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Litter fall and nutrient status of green leaves and leaf litter at various compound ratios of fertilizer in sawtooth oak stands, Korea

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Abstract. This study was conducted to evaluate the litter fall and nutrient status of green leaves and leaf litter at various compound ratios of fertilizer in 28-year-old sawtooth oak (*Quercus acutissima* Carruth.) stands. The compound ratios of the fertilizer were $N_3P_4K_1$ (100 kg N ha^{-1}, 133 kg P ha^{-1}, and 33 kg K ha^{-1}), $N_6P_4K_1$, $N_2P_2K_1$, $N_3P_8K_1$, $N_3P_4K_2$, and $N_0P_0K_0$ (control). Varying ratios of NPK were applied for three years (2002 - 2004), and the litter fall and green leaves were collected for one year (May 2005 - May 2006) and at the end of growing season (September 2005). Leaf litter was significantly higher ($P < 0.05$) in the $N_3P_4K_2$ (3,423 kg ha^{-1} year^{-1}) than in the $N_3P_8K_1$ (2,741 kg ha^{-1} year^{-1}) and $N_2P_2K_1$ (2,891 kg ha^{-1} year^{-1}) treatments. The N concentrations of the green leaves were significantly higher in the compound ratios of fertilizer ($N_3P_4K_1$, $N_6P_4K_1$, $N_3P_8K_1$) than in the $N_0P_0K_0$ treatment, but the N concentrations of the leaf litter were not affected by the fertilizer. The P and K concentrations in the green leaves were significantly higher in the highest dose ($N_3P_8K_1$ and $N_3P_4K_2$) of these nutrients than in the $N_0P_0K_0$ treatment. The nutrient inputs by the leaf litter corresponded to the differences in the leaf litter mass or nutrient concentrations rather than the various compound ratios of fertilizer. Nutrient use and resorption efficiencies were only weakly controlled by various compound ratios of fertilizer. The results indicate that the nutrient status of green leaves may serve as an indicator of various compound ratios of fertilizer, whereas litter fall, nutrient use and resorption efficiency can be attributed to inherent soil conditions or stand characteristics following fertilizer application in sawtooth oak stands.
Keywords forest fertilization, litter fall, nutrient cycling, oak, soil property.

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Introduction

The foliar nutrient concentrations of trees are an important parameter in the assessment of the nutritional status of forests after fertilizer application (Weetman & Wells 1990, Smith et al. 2000, Tausz et al. 2004) because the addition of fertilizer to improve forest productivity can affect the quality and quantity of foliage. Generally, nutrient concentrations of foliage have been accepted as good indicators of growth and soil fertility on site (Bauer et al. 1997), although the nutrient status in foliage could be attributed to many environmental factors, such as soil properties, season length, and water supply (Weetman & Wells 1990).

Understanding the resultant change in the litter fall amounts at fertilizer application is important because annual litter fall production can be used to estimate the foliage biomass, which may be a factor in determining the response to fertilizer application. However, fertilizer application has been shown to increase (O'connell & Grove 1993, Laclau et al. 2009), decrease and exert no discernible effect (Smaill et al. 2008, Kim et al. 2011) on the litter fall production in forest ecosystems. Also, the nutrient dynamic of litter fall following fertilizer application is likely to modify nutrient distribution on the forest floor (O'connell & Grove 1993, Smith et al. 2000), but litter nutrient processes have been shown to be affected by the type of fertilizer applied (Laclau et al. 2009) and the application rate (Nelson et al. 1995, Finér 1996).

Despite many studies on the nutrient status of forest stands following fertilizer application (Byun et al. 2006, Son et al. 2007, Park et al. 2008), there is still a lack of knowledge about the litter fall and nutrient responses of the foliage involved in various compound ratios of the fertilizer in Korean forest stands. Furthermore, understanding more information that may be used to evaluate the effects of litter fall and nutrient inputs at various compound ratios of fertilizer is needed because of a myriad of nutritional problems, such as nutrient deficiency, in forest stands in Korea (Byun et al. 2006, Hwang et al. 2007, Son et al. 2007). In addition, the application of the suitable fertilization ratio, considering the soil environmental conditions and tree growth characteristics, is one of the most effective ways to reduce cost and fertilizer waste and pollution.

The objectives of this study were: (i) to determine the amount of litter fall, (ii) to measure the nutrient status and associated parameters, such as resorption, concentration, and quantity of the nutrients in green leaves and in leaf litter, at various compound ratios of fertilizer in mature oak stands which are the most widespread hardwood tree species throughout the country.

Materials and methods

The study was conducted in a national forest (127º 35' 43" E, 36 º 35' 40" N, elevation 250 m) in Choojeongri, Nangseong-myon, Cheongwon-gun, central Korea. The study sites were classified as a slightly dry dark reddish brown forest soil (mostly Inceptisol, USDA soil classification system) originating from sandstone. The average annual precipitation at the study sites is 1,225 mm, and the average temperature is 12.3°C. The aspect of the site was north-facing, and the slopes ranged from 25° to 30°. The mean age of the natural sawtooth oak stands was approximately 28 years. The dominant understory species in the site were *Lindera erythrocarpa* Makino, *Q. aliena* Blume, *Ulmus davidiana* var. *japonica* Nakai, *Prunus sargentii* Rehder, *Euonymus alatus* Sieb., *Rosa multiflora* Thunb., *Philadelphus schrenckii* Rupr., *Rhus trichocarpa* Miq., *Ligustrum obtusifolium* Sieb. et Zucc., and *Staphylea bumalda* DC.

The experimental design consisted of a randomized complete design with six different treatments in the sawtooth oak stands. The treatment plots were divided into eighteen 20 m × 20 m plots (6 treatment plots [five fertilized plots with one control] × 3 replicates) and were randomly assigned, with a 5 m buffer zone between each plot. The fertilizers were manually applied to the forest floor surface during the spring for each of three years between 2002 and 2004. Urea, fused superphosphate, and potassium chloride fertilizers were used as sources of nitrogen (N), phosphorus (P), and potassium (K), respectively. The compound ratios of the fertilizers were $N_3P_4K_1$ (100 kg N ha^{-1}, 133 kg P ha^{-1} , and 33 kg K ha^{-1}), $N_3P_8K_1$ (100 kg N ha^{-1}, 266 kg P ha^{-1}, and 33 kg K ha^{-1}), $N_3P_4K_2$ (100 kg N ha^{-1}, 133 kg P ha^{-1}, and 66 kg K ha^{-1}), $N_6P_4K_1$ (200 kg N ha^{-1}, 133 kg P ha^{-1}, and 33 kg K ha^{-1}), $N_2P_2K_1$ (66 kg N ha^{-1}, 67 kg P ha^{-1}, and 33 kg K ha^{-1}), and $N_0P_0K_0$ (control). The ratios of the $N_3P_4K_1$ fertilizer were generally recommended for the improvement of growth within mature forests in Korea (Joo et al. 1983). The mean diameter at breast height (DBH) was 22.8 cm in the $N_0P_0K_0$ treatment and 20.1 - 22.8 cm in the fertilizer treatments, whereas the stand basal area was lower in the $N_3P_8K_1$ (8.9 m^2 ha^{-1}) than in the $N_2P_2K_1$ (15.5 m^2 ha^{-1}) treatment (Table 1).

A soil pit was dug near the center of each plot before (2002) and after (2005) the fertilizer treatments. Soil samples were collected from each soil horizon (A and B). The soil samples were air dried, passed through a 2-mm sieve, and used for soil chemical analyses. Soil pH (1:5 soil : water suspension) was measured by glass electrode. The soil samples were digested by the Kjeldahl procedure to determine the total N. Available P was determined by the Lancaster method (National Institute of Agricultural Science and Technology 2000). Calcium (Ca), magnesium (Mg), sodium (Na) and potassium (K) were determined by ICP (Jobin Yvon, Model Ultima-2). The soil chemical properties before and after the application of the fertilizer treatments are given in Table 2.

Litter fall was collected by litter traps from three sampling points within each treatment plot. Litter traps using a 1.5 mm nylon net with a collective area of 0.25 m^2 were placed randomly within each treatment plot (a total of 54 traps: 6 treatment plots × 3 replication plots × 3 traps in each plot). Litter was collected at approximately monthly intervals for one year, from May 2005 to May 2006. Litter collected from each trap was transported to the laboratory and oven-dried at 65°C for 48 h. All dried samples were separated into leaves, branches, bark, and miscellaneous components, and each portion was weighed. The collected litter was composited by two seasonal inputs. The litter of the growing season was defined as 15 May - 24 September 2005, and the litter of the later season was defined as 24 September 2005 - 12 May 2006. Leaf litter collected in the heaviest litterfall season (November and early December) was ground in a Wiley mill, using a 40-mesh stainless steel sieve for the chemical analysis. The nutrients (N, P, K, Ca, Mg) in

Table 1 Stand characteristics of various compound ratios of fertilizer and control treatments in the sawtooth oak stands (*n* = 3)

Treatment	Tree density (trees ha^{-1})	Mean DBH (cm)	Mean height (m)	Basal area (m^2 ha^{-1})
$N_0P_0K_0$	250 (76)	22.8 (0.60)	17.3 (1.30)	11.1 (3.54)
$N_3P_4K_1$	283 (30)	20.1 (1.55)	17.0 (1.46)	9.7 (1.21)
$N_6P_4K_1$	342 (58)	20.5 (0.95)	17.4 (1.29)	11.5 (1.07)
$N_2P_2K_1$	367 (68)	22.8 (0.13)	19.0 (0.29)	15.5 (2.75)
$N_3P_8K_1$	250 (63)	21.3 (1.18)	18.8 (2.11)	8.9 (1.23)
$N_3P_4K_2$	342 (36)	20.2 (1.12)	17.4 (1.58)	11.8 (1.60)

Note. Values in parentheses are one stand error.

Table 2 Soil characteristics of various compound ratios of fertilizer and control treatments in the sawtooth oak stands (*n* = 3)

Treatment	Horizon	Year	Soil pH	Organic matter (%)	Total nitrogen (%)	Avail. phosphorus (mg kg^{-1})	Exchangeable (cmol$_c$ kg^{-1}) K^+	Na^+	Ca^{2+}	Mg^{2+}
$N_0P_0K_0$	A	2002	5.94 (0.27)	5.63 (0.35)	0.37 (0.04)	4.84 (1.04)	1.30 (0.10)	0.12 (0.01)	7.00 (2.55)	1.97 (0.25)
		2005	5.79 (0.20)	5.31 (0.63)	0.33 (0.04)	12.58 (4.14)	0.94 (0.17)	0.11 (0.01)	7.73 (1.32)	1.97 (0.18)
	B	2002	5.67 (0.28)	4.58 (1.31)	0.28 (0.07)	4.19 (0.16)	0.99 (0.14)	0.12 (0.01)	6.89 (4.50)	1.19 (0.15)
		2005	5.62 (0.21)	4.09 (0.80)	0.24 (0.04)	8.45 (4.40)	0.73 (0.14)	0.12 (0.01)	6.98 (2.23)	1.46 (0.20)
$N_3P_4K_1$	A	2002	5.29 (0.01)	3.56 (0.70)	0.23 (0.04)	9.81 (2.35)	0.85 (0.14)	0.08 (0)	2.68 (0.66)	0.96 (0.12)
		2005	5.25 (0.02)	4.50 (0.57)	0.21 (0.03)	58.92 (37.15)	0.82 (0.07)	0.07 (0.006)	3.98 (0.63)	1.14 (0.11)
	B	2002	5.37 (0.28)	3.52 (0.12)	0.21 (0.01)	8.83 (1.50)	0.69 (0.16)	0.09 (0.01)	2.69 (1.30)	1.42 (0.47)
		2005	5.26 (0.14)	3.38 (0.24)	0.21 (0.02)	33.8 (16.6)	0.62 (0.08)	0.07 (0.01)	2.27 (0.61)	1.05 (0.27)
$N_6P_4K_1$	A	2002	5.70 (0.25)	4.29 (0.62)	0.26 (0.04)	9.35 (2.40)	1.22 (0.10)	0.10 (0)	5.60 (2.02)	1.63 (0.25)
		2005	5.52 (0.15)	4.49 (0.47)	0.26 (0.02)	79.6 (46.2)	1.06 (0.11)	0.07 (0.009)	5.18 (1.10)	1.52 (0.14)
	B	2002	5.39 (0.14)	2.95 (0.38)	0.19 (0.02)	4.91 (0.94)	0.87 (0.11)	0.09 (0.01)	2.82 (0.94)	1.06 (0.09)
		2005	5.36 (0.07)	3.66 (0.37)	0.21 (0.02)	47.1 (27.1)	0.84 (0.06)	0.08 (0.007)	3.73 (0.63)	1.13 (0.07)
$N_2P_2K_1$	A	2002	5.25 (0.10)	3.46 (0.34)	0.21 (0.02)	6.19 (0.51)	0.80 (0.03)	0.12 (0)	3.19 (0.95)	0.85 (0.09)
		2005	5.18 (0.12)	3.77 (0.29)	0.22 (0.01)	7.00 (0.72)	0.83 (0.10)	0.11 (0.01)	4.60 (1.61)	1.24 (0.31)
	B	2002	5.31 (0.09)	1.92 (0.32)	0.13 (0.02)	4.05 (1.38)	0.64 (0.08)	0.13 (0.01)	1.46 (0.42)	0.52 (0.13)
		2005	5.17 (0.10)	2.34 (0.29)	0.14 (0.01)	10.54 (4.11)	0.56 (0.06)	0.10 (0.01)	1.87 (0.38)	0.58 (0.08)
$N_3P_8K_1$	A	2002	5.99 (0.17)	2.48 (1.65)	0.16 (0.08)	7.83 (2.58)	1.00 (0.02)	0.12 (0)	4.17 (1.50)	1.33 (0.16)
		2005	5.97 (0.90)	5.61 (0.33)	0.33 (0.04)	159.1 (86.4)	1.17 (0.09)	0.09 (0.01)	8.65 (1.08)	2.01 (0.14)
	B	2002	5.99 (0.19)	2.48 (0.10)	0.16 (0.01)	7.83 (1.79)	1.00 (0.06)	0.12 (0.02)	4.17 (0.50)	1.33 (0.09)
		2005	5.65 (0.17)	2.97 (0.30)	0.20 (0.02)	62.4 (26.6)	0.84 (0.08)	0.09 (0.02)	4.31 (0.31)	1.17 (0.09)
$N_3P_4K_2$	A	2002	5.66 (0.10)	6.60 (0.46)	0.41 (0.03)	8.29 (1.22)	1.34 (0.10)	0.12 (0)	7.90 (0.49)	1.58 (0.07)
		2005	5.69 (0.13)	5.90 (0.55)	0.35 (0.04)	60.2 (43.6)	1.21 (0.09)	0.09 (0.01)	8.51 (1.36)	1.74 (0.20)
	B	2002	5.38 (0.14)	3.95 (0.23)	0.25 (0.03)	5.27 (0.58)	0.83 (0.10)	0.11 (0)	3.43 (0.63)	0.93 (0.02)
		2005	5.33 (0.10)	3.52 (0.29)	0.22 (0.02)	26.1 (20.0)	0.78 (0.07)	0.09 (0.01)	3.69 (0.54)	1.00 (0.09)

Note. Values in parentheses are one stand error the leaf litter were analyzed by the method described by the National Institute of Agriculture Science and Technology (2000).

Fresh green leaf samples used to measure the nutrient response of the leaves at various compound ratios of fertilizer were collected at the end of the growing season (24th September, 2005). The leaf samples were collected from the mid-crown of two dominant trees in each treatment plot. The samples were transported to the laboratory and oven-dried at 65°C for 48 hours. The dried leaf samples were ground in a Wiley mill to pass through a 40-mesh stainless steel sieve for the chemical analysis. The seasonal nutrient concentrations were multiplied by the mass of the seasonal litter fall to provide the relevant total nutrient values. The nutrient use efficiency was defined as the ratio of the dry matter to the nutrient content of the leaf litter (Vitousek 1982). The nutrient resorption efficiency between the green leaves and leaf litter was calculated as:

$$\textit{Nutrient resorption efficiency} = \textit{Nutrient}_{green\ leaf} - \textit{Nutrient}_{leaf\ litter} / \textit{Nutrient}_{green\ leaf} \times 100$$

All data were evaluated by analysis of covariance (Milliken & Johnson 2002) with the General Linear Models procedure in SAS (SAS Institute Inc. 2003). The basal area of each treatment plot was considered to be a possible covariate in the analysis. When significant differences at $P < 0.05$ occurred, a comparison of the treatment means was performed using least squares means and *P*-values (Milliken & Johnson 2002).

Results

Litter fall

The litter fall production in the growing season and late season varied significantly ($P < 0.05$) among the various compound ratios of fertilizer. The leaf litter in the growing season was significantly higher in the $N_3P_8K_1$ treatment than in the other ratios of fertilizer or $N_0P_0K_0$ treatments (Table 3), but the leaf litter in the late season was significantly lower in the $N_3P_8K_1$ and $N_2P_2K_1$ treatments than in the other ratios of fertilizer or $N_0P_0K_0$ treatments. The total leaf litter showed a similar trend, with the lowest values occurring in the $N_3P_8K_1$ treatment, which involved the lowest stand basal area or tree density compared with the other treatments (Table 1).

Nutrient concentration and content of green leaves and leaf litter

Nutrient concentrations within the green leaves and leaf litter differed significantly ($P < 0.05$) with the application of varying amounts of fertilizer (Table 4). The N concentration of the green leaves was shown to be significantly higher in the fertilizer ($N_3P_4K_1$, $N_6P_4K_1$, $N_3P_8K_1$) treatments than in the $N_0P_0K_0$ treatment, but the N concentration did not differ significantly among the various N ratios of the fertilization treatments, such as the $N_3P_4K_1$, $N_6P_4K_1$ and $N_2P_2K_1$ treatments.

The P concentrations in the green leaves and leaf litter were significantly different among the fertilizer treatments. The highest concentration of P was found in the highest dose ($N_3P_8K_1$) of P fertilizer (Table 4). Similarly, the K concentration in the green leaves was the highest concentration in the highest dose of K fertilizer ($N_3P_4K_2$), whereas that of the leaf litter was the lowest concentration in the ratios of the fertilizer.

The varying compound ratios of fertilizer had minor effects on the Ca and Mg concentrations within the green leaves and leaf litter, although the concentrations of both were significantly different among the fertilizer treatments (Table 4). The N, P, and K concentrations at the various compound ratios of the fertilizer treatments decreased substantially during senescence, but the Ca and Mg concentrations increased.

Table 3 Litter fall production in the growing and late seasons for various compound ratios of fertilizer and control treatments in the sawtooth oak stands (*n* = 9)

Season	Treatment	Litter component (kg ha^{-1}year^{-1})						
		Leaf	Bark	Branch	Flower	Acorn and cup	Miscella-neous	Total litter fall
Growing season	$N_0P_0K_0$	96.8 (9.7)^{b}	4.3 (1.5)^{ab}	270.2 (50.9)^{b}	46.7 (9.7)^{b}	3.5 (2.3)^{b}	289.4 (21.4)^{bc}	710.9 (63.9)^{bc}
	$N_3P_4K_1$	91.8 (4.1)^{bc}	0.0 (0.0)^{b}	660.3 (84.0)^{a}	113.7 (20.8)^{a}	0.0 (0.0)^{b}	337.0 (17.5)^{b}	1,202.8 (111.6)^{a}
	$N_6P_4K_1$	73.0 (4.4)^{bc}	48.1 (18.4)^{a}	240.8 (53.5)^{b}	51.3 (2.8)^{b}	0.0 (0.0)^{b}	300.8 (11.4)^{bc}	714.0 (65.2)^{b}
	$N_2P_2K_1$	66.8 (3.4)^{c}	12.1 (11.0)^{ab}	380.4 (119.2)^{ab}	43.9 (2.5)^{b}	0.0 (0.0)^{b}	330.8 (5.7)^{bc}	834.0 (120.7)^{ab}
	$N_3P_8K_1$	180.4 (32.1)^{a}	33.6 (16.6)^{ab}	189.6 (38.1)^{b}	39.1 (4.0)^{b}	9.0 (1.8)^{a}	241.2 (13.3)^{c}	692.8 (49.4)^{c}
	$N_3P_4K_2$	84.8 (5.2)^{b}	0.7 (0.3)^{b}	459.6 (176.7)^{ab}	149.1 (21.6)^{a}	1.0 (1.0)^{b}	514.5 (42.7)^{a}	1,209.5 (195.7)^{a}
Late season	$N_0P_0K_0$	3,120.8 (241.2)^{b}	13.3 (5.8)^{a}	573.9 (121.5)^{a}	130.1 (22.8)^{a}	136.6 (52.4)^{ab}	491.3 (89.5)^{ab}	4,466.0 (254.6)^{ab}
	$N_3P_4K_1$	3,293.2 (165.7)^{ab}	45.7 (34.2)^{a}	269.6 (52.3)^{a}	126.1 (9.3)^{a}	120.8 (49.8)^{ab}	362.5 (35.3)^{ab}	4,218.0 (197.9)^{ab}
	$N_6P_4K_1$	3,277.4 (117.1)^{ab}	12.8 (5.7)^{a}	610.1 (269.2)^{a}	112.5 (9.3)^{a}	79.2 (30.3)^{b}	389.8 (28.3)^{ab}	4,481.9 (304.4)^{ab}
	$N_2P_2K_1$	2,823.7 (138.6)^{c}	11.7 (6.3)^{a}	350.5 (131.1)^{a}	114.9 (11.6)^{a}	97.8 (33.6)^{ab}	548.4 (55.3)^{a}	3,947.0 (257.0)^{b}
	$N_3P_8K_1$	2,560.7 (66.0)^{c}	76.4 (40.7)^{a}	292.8 (108.7)^{a}	119.7 (26.0)^{a}	65.8 (17.7)^{b}	358.7 (36.3)^{b}	3,474.0 (158.7)^{b}
	$N_3P_4K_2$	3,338.6 (142.6)^{a}	10.9 (4.0)^{a}	654.4 (280.3)^{a}	143.6 (7.6)^{a}	239.2 (67.2)^{b}	407.5 (45.5)^{ab}	4,794.4 (356.6)^{a}
Total	$N_0P_0K_0$	3,217.6 (248.1)^{ab}	17.6 (6.3)^{ab}	844.1 (138.4)^{ab}	176.8 (22.9)^{b}	140.1 (52.3)^{ab}	780.7 (102.9)^{ab}	5,176.9 (280.6)^{b}
	$N_3P_4K_1$	3,385.1 (168.8)^{ab}	45.7 (34.2)^{ab}	929.9 (97.0)^{ab}	239.8 (17.4)^{ab}	120.8 (49.79)^{ab}	699.5 (38.4)^{bc}	5,420.8 (224.8)^{ab}
	$N_6P_4K_1$	3,350.4 (118.4)^{ab}	60.9 (21.9)^{ab}	850.9 (290.8)^{ab}	163.9 (10.62)^{c}	79.2 (30.3)^{b}	690.5 (28.3)^{bc}	5,195.8 (348.3)^{b}
	$N_2P_2K_1$	2,890.6 (140.6)^{b}	23.8 (11.3)^{ab}	730.9 (157.5)^{ab}	158.8 (11.67)^{c}	97.8 (33.6)^{ab}	879.2 (54.7)^{ab}	4,781.1 (303.3)^{bc}
	$N_3P_8K_1$	2,741.1 (78.1)^{b}	109.9 (45.9)^{a}	482.4 (129.4)^{b}	158.8 (27.6)^{c}	74.8 (17.0)^{b}	600.0 (32.2)^{c}	4,166.9 (182.8)^{c}
	$N_3P_4K_2$	3,423.4 (141.7)^{a}	11.6 (4.0)^{b}	1,114.0 (286.7)^{a}	292.7 (25.5)^{a}	240.2 (67.1)^{a}	922.0 (53.3)^{a}	6,003.9 (407.6)^{a}

Note. Values in parentheses are one stand error. Different letters in each column indicate a significant difference at $P < 0.05$ among the treatments.

The nutrient (N, P, K, Ca, Mg) content by the total leaf litter fall was significantly different at the various compound ratios of fertilizer. The nutrient content by the leaf litter fall was closely related to change in the leaf litter fall amounts rather than the various compound ratios of the fertilizer treatments (Table 5).

Table 4 Nutrient concentrations of the green leaves and leaf litters between various compound ratios of fertilizer and control treatments in the sawtooth oak stands (n = 9)

Leaf component	Treatment	Nutrient (%)				
		N	P	K	Ca	Mg
Green leaf	$N_0P_0K_0$	1.50 (0.01)[b]	0.08 (0.01)[b]	1.02 (0.03)[b]	0.77 (0.03)[a]	0.19 (0.01)[a]
	$N_3P_4K_1$	2.13 (0.15)[a]	0.10 (0.01)[ab]	1.22 (0.05)[ab]	0.47 (0.01)[b]	0.19 (0.01)[a]
	$N_6P_4K_1$	1.98 (0.09)[a]	0.09 (0.01)[b]	1.17 (0.03)[ab]	0.66 (0.06)[a]	0.15 (0.01)[a]
	$N_2P_2K_1$	1.82 (0.08)[ab]	0.11 (0.01)[ab]	1.13 (0.03)[b]	0.69 (0.03)[a]	0.20 (0.01)[a]
	$N_3P_8K_1$	2.16 (0.13)[a]	0.13 (0.01)[a]	1.13 (0.03)[b]	0.77 (0.11)[a]	0.19 (0.05)[a]
	$N_3P_4K_2$	1.83 (0.20)[ab]	0.10 (0.01)[ab]	1.25 (0.08)[a]	0.62 (0.07)[ab]	0.12 (0.01)[a]
Leaf litter	$N_0P_0K_0$	0.91 (0.01)[a]	0.04 (0.01)[b]	0.77 (0.03)[a]	1.20 (0.08)[a]	0.23 (0.01)[a]
	$N_3P_4K_1$	0.94 (0.02)[a]	0.06 (0.01)[ab]	0.63 (0.02)[b]	0.95 (0.01)[b]	0.22 (0.01)[ab]
	$N_6P_4K_1$	0.91 (0.05)[a]	0.05 (0.01)[ab]	0.69 (0.06)[ab]	1.00 (0.02)[ab]	0.21 (0.01)[ab]
	$N_2P_2K_1$	0.87 (0.03)[a]	0.05 (0.01)[ab]	0.67 (0.02)[ab]	1.10 (0.02)[ab]	0.23 (0.01)[a]
	$N_3P_8K_1$	0.99 (0.03)[a]	0.07 (0.01)[a]	0.67 (0.03)[ab]	1.00 (0.01)[ab]	0.19 (0.01)[b]
	$N_3P_4K_2$	0.94 (0.03)[a]	0.06 (0.01)[ab]	0.64 (0.02)[b]	1.20 (0.07)[a]	0.19 (0.01)[b]

Note. Values in parentheses are one stand error. Different letters in each column indicate a significant difference at $P < 0.05$ among the treatments.

Table 5 Nutrient content by the leaf litter fall between the various compound ratios of the fertilizer and control treatments in the sawtooth oak stands (n = 9)

Season	Treatment	Nutrient (kg $ha^{-1}year^{-1}$)				
		N	P	K	Ca	Mg
Growing season	$N_0P_0K_0$	1.45 (0.21)[b]	0.08 (0.01)[b]	0.99 (0.17)[a]	0.74 (0.11)[a]	0.18 (0.03)[a]
	$N_3P_4K_1$	1.98 (0.27)[ab]	0.09 (0.01)[b]	1.12 (0.09)[a]	0.43 (0.04)[a]	0.18 (0.03)[a]
	$N_6P_4K_1$	1.47 (0.20)[b]	0.07 (0.02)[b]	0.85 (0.08)[a]	0.49 (0.08)[a]	0.11 (0.01)[a]
	$N_2P_2K_1$	1.21 (0.01)[b]	0.08 (0.01)[b]	0.75 (0.02)[a]	0.46 (0.01)[a]	0.14 (0.01)[a]
	$N_3P_8K_1$	3.77 (1.05)[a]	0.24 (0.07)[a]	2.08 (0.68)[a]	1.51 (0.61)[a]	0.39 (0.16)[a]
	$N_3P_4K_2$	1.53 (0.15)[b]	0.08 (0.01)[b]	1.06 (0.13)[a]	0.52 (0.07)[a]	0.10 (0.02)[a]
Late season	$N_0P_0K_0$	28.21 (2.01)[b]	1.38 (0.04)[b]	23.70 (1.66)[a]	37.73 (4.76)[ab]	7.28 (0.23)[a]
	$N_3P_4K_1$	31.07 (2.76)[ab]	1.88 (0.20)[ab]	20.72 (1.28)[ab]	31.46 (1.91)[ab]	7.19 (0.43)[a]
	$N_6P_4K_1$	29.98 (2.71)[ab]	1.82 (0.17)[ab]	22.52 (1.45)[ab]	32.79 (0.70)[ab]	6.97 (0.14)[a]
	$N_2P_2K_1$	24.49 (0.74)[b]	1.43 (0.01)[b]	19.54 (1.29)[ab]	31.06 (1.45)[ab]	6.64 (0.54)[a]
	$N_3P_8K_1$	25.28 (0.76)[ab]	1.75 (0.08)[ab]	16.84 (0.62)[b]	25.46 (0.87)[b]	4.79 (0.47)[b]
	$N_3P_4K_2$	31.16 (0.69)[a]	2.00 (0.07)[a]	21.44 (1.00)[ab]	40.15 (3.96)[a]	6.30 (0.28)[a]
Total	$N_0P_0K_0$	29.66 (2.20)[ab]	1.46 (0.06)[ab]	24.70 (1.84)[a]	38.48 (4.98)[ab]	7.47 (0.26)[a]
	$N_3P_4K_1$	33.05 (3.03)[a]	1.97 (0.21)[a]	21.84 (1.36)[ab]	31.88 (1.95)[ab]	7.37 (0.44)[a]
	$N_6P_4K_1$	31.44 (2.89)[ab]	1.89 (0.18)[ab]	23.37 (1.48)[ab]	33.28 (0.78)[ab]	7.08 (0.15)[ab]
	$N_2P_2K_1$	25.70 (0.75)[b]	1.51 (0.01)[b]	19.77 (1.35)[ab]	31.52 (1.45)[ab]	6.78 (0.55)[ab]
	$N_3P_8K_1$	29.05 (1.78)[ab]	1.99 (0.15)[ab]	18.92 (0.26)[b]	26.98 (1.08)[b]	5.18 (0.56)[b]
	$N_3P_4K_2$	32.69 (0.55)[a]	2.09 (0.07)[a]	22.50 (0.60)[ab]	40.66 (3.98)[a]	6.40 (0.26)[ab]

Note. Values in parentheses are one stand error. Different letters in each column indicate a significant difference at $P < 0.05$ among the treatments.

Nutrient use efficiency and nutrient resorption efficiency of leaf litter

The nutrient use efficiency of the leaf litter could be lower in the fertilizer treatments than in the $N_0P_0K_0$ treatment (Figure 1). For example, the fertilizer treatments had lower P use efficiency (1,389 - 1,916) compared with the $N_0P_0K_0$ (2,195) treatment (Figure 1). In contrast to P use efficiency, the K and Mg use efficiencies were higher in the fertilizer treatments than in the $N_0P_0K_0$ treatment due to the low resorption efficiency of this nutrient (Figure 2). However, the N use efficiency was not affected by the various compound ratios of the fertilizer treatments.

The nutrient resorption efficiency between the green leaves and leaf litter was unaffected by the various compound ratios of fertilizer for all nutrients, except for P and K (Figure 2). However, the N and K resorption efficiencies were generally higher in the fertilizer treatments than in the $N_0P_0K_0$ treatment. The P resorption efficiency was the highest in the low-dose P fertilization ratio ($N_2P_2K_2$) compared with the other compound ratios of fertilizer. The Ca resorption efficiency was significantly different where different ratios of fertilizer were applied, whereas the Mg resorption efficiency was not significantly different between the various compound ratios of the fertilizer and $N_0P_0K_0$ treatments (Figure 2).

Discussion

Litter fall

As growth and development in foliage following fertilizer application could be regulated by physiological responses such as uptake and allocation of carbon and nutrient in tree components (Gough et al., 2004), fertilization response potential can be estimated from increase of foliage biomass in tree levels. However, the application of high doses of fertilizers had little influence on the leaf mass of sawtooth oak stands. For example, the similar productions of leaf litter fall at the various compound ratios of fertilizer (e.g., $N_3P_4K_1$, $N_6P_4K_1$, $N_3P_4K_2$) and the $N_0P_0K_0$ treatment could be due to the similar basal area or tree density in the treatments (Table 1) or to factors relating to canopy closure during the 5 years after the last thinning (2000). In addition, there were no significant correlations ($P > 0.05$) between the leaf litter and stand basal area or tree density in this oak stand (Kim et al. 2008). The lack of significant relationships between the leaf litter fall amounts and the various compound ratios of fertilizer could be due to the closed canopy in this mature oak stand because the annual leaf litter fall has been shown to remain relatively constant after canopy closure (Bray & Gorham 1964, Berg & Laskowski 2006). In contrast to this result, the leaf litter fall increased following fertilizer application in a eucalyptus forest in Australia (O'connell & Grove 1993) and in a sweetgum forest in the USA (Nelson et al. 1995). Furthermore, the leaf litter inputs in the sweetgum were higher at higher rates of fertilization (400 kg N ha^{-1}) than lower rates (100 kg N ha^{-1}) (Nelson et al. 1995).

The total woody litter consisting of branches and bark was not significantly different between the fertilizer treatments and the $N_0P_0K_0$ treatment, which could be explained due to the fact that woody litter inputs may be affected by additional environmental factors, such as storms or strong winds (Kim et al. 2011). The total amount of litter fall in this study was comparable with the 5,671 kg ha^{-1} $year^{-1}$of 35-year-old sawtooth oak stands (Mun & Joo 1994).

Nutrient concentration and content of green leaves and leaf litter

The fertilizer application affected the concentration and amounts of the nutrients in the green leaves. The N, P and K concentrations in the green leaves showed increased responses to the fertilizer application, whereas the nutrient

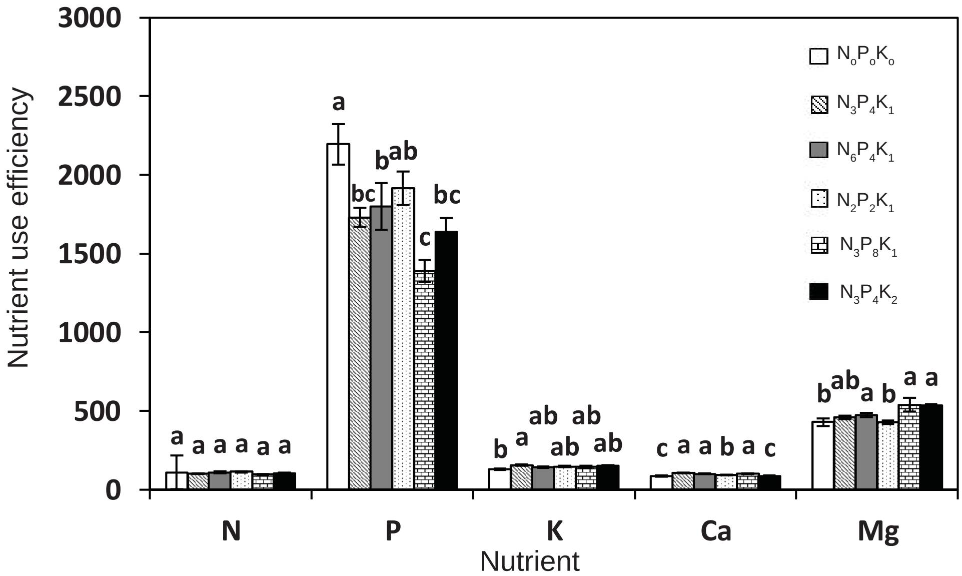

Figure 1 Nutrient use efficiency by the leaf litter fall between various compound ratios of the fertilizer and control treatments in the sawtooth oak stands (n = 9). Vertical bars are one stand error. Different letters in each bar indicate a significant difference at $P < 0.05$ among the treatments

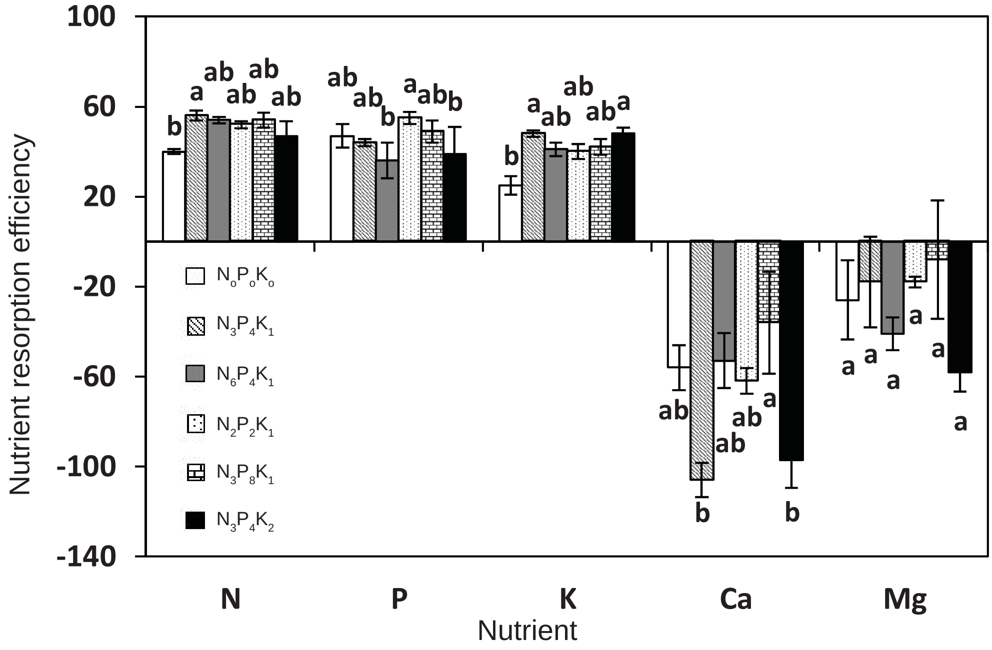

Figure 2 Nutrient resorption efficiency by leaf litter fall between various compound ratios of the fertilizer and control treatments in the sawtooth oak stands (n = 9). Vertical bars are one stand error. Different letters in each bar indicate a significant difference at $P < 0.05$ among the treatments

concentrations were not affected by the various compound ratios of the fertilizer applied. A high concentration of N in the green leaves is likely due to increased N uptake after the fertilizer treatments (Berg & Laskowski 2006), as tree species with high N availability tend to produce green leaves with high N concentrations (Sariyildiz & Anderson 2005). In contrast to the N concentration of green leaves, the N concentration within the leaf litter did not appear to be affected by the fertilizer treatments, most likely because the N concentration in the leaf litter was controlled by such factors as the combined effect of the soil available N status, tree growth, climate factors and N resorption rates. In addition, the nutrient concentrations in the green leaves or leaf litter could be affected by the diluting effect of leaf growth with increased nutrient supply levels.

The P concentration in the green leaves and leaf litter was also significantly different among the fertilizer treatments, with the concentration significantly higher in the application of high doses of P ($N_3P_8K_1$) than in that of the $N_0P_0K_0$ treatment (Table 3). Generally, the P concentration in the leaves of broad-leaf trees was increased after P fertilizer application (O'Connell & Grove 1993), which can be attributed to the enhanced uptake and mineralization in the rhizosphere. Similarly, the highest K concentration in the $N_3P_4K_2$ treatments of green leaves could be directly related to the rates of K used in the applied fertilizers, whereas the low K concentration in the fertilizer treatments of the leaf litter could be more withdrawn prior to leaf senescence or leached by rain from the tree canopy. For example, higher fluxes of K in the throughfall were found at more fertile sites compared with sites with a poorer nutrient status (Hagen-Thorn et al. 2006). The varying compound ratios of fertilizer had minor effects on the Ca concentrations within the green leaves or leaf litter (Table 4). However, the lowest Ca concentration was observed in the $N_3P_4K_1$ treatment, which might be attributed to the lowest Ca in the soil horizons (Table 2) because the soil nutrients have been shown to be positively correlated with the nutrient concentrations of the leaf litter (Gower & Son 1992, Kim et al. 2005).

The nutrient content by leaf litter fall at the various compound ratios of fertilizer treatments (Table 5) corresponded to differences in the leaf litter amount or nutrient concentrations. The low N content in the $N_2P_2K_1$ treatment can be attributed to the lower N concentration compared with the other fertilizer treatments. However, the Ca and Mg content was closely related to the change in the leaf litter mass rather than to the Ca and Mg concentrations within the leaf litter (Table 4).

Nutrient use efficiency and nutrient resorption efficiency of leaf litter

Nutrient use efficiency is an effective index of nutrient availability and soil fertility, as plants with a lower nutrient status have a high nutrient use efficiency (Vitousek 1982). The nutrient use efficiency of the leaf litter could be lower in the fertilizer than in the $N_0P_0K_0$ treatments, as the leaf litter accumulated higher levels of nutrients through fertilizer application. In addition, the lowest P use efficiency was exhibited for the highest dose of fertilizer, such as the $N_3P_8K_1$ treatment. In contrast to the P use efficiency (Figure 1), the K use efficiency was higher in the fertilizer treatments than in the $N_0P_0K_0$ treatment due to the low resorption efficiency of this nutrient (Figure 2) and may be partially explained by the difference in the inherent soil nutrients rather than the subsequent fertilizer applications.

The resorption of nutrients before leaf abscission is an important mechanism in the conservation of tree nutrients and may increase generally as an inverse function of the soil nutrient availability (Nambiar & Fife 1991, Hagon-Thorn et al. 2006). The N and P resorption efficiency between the green leaves and leaf litter was generally higher in the fertilizer treatments rather than in the $N_0P_0K_0$ treatment (Figure 2). The high resorption efficiencies of N and K could be due to an increase in the availability of N and K after fertilization. However, the N and K resorption efficiencies were not responsible for the increased dose of the fertilizer. In addition, the P resorption efficiency in the fertilizer treatments was unaffected by varying the compound ratios of P. The Ca resorption efficiency was generally related to the inherent soil chemical properties rather than to the application level of the fertilizer. For example, the $N_3P_4K_1$ treatment showed the highest Ca resorption efficiency with the lowest soil Ca, whereas the $N_3P_8K_1$ treatment showed the lowest Ca resorption efficiency with the highest soil Ca (Table 2). Similarly, the lowest resorption of Mg in the $N_3P_8K_1$ treatment could be attributed to the highest Mg in the soil horizons.

Conclusions

Growth characteristics, such as leaf litter fall, were not affected by various compound ratios of fertilizer, whereas the fertilizers with high doses of N or P produced high N or P concentrations in the green leaves of a sawtooth oak. However, the nutrient concentration and content in the leaf litter were barely affected by the various compound ratios of fertilizer. Nutrient use and resorption efficiencies are only weakly controlled by various compound ratios of fertilizer application, except for the highest dose of P fertilizer. The results indicate that the status of nutrient in green leaves was depended on fertilizer doses, although there was no clear effect on the litter fall or nutrient status in leaf litter at various compound ratios of fertilizer application.

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