

Carbon Storage of *Quercus mongolica* Stands by Latitude and Altitude in Korea

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Abstract : The study was conducted to investigate the differences in carbon storage of *Quercus mongolica* stands with respect to latitude and altitude in Korea. Study sites were located in Mt. Joongwang, Pyeongchang-gun, Gangwon-do (altitudes 1,300 m, 1,000 m, and 800 m), Mt. Taehwa, Gwangju-si, Gyeonggi-do (altitude 350 m), Mt. Wolak, Jecheon-si, Chungcheongbuk-do (altitude 300 m), Mt. Baekwoon, Gwangyang-si, Jeollanam-do (altitude 800 m), and Mt. Halla, Jeju-do (altitude 1,000 m). Total carbon storage and annual carbon storage of *Q. mongolica* stands were 85-210 tonC/ha and 7.2-10.6 tonC/ha, respectively. Lower latitude (NE) stands of *Q. mongolica* showed more carbon storage and annual carbon storage than higher latitude stands. Carbon storage and annual carbon storage of *Q. mongolica* stands were increased in low altitude. Carbon storage of *Q. mongolica* stands was higher in the northern aspect than in the southern aspect. However, there were no significant differences in annual carbon storage between the aspects.

Key words : *Quercus mongolica*, biomass, carbon storage, latitude, altitude

Introduction

Today, one of the major issues of global concern is the rapidly increasing levels of CO₂ (at 2 ppm/yr) in the atmosphere and its potential to change the world climate. Elevated levels of CO₂ and other greenhouse gases in the atmosphere have increased global average surface temperature by 0.6±.2°C (IPCC, 1996a). The rising CO₂ levels have severe implications on the functioning of physical and biological systems of the world. In order to mitigate this problem, IPCC (1996b) advocated an increase in the size of the carbon pools such as forests.

The contribution of biomass production to climate change mitigation is recognized by their ability to uptake CO₂ from atmosphere through photosynthesis as for the strong capacity in biotic and abiotic components (Laclau, 2003). By complex relationships with vegetation species and the environment, each growing tree is a control factor of carbon emissions the same as a reservoir that increases its storing capacity overtime until it reaches a steady state in late succession stage. Increased biomass production through large scale silvicultural tending is one among the viable actions to mitigate the rising levels of CO₂.

The biomass productivity and distribution of trees is generally influenced by the climatic and geographical variations (Rawat and Singh, 1988; Wang, 2003). Understanding biomass and carbon storage of a stand along latitude and altitude will help in evolving suitable strategies of forest management for assessment and estimation of regional carbon storage of the stand.

In the natural forests of Korea, oaks and pines are the two common representatives of the native genera. Oaks occupy 75% of the total natural broadleaved forests by area and comprise more than 27% of the total standing stock volume (Lee *et al.*, 1990).

Quercus mongolica is a deciduous oak species that grows throughout the Korean Peninsula, Japan, northeast China, and Siberia (Kim and Manyko, 1994; Kim, 1992). This species grows from 100 m to 1,800 m above the sea level, but is most abundant at altitudes near 700 m above the sea level (Chung and Lee, 1965).

The objective of the study was to investigate the carbon storage and annual carbon storage of *Q. mongolica* stands in Korea and to analyze their differences with respect to latitude and altitude.

Materials and Methods

1. Study Area

The biomass and carbon storage of *Q. mongolica*

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Figure 1. Location of the study sites.

stands were studied at Mt. Joongwang, Pyeongchang-gun, Gangwon-do (altitudes 1,300 m, 1,000 m, and 800 m), Mt. Taehwa, Gwangju-si, Gyeonggi-do (altitude 350 m), Mt. Wolak, Jecheon-si, Chungcheongbuk-do (altitude 300 m), Mt. Baekwoon, Gwangyang-si, Jeollanam-do (altitude 800 m), and Mt. Halla, Jeju-do (altitude 1,000 m) in the northern and southern aspects. Figure 1 shows the location of the study areas and Table 1 summarizes the characteristics of each site.

Climatic data in the study areas were obtained for the full one-year of the study period from the automatic weather station (CR10X, Campbell Scientific, INC.) nearby the study sites (Table 2).

The mother rocks of the study areas except for Mt. Joongwang are granite partly mixed with gneiss and that of Mt. Joongwang is gneiss mixed with limestone (Suh and Lee, 1998; Jung *et al.*, 2004). The soil samples of A-layer were dried in the shade, sifted with a 2 mm sieve and stored for analyzing physical and chemical characteristics of the soil. The dominant soils of *Q. mongolica* stands are acidic (Table 3). 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 the nearby large damp ground.

2. Material Sampling

Data were collected using the quadrat sampling method. The size of each quadrat was 400 m². Species, diameter at breast height (DBH) and tree height were recorded for

each tree in a plot. The number of quadrats surveyed at Mt. Joongwang, Mt. Taehwa, Mt. Wolak, Mt. Baekwoon, and Mt. Halla were 18, 3, 3, 6, and 6, respectively. Field survey at Mt. Joongwang was carried out in 2004 and the other four areas were surveyed in 2003.

To develop *Q. mongolica* carbon storage equations, tree roots and complete individuals of *Q. mongolica* sample areas ranging 6-35 cm in DBH were selected for harvest. The number of sample trees for investigating aboveground carbon storage in Mt. Joongwang with alt. of 1,300 m (northern aspect), Mt. Joongwang (alt. 1,300 m, southern aspect), Mt. Joongwang (alt. 1,000 m, northern aspect), Mt. Joongwang (alt. 1,000 m, southern aspect), Mt. Joongwang (alt. 800 m, northern aspect), Mt. Joongwang (alt. 800 m, southern aspect), Mt. Taehwa (alt. 350 m, southern aspect), Mt. Wolak (alt. 300 m, northern aspect), Mt. Baekwoon (alt. 800 m, northern aspect), Mt. Baekwoon (alt. 800 m, southern aspect), Mt. Halla (alt. 1,000 m, northern aspect), and Mt. Halla (alt. 1,000 m, southern aspect) were 7, 6, 7, 6, 6, 5, 8, 10, 6, 9, 5, and 5, respectively. The number of tree samples grown from seedlings for investigating root carbon storage was 18 from all sample areas. All selected trees were measured and weighted between late August and early September of 2004 at Mt. Joongwang and of 2003 at the other four sites.

Foliage and woody tree components (branches, stem bark, stem wood, and roots) were separated and weighted. Sapwood and heartwood volumes were measured using Smalian rule and transformed into dry matter by multiplying it by its specific density. The density values were from 0.685-0.796 kg dm⁻³ for sapwood and 0.705-0.865

Table 1. The characteristics of the study sites.

Sites	Plot no.	Altitude (m)	Topo.*	Aspect (°)	Slope (°)	Age (yr)	SV** (%)	No. of trees per ha	No. of sample trees***	Sub-major species****
Mt. Joongwang	J-01	1,275	US	NE70	19	70	75.9	1,725	-	PD, APM
	J-02	1,300	US	NE10	25	70	90.7	1,375	7	-
	J-03	1,275	R	NE50	18	70	83.4	1,225	-	MA
	J-04	1,300	US	SE45	15	70	94.5	1,250	6	-
	J-05	1,275	R	SE58	22	70	71.8	1,300	-	UD, APM
	J-06	1,250	US	SE20	35	70	80.2	1,450	-	APM
	J-07	1,000	MS	NE8	23	60	89.7	1,600	7	-
	J-08	1,000	MS	NE42	25	60	98.4	1,250	-	KS
	J-09	950	MS	NE54	25	60	91.3	1,075	-	TA, APM
	J-10	1,000	MS	SE15	27	70	93.2	1,250	6	-
	J-11	1,000	MS	SE40	20	70	89.7	1,175	-	FR
	J-12	1,050	MS	SE20	25	70	91.4	1,100	-	FR
	J-13	770	R	NW30	5	60	82.4	1,275	6	FR
	J-14	780	V	NE35	30	60	75.6	1,575	-	APM, FR
	J-15	825	LS	NW25	27	60	72.3	1,750	-	MA, FR
	J-16	800	MS	SE60	25	60	88.5	1,200	5	PDS
	J-17	825	MS	SE80	23	60	87.4	1,275	-	PDS, MA
	J-18	890	R	SE85	25	60	86.8	1,325	-	FR
Mt. Taehwa	T-01	350	MS	SW50	15	35	80.5	1,875	8	QV, CC
	T-02	340	MS	SW45	15	35	78.7	1,775	-	QV, CC
	T-03	380	MS	SW70	20	35	79.4	1,950	-	QV, PS
Mt. Wolak	W-01	300	LS	NE65	10	35	80.8	2,425	10	QV, SO
	W-02	320	LS	NE60	15	35	84.4	2,050	-	QV, SO
	W-03	275	LS-V	NE80	10	35	82.5	2,475	-	QV, SO
Mt. Baekwoon	B-01	800	US	NW70	38	60	85.3	1,325	6	AP, SB
	B-02	780	US	NW75	38	60	86.5	1,375	-	AP, SO, SB
	B-03	770	MS	NW75	35	60	78.8	1,400	-	QS, CL, SB
	B-04	810	US	SW40	35	70	80.8	1,525	9	CL, RS
	B-05	790	US	SW40	35	70	87.5	1,575	-	RS, SB
	B-06	820	US	SW30	38	70	85.8	1,500	-	RS, SB
Mt. Halla	H-01	1,020	MS	NE20	10	60	77.4	2,450	-	QS, AP
	H-02	1,000	MS	NE10	10	60	89.5	2,033	5	QS, AH, SB
	H-03	980	MS	NW5	10	60	83.7	2,475	-	QS, AP, SB
	H-04	1,040	MS	SW10	10	60	88.3	2,850	-	UD, AP, SB
	H-05	1,010	MS	SW25	10	60	72.6	3,500	-	UD, SB
	H-06	1,000	MS	SE10	10	60	81.9	2,800	5	APM, SB

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

**SV : Synthetic Value of *Quercus mongolica*, $SV = (RD + RC)/2$

***Sample trees collected for the measurement of biomass and carbon storage

****Sub-major species : AH; *Abies holophylla*, AP; *Acer pseudosieboldianum*, APM; *Acer pictum* subsp. *mono*, CC; *Castanea crenata*, CL; *Carpinus laxiflora*, FR; *Fraxinus rhynchophylla*, KS; *Kalopanax septemlobus*, MA; *Maackia amurensis*, PD; *Populus davidiana*, PDS; *Pinus densiflora*, PS; *Prunus sargentii* var. *sargentii*, QS; *Quercus serrata*, QV; *Quercus variabilis*, RS; *Rhododendron schlippenbachii*, SB; *Sasa borealis*, SO; *Styrax obassia*, TA; *Tilia amurensis*, UD; *Ulmus davidiana*

kg dm⁻³ for heartwood in each sample trees. Sub-samples of each were oven-dried (more than 48 h, 80°C), and the resulting dry matter coefficients were used to calculate total dry matter. These dry matter values were scaled to a hectare basis. Other tree components like fine

roots, acorns, coarse woody debris or understory species were considered negligible and were not measured.

3. Carbon Content of Biomass

Biomass carbon content was analyzed twice in each

Table 2. Meteorological data in the study sites.

Sites	Latitude (°)	Altitude* (m)	Warmth Index (°C · month)	Precipitation (mm)	Solar radiation (MJ/m ²)
Mt. Joongwang**	37.48	1,050	63.62	1,890.0	3,394.48
Mt. Taehwa	38.18	100	88.00	1,806.5	3,389.83
Mt. Wolak	36.85	200	96.67	1,851.0	3,735.40
Mt. Baekwoon	35.10	450	87.67	1,887.2	4,586.10
Mt. Halla	33.35	5	134.55	2,100.6	5,826.50

*Location of the automatic weather station

**The meteorological data of Mt. Joongwang collected in 2003-2004, and other sites in 2002-2003.

Table 3. Soil characteristics of the *Quercus mongolica* stands in study sites.

Site	Soil moisture (%)	pH (1:5H ₂ O)	Al (mg/kg)	Organic matter (%)	Total N (%)	Av. P ₂ O ₅ (mg/kg)	Exchangeable cations (cmolc/kg)			CEC (cmolc/kg)	EC (dS/m)	Soil texture (USDA)
							K	Ca	Mg			
J-01	41.81	4.41	175	9.9	0.5	28.5	0.19	1.32	0.40	14.2	0.9	SCL
J-02	35.08	5.23	203	8.8	0.6	27.8	0.17	0.58	0.37	18.7	1.1	SCL
J-03	43.33	4.64	164	13.1	0.6	30.4	0.09	0.86	1.01	16.9	1.0	SCL
J-04	35.58	4.59	155	9.0	0.3	22.8	0.98	0.95	0.34	20.4	0.8	SCL
J-05	33.72	4.82	112	14.5	0.7	27.4	0.12	2.14	0.31	18.8	0.6	SCL
J-06	38.16	4.61	171	18.5	0.4	26.5	0.11	0.82	0.22	25.2	0.7	SL
J-07	37.32	4.58	165	7.6	0.2	25.8	0.08	0.45	0.20	12.6	0.5	SCL
J-08	43.80	4.45	141	11.9	0.6	26.3	0.20	3.84	1.21	24.8	1.6	SCL
J-09	43.12	4.25	255	13.1	0.5	31.4	0.26	1.00	0.57	22.2	1.5	SCL
J-10	29.30	5.00	196	10.6	0.2	28.8	0.17	1.25	0.48	21.9	1.1	SCL
J-11	29.99	4.57	155	8.4	0.3	26.7	0.18	1.34	0.45	14.8	0.9	CL
J-12	28.71	4.58	114	10.2	0.7	27.3	0.20	0.56	0.29	19.8	1.0	SCL
J-13	28.34	4.04	281	15.0	0.7	28.3	0.19	0.35	0.35	26.8	1.3	SCL
J-14	34.96	4.57	144	9.5	0.2	26.8	0.11	0.36	0.27	10.4	0.6	SCL
J-15	35.19	4.51	158	9.1	0.2	34.9	0.10	0.46	0.29	11.6	0.5	SCL
J-16	36.52	4.44	115	8.9	0.2	32.8	0.11	0.47	0.30	8.4	0.6	SL
J-17	36.30	5.12	108	7.9	0.2	33.6	0.14	0.50	0.21	9.8	0.5	L
J-18	26.99	4.77	86	8.4	0.1	41.7	0.11	0.77	0.25	6.7	0.5	SL
T-01	23.12	4.73	224	12.4	1.0	27.4	0.17	0.39	0.45	11.1	0.4	SL
T-02	12.85	4.79	58	4.9	0.1	34.7	0.10	0.97	0.31	7.0	0.3	SL
T-03	24.78	5.08	96	11.8	1.0	35.5	0.11	0.88	0.29	6.5	0.2	SL
W-01	26.03	5.68	19	2.6	0.3	17.4	0.11	2.14	0.34	4.0	0.1	SL
W-02	38.20	4.45	102	4.8	0.2	25.1	0.23	0.87	0.31	6.1	0.7	SCL
W-03	36.09	4.53	88	5.6	0.1	32.0	0.14	0.77	0.34	7.1	0.7	SCL
B-01	37.46	4.25	161	10.2	0.4	13.5	0.22	0.20	0.19	21.4	0.5	SCL
B-02	38.49	4.51	107	16.6	0.2	16.2	0.14	0.99	0.28	10.5	0.5	SCL
B-03	36.74	4.25	212	12.7	0.7	33.7	0.19	0.32	0.38	26.2	0.6	SCL
B-04	38.14	3.97	222	11.1	0.5	46.5	0.22	0.33	0.23	23.3	1.0	SCL
B-05	33.48	4.40	74	12.8	0.2	13.5	0.12	0.76	0.48	18.7	0.4	SCL
B-06	29.32	4.40	131	12.1	0.1	17.5	0.08	0.24	0.21	15.5	0.2	SL
H-01	46.56	4.16	173	22.1	1.1	27.0	0.29	1.21	0.94	31.5	2.1	SiC
H-02	48.37	4.10	193	23.7	1.3	42.8	0.39	0.54	1.07	31.5	2.2	C
H-03	48.77	4.28	167	24.9	1.3	33.7	0.42	2.10	1.08	39.7	2.7	C
H-04	53.70	4.80	128	24.6	1.2	25.1	0.41	0.08	0.69	29.2	1.0	C
H-05	53.31	4.38	168	20.6	1.0	20.4	0.26	0.16	0.70	26.0	1.9	SiCL
H-06	50.30	4.13	172	22.0	1.1	22.3	0.29	0.64	0.90	28.3	2.4	C

compartment (leaves, branches, stem bark, stem wood, and roots) of 80 tree samples. Representative sub-samples of all tree components were re-dried to a constant weight at 90°C and the carbon content was analyzed using the combustion furnace method (Chapman, 1976).

4. Prediction Equations

Allometric regression equations relating organic carbon storage (in grams) of each compartment with DBH (cm) and tree height (m) for each study area were performed. Annual carbon storage of aboveground and roots was estimated from the difference between the carbon storage of last year and current year within the sample sites. The resulting equations were used to estimate carbon storage at stand level in each area.

5. Statistical Analysis

The data of annual carbon storage in *Q. mongolica* stands were analyzed by the use of two-way analysis of variance (ANOVA) treating latitude and aspect as the main factors and sampling quadrat as three replications. The sampling areas that used this analysis were Mt. Joongwang (alt. 1,000 m and alt. 800 m), Mt. Baekwoon (alt. 800 m), and Mt. Halla (alt. 1,000 m) in the northern and southern aspect. These stands have similar mean age of upper layer and topographical factors but different latitude.

The two-way analysis of variance was also used in Mt. Joongwang (northern and southern aspect) having altitudes of 1,300 m, 1,000 m, and 800 m treating altitude and aspect as the factors and sampling quadrat as three replications.

The allometric regression equations and ANOVA were conducted using Statistical Analysis System version 9.1.3 (SAS Inc., 2005) Program.

Results and Discussion

1. Carbon Storage of *Quercus mongolica* Stands

Allometric relations deduced from the carbon storage of each aboveground component for the tree samples are summarized in Table 4. Determination coefficients between D²H and biomass compartments were high (more than 0.9 except for live branches and leaves in northern aspect of Mt. Baekwoon). The carbon storage of each component was significantly related to the respective DBH and height in most equations. Allometric relation for root was deduced as $\log C_R = 1.276 + 0.808 \log D^2H$ (adj. $R^2 = 0.97$), where CR is carbon storage (g) of root and D²H is the value of multiplying square of DBH (cm) by tree height (m).

The carbon storage of *Q. mongolica* stand, substituting D²H of trees existing within the quadrats for equations, was estimated. Table 5 shows the mean carbon storage for each above and below ground biomass compartment in a hectare basis. The total carbon storage ranged between 85.0 and 217.2 tonC/ha, the lowest being for the stand in Mt. Taehwa and the highest for the stand on northern aspect in Mt. Halla.

Among the tree components, the stemwood accounted for the maximum carbon storage that ranged from 49% (Mt. Taehwa) to 63% (Mt. Joongwang, alt. 800 m in southern aspect) of the total. It was followed by live branches, having 12% to 24% carbon storages in the southern aspect of Mt. Joongwang (alt. 800 m and alt. 1,300 m, respectively), roots (13% to 21% in the northern aspect of Mt. Baekwoon and Mt. Wolak, respectively), stembark (5% to 9% in the southern aspect of Mt. Joongwang (alt. 1,300 m) and Mt. Wolak, respectively), and foliage (1% to 5% in the southern aspect of Mt. Joongwang (alt. 1,000 m) and Mt. Wolak, respectively). These ratios approximated to that of the carbon storage of 39-year-old *Q. mongolica* stand in mid-part of Korea with 65% carbon storage for the woody ratio and 5% for the foliage ratio (Park, 1999), and that of 67-year-old with 58% and 2%, respectively (Song *et al.*, 1997). According to Rodin and Brazilevich (1967), in a temperate deciduous forest the woody biomass ratio usually is 60% to 85% and the foliage ratio is 1.5% to 3%. The sapwood ranged from 33% (Mt. Halla, alt. 1,000 m in southern aspect) to 55% (Mt. Joongwang, alt. 800 m in northern aspect) of the stemwood. The proportions of carbon storage of sapwood to total in Mt. Joongwang (alt. 800 m, northern aspect) and Mt. Wolak (alt. 300 m, northern aspect) were 32% and 27%, respectively. The values were greater than that of heartwood, whereas in other study areas, the carbon storage of heartwood was greater than sapwood. The proportion of stem increased with increasing mean DBH and age while that of foliage decreased (Tables 1 and 5).

The carbon storage of aboveground ranged from 67.9 to 185.3 tonC/ha. These values were greater than that of 39-year-old *Q. mongolica* stand with 48.9 tonC/ha, 67-year-old *Q. variabilis* stand with 57.5 tonC/ha (Park, 1999), 67-year-old *Q. mongolica* stand with 60.5 tonC/ha, and 62-year-old *Q. variabilis* stand with 62.2 tonC/ha (Song *et al.*, 1997). This was because the mean DBH and stand density of the study sites was greater than the others. Whittaker and Likens (1975) have estimated that the biomass for the temperate deciduous forest ranged from 60 to 600 tonC/ha, and biomass carbon storage estimated using a standard coefficient of 0.5 (IPCC, 1996b) ranged from 30 to 300 tonC/ha.

Table 4. Regression coefficients and R² when aboveground carbon storage of *Quercus mongolica* was regressed on D²H [$\log Y = A + B \log X$; Y, carbon storage (g); X, DBH (cm)² × height (m)]

Parameter (Y)	A	B	R ²	Prob. level	A	B	R ²	Prob. level
	Mt. Joongwang (1,300 m, N)				Mt. Taehwa (350 m, S)			
Stem wood	1.075	1.000	0.99	< 0.001	1.009	0.994	0.99	< 0.001
Sapwood	0.482	1.099	0.98	< 0.001	1.545	0.748	0.98	< 0.001
Heartwood	0.443	0.911	0.98	< 0.001	-1.077	1.513	0.96	< 0.001
Stem bark	-0.594	1.307	0.91	< 0.001	0.842	0.812	0.97	< 0.001
Live branches	-0.029	0.869	0.97	< 0.001	-0.936	1.419	0.99	< 0.001
Leaves	0.232	0.868	0.97	< 0.001	-0.764	1.193	0.90	< 0.001
	Mt. Joongwang (1,300 m, S)				Mt. Wolak (300 m, N)			
Stem wood	0.864	1.045	0.99	< 0.001	1.288	0.920	0.93	< 0.001
Sapwood	1.032	0.899	0.93	< 0.001	1.431	0.801	0.91	< 0.001
Heartwood	0.482	1.099	0.98	< 0.001	0.249	1.121	0.93	< 0.001
Stem bark	0.443	0.911	0.98	< 0.001	1.239	0.713	0.93	< 0.001
Live branches	-0.594	1.307	0.91	< 0.001	0.410	0.995	0.96	< 0.001
Leaves	-0.029	0.869	0.97	< 0.001	0.071	0.947	0.98	< 0.001
	Mt. Joongwang (1,000 m, N)				Mt. Baekwoon (800 m, N)			
Stem wood	1.150	0.975	0.99	< 0.001	0.583	1.133	0.99	< 0.001
Sapwood	1.059	0.917	0.98	< 0.001	0.785	1.005	0.99	< 0.001
Heartwood	0.596	1.043	0.99	< 0.001	-0.536	1.343	0.98	< 0.001
Stem bark	0.590	0.872	0.99	< 0.001	0.431	0.947	0.97	< 0.001
Live branches	-1.135	1.441	0.94	< 0.001	-0.025	1.178	0.87	0.004
Leaves	0.008	0.866	0.98	< 0.001	-0.030	0.889	0.86	0.004
	Mt. Joongwang (1,000 m, S)				Mt. Baekwoon (800 m, S)			
Stem wood	0.956	1.027	0.99	< 0.001	0.859	1.071	0.99	< 0.001
Sapwood	1.244	0.836	0.96	< 0.001	1.079	0.927	0.96	< 0.001
Heartwood	0.147	1.184	0.99	< 0.001	-0.341	1.318	0.99	< 0.001
Stem bark	0.227	0.997	0.99	< 0.001	0.612	0.909	0.97	< 0.001
Live branches	-0.074	1.144	0.97	< 0.001	0.069	1.150	0.97	< 0.001
Leaves	0.155	0.793	0.98	< 0.001	-0.109	0.930	0.94	< 0.001
	Mt. Joongwang (800 m, N)				Mt. Halla (1,000 m, N)			
Stem wood	1.236	0.947	0.99	< 0.001	0.680	1.117	0.98	< 0.001
Sapwood	0.997	0.941	0.99	< 0.001	0.984	0.938	0.91	0.007
Heartwood	0.874	0.948	0.94	< 0.001	-0.912	1.483	0.98	< 0.001
Stem bark	0.712	0.841	0.99	< 0.001	-0.056	1.081	0.97	0.001
Live branches	-1.084	1.444	0.96	< 0.001	-0.453	1.276	0.99	< 0.001
Leaves	-1.306	1.198	0.92	0.001	0.652	0.667	0.97	0.001
	Mt. Joongwang (800 m, S)				Mt. Halla (1,000 m, S)			
Stem wood	0.983	1.036	0.99	< 0.001	0.686	1.109	0.98	< 0.001
Sapwood	0.828	0.977	0.99	< 0.001	1.110	0.879	0.92	0.006
Heartwood	0.580	1.077	0.96	0.002	-0.926	1.501	0.98	< 0.001
Stem bark	0.778	0.850	0.98	< 0.001	-0.073	1.076	0.98	< 0.001
Live branches	-0.702	1.283	0.90	0.008	-0.456	1.274	0.98	< 0.001
Leaves	-0.235	0.898	0.98	< 0.001	0.624	0.698	0.93	0.005

1) Carbon storage along latitude gradient

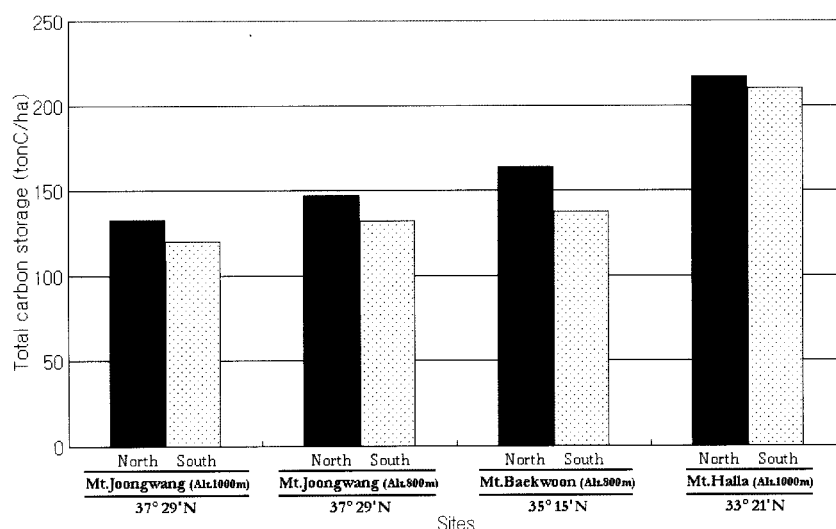
Figure 2 shows the trend of increasing total carbon storage with lower latitude (NE) stands of *Q. mongolica*. Total carbon storage for the stand in northern aspect of Mt. Joongwang (alt. 1,000 m), Mt. Joongwang (alt. 800 m), Mt. Baekwoon (alt. 800 m), and Mt. Halla (alt.

1,000 m) was 132.7 tonC/ha, 146.6 tonC/ha, 164.0 tonC/ha, and 217.2 tonC/ha, respectively, and showed an increasing trend with lower latitude. For the southern aspect, the total carbon storage of the stand in Mt. Joongwang (alt. 1,000 m), Mt. Joongwang (alt. 800 m), Mt. Baekwoon (alt. 800 m), and Mt. Halla (alt. 1,000m)

Table 5. The carbon storage (tonC/ha) of *Quercus mongolica* stands in the study sites.

Site		Stemwood	Bark	Live branch	Leaf	Aboveground total	Root	Total
Mt. Joongwang	Alt. 1,300 m, Northern aspect	68.1 (56.7)	7.2 (6.1)	23.0 (19.1)	1.7 (1.4)	100.2 (83.3)	20.0 (16.7)	120.2 (100.0)
	Alt. 1,300 m, Southern aspect	60.5 (53.2)	6.1 (5.4)	27.4 (24.1)	1.5 (1.3)	95.6 (84.0)	18.2 (16.0)	113.8 (100.0)
	Alt. 1,000 m, Northern aspect	76.2 (57.5)	9.5 (7.2)	21.7 (16.4)	2.3 (1.7)	109.8 (82.7)	22.9 (17.3)	132.7 (100.0)
	Alt. 1,000 m, Southern aspect	69.9 (58.2)	9.9 (8.2)	19.3 (16.1)	1.3 (1.1)	100.4 (83.6)	19.6 (16.4)	120.1 (100.0)
	Alt. 800 m, Northern aspect	84.0 (57.1)	10.7 (7.3)	25.8 (17.6)	1.6 (1.1)	122.1 (83.3)	24.4 (16.7)	146.6 (100.0)
	Alt. 800 m, Southern aspect	83.3 (63.1)	9.7 (7.4)	16.4 (12.4)	1.5 (1.1)	110.9 (84.0)	21.0 (16.0)	132.0 (100.0)
Mt. Taehwa	Alt. 350 m, Southern aspect	41.9 (49.3)	6.5 (7.6)	15.9 (18.7)	3.6 (4.3)	67.9 (79.9)	17.1 (20.1)	85.0 (100.0)
Mt. Wolak	Alt. 300 m, Northern aspect	59.2 (52.9)	9.7 (8.7)	14.9 (13.4)	4.5 (4.0)	88.4 (79.1)	23.3 (20.9)	111.7 (100.0)
Mt. Baekwoon	Alt. 800 m, Northern aspect	93.8 (57.2)	11.3 (6.9)	35.2 (21.5)	2.3 (1.4)	142.5 (86.9)	21.4 (13.1)	164.0 (100.0)
	Alt. 800 m, Southern aspect	79.2 (57.5)	10.3 (7.5)	26.5 (19.2)	2.4 (1.7)	118.4 (86.1)	19.1 (13.9)	137.6 (100.0)
Mt. Halla	Alt. 1,000 m, Northern aspect	129.4 (59.5)	16.2 (7.5)	37.5 (17.3)	2.2 (1.0)	185.3 (85.3)	31.9 (14.7)	217.2 (100.0)
	Alt. 1,000 m, Southern aspect	110.9 (52.6)	17.0 (8.1)	39.4 (18.7)	3.4 (1.6)	170.7 (81.1)	39.7 (18.9)	210.5 (100.0)

*The date in parenthesis indicate the percentage of each organ to the total.

**Figure 2. Carbon storage of *Q. mongolica* stands by latitude.**

was 120.1 tonC/ha, 132.0 tonC/ha, 137.6 tonC/ha, and 210.5 tonC/ha, respectively, and showed the same trend in the northern aspect.

The carbon storage of the *Q. mongolica* stand in northern aspect is higher than the southern aspect in all

study areas. Also, species diversity and biomass in the northern aspect is higher because of more soil moisture content and less vegetation transpiration (Minckler, 1961; Finney *et al.*, 1962; Choi and Yim, 1984; Park, 1987; Oh *et al.*, 1988; Shin and Lee, 1990; Kwak, 1991;

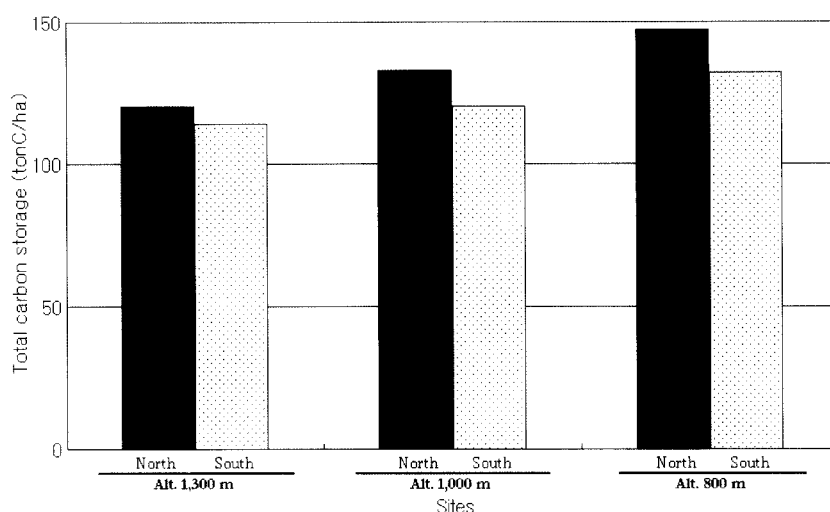


Figure 3. Carbon storage of *Q. mongolica* stands in Mt. Joongwang by altitude.

Kwon, 1998).

2) Carbon storage along altitude gradient

Figure 3 shows the trend of increasing total carbon storage with lower altitude stands in Mt. Joongwang. Total carbon storage for the stand in northern aspect of altitudes 1,300 m, 1,000 m, and 800 m above sea level in Mt. Joongwang was 120.2 tonC/ha, 132.7 tonC/ha, and 146.6 tonC/ha, respectively, and showed an increasing trend with lower altitude. For the southern aspect in Mt. Joongwang, the total carbon storage of the stand was 113.8 tonC/ha, 120.1 tonC/ha, and 132.0 tonC/ha, respectively, and showed the same trend in the northern aspect.

2. Annual Carbon Storage of *Quercus mongolica* Stands

Table 6 shows the mean annual carbon storage for each above and below ground biomass compartment in a hectare basis. The total annual carbon storage ranged from 7.1 to 10.5 tonC/ha/yr, the lowest for the stand in the northern aspect of Mt. Joongwang (alt. 1,300 m) and the highest for the stand in the southern aspect of Mt. Halla (alt. 1,000 m).

Among the tree components, stemwood accounted for the maximum annual carbon storage and ranged from 29% (Mt. Taehwa) to 50% (Mt. Joongwang, alt. 800 m in southern aspect) of the total, followed by foliage (16% in southern aspect of Mt. Joongwang (alt. 1,000 m) to 35% in Mt. Taehwa), roots (14% in southern aspect of Mt. Baekwoon to 21% in southern aspect of Mt. Halla), live branches (6% in Mt. Wolak to 20% in southern aspect of Mt. Joongwang (alt. 1,300 m)), and stembark (3% in Mt. Wolak to 6% in southern aspect of Mt. Joongwang, alt. 1,000 m). Allocation of the net production was much more made to both stem and leaves

and such trend was conspicuous as the stand aged (Kwak and Kim, 1992). Allocation of the annual carbon storage in this study is similar to Satoo's report (1970) that allocation of Japanese deciduous forests occurred 34-64% for stem, 10-24% for branches and 24-41% for foliage, but slightly differs to Rana *et al.*'s study (1989) that annual net production of *Quercus* forests in Central Himalayan allocated 23-34% for stem and 21-37% for foliage.

The annual carbon storage of aboveground ranged from 5.9 to 8.7 tonC/ha/yr. These values were greater than that of 39-year-old *Q. mongolica* stand with 5.9 tonC/ha/yr (Park, 1999) and 67-year-old with 4.8 tonC/ha/yr (Song *et al.*, 1997). Joo (1995) has estimated that the annual carbon storage of oaks was 4.62 tonC/ha/yr. In general, annual carbon storage of temperate deciduous forest was estimated to range of 3 to 15 tonC/ha/yr (Kira and Shidei, 1967) or 3 to 13 tonC/ha/yr (Whittaker and Likens, 1975) as 50% of their respective biomass. Kwak and Kim (1992) reported that annual productivity for the tree layer in the forest has heavy fluctuation year by year because of changing density and mortality. The reason for high annual carbon storage in the study areas was assumed that the sites are situated in the national park or national forest managed intensively without human disturbance.

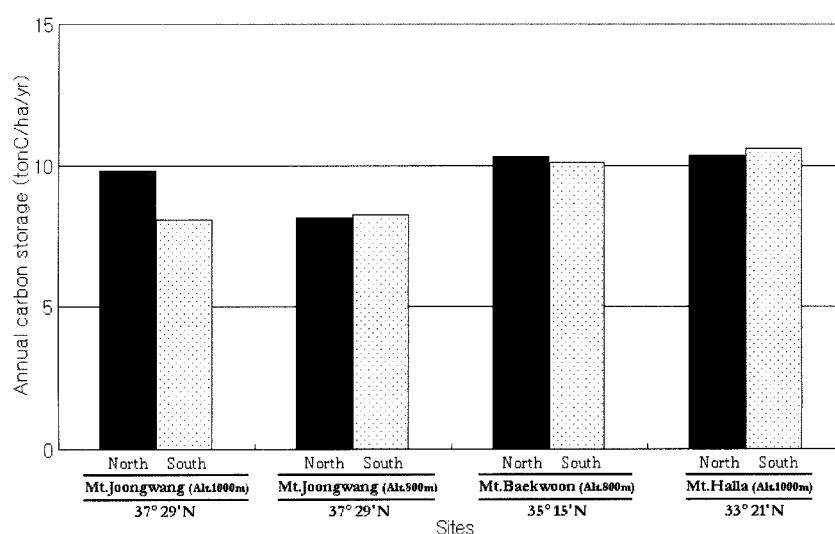
1) Annual carbon storage along latitude gradient

Figure 4 shows the trend of increasing annual carbon storage with lower latitude stands. Annual carbon storage for the stand in the northern aspect of Mt. Joongwang (alt. 1,000 m), Mt. Joongwang (alt. 800 m), Mt. Baekwoon (alt. 800 m), and Mt. Halla (alt. 1,000 m) was 9.8 tonC/ha/yr, 8.1 tonC/ha/yr, 10.3 tonC/ha/yr, and 10.3 tonC/ha/yr, respectively. For the southern aspect, annual

Table 6. Annual carbon storage (tonC/ha/yr) of *Quercus mongolica* stands in the study sites.

Site		Stemwood	Bark	Live branch	Leaf	Aboveground total	Root	Total
Mt. Joongwang	Alt. 1,300 m, Northern aspect	2.8 (40.3)	0.2 (4.1)	1.0 (15.1)	1.7 (23.6)	5.9 (83.1)	1.2 (16.9)	7.1 (100.0)
	Alt. 1,300 m, Southern aspect	3.2 (41.3)	0.3 (3.8)	1.5 (19.9)	1.5 (18.7)	6.5 (83.8)	1.3 (16.2)	7.8 (100.0)
	Alt. 1,000 m, Northern aspect	3.7 (38.1)	0.3 (3.6)	1.8 (19.1)	2.3 (23.1)	8.2 (84.0)	1.6 (16.0)	9.8 (100.0)
	Alt. 1,000 m, Southern aspect	3.8 (47.3)	0.5 (6.5)	1.1 (13.7)	1.3 (16.1)	6.7 (83.6)	1.3 (16.4)	8.0 (100.0)
	Alt. 800 m, Northern aspect	3.2 (40.3)	0.3 (4.5)	1.5 (19.3)	1.6 (19.1)	6.8 (83.1)	1.3 (16.9)	8.1 (100.0)
	Alt. 800 m, Southern aspect	4.1 (49.8)	0.4 (5.0)	0.9 (11.5)	1.5 (17.6)	6.9 (83.9)	1.3 (16.1)	8.2 (100.0)
	Alt. 350 m, Southern aspect	2.9 (28.8)	0.3 (3.4)	1.3 (12.8)	3.6 (35.1)	8.3 (80.1)	2.0 (19.9)	10.3 (100.0)
Mt. Wolak	Alt. 300 m, Northern aspect	6.5 (43.8)	0.4 (3.1)	0.8 (6.0)	4.5 (30.3)	12.3 (83.3)	2.5 (16.7)	14.8 (100.0)
Mt. Baekwoon	Alt. 800 m, Northern aspect	4.4 (42.6)	0.4 (4.4)	1.6 (16.0)	2.3 (22.0)	8.8 (85.1)	1.5 (14.9)	10.3 (100.0)
	Alt. 800 m, Southern aspect	4.3 (43.1)	0.5 (4.9)	1.4 (14.6)	2.4 (23.5)	8.7 (86.1)	1.4 (13.9)	10.1 (100.0)
Mt. Halla	Alt. 1,000 m, Northern aspect	4.6 (44.7)	0.5 (5.5)	1.4 (13.5)	2.2 (21.1)	8.7 (84.8)	1.6 (15.2)	10.3 (100.0)
	Alt. 1,000 m, Southern aspect	3.2 (30.8)	0.5 (5.0)	1.1 (11.2)	3.4 (32.2)	8.3 (79.1)	2.2 (20.9)	10.5 (100.0)

*The date in parenthesis indicate the percentage of each organ to the total.

**Figure 4. Annual carbon storage of *Q. mongolica* stands by latitude.**

carbon storage of the stand in Mt. Joongwang (alt. 1,000 m), Mt. Joongwang (alt. 800 m), Mt. Baekwoon (alt. 800 m), and Mt. Halla (alt. 1,000 m) was 8.0 tonC/ha/yr, 8.2 tonC/ha/yr, 10.1 tonC/ha/yr, and 10.5 tonC/ha/yr, respectively. It was assumed that the reason for higher

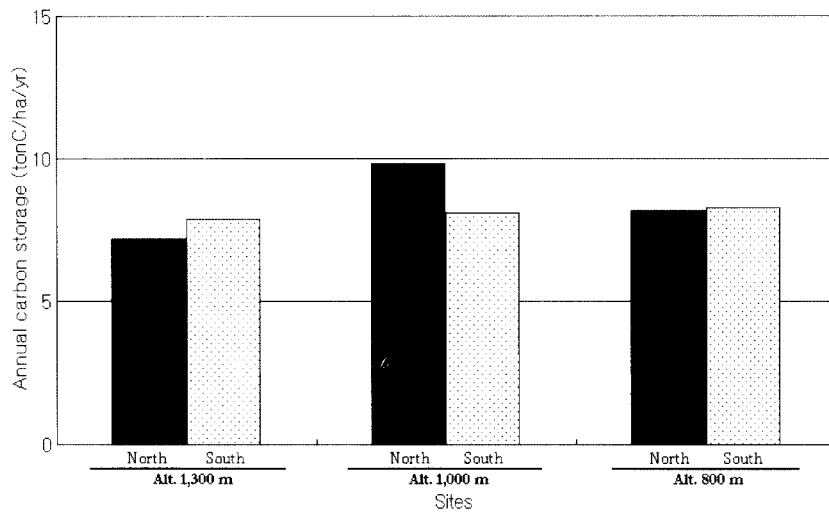
carbon storage in the northern aspect of Mt. Joongwang (alt. 1,000 m) was due to more moisture and bigger mean DBH in this site which are more favored by the growing oaks (Tables 1 and 3). This result is also similar to Lee *et al.*'s report (1994) that *Q. mongolica* at altitude

Table 7. ANOVA for annual carbon storage of *Q. mongolica* stands by latitude and aspect of the study sites.

Source	df	Mean Squares	Pr > F
Latitude	3	6.79	0.000
Aspect	1	0.95	0.206
Latitude*Aspect	3	1.25	0.118
Error	16	0.55	

Table 8. ANOVA for annual carbon storage of *Q. mongolica* stands by altitude and aspect in Mt. Joongwang.

Source	df	Mean Squares	Pr > F
Altitude	2	3.13	0.012
Aspect	1	0.46	0.343
Altitude*Aspect	2	2.40	0.026
Error	12	0.48	

**Figure 5.** Annual carbon storage of *Q. mongolica* stands in Mt. Joongwang by altitude.

1,100 m of Mt. Joongwang has shown the best growth.

Result of the ANOVA for annual carbon storage of *Q. mongolica* stands by latitude and aspect of the study sites is shown in Table 7. It shows that the main effect of latitude is significant at 0.001 level, but aspect is not significant. The interaction between latitude and aspect also is not significant. That is, the annual carbon storage of stands in the study sites differed along the latitude, but not in the aspect. The annual carbon storage along latitude does not show interaction with the aspect.

2) Annual carbon storage along altitude gradient

In Figure 5 and Table 6, annual carbon storage for the stand in northern aspect of altitudes 1,300 m, 1,000 m, and 800 m above sea level in Mt. Joongwang was 7.1 tonC/ha/yr, 9.8 tonC/ha/yr, and 8.1 tonC/ha/yr, respectively. For the southern aspect in Mt. Joongwang, the annual carbon storage of the stand was 7.8 tonC/ha/yr, 8.0 tonC/ha/yr, and 8.2 tonC/ha/yr, respectively. It was assumed that the reason for having low annual carbon storage in the northern aspect of Mt. Joongwang (alt. 1,300 m) was because of low temperature, and infertile site (Table 3).

The result of ANOVA for annual carbon storage of *Q. mongolica* stands by latitude and aspect of the study sites is summarized in Table 8. It shows that the main effect of altitude is significant ($p < 0.05$), but for the

aspect is not significant. However, the interaction between altitude and aspect is significant ($p < 0.05$). That is, the annual carbon storage of stands in the study sites differed along the altitude but not in aspect. The annual carbon storage along the altitude shows interaction with aspect in this study.

Conclusion

The use of individual carbon storage models complemented by surveys with respect to latitude, altitude and aspect is a suitable methodology for assessing carbon storage at stand level. Once local equations have been adjusted, and DBH and height of all individual trees in the stand are measured, the stand carbon storage estimation is easy to determine. Nevertheless, validation of the developed equations is necessary to apply these estimates to broader site conditions.

The carbon storage of *Q. mongolica* stands along stand conditions and environmental factors demonstrated distinct patterns. With low latitude and altitude, the biomass carbon pools and annual carbon storage in the stand increased. carbon storage of *Q. mongolica* stands was higher in the northern aspect than southern aspect. However there were no significant differences in annual carbon storage between the aspects.

The total biomass carbon storage of *Q. mongolica*

stand in this study areas ranged from 85.0 to 217.2 tonC/ha, the lowest being for the 35-year-old stand in Mt. Taehwa and the highest for the 60-year-old stand in northern aspect of Mt. Halla. The annual carbon storage of the stand ranged from 7.1 to 10.5 tonC/ha/yr, the lowest for the 70-year-old stand in northern aspect of Mt. Joongwang (alt. 1,300 m) and the highest for the 60-year-old stand in southern aspect of Mt. Halla (alt. 1,000 m). Among the tree components, stemwood accounted for the maximum annual carbon storage and ranged from 29 to 50% of the total, followed by foliage (16-35%), roots (14-21%), live branches (6-20%), and stem bark (3-6%).

Carbon storage and its allocation to each compartment were reflected not only by the differential climate such as temperature and precipitation, but also by stand age, structure, and topographical characteristics. The proportion of the stem in the *Q. mongolica* stand increased with increasing age and altitude, while that of foliage decreased. Since pruning and thinning can influence both carbon storage and allocation at tree and stand levels, further research should be carried out to understand the impacts of forest management on the total biomass carbon storage and annual carbon storage. Also, it would be necessary to improve the forest management design for increasing carbon uptake, including other related vegetation types and environmental variables, with some kind of forest potential.

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