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Allometry, Biomass and Productivity of *Quercus* Forests in Korea: A Literature-based Review

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Abstract : Publications with the data on allometric equation, biomass and productivity of major oak forests in Korea were reviewed. Different allometric equations of major oak species showed site- or species-specific dependences. The biomass of major oak forests varied with age, dominant species, and location. Aboveground tree biomass over the different oak species was expressed as a power equation of the stand age. The proportion of tree component (stem, branch and leaf) to total aboveground biomass differed among oak species, however, biomass ranked stem > branch > leaf in general. The leaf biomass allocation over the different oak species was expressed as a power equation of total aboveground biomass while there were no significant patterns of biomass allocation from stem and branch to the aboveground biomass. Tree root biomass continuously increased with the aboveground biomass for the major oak forests. The relationship between the root to shoot ratio and the aboveground tree biomass was expressed by a logarithmic equation for major oak forests in Korea. Thirteen sets of data were used for estimating the net primary production (NPP) and net ecosystem production (NEP) of oak forests. The mean NPP and NEP across different oak forests was 10.2 and 1.9 Mg C $ha^{-1}year^{-1}$. The results in biomass allocation, NPP and NEP generally make Korean oak forests an important carbon sinks.

Key words **:** *allometric equation, living biomass increment, net ecosystem production, net primary production, root to shoot ratio*

1. Introduction

Oak species as a most dominant species are widely found in natural deciduous and mixed forests throughout Korea (Son *et al*., 2004a, 2007; Park *et al*., 2005b; Kwon and Lee, 2006a; Noh *et al*., 2007). The oaks play an important role in ecological, social and economic aspects in terms of increase in biodiversity, cultural significance and wood production across this country. The most common six species are *Quercus mongolica* Fisch., *Q. variabilis* Bl., *Q. acutissima* Carruth., *Q. dentata* Thunb., *Q. serrata* Thunb., and *Q. aliena* Bl., whereas the five evergreen oak species (*Q. acuta* Thunb., *Q. gilva* Bl., *Q. glauca* Thunb., *Q. myrsinaefolia* Bl., and *Q. salicina* Bl.) are found along the southern coasts and islands (Son *et al*., 2004a; 2004b; Noh *et al*., 2007).

Over the past several decades, the data on biomass and productivity of deciduous oak forests using the allometric method have been published with the large accumulation of field survey data, particularly focusing on the species of *Quercus mongolica* and *Q. variabilis* (Song *et al*., 1997; Park *et al*., 2003, 2005b; Son *et al*., 2004b). Some studies also examined the carbon fluxes in the oak forest ecosystems, which includes litter production and carbon emissions from soil respiration (Son *et al*., 2007). In *Quercus* forests, the bulk of NPP stands for the annual litter production and the rates of growth increment in stem, branch, leaf and root. NEP is usually used to judge carbon fixation from NPP and the rate of soil respiration.

This review discussed the present status of studies on allometric equations, biomass allocation, and productivity of major oak forests in Korea. This review also showed some examples of oak forests for estimating the NPP and NEP.

Allometric Equation

According to the basic theory of allometric relationships,

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Table 1. Allometric models and parameters for *Quercus mongolica* (Qm), *Q. variabilis* (Qv), *Q. serrata* (Qs), *Q. acutissima* (Qa) and *Q. dentata* (Qd) based on DBH or DBH^2H (DBH: diameter at breast height, H: height, Ws: stem dry weight in kg or g, Wa: aboveground tree dry weight in kg or g, Wr: tree roots dry weight in kg or g).

Species	Location	Equation	Tree samples	a	b	c	R^2	Reference
Qm	Chuncheon	LogWa = a+bLog(DBH)	10	2.076	2.579		0.969	Park *et al.* 2003; Son *et al.* 2007
	Kwangyang	$Wa = a(DBH)^b$	9	1.909	2.410		0.98	Park 2003
	Pyungchang		9	1.745	2.587		0.99	
	Youngdong		9	1.865	2.486		0.98	
	Chungju	$Wa = a(DBH)^bH^c$	10	1.002	3.866	-2.746	0.98	Song and Lee 1996
	Suncheong	LogWa = a+bLog(DBH)	10	1.982	2.546		0.97	Park and Moon 1994
	Kwangju	LogWa = a+bLog(DBH)	10	2.144	2.366		0.994	Park *et al.* 1996
	Pyungchang	LogWa = a+bLog(DBH^2H)	7	1.391	0.976		0.99	Lee and Kwon 2006
			6	1.197	1.028		0.99	
	Jecheon		10	1.531	0.920		0.93	
	Pyungchang	LogWs = a+bLog(DBH^2H)	7	5.600	1.002		0.99	Kwon and Lee 2006a
			6	5.397	1.045		0.98	
			7	5.691	0.974		0.99	
			6	5.464	1.034		0.99	
			6	5.765	0.949		0.99	
			5	5.522	1.035		0.99	
	Gwangyang	LogWs = a+bLog(DBH^2H)	6	0.823	1.134		0.99	Kwon and Lee 2006b
			9	1.101	1.071		0.98	
	Jeju		5	0.923	1.117		0.98	
			5	0.928	1.109		0.98	
	Pyeongchang Gwangju Jecheon Kwangyang Jeju	LogWa = a+bLog(DBH^2H)	18	1.243	1.013		0.97	Kwon and Lee 2006c
	Gwangyang	LogWa = a+bLog(DBH)	10	2.102	2.360		0.979	Park *et al.* 2005a
	Seoul	LogWa = a+bLog(DBH)	10	2.339	2.381		0.996	Park *et al.* 2005b
	Chungju	LogWa = a+bLog(DBH)	10	1.632	2.505		0.980	Park 1999
	Gwangju	LogWs = a+bLog(DBH^2H)	10	-1.285	0.901		0.978	Lee and Park 1987
	Chungju	$Wa = a(DBH)^bH^c$	10	1.002	4.320	-3.624	0.985	Song *et al* 1997
	Pyoengchang	LogWs = a+bLog(DBH^2H)		-2.029	1.096			Kwak and Kim 1992
	Gwangju	LogWa = a+bLog(DBH)	10	2.340	2.390		0.955	Son *et al.* 2004b
Qv	Chuncheon	LogWa = a+bLog(DBH)	10	2.030	2.560		0.976	Park *et al.* 2003; Son *et al.* 2007
	Gongju	$Wa = a(DBH)^b$	10	1.702	2.678		0.990	Park and Lee 2001
	Pohang		10	1.571	2.759		0.990	
	Yangyang		10	1.329	2.823		0.980	
	Sancheong	LogWs = a+bLog(DBH)	12	1.606	0.868		0.952	Kim and Jeong 1985
	Jinju		12	1.000	1.124		0.985	
	Chungju	$Wa = a(DBH)^bH^c$	10	1.000	2.925	-1.638	0.980	Song and Lee 1996
	Suncheong	LogWa = a+bLog(DBH)	10	1.916	2.377		0.968	Choi and Park 1993
	Suncheong	LogWa = a+bLog(DBH)	10	2.063	2.445		0.990	Park and Moon 1994
	Kwangju	LogWa = a+bLog(DBH)	10	1.944	2.470		0.991	Park *et al.* 1996
	Gwangyang	LogWa = a+bLog(DBH)	10	1.905	2.545		0.962	Park *et al.* 2005a
	Gwangju	LogWa = a+bLog(DBH)	10	2.234	2.518		0.988	Son *et al.* 2004b
	Chungju	LogWa = a+bLog(DBH)	10	1.443	2.645		0.990	Park 1999
	Chungju	$Wa = a(DBH)^bH^c$	10	1.000	3.244	-2.340	0.985	Song *et al.* 1997
Qs	Kwangyang	$Wa = a(DBH)^b$	9	1.904	2.519		0.99	Park and Lee 2002
	Muju		9	2.300	2.257		0.99	
	Pohang		9	1.869	2.602		0.99	
	Suncheong	LogWa = a+bLog(DBH)	10	2.116	2.446		0.99	Park and Moon 1994
Qa	Suncheong	LogWa = a+bLog(DBH)	10	2.094	2.417		0.99	Park and Moon 1994
	Kwangju	LogWa = a+bLog(DBH)	10	1.799	2.693		0.994	Park *et al.* 1996
	Chungju	LogWa = a+bLog(DBH)	15	-1.009	1.772		0.986	Noh *et al.* 2007
		LogWr = a+bLog(DBH)	7	-0.634	1.772		0.962	
Qd	Gwangju	LogWa = a+bLog(DBH)	10	1.883	2.560		0.99	Park *et al.* 1996

the growth rate of one part of a tree is proportional to that of another. Therefore, the diameter at breast height (DBH) of a tree, for example, is highly correlated with tree stem weight. A regression equation can be deduced for predicting tree weight when a range of tree dimensions is measured. Allometric relationships for major oak species have been developed for several decades to estimate biomass and subsequent growth in Korea (Table 1). Most studies used the destructive harvest method to develop allometric equations. The commonly used equations for estimating the biomass of different oak species are the following forms:

$$W = a(DBH)^b \text{ or } LogW = a + bLog(DBH) \quad (1)$$

$$W = a(DBH^2H)^b \text{ or } LogW = a + bLog(DBH^2H) \quad (2)$$

$$W = a(DBH)^bH^c \text{ or } LogW = a + bLog(DBH) + cLogH \quad (3)$$

where W, X, and H are component biomass (kg or g), trunk diameter (cm), and tree height (m), respectively, and a and b are constants for a site or specific species. Since biomass is strongly related to the DBH and H, the allometric equation is useful for estimating the whole or partial weight of a tree from DBH or DBH and height together (Kim and Jeong, 1985; Park *et al*., 1996; Kwon and Lee, 2006a). Constants in each equation form often showed site- or species-specific dependences, and coefficient of determination (R^2) showed relatively high value (over 0.93) for each oak species (Table 1). Comparisons of different equation forms were reported in the literature (Choi and Park, 1993; Park and Moon, 1994; Song and Lee, 1996; Song *et al*. 1997). While some studies reported that the equation form of $W = a(DBH)^bH^c$ was more adequate than the other forms for *Q. mongolica* and *Q. variabilis* (Song and Lee, 1996; Song *et al*. 1997), other studies suggested that there was little difference in accuracy among the three equation forms for oak species (Choi and Park, 1993; Park and Moon, 1994).

These contradictory results in literature may be due to the measuring error of tree sizes and differences in various biotic and abiotic factors among locations. For example, Son *et al*. (2007) compared the three equation forms for *Q. mongolica*, and suggested that there is priority for using the equation form of $W = a(DBH)^b$ when the measuring error of tree stem height and tree crown height, and estimate of stem productivity based on radial growth were taken into account. In addition, Park and Moon (1994) proposed the use of a common allometric equation for *Quercus* species to overcome the disadvantage of both the species- and site-specific allometric relationship.

Biomass Allocation

The data from literature on biomass of major oak species are listed in Table 2. Most studies dealt with both aboveground and belowground tree biomass, and only 15 focused on ground vegetation (shrub plus herb) biomass. Aboveground tree biomass over the different oak species was expressed as a power equation of the stand age (Figure 1). Aboveground tree biomass (Mg/ha) for *Q. mongolica* ranged from 62.4 in a 42-year-old stand of Kwangyang area to 438.0 in a 50-year-old stand of Chuncheon area. Aboveground tree biomass (Mg/ha) for *Q. variabilis* ranged from 38.5 in a 19-year-old stand of Sancheong area to 279.9 in a 49-year-old stand of Chuncheon area. Aboveground tree biomass (Mg/ha) for *Q. serrata* ranged from 42.0 in a 25-year-old stand of Muju area to 97.2 in a 29-year-old stand of Suncheong area. Aboveground tree biomass (Mg/ha) for *Q. acutissima* ranged from 66.0 in an 11-year-old stand to 237.1 in a 44-year-old stand of Chungju area (Table 2). Total biomass seemed to be significantly different among oak species. Park *et al*. (2005a) investigated the total biomass of three stands in *Q. mongolica* and *Q. variabilis* forests with similar ages. Although the three stands were regenerated in a similar environment, the measured values of total biomass varied from approximately 108.4 Mg/ha in a *Q. variabilis* forest stand to 132.0 Mg/ha in a *Q. mongolica* forest stand. Son *et al*. (2004b) reported that the total biomass stored in a *Q. variabilis* mixed with *Q. mongolica* forests stand was 253.3 Mg/ha, which was almost twice greater than 138.8 Mg/ha stored in a *Q. variabilis* forest stand with same ages. In this study, 15 data sets of ground vegetation biomass were only found in *Q. variabilis* and *Q. mongolica* forests, ranging from 0.4 for a 46-year-old *Q. mongolica* forest stand to 25.1 Mg/ha for a *Q. variabilis* forest stand. Mean ground vegetation biomass (5.3 Mg/ha) in *Q. mongolica* forest seemed to be slightly lower than 8.8 Mg/ha in *Q. variabilis* forest.

The pattern of biomass allocation to the aboveground components (stem, branch and leaf) of *Quercus* stands is presented in Figure 2. The leaf biomass allocation over the different oak species was expressed as a power equation of total aboveground biomass (R^2=0.47, $p<0.0001$), while there were no significant patterns of biomass allocation from stem and branch to the aboveground biomass. Stem contained approximately more than 50% of aboveground tree biomass. The proportion of each tree component to total aboveground biomass differed among oak species, however, biomass ranked stem > branch > leaf in general. The mean proportion of stem, branch and leaf to total aboveground biomass over major oak species was 76.1, 20.6 and 3.0%, respectively, which was very close to the results reported by Son *et al*. (2004a).

Direct field measurements of the root biomass are difficult and time consuming. In practice, the root biomass is usually estimated from the aboveground tree biomass

Table 2. Biomass (Mg/ha) of *Quercus mongolica* (Qm), *Q. variabilis* (Qv), *Q. serrata* (Qs), *Q. acutissima* (Qa) and *Q. dentata* (Qd) forests by component in Korea.

Species	Location	Mean stand age (years)	Mean DBH (cm)	Stand density (*n*/ha)	Mean height (m)	Stem	Branch	Foliage	Above-ground tree	Tree roots	Whole tree	Ground vegetation	Total	Reference
Qm	Chuncheon	50	26.9	650	20.4	345.0	88.1	4.8	438.0	57.1	495.1	5.2	500.3	Park *et al*. 2003; Son *et al*. 2007
	Kwangyang	42	33.2	450	10.7	43.1	17.2	2.1	62.4					Park 2003
	Pyungchang	52	37.2	660	12.5	117.6	28.4	3.4	156.0					
	Youngdong	36	33.1	672	9.8	64.7	41.5	4.1	110.3					
	Chungju	67	24.0	875	12.1	91.0	33.1	5.1	130.6			15.8	146.3	Song and Lee 1996
	Suncheong	36	12.9	1040	9.7	70.4	23.1	4.3	97.8	21.0	118.8			Park and Moon 1994
	Kwangju	34	15.0	705	11.6	40.7	28.8	2.7	72.1					Park *et al*. 1996
	Pyungchang	54	18.7	1308	14.4	153.8	54.3	4.1	212.2	40.7	252.9			Lee and Kwon 2006
		66	18.2	1175	14.8	141.0	34.0	2.4	177.4	34.9	212.3			
	Jecheon	34	10.2	2316	11.1	122.8	26.4	8.1	157.3	41.9	198.7			
	Pyungchang	63	19.5	1375	12.9	132.6	40.4	3.1	176.0	35.6	211.6			Kwon and Lee 2006a
		47	18.1	1250	11.4	117.2	48.2	2.6	168.0	32.3	200.3			
		54	18.3	1600	14.5	153.8	54.3	4.1	212.2	40.7	252.9			
		66	18.2	1250	14.8	141.0	34.0	2.3	177.4	34.9	212.3			
		49	17.5	1275	15.2	149.0	61.4	2.8	213.3	43.4	256.7			
		38	14.9	1200	13.4	163.5	28.8	2.7	195.0	37.4	232.4			
	Gwangyang	53	17.7	1367	12.1	184.6	61.7	4.1	250.4	38.0	288.4			Kwon and Lee 2006b
		56	12.4	1533	8.4	157.1	46.4	4.3	207.9	34.0	241.9			
	Jeju	51	15.6	2319	11.5	242.0	65.7	4.1	311.8	56.6	368.4			
		36	13.5	3050	9.9	232.9	62.1	5.8	300.9	63.5	364.3			
	Pyeongchang	59	17.2	1375	12.7				208.3	40.4	248.7			Kwon and Lee 2006c
		43	20.4	1250	12.5				194.1	35.9	230.0			
		39	15.3	1600	12.3				216.0	42.3	258.3			
		35	18.9	1250	13.8				200.2	40.0	240.2			
		27	13.1	1750	10.0				222.2	39.2	261.4			
		21	17.9	1200	12.9				191.0	35.8	226.8			
	Gwangju	31	11.9	1875	10.1				110.5	29.1	139.6			
	Jecheon	34	10.7	2425	10.7				151.6	39.9	191.5			
	Kwangyang	35	22.0	1325	14.8				255.7	38.9	294.6			
		43	21.0	1525	13.7				209.1	34.4	243.5			
	Jeju	36	15.3	2033	9.7				326.7	54.4	381.1			
		30	13.8	2800	10.0				236.9	56.9	293.7			
	Gwangyang	36	9.0	3175	12.7	73.5	7.1	2.5	83.1	27.2	110.3	5.3	115.6	Park *et al*. 2005a
	Seoul	46	16.2	775	14.0	188.6	52.4	3.3	244.3	34.3	278.6	0.4	279.0	Park *et al*. 2005b
		46	14.7	900	15.3	101.6	23.1	2.4	127.1	24.8	151.9	0.6	152.5	Son *et al*. 2007
		52	13.4	1050	14.3	97.5	21.8	2.5	121.8	24.8	146.6	1.7	148.3	
	Chungju	39	30.0	907	14.1	72.2	19.1	4.9	97.7					Park 1999
	Gwangju	22	12.4	1600	10.2	78.3	28.9	5.4	112.6	35.4	148.0	8.0	156.0	Lee and Park 1987
	Chungju	67	24.0	875	12.1	87.6	28.7	4.8	121.0					Song *et al*. 1997

Table 2. Continued.

Species	Location	Mean stand age (years)	Mean DBH (cm)	Stand density (*n*/ha)	Mean height (m)	Stem	Branch	Foliage	Above-ground tree	Tree roots	Whole tree	Ground vegetation	Total	Reference
Qv	Chuncheon	49	21.4	825	18.1	227.7	49.4	2.8	279.9	37.5	317.5	3.7	321.2	Park *et al*. 2003; Son *et al*. 2007
	Gongju	41	26.8	1137	14.4	76.6	12.6	2.1	91.3					Park and Lee 2001
	Pohang	45	36.9	778	15.3	172.9	32.2	2.5	207.6					
	Yangyang	54	30.0	873	12.5	58.8	10.5	2.1	71.4					
	Sancheong	19	5.1	6600	7.0	29.4	6.6	2.5	38.5					Kim and Jeong 1985
	Jinju	20	9.2	4300	8.1	45.0	6.2	2.8	53.9					
	Chungju	62	24.0	883	11.8	100.7	27.2	3.8	137.4			25.1	162.5	Song and Lee 1996
	Suncheong	20	11.3	983	9.2	22.0	7.3	2.0	31.3					Choi and Park 1993
	Suncheong	28	14.6	1280	11.1	95.3	31.3	8.3	134.9	24.0	158.9			Park and moon 1994
	Kwangju	32	14.9	1129	14.4	72.3	12.5	2.2	87.0					Park *et al*. 1996
	Gwangju	33	11.8	980	13.0	50.0	8.4	3.2	61.6					Lee and Kim 1997
	Gwangyang	37	9.2	2450	10.3	61.5	7.6	1.7	70.8	18.7	89.5	18.9	108.4	Park *et al*. 2005a
		38	10.2	2900	14.3	87.6	10.7	2.4	100.7	26.4	127.1	4.3	132.0	
	Gwangju	34	16.6	525	17.7	98.3	18.7	2.5	119.5	13.4	132.9	5.9	138.8	Son *et al*. 2004b
		31	12.1	1425	18.7	154.3	32.9	4.1	191.2	22.6	213.8	2.4	216.2	
		33	13.7	1475	18.3	184.9	34.5	4.7	224.1	27.0	251.2	2.2	253.3	
	Chuncheon	44	18.3	1050	18.9	217.0	44.4	2.6	264.1	36.7	300.8	7.9	308.7	Son *et al*. 2007
	Chungju	40	30.0	835	13.5	89.8	19.2	3.4	115.0					Park 1999
	Chungju	62	24.0	883	11.8	96.9	23.7	3.8	124.4					Song *et al*. 1997
Qs	Kwangyang	34	33.3	413	14.1	40.7	13.7	1.6	56.1					Park and Lee 2002
	Muju	25	29.3	339	12.8	31.2	9.3	1.5	42.0					
	Pohang	37	29.5	469	13.6	63.1	23.8	1.4	88.3					
	Suncheong	29	12.6	1120	10.8	68.8	23.9	4.5	97.2	18.1	115.3			Park and Moon 1994
Qa	Suncheong	26	14.3	1410	11.5	99.8	31.6	8.7	140.1	23.9	164.0			Park and Moon 1994
	Kwangju	38	21.3	437	15.3	94.8	26.1	1.9	122.7					Park *et al*. 1996
	Chungju	11	7.9	2100		49.6	12.1	4.3	66.0	22.7	88.7			Noh *et al*. 2007
		38	17.1	800		85.3	32.2	6.3	123.8	31.1	154.9			
		44	20.7	733		170.5	58.0	8.6	237.1	41.0	278.1			
Qd	Kwangju	38	11.7	789	9.7	22.2	14.5	1.9	38.6					Park *et al*. 1996

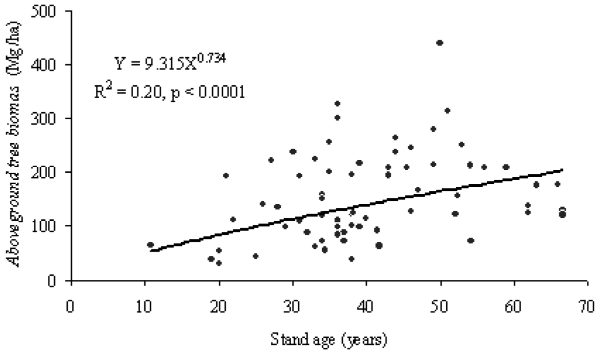

Figure 1. Relationship between aboveground tree biomass and stand age for major oak forests in Korea.

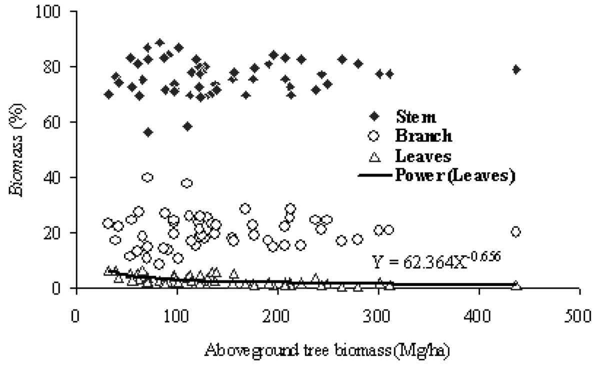

Figure 2. Aboveground tree biomass allocation to each component of major oak species in Korea.

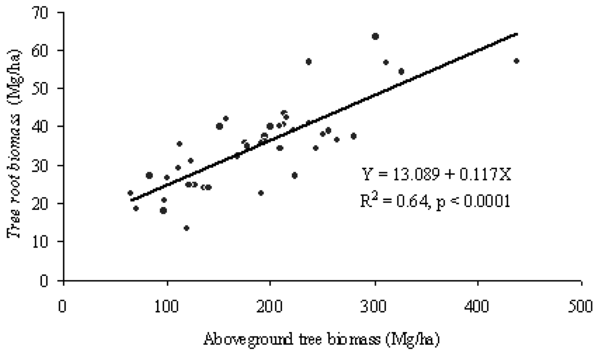

Figure 3. Relationship between tree root biomass and aboveground tree biomass for major oak forests in Korea.

based on the root to shoot ratio (shoot including stem, branch and leaf) or an allometric relationship between the aboveground tree biomass and root biomass (Cairns *et al.*, 1997; Fang *et al.*, 2005). In this study, the root biomass continuously increased with the aboveground biomass for the major oak forests (Figure 3). The relationship between the root to shoot ratio and the aboveground tree biomass was expressed by a logarithmic equation for major oak forests in Korea (Figure 4).

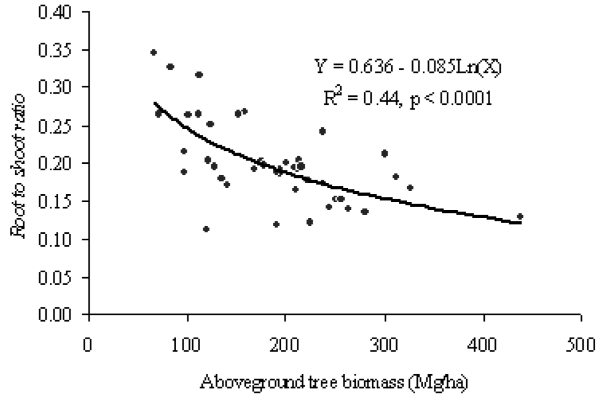

Figure 4. Relationship between root to shoot ratio and aboveground tree biomass for major oak forests in Korea.

NPP and NEP are fundamental property of ecosystems. Woodwell and Whittaker (1968) firstly defined NEP as the difference between the amount of organic carbon photosynthesized by green plant in an ecosystem (gross primary production, or GPP) and total ecosystem respiration (autotrophic respiration plus heterotrophic respiration). According to Luyssaert *et al.* (2007), NPP consists of two different ecosystem components: living biomass increment (LB, including increments in tree and ground vegetation) and litter production (LP). NPP also includes a number of additional components that are difficult to measure and often ignored, such as volatile organic compounds (VOC), methane (CH_4) and exudates exuded from roots or transferred to mycorrhizae, whereas biomass removal by harvest, insects and mammals should be taken into account. In this paper, NPP of oak forests denotes the sum of LB and LP because of rare measurement for additional components. NEP is equal to the result of NPP minus heterotrophic respiration (R_h).

LB of major oak forests was estimated by the allometric equations (Table 3). Aboveground tree biomass increment (Mg ha^{-1}year^{-1}) were different among oak species, ranging from 3.5 for a 38-year-old *Q. dentata* stand to 22.5 for a 26-year-old *Q. acutissima* stand. Aboveground tree biomass increment seemed to change with stand age. Living biomass increment of aboveground tree increased with aboveground tree biomass over oak species, and the relationship was expressed as a power equation (Figure 5). Our findings were very close to the results reported by Son *et al.* (2004a). 13 studies estimated biomass increment in ground vegetation, and ranged from 0.1 for two 46-year-old *Q. mongolica* stands to 4.8 Mg ha^{-1}year^{-1} for a 37-year-old *Q. acutissima* stand. Therefore, ground vegetation may considerably contribute to the carbon pool of oak forests.

Thirteen sets of data were used for estimating NPP and NEP of oak forests (Table 4). NPP ranged from a low of 5.95 Mg C ha^{-1}year^{-1} in a 46-year-old *Q. mongolica* stand to a relatively high value of 18.19 Mg C ha^{-1}year^{-1} in

Table 3. Living biomass increment (Mg ha^{-1}year^{-1}) of *Quercus mongolica* (Qm), *Q. variabilis* (Qv), *Q. serrata* (Qs), *Q. acutissima* (Qa) and *Q. dentata* (Qd) forests by component in Korea.

Species	Location	Mean stand age (years)	Stem	Branch	Foliage	Above-ground tree	Tree roots	Whole tree	Ground vegeta-tion	Total	Reference
Qm	Chuncheon	50	8.9	4.1	4.8	17.8	1.7	19.5	2.4	21.9	Park *et al.* 2003; Son *et al.* 2007
	Kwangyang	42	1.4	2.4	2.1	5.8					Park 2003
	Pyungchang	52	3.5	3.4	3.4	10.3					
	Youngdong	36	3.7	3.5	4.1	11.4					
	Chungju	67	2.3	2.6	5.1	10.0					Song and Lee 1996
	Suncheong	36	5.3	1.5	4.3	11.1	1.5	12.6			Park and Moon 1994
	Kwangju	34	2.7	2.2	2.7	7.5					Park *et al.* 1996
	Pyungchang	54	7.2	3.3	4.1	14.5	2.8	17.3			Lee and Kwon 2006
		66	7.6	2.0	2.4	11.9	2.3	14.2			
	Jecheon	34	7.0	1.6	8.1	16.8	4.4	21.2			
	Pyungchang	63	5.6	1.9	3.1	10.5	2.2	12.7			Kwon and Lee 2006a
		47	6.3	2.8	2.6	11.7	2.3	14.0			
		54	7.2	3.3	4.1	14.5	2.8	17.3			
		66	7.6	1.9	2.3	11.9	2.3	14.2			
		49	6.4	2.8	2.8	12.0	2.4	14.5			
		38	8.0	1.7	2.7	12.3	2.3	14.6			
	Gwangyang	53	10.3	3.6	4.1	18.0	2.7	20.8			Kwon and Lee 2006b
		56	8.3	2.6	4.3	15.2	2.5	17.7			
	Jeju	51	9.4	2.6	4.1	16.1	2.9	19.1			
		36	9.3	2.5	5.8	17.5	3.7	21.3			
	Gwangyang	36	4.6	1.7	2.5	8.8	2.1	10.9	1.6	12.6	Park *et al.* 2005a
	Seoul	46	4.5	2.2	3.3	10.1	1.0	11.1	0.1	11.1	Park *et al.* 2005b
		46	2.5	1.2	2.4	6.1	0.8	6.9	0.1	7.0	Son *et al.* 2007
		52	2.4	1.2	2.5	6.1	0.8	6.9	0.2	7.1	
	Chungju	39	3.0	3.6	4.9	11.5					Park 1999
	Gwangju	22	5.9	2.7	5.4	14.1	4.4	18.5	1.9	20.4	Lee and Park 1987
	Chungju	67	2.2	2.6	4.8	9.6					Song *et al.* 1997
	Pyungchang		5.5	0.3	3.8	9.7	1.4	11.0			Kwak and Kim 1992
Qv	Chuncheon	49	9.0	2.6	2.8	14.4	1.6	15.9	1.4	17.3	Park *et al.* 2003; Son *et al.* 2007
	Gongju	41	3.2	2.5	2.1	7.8					Park and Lee 2001
	Pohang	45	5.4	3.7	2.5	11.5					
	Yangyang	54	3.1	1.2	2.1	6.4					
	Sancheong	19	3.7	0.5	2.5	6.7					Kim and Jeong 1985
	Jinju	20	5.9	0.3	2.8	9.0					
	Chungju	62	2.7	2.1	3.8	8.6					Song and Lee 1996
	Suncheong	20	1.7	0.6	2.0	4.3					Choi and Park 1993
	Suncheong	28	9.5	3.0	8.3	20.8	2.4	23.2			Park and moon 1994
	Kwangju	32	3.4	0.8	2.2	6.5					Park *et al.* 1996
	Gwangyang	37	3.3	0.9	1.7	5.8	1.1	7.0	4.8	11.7	Park *et al.* 2005a
		38	4.6	1.3	2.4	8.3	1.6	9.9	1.2	11.1	
	Gwangju	34	4.7	1.3	2.5	8.5	0.7	9.2	2.0	11.2	Son *et al.* 2004b
		31	7.7	2.5	4.1	14.2	1.2	15.5	1.2	16.6	
		33	9.2	2.7	4.7	16.6	1.5	18.0	1.7	19.7	
	Chuncheon	44	8.5	2.4	2.6	13.5	1.5	15.0	2.3	17.3	Son *et al.* 2007
	Chungju	40	4.3	2.2	3.4	9.9					Park 1999
	Chungju	62	2.7	2.1	3.8	8.6					Song *et al.* 1997
Qs	Kwangyang	34	2.3	2.3	1.6	6.2					Park and Lee 2002
	Muju	25	2.2	2.8	1.5	6.5					
	Pohang	37	4.0	2.3	1.4	7.7					
	Suncheong	29	6.4	1.9	4.6	12.9	1.6	14.5			Park and Moon 1994
Qa	Suncheong	26	10.4	3.4	8.7	22.5	2.5	25.0			Park and Moon 1994
	Kwangju	38	3.2	1.0	1.9	6.1					Park *et al.* 1996
Qd	Kwangju	38	0.9	0.7	1.9	3.5					Park *et al.* 1996

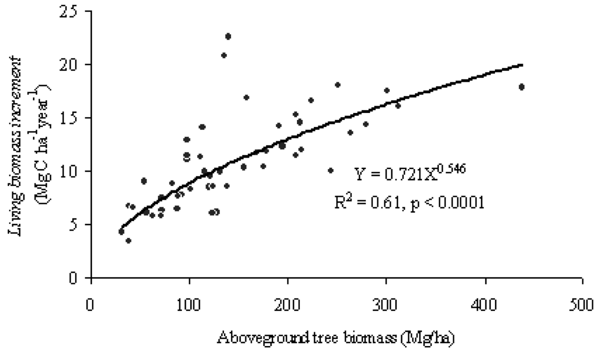

Figure 5. Relationship between living biomass increment of aboveground tree and aboveground tree biomass for major oak forests in Korea.

a 35-year-old *Q. acutissima* stand. The contribution of LB to NPP across the three oak forests was (71.9%) higher than that (28.1%) of LP to NPP. Mean NPP across the three oak forests was 10.2 Mg C ha^{-1}year^{-1}, which was slight higher than the mean value of 7.1 Mg C ha^{-1}year^{-1} in temperate forests reported by Pregitzer and Euskirchen (2004). For a better understanding of estimation of NPP, we must refer to belowground litter. Few studies have examined the production of belowground litter, especially the litter production of fine root, which is very difficult to study and therefore poses a major obstacle in obtaining a total understanding of NPP in oak forests. The amount of R$_h$ from micro- and macro-organisms in the soil must also be estimated in order to estimate the NEP (Table 4). In this study, it is impossible to separate R$_h$ from root respiration in the soil because of lack of data. The mean R$_h$ across the three oak forests was 8.3 Mg C ha^{-1}year^{-1}, which ranged within the values of 2.8-9.7 Mg C ha^{-1}year^{-1} in temperate forests (Pregitzer and Euskirchen, 2004). The NEP varied widely, from -3.27 in a 46-year-old *Q. mongolica* stand to 6.95 Mg C ha^{-1}year^{-1} in a 35-year-old *Q. acutissima* stand. The mean NEP across all age classes was 1.9 Mg C ha^{-1}year^{-1}, which was slightly higher than the mean value (1.13 Mg C ha^{-1}year^{-1}) of NEP across different methods (inventory, ecological site and vegetation model) in the European forest reported by Luyssaert *et al.* (2010). According to Pregitzer and Euskirchen (2004), the values of NEP vary with forest age, and are high in 30- to 120-year-old stands while may be negative (-1.9 Mg C ha^{-1}year^{-1}) in 0- to 10-year-old stands. In our study, the mean NEP in three stands showed negative values (source of carbon dioxide) from -3.27 to -0.29 Mg C ha^{-1}year^{-1} while the stand ages were over 10 years. Deficiency of data on the root respiration and belowground litter may contribute to

Table 4. Estimation of net primary production (NPP, Mg C ha^{-1}year^{-1}) and net ecosystem production (NEP, Mg C ha^{-1} year^{-1}) of oak (*Quercus*) forests in Korea.

Forest type	Location	Mean stand age (years)	Living biomass increment (Mg C ha^{-1} year^{-1})	Litter production (Mg C ha^{-1}year^{-1})	NPP	Heterotrophic respiration (Mg C ha^{-1}year^{-1})	NEP	Reference
Q. variabilis	Chuncheon	44	8.63	2.69	11.32	8.86	2.45	Son *et al.* 2007; Yi 2003
Q. variabilis		49	8.66	2.51	11.16	9.52	1.64	Son *et al.* 2007; Yi 2003; Park *et al.* 2003
Q. variabilis	Gwangju	34	5.86	2.86	8.72	6.76	1.95	Son *et al.* 2007
Q. variabilis + *Q. mongolica*		31	6.28	3.06	9.34	7.06	2.28	Son *et al.* 2004b
Q. variabilis + *Q. mongolica*		33	5.56	3.06	8.61	7.15	1.47	
Q. variabilis	Gwangyang	37	5.60	1.57	7.17	8.32	-1.15	Son *et al.* 2007; Park *et al.* 2005b
Q. variabilis		38	9.84	1.53	11.36	8.78	2.58	
Q. mongolica	Seoul	46	5.56	3.10	8.66	8.05	0.61	Son *et al.* 2007
Q. mongolica		46	3.48	2.47	5.95	9.22	-3.27	
Q. mongolica		52	3.57	2.99	6.55	6.85	-0.29	
Q. mongolica	Chuncheon	50	10.94	3.80	14.74	9.33	5.41	Son *et al.* 2007; Yi 2003; Park *et al.* 2003
Q. mongolica	Gwangyang	36	8.32	2.15	10.47	6.44	4.04	Son *et al.* 2007; Park *et al.* 2005b
Q. acutissima	Kongju	35	15.84*	2.35	18.19	11.24	6.95	Lee and Mun 2005

*Excluding ground vegetation.
NPP = Living biomass increment + Litter production; NEP = NPP – Heterotrophic respiration.
A factor of 0.5 was used to convert carbon content from biomass.

the variability in NEP.

Our findings suggest that oak forests are generally carbon sinks and play a key role in the carbon cycle in Korean forest. However, future studies should cover detailed measurement on each component of carbon fluxes, especially the dynamics of the belowground fraction including fine roots.

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