Hellmers and Bonner, 1959; Kira, 1971; Satoo and

Table 8. Correlations among annual energy accumulation, photosynthetic efficiency and environmental factors of *Q. mongolica* stands in the study sites.

	WI	Prec.	$Solar_1$	$Solar_2$	OM	MO	Lat.
Annual energy accumulation	0.91***	-0.21	-0.20	0.04	-0.33	0.03	-0.04
Photosynthetic efficiency	0.82***	-0.50*	-0.59*	-0.29	-0.53*	-0.30	0.33

*** Indicates significance at 0.001 and * 0.05.

Madgwick, 1982; Ovington and Heitkamp, 1960; Kimmins, 1997). In this study, the annual energy accumulation and photosynthetic efficiency of *Q. mongolica* stands were greatly affected by temperature, but further study is needed to define the relations between photosynthetic efficiency and air temperature (Kwon and Lee, 2006).

Conclusion

The total energy content of 60 to 70-year-old *Q, mongolica* stands ranged from 4,181 to 6,435 GJ/ha, while that of 35-year-old stands was from 2,916 to 3,796 GJ/ha. The annual energy accumulation of 60 to 70-year-old stands ranged from 284 to 360 GJ/ha/yr, while that of 35-year-old stands was from 365 to 441 GJ/ha/yr. The photosynthetic efficiencies of 60 to 70-year-old stands and 35-year-old stands were 1.19-1.34% and 1.87-1.95%, respectively. These values were within the range of stands in temperate hardwood forests.

The photosynthetic efficiency of *Q. mongolica* stands along stand conditions and environmental factors demonstrated distinct patterns. At lower latitude, the energy contents and annual energy accumulation in the stand increased but the photosynthetic efficiency was constant. However, the influence of a slope aspect on the photosynthetic efficiency was not effective in this study. Further study is needed to investigate its differences among slope aspects, especially northern and southern aspect.

Photosynthetic efficiency, energy accumulation and its allocation to each tree component were reflected not only by the differences in temperature, but by stand age, structure, and topographical characteristics. As the stand age became old, the ratio of the stem and branches increased while that of roots and foliage decreased. Since pruning and thinning can influence both energy accumulation and allocation at individual tree and stand levels, further research should be carried out to understand the impacts of forest tending operations on the total biomass, energy accumulation and photosynthetic efficiency.

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