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Fertilisation Effects on Edaphic Properties in Different Soil Types in Relation to *Castanopsis sieboldii* Sapling Growth

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Abstract. Background: Urban soils often have low-nutrient levels, reduced biota, and frequently depauperate humus. *Castanopsis sieboldii* trees planted in cities may grow poorly in some areas. This study investigated the effects of soil chemical and biological properties on *C. sieboldii* growth. Methods: Individual and compound impacts of N (nitrogen), P (phosphorus), K (potassium), and Ca (calcium) on saplings grown in humic topsoil, humic subsoil, and river sand were investigated. Results: Addition of N alone and combined with P, K, and Ca affected *C. sieboldii* growth in humic topsoil and subsoil. Applications of N alone, in river sand with low levels of available nutrients, had no impact. However, combined nutrients such as N with P, K, and Ca increased shoot and root dry weights, number of leaves, and soil and plant analyser development (SPAD). Additionally, NPCa and NPK resulted in higher values than individual N for dry weights of shoots and roots as well as for shoot dry weights in river sand. NPKCa application resulted in increased diameter at the base of the first branch in humic topsoil over N alone. NPK produced more leaves in humic subsoil than just N. Moreover, *C. sieboldii* produced the greatest growth in humic topsoil, followed by humic subsoil, and finally unfertilised river sand. Conclusion: Nitrogen application with additional P, K, and Ca was beneficial to growth under test conditions. *Castanopsis sieboldi* growth was enhanced under field conditions with humic topsoil and combined nutrients. Low available P, K, and Ca may be limiting factors restricting performance impacts of N when added alone to low-nutrient soils.

Keywords. Humic; Leaf Litter; Nitrogen; Soil Biological Property; Soil Nutrition.

INTRODUCTION

Many Japanese cities are located on flat land prone to flooding or stagnant conditions. The physical properties of soils in these areas tend to include low gaseous ratios due to stagnant water, paving, or trampling (Masuda et al. 1981). Stagnant water and low gas content influence the distribution of trees and other plants, favouring species tolerant of these conditions. Additionally, urban soils have less vegetation cover and fewer fallen leaves than soils in natural conditions, and this affects nutrient cycling and availability. Autumnal leaf litter is often removed rather than being left to decompose, resulting in lower levels of available nutrients, reduced carbon content, and diminished soil biotas (Schaffert et al. 2022). Clearly, urban soils and associated factors influence the distribution of trees and other plants so that species in towns and cities are those tolerant of such conditions.

Castanopsis sieboldii (Makino) Hatusima ex Yamazaki et Mashiba (Fagaceae) is an evergreen broadleaf tree distributed in the warm temperate zone from Central to Southern Japan (Numata and Iwase 1975). It is planted in a range of situations such as parks and gardens. However, due to factors such as soil compaction associated with human trampling, some specimens do not grow well in urban situations. Consequently, giant *C. sieboldii* trees with broken crowns, trunks, and branches, or with fungal infections, are often observed in gardens, parks, temples, and shrines, such as in Tokyo and its suburbs (Xu et al. 2018). This is a concern for site managers.

The effects of soil physical properties, particularly the gaseous phase ratios on the growth of *C. sieboldii*, have been reported. Giant trees were mostly distributed above the 10-m contour line, on plateaux or hills, and especially on slopes along the edges of the 10-, 30-, 120-, 170-, and 210-m contour lines on flat uplands. Trees growing on slopes, plateaux, and hilltops or mountain tops, or along the edges of plateaux, represent 80% of the total recorded trees (Watanabe et al. 2021). As water flows easily in these landforms (Anderson et al. 1997; Montgomery et al. 1997), soil physical properties, especially the gaseous, liquid, and solid phase ratios in the soil, might be the significant factors controlling growth. Therefore, experiments were performed with different physical properties using young plants planted in pots. This was achieved by mixing in soil-improving materials or exposing the plants to water stagnation in sand. The results showed that the gaseous-phase ratio had a stronger effect on the growth of *C. sieboldii* than on species such as *Cinnamomum camphora* (Matsunaga et al. 2024; Matsunaga et al. 2025).

There were some exceptions to the landforms normally associated with the distribution of *C. sieboldii*, with just a few giant trees located below the 10-m contour line in low-lying or reclaimed lands and in areas that experience stagnant conditions (Watanabe et al. 2021). It appears, therefore, that the growth of *C. sieboldii* cannot be determined solely by soil physical properties. The apparent exceptions in the distribution of giant trees, as well as the poor growth of some trees in urban areas, may be attributed to chemical and biological soil properties in addition to the soil physical characteristics. Some studies have indicated that humus influences *C. sieboldii* growth (Watanabe and Maruta 1992; Sahara et al. 2023). However, the specific effects of these nutrients have not yet been clarified.

In this study, the effects of individual or compound N (nitrogen), P (phosphorus), K (potassium), and Ca (calcium) in humus derived from leaf litter on the growth of *C. sieboldii* saplings were investigated. In addition, these experiments were performed using humic topsoil, humic subsoil, and river sand containing high levels of available N, P, K, and Ca with either high or low levels of humus to determine. The experimental treatments were intended to shed light on *C. sieboldii* growth under natural conditions.

The research questions were as follows: (1) is the growth of *C. sieboldii* seedlings under controlled experimental conditions restricted or facilitated by specific additions of macronutrients alone or in combination; (2) do any effects of nutrient additions vary between typical soil types from urban areas where *C. sieboldii* is found; and (3) do the findings from controlled growth experiments in pots provide insights into the performance of *C. sieboldii* in the field?

MATERIALS AND METHODS

Fertiliser Experiments and Analysis of Nutrient Impacts

The impacts of nutrients and soil type on *C. sieboldii* growth using 0.05-m^2 Wagner pots in the Tokyo University of Agriculture field site (35.642649, 139.630235) were investigated (Figure 1). The outdoor sites were unshaded (open area) and were well ventilated. The growing tree saplings were watered by hand daily with 1 L in the summer, i.e., July to mid-September. The average annual temperature and precipitation at the site are 15.8 °C and 1,598.2 mm, respectively (Japanese Meteorological Agency 2025).

The 4 fertilisers used in the tests were N, P, K, and Ca. Based on previous fertiliser tests (Sugiyama et al. 2002), 10 pot treatments were used with the 4 nutrients in 3 replicates: pots unfertilised (control), N pot, P pot, K pot, Ca pot, without N pot (PKCa pot), without P pot (NKCa pot), without K pot (NPCa pot), without Ca pot (NPK pot), and the NPKCa pot.

Firstly, impacts of individual N, P, K, and Ca were determined by calculating the differences in growth values between PKCa, NKCa, NPCa, NPK, and NPKCa to evaluate the individual impacts. Each N, P, K, and Ca addition was considered to have an impact if there was a negative difference between the treatments.

Secondly, the impacts were assessed by calculating the differences in values between unfertilised pots and those with individual N, P, K, and Ca added. Each N, P, K, and Ca pot was considered to have an effect if there were positive differences in growth.

Thirdly, if there were both impacts between PKCa, NKCa, NPCa, NPK, and NPKCa, and between N, P, K, Ca, and unfertilised, the individual N, P, K, and Ca applications were considered to affect *C. sieboldii* growth. For example, N influenced the number of *C. sieboldii* leaves when PKCa application growth was less than NPKCa. Growth with N was generally greater than in unfertilised soil.

The compound impact was determined by calculating the difference between PKCa, NKCa, NPCa, NPK, NPKCa, and unfertilised or individual N. If the growth with compound fertiliser was greater than that of the unfertilised or N alone, the compound fertiliser had a positive impact.

Figure 1. Experimental pots with humic topsoil (left), humic subsoil (centre), and river sand (right) on 2019 April 16.

Two-way repeated ANOVA ($P < 0.05$) with elements of soil types, fertilisation, and their interactions were used to confirm statistical differences in all measured values. Tukey's tests ($P < 0.05$) were conducted at difference between PKCa, NKCa, NPCa, NPK, and NPKCa, and between unfertilised and individual N, P, K, Ca to determine the individual impacts, and the differences between PKCa, NKCa, NPCa, NPK, NPKCa, and unfertilised/N to gauge compound impacts.

Table 1. Plant materials used for the fertiliser test. Values in each column represent the average (above) and the standard deviation (below). Avg (average); Std (standard deviation); MTD (main truk diameter close to the ground); DBF (diameter at the base of the first branch).

		Humic topsoil	Humic subsoil	River sand
Weight of both shoots and roots (g)	Avg.	48.3	51.4	49.6
	Std.	18.0	15.8	11.3
Length of main root (cm)	Avg.	39.8	36.2	44.2
	Std.	12.9	15.8	8.5
Number of leaves	Avg.	43.5	55.9	59.5
	Std.	21.5	15.9	20.7
Tree height (cm)	Avg.	35.8	36.9	53.8
	Std.	5.3	4.5	5.7
MTD (mm)	Avg.	7.0	7.5	7.4
	Std.	2.1	1.5	1.4
Number of first branches	Avg.	7.9	8.4	8.6
	Std.	2.7	2.2	2.0
DBF (mm)	Avg.	2.6	1.2	1.9
	Std.	0.8	1.2	0.6
Length of first branch (cm)	Avg.	9.1	9.1	9.0
	Std.	6.7	5.1	5.3

Growth Differences Under Three Soil Types

Growth was measured in unfertilised pots to evaluate the effects of humic topsoil, humic subsoil, and river sand with varying humus content (C-N) on *C. sieboldii* to mimic soil conditions in the field.

Plant Materials and Experimental Pots

Small plants (90 samples), each approximately 60 cm tall, were used for pot experiments. The weights of both shoots and roots and the lengths of their main roots are presented in Table 1. At planting, the average weight and main root length of the plants were 48.3 g to 51.4 g and 36.8 cm to 44.2 cm, respectively. The experiment began after saplings had been planted and acclimatised for 1 to 2 months to eliminate any influences of plant health or problems with vigour.

The pots used for the experiment were Wagner pots with a surface area of 0.05 m^2. They were made from white high-impact styrene resin. Each pot measured φ256 (upper diameter) × φ234 (lower diameter) × 297 mm (height). The distance between each other was approximately 30 cm. Gravel (3.1 kg) of 0.5 cm to 1.0 cm diameter was placed in the pot as the base, and 2 kg of river sand was poured onto the gravel in all pots. Additionally, 17.9 kg of river sand, 8.4 kg of humic subsoil, or 9.0 kg of humic topsoil were added to the Wagner pots containing gravel and river sand.

Soil Materials for Experiments

The soils used for the fertiliser experiments were humic topsoil, humic subsoil, and river sand. The humic topsoil was Kanto loam topsoil with humus. The humic subsoil was a Kanto loam subsoil widely found in Eastern Japan (Ohkura et al. 1993). The humic topsoil is referred to as Kurobokudo (Hosono and Sase 2015) and classified as Andosols according to the IUSS (2007). The soil is black with a high level of humus, a high phosphate absorption coefficient, and is present in most soil A horizons. It is referred to as the Kanto loam humic soil layer (allophane). The humic subsoil is below the humic topsoil and is present in most of the brown soil horizons (soil B horizon). Brown forest soils are classified as Cambisols by FAO (1998) and are referred to as Kanto loam subsoils (light soils without humus). In general, humic subsoils have a low base saturation percentage (Hatano et al. 2021). River sand consisted of fine (0.02 mm to 0.2 mm) and coarse (0.2 mm to 2.0 mm) sand without nutrients. Humic topsoil was used because it is the natural substrate in which *C. sieboldii* occurs. Humic subsoil was used for comparison with humic topsoil, which had the same loam soil but without humus. River sand was used as a control to compare the humic topsoil and subsoil.

The concentrations of NH_4^+, NO_3^-, PO_4^{3-}, K^+, Ca^{2+}, C, and N were measured to evaluate the soil chemical properties, and liquid, gaseous, and solid phases. This was used to evaluate the physical properties of soil in the Wagner pots during the experimental period. Two soil samples were collected from the surface of each pot for soil chemical analysis in December 2019 for the river sand and in August 2020 for the humic topsoil and subsoil. The soil taken from the Wagner pots was oven-dried at 105 °C for 18 hr. Thereafter, 12 g of dried soil sample was added to 30-mL ultra-pure water in a 50-mL plastic filtration bottle with a 3.5-cm diameter. Filter paper was placed between the two bottles without a lid. The bottle containing the soil and water was shaken for 3 min and left to stand until 20 mL was filtered. Then, the filtered soil water was poured into 50-mL conical tubes and stored in a refrigerator for 1 day. Soil pH was then measured using a pH meter (HM-60G; DKK-TOA Corporation, Tokyo, Japan). The NH_4^+, NO_3^-, PO_4^{3-}, K^+, and Ca^{2+} were measured to determine the N, P, K, and Ca concentrations using laboratory analysers and an ion analyser (IA-300; DKK-TOA Corporation, Tokyo, Japan). C/N was measured using a Vario MAX CN Macro Elemental Analyser (Elementar Analysensysteme GmbH, Langenselbold, Germany). The ratios of the liquid, gaseous, and solid phases were measured using a digital voluminometer (DIK-1150; Daiki Rika Kogyo Co., Ltd, Hongsu City, Japan).

As shown in Table 2, both the humic topsoil and subsoil were weakly acidic, whereas the pH of river sand was nearly neutral. The humic topsoil had high NO_3^- and NH_4^+. PO_4^{3-} and K^+ concentrations were lower in the humic topsoil than in the humic subsoil and river sand. The lowest Ca^{2+} concentration was found in the river sand, and the highest was found in the humic topsoil. The highest C and N contents were found in the humic topsoil, followed by the humic subsoil. River sand contained only small amounts of C and N. Regarding soil physical characteristics, both humic topsoil and subsoil showed clay and clay loam properties, and river sand contained 85% to 100% sand. The solids ratio of the river sand was twice that

Table 2. Chemical, biological, and physical properties of soils used for the fertiliser test.

Soil property		Humic topsoil	Humic subsoil	River sand
Chemical	pH	5.6	6.2	6.6
	NO_3^- (mg/L)	145.3	63.0	17.1
	NH_4^+ (mg/L)	4.9	2.3	1.5
	PO_4^{3-} (mg/L)	25.0	9.5	4.3
	K^+ (mg/L)	6.9	7.5	8.4
	Ca^{2+} (mg/L)	53.7	9.8	2.3
Biological	C (%)	23.77	4.87	0.24
	N (%)	1.82	0.42	0.01
	C/N	13.1	11.6	20.9
Physical	Solid ratio (%)	27.6	21.4	56.9
	Gaseous ratio (%)	20.2	26.6	41.7
	Volumetric water content (liquid ratio) (%)	52.2	52.0	1.4

of the humic topsoil and subsoil. The gaseous ratio was highest in river sand, followed by humic subsoil and humic topsoil. The volumetric water content (liquid ratio) was approximately 50% for humic topsoil and subsoil but was only 1.4% for river sand.

Fertilisers for Experiments

The fertilisers used for these experiments were urea $(NH_2)_2CO$, which contains 46% N; calcium superphosphate ($Ca[H_2PO_4]_2$), which contains 17.5% water-soluble phosphoric acid; potassium chloride (KCl), which contains 60% water-soluble potassium; and slaked lime ($Ca[OH]_2$), which contains 70% CaO equivalent. Each fertiliser element was supplied at 10 g/m^2 under pure-element conditions: N, 1.09 g; P_2O_5, 3.45 g; K_2O, 0.83 g; and $Ca(OH)_2$, 0.71 g/year. These were slow-release, granule-type, uncoated fertilisers. The granules were ground into powder and mixed thoroughly with the soil in each pot before application.

Fertiliser was applied 6 times (August 2017, July 2018, and January, April, July, and October 2019) in river sand pots, and 3 times (August 2018, February 2020, and November 2020) in humic subsoil and topsoil (Table 3).

Table 3. Experimental design for fertilisation effects on edaphic properties in different soil types in relation to *Castanopsis sieboldii* sapling growth.

Date	Humic topsoil and subsoil	River sand
2017 June 30		Planted in pots
2017 August		First fertilisation
2017 August 24		Measurement (0 months)
2017 October 3		Measurement (2 months)
2017 December 16		Measurement (4 months)
2018 February 14		Measurement (6 months)
2018 April 10		Measurement (8 months)
2018 June 13		Measurement (10 months)
2018 June 17	Planted in pots	
2018 July		Second fertilisation
2018 July 20	Measurement (0 months)	
2018 August	First fertilisation	
2018 August 17		Measurment (12 months)
2018 September 28	Measurement (2 months)	
2018 October 20		Measurment (14 months)
2018 November	Measurement of soil physical properties (4 months)	Measurement of soil physical properties (15 months)
2018 November 26	Measurement (4 months)	
2018 December 15		Measurement (16 months)
2019 January		Third fertilisation
2019 February 18		Measurement (18 months)
2019 April		Fourth fertilisation
2019 April 16	Measurement (9 months)	
2019 April 20		Measurement (20 months)
2019 June 11		Measurement (22 months)
2019 July		Fifth fertilisation
2019 July 5	Measurement (12 months)	
2019 August 17		Measurement (24 months)

Table 3 continued on next page

Table 3. Continued.

Date	Humic topsoil and subsoil	River sand
2019 September 26	Measurement (14 months)	
2019 October		Sixth fertilisation
2019 October 20		Measurement (26 months)
2019 December		Measurement of soil chemical properties (28 months)
2019 December 19		Measurement (28 months)
2020 February	Second fertilisation	
2020 February 17		Measurement (33 months)
2020 August	Measurement of soil chemical properties (25 months)	
2020 August 1	Measurement (25 months)	
2020 August 9		Measurement (40 months)
2020 May 10		Measurement (46 months)
2020 November	Third fertilisation	
2020 November 11	Measurement (28 months)	
2021 April 27	Measurement (33 months)	
2021 November 1	Measurement (40 months)	
2022 May 17	Measurement (46 months)	
2022 September 21		Measurement of shoots and roots (5 years 3 months)
2022 November 20	Measurement of shoots and roots (4 years 5 months)	

Experimental Periods and Place

As shown in Table 3, the saplings in river sand were planted 2017 June 30 after measuring the plant weight and main root length. The experiment concluded 2022 September 21 (5 years and 3 months later) following measurements of shoot and root weights. The experimental materials in humic topsoil and humic subsoil were planted 2018 June 17 after measuring the plant weight and main root length, and concluded 2022 November 20 (4 years and 5 months later) following measurements of shoot and root weights. The pots were placed at a field site (35.642824, 139.630212) at the Tokyo University of Agriculture, Setagaya Campus, Sakuragaoka, Setagaya-ku, Tokyo, Japan. The pots were arranged in rows for each of the humic topsoil, subsoil, and river sand, but to eliminate any influence on growth because of positioning, the rows and the locations of individual pots within the rows were rotated once a month.

Evaluation of Growth

Eight attributes were measured to compare the *C. sieboldii* growth under different soil conditions: (1) dry weights of shoots and/or roots; (2) number of leaves; (3) tree height; (4) main trunk diameter close to the ground (MTD); (5) soil and plant analyser development (SPAD) value; (6) length of the first branch; (7) number of first branches; and (8) diameter at the base of the first branch (DBF).

1. The dry weights of shoots and roots were measured after drying using a hot air drier at 105 °C for 18 hr. This was after completion of the experiment on 2022 November 20 in humic topsoil and humic subsoil and 2022 September 21 in river sand.
2. The leaves on all first branches that grew from the main stem were counted as the number of leaves on all branches of the plant in each pot.
3. Tree height was measured from the base to the top of the trunk using a measuring tape.
4. The MTD was measured using an electronic micrometre calliper.
5. The SPAD value, i.e., the difference between the transmittance of red (650 nm) and infrared (940 nm) light through the leaf, was measured

using SPAD-502 Plus software (Konica Minolta, Inc., Tokyo, Japan).

6. The length from the base to the tip of the first branch was measured using a measuring tape.
7. The numbers of living first branches were counted.
8. The DBF was measured using an electronic micrometre calliper.

All data were collected at 2- or 6-month intervals and used to calculate averages and differences between data at the first and each collection date, except for the SPAD value.

RESULTS

Two-Way Repeated ANOVA for the Effects of Soil Types and Fertilisation on *Castanopsis sieboldii* Growth

There were statistically significant differences shown for soil types, fertilisation, and interactions between them on dry weight of shoots and roots, dry weight of roots, number of leaves, MTD, SPAD, DBF, and length of first branch. Significant differences were demonstrated for fertilisation, and interaction between dry weight of shoots, soil types, and fertilisation in tree height, and fertilisation at number of first branches were detected (Table 4).

Table 4. Two-way repeated ANOVA of soil types, fertilisation, and the interaction between them. SS (sum of squares); DF (degrees of freedom); MS (mean squares); *F* (*F*-value); MTD (main trunk diameter close to the ground); SPAD (soil and plant analyser development); DBF (diameter at the base of the first branch).

		Factor	SS	DF	MS	*F*	*P*	
Dry weight	Shoots and roots	Soil types	14635.6327	2	7317.8163	12.1098	$P < 0.001$	**
		Fertilisation	179192.1743	9	19910.2416	32.9483	$P < 0.001$	**
		Interaction	34639.2273	18	1924.4015	3.1846	$P < 0.001$	**
		Error	36257.2467	60	604.2874			
		All	264724.2810	89				
	Shoots	Soil types	434.8869	2	217.4434	2.3514	0.1040	
		Fertilisation	40262.6810	9	4473.6312	48.3768	$P < 0.001$	**
		Interaction	11006.6487	18	611.4805	6.6124	$P < 0.001$	**
		Error	5548.4867	60	92.4748			
		All	57252.7032	89				
	Roots	Soil types	8574.4320	2	4287.2160	13.5007	$P < 0.001$	**
		Fertilisation	59746.5462	9	6638.5051	20.9050	$P < 0.001$	**
		Interaction	10967.6391	18	609.3133	1.9188	0.0313	*
		Error	19053.3067	60	317.5551			
		All	98341.9240	89				
Number of leaves		Soil types	109585.9305	2	54792.9653	63.0843	$P < 0.001$	**
		Fertilisation	339177.8766	9	37686.4307	43.3892	$P < 0.001$	**
		Interaction	54611.4638	18	3033.9702	3.4931	$P < 0.001$	**
		Error	52114.0583	60	868.5676			
		All	555489.3292	89				
Tree height		Soil types	2271.3534	2	1135.6767	30.6235	$P < 0.001$	**
		Fertilisation	2683.0389	9	298.1154	8.0387	$P < 0.001$	**
		Interaction	834.8057	18	46.3781	1.2506	0.2534	
		Error	2225.1082	60	37.0851			
		All	8014.3062	89				

Table 4 continued on next page

Table 4. Continued.

	Factor	SS	DF	MS	*F*	*P*	
MTD	Soil types	156.5943	2	78.2972	65.5153	$P < 0.001$	**
	Fertilisation	285.5618	9	31.7291	26.5494	$P < 0.001$	**
	Interaction	83.0509	18	4.6139	3.8607	$P < 0.001$	**
	Error	71.7058	60	1.1951			
	All	596.9129	89				
SPAD	Soil types	586.7505	2	293.3753	38.9315	$P < 0.001$	**
	Fertilisation	2095.7964	9	232.8663	30.9019	$P < 0.001$	**
	Interaction	326.6201	18	18.1456	2.4080	0.0058	**
	Error	452.1402	60	7.5357			
	All	3461.3072	89				
Number of first branches	Soil types	3.0616	2	1.5308	0.3861	0.6814	
	Fertilisation	279.9542	9	31.1060	7.8446	$P < 0.001$	**
	Interaction	46.7621	18	2.5979	0.6552	0.8396	
	Error	237.9163	60	3.9653			
	All	567.6943	89				
DBF	Soil types	3785.4408	2	1892.7204	71.7535	$P < 0.001$	**
	Fertilisation	5105.0735	9	567.2304	21.5038	$P < 0.001$	**
	Interaction	2767.8124	18	153.7674	5.8294	$P < 0.001$	**
	Error	1582.6858	60	26.3781			
	All	13241.0124	89				
Length of first branch	Soil types	376.2201	2	188.1100	32.4283	$P < 0.001$	**
	Fertilisation	791.8296	9	87.9811	15.1671	$P < 0.001$	**
	Interaction	214.4189	18	11.9122	2.0535	0.0198	*
	Error	348.0478	60	5.8008			
	All	1730.5163	89				

*$P < 0.05$
**$P < 0.01$

Individual or Compounds of N, P, K, and Ca on *Castanopsis sieboldii* Growth

Dry Weight of Shoots and Roots

Addition of N alone produced significant impact on *C. sieboldii* growth, with PKCa lower than NPKCa. Added N resulted in higher growth than that in unfertilised pots in humic topsoil and humic subsoil, but there was no impact of individual nutrients in river sand. In both humic topsoil and humic subsoil, the compound impacts on growth of NKCa, NPCa, NPK, and NPKCa were higher than those of the unfertilised treatment. In river sand, those of NPCa and NPK were higher than those of the unfertilised treatment.

In river sand, comparison of the compound impacts with individual N, NPCa, and NPK additions resulted in higher growth effects than just N (Table 5).

Dry Weight of Shoots

For individual nutrients, N in the humic topsoil and humic subsoil resulted in increased growth. NPKCa was greater than PKCa, and N was higher than unfertilised. There was no impact of N on shoots in river sand. In both humic topsoil and humic subsoil, the

Table 5. Individual and compound impacts of nutrients in the fertiliser test. Individual impact is difference between PKCa, NKCa, NPCa, NPK, and NPKCa, and between unfertilised and individual N, P, K, Ca. Compound impact is difference between PKCa, NKCa, NPCa, NPK, NPKCa, and unfertilised/N which represent significant differences using Tukey's test in *$P < 0.05$ and **$P < 0.01$. N (nitrogen); P (phosphorus); K (potassium); Ca (calcium); MTD (main trunk diameter close to the ground); SPAD (soil and plant analyser development); DBF (diameter at the base of the first branch).

		Individual impact Difference from NPKCa				Individual impact Difference from unfertilised				Compound impact Difference from unfertilised					Compound impact Difference from N				
		PKCa	NKCa	NPCa	NPK	N	P	K	Ca	PKCa	NKCa	NPCa	NPK	NPKCa	PKCa	NKCa	NPCa	NPK	NPKCa
Humic topsoil	Dry weight of shoots and roots	−71.3*	33.5	45.7	23.5	90.0**	−15.1	−0.1	−19.7	−4.0	100.8**	113.0**	90.9**	67.3*	−94.0**	10.8	23.0	0.9	−22.7
	Dry weight of shoots	−34.0**	6.8	4.0	−4.7	31.7**	−5.0	6.2	−3.4	4.0	44.8**	42.0**	33.3**	38.0**	−27.7*	13.1	10.3	1.6	6.3
	Dry weight of roots	−37.3	26.7	41.7	28.2	58.3**	−10.1	−6.3	−16.3	−8.0	56*	71.0**	57.5**	29.3	−66.3**	−2.3	12.7	−0.7	−28.9
	Number of leaves	−77.9	21.2	36.0	−10.5	101.2**	−36.1	1.3	−38.3	35.8	134.9**	149.8**	103.3**	113.8**	−65.4	33.7	48.6	2.1	12.5
	Tree height	−12.3	−7.8	−6.6	−5.9	11.8	4.5	0.9	1.7	3.1	7.6	8.7	9.5	15.4	−8.7	−4.2	−3.0	−2.3	3.6
	MTD	−6.3**	−0.6	−1.8	−0.6	2.4	−0.5	−0.6	−0.2	−1.5	4.2**	3.0*	4.2**	4.9**	−3.8**	1.9	0.7	1.9	2.5
	SPAD	−7.5*	−0.7	0.0	0.0	7.5*	3.7	−0.3	−1.0	1.0	7.8*	8.5*	8.4*	8.5*	−6.5	0.2	1.0	0.9	0.9
	Number of first branches	−8.0**	−4.1	−3.6	−2.8	1.3	0.3	−0.9	−1.1	−2.5	1.3	1.9	2.7	5.5*	−3.9	0.0	0.5	1.3	4.1
	DBF	−34.4**	−14.7*	−14.6*	−10.1	11.2	1.7	−4.6	−5.9	−4.0	15.7*	15.9*	20.3**	30.5**	−15.2*	4.5	4.7	9.1	19.2**
	Length of first branch	−8.0*	−3.3	−6.5	0.4	2.7	−1.8	0.9	−1.3	−0.6	4.1	1.0	7.8**	7.4*	−3.3	1.4	−1.7	5.2	4.7
Humic subsoil	Dry weight of shoots and roots	−75.0*	14.4	39.6	7.9	134.6**	14.6	−4.9	0.4	24.1	113.5**	138.7**	107.1**	99.1**	−110.4**	−21.0	4.2	−27.5	−35.4
	Dry weight of shoots	−43.1**	−2.2	5.1	−2.3	60.2**	7.9	0.3	4.2	13.2	54.1**	61.5**	54.0**	56.3**	−47.0**	−6.0	1.3	−6.2	−3.8

Table 5 continued on next page

Table 5. Continued.

		Individual impact Difference from NPKCa				Individual impact Difference from unfertilised				Compound impact Difference from unfertilised					Compound impact Difference from N				
		PKCa	NKCa	NPCa	NPK	N	P	K	Ca	PKCa	NKCa	NPCa	NPK	NPKCa	PKCa	NKCa	NPCa	NPK	NPKCa
Humic subsoil	Dry weight of rootss	−31.9	16.6	34.5	10.3	74.4**	6.7	−5.1	−3.8	10.9	59.4**	77.3**	53.1*	42.8	−63.5**	−15.0	2.9	−21.3	−31.6
	Number of leaves	−138.7**	−13.0	18.9	40.7	115.8**	25.6	−14.2	−8.8	23.3	149**	180.9**	202.7**	162.0**	−92.5*	33.2	65.1	86.8*	46.2
	Tree height	−19.7**	−6.9	0.6	−1.0	16.4*	0.0	−0.5	2.2	0.7	13.5	21.0**	19.4**	20.4**	−15.7	−2.9	4.6	3.0	4.0
	MTD	−6.2**	−1.3	−0.5	−1.5	4.1**	0.6	−0.1	0.5	0.2	5.1**	5.9**	4.9**	6.4**	−3.9**	1.0	1.7	0.8	2.3
	SPAD	−15.5**	−1.7	−3.2	−3.2	14.9**	2.1	−0.4	−0.8	0.7	14.4**	12.9**	12.9**	16.1**	−14.3**	−0.6	−2.1	−2.0	1.2
	Number of first branches	−6.1*	−4.5	−2.4	−2.3	3.8	0.8	−0.7	−0.3	−0.3	1.2	3.3	3.5	5.7*	−4.1	−2.6	−0.5	−0.3	1.9
	DBF	−26.6**	−12.8	−18.1**	−1.6	23.5**	4.3	−1.0	1.4	2.2	16.0*	10.7	27.2**	28.8**	−21.3**	−7.5	−12.8	3.7	5.3
	Length of first branch	−7.2*	−0.9	3.9	2.2	5.6	0.2	−0.4	1.5	0.5	6.8*	11.7**	9.9**	7.7**	−5.1	1.2	6	4.3	2.1
River sand	Dry weight of shoots and roots	−5.0	16.7	46.7	73.3*	11.7	13.3	−1.7	18.3	30	51.7	81.7**	108.3**	35	18.3	40	70*	96.7**	23.3
	Dry weight of shoots	−8.3	6.7	61.7**	41.7**	−5	5	−3.3	8.3	5	20	75**	55**	13.3	10	25	80**	60**	18.3
	Dry weight of roots	3.3	10	21.7	31.7	16.7	8.3	1.7	10	25	31.7	43.3	53.3*	21.7	8.3	15	26.7	36.7	5
	Number of leaves	−91.7*	−65.6	−65.1	−44.1	74	31.7	22.9	19.6	53.9	79.9*	80.5*	101.5**	145.5**	−20.2	5.9	6.4	27.4	71.5
	Tree height	−6	−9.9	−2.5	−2.2	4.4	2.2	0.1	3.3	4.2	0.3	7.7	7.9	10.2	−0.2	−4.1	3.3	3.6	5.8
	MTD	−0.7	−0.6	0.2	0.7	1.1	0.2	0.4	0.5	0.8	0.8	1.7	2.2	1.5	−0.3	−0.3	0.6	1.1	0.4
	SPAD	−2.3	4.8	−0.3	−0.5	8.1*	1.9	0.5	−2.3	4.1	11.2**	6.1	5.9	6.4	−4.1	3.1	−2	−2.3	−1.7

Table 5. Continued.

		Individual impact Difference from NPKCa				Individual impact Difference from unfertilised				Compound impact Difference from unfertilised					Compound impact Difference from N				
		PKCa	NKCa	NPCa	NPK	N	P	K	Ca	PKCa	NKCa	NPCa	NPK	NPKCa	PKCa	NKCa	NPCa	NPK	NPKCa
River sand	Number of first branches	−2.4	−0.6	−0.6	−0.4	3.4	1	1.3	2	1.9	3.6	3.7	3.8	4.2	−1.6	0.2	0.2	0.4	0.8
	DBF	−0.4	−0.4	0.2	0.1	0.4	0	0	−0.3	0	0	0.6	0.5	0.4	−0.3	−0.4	0.2	0.1	0
	Length of first branch	−2.6	−2.9	0.6	1	3.2	1.2	0.2	0.2	2.1	1.9	5.3	5.8	4.7	−1.1	−1.4	2.1	2.5	1.5

growth with compound nutrients (NKCa, NPCa, NPK, and NPKCa) were higher than for unfertilised soil, but NPCa and NPK had significant impacts in river sand. As with the shoots and roots, NPCa and NPK gave higher growth than N alone in river sand (Table 5).

Dry Weight of Roots

Individual nutrient additions in humic topsoil, subsoil, and river sand did not affect root weight. With compound additions (NKCa, NPCa, and NPK), impacts on roots were greater than unfertilised treatment in humic topsoil and humic subsoil. NPK addition resulted in higher growth than unfertilised river sand (Table 5).

Number of Leaves

Individual nutrient additions did not affect number of leaves in humic topsoil or river sand. In humic subsoil, individual N had an impact with PKCa lower than NPKCa, and N addition meant more leaves than for unfertilised. For all compound nutrients (i.e., NKCa, NPCa, NPK, and NPKCa), number of leaves was higher than for unfertilised humic topsoil, humic subsoil, or river sand. Comparison of compound nutrient impacts with individual N and NPK showed stronger effects than N in humic subsoil (Table 5).

Tree Height

There was no impact on tree height of individual nutrients in humic topsoil or river sand. For the humic subsoil, N gave PKCa lower than NPKCa, and higher than unfertilised. Compound nutrient additions NPCa, NPK, and NPKCa, resulted in higher tree height than the unfertilised treatment in the humic subsoil. There was no difference between the compound and unfertilised treatments in the humic topsoil and river sand (Table 5).

Main Trunk Diameter Close to the Ground (MTD)

Individual nutrients did not affect MTD in the humic topsoil or river sand. N had an impact for MTD in humic subsoil, with the PKCa result lower than for NPKCa, and individual N impact was higher than the unfertilised treatment. Regarding compound nutrient impacts, NKCa, NPCa, NPK, and NPKCa were higher than the unfertilised treatment in humic topsoil and humic subsoil. There was no difference between the compound and unfertilised treatments in river sand (Table 5).

Soil and Plant Analyser Development (SPAD) Value

In terms of individual nutrient impacts, N had impact in humic topsoil and subsoil, with PKCa lower than for NPKCa and N higher than the unfertilised treatment. There was no impact on SPAD in river sand.

With compound nutrients, the impacts of NKCa, NPCa, NPK, and NPKCa in humic topsoil and humic subsoil, and NKCa in river sand, were higher than the unfertilised treatment (Table 5).

Number of First Branches

For the individual nutrient impacts, individual N, P, K, and Ca did not affect the number of first branches in humic topsoil, subsoil, and river sand. With compound nutrient application (NPKCa), the impact was higher than the unfertilised treatment only in humic topsoil and humic subsoil. In river sand, the number of first branches was unaffected by compound fertilisation treatments (i.e., PKCa, NKCa, NPCa, NPK, and NPKCa)(Table 5).

Diameter at the Base of the First Branch (DBF)

In terms of individual nutrients impacts, DBF was unaffected in humic topsoil and river sand. In humic subsoil, N had an impact with PKCa lower than NPKCa and N higher than unfertilised treatment. In the humic topsoil and subsoil, the impacts of NKCa, NPK, and NPKCa were higher than those of the unfertilised treatment. Additionally, NPCa was higher than unfertilised treatment in humic topsoil. There was no impact of compound nutrients in river sand. Comparing compound nutrient and individual N impacts, NPKCa showed higher DBF value than N humic topsoil (Table 5).

Length of First Branch

For the individual fertiliser impacts, there was no impact of individual nutrients in humic topsoil, subsoil, or river sand. With the compound nutrients, NPK and NPKCa gave higher growth than unfertilised treatment in humic topsoil. NKCa, NPCa, NPK, and NPKCa growth impacts were higher than unfertilised treatment in humic subsoil. In compound nutrient combinations (PKCa, NKCa, NPCa, NPK, and NPKCa) there was no impact on length of first branch in river sand (Table 5).

Comparison of *Castanopsis sieboldii* Growth Under Unfertilised Conditions

Dry Weight (T/R Ratio)

The total dry weights of shoots and roots in the humic topsoil, humic subsoil, and river sand were 86.9 g, 53.7 g, and 63.3 g, respectively, under unfertilised conditions (Figure 2), with no significant differences. Dry weight of shoots was the highest in the humic topsoil, followed by river sand, then humic subsoil.

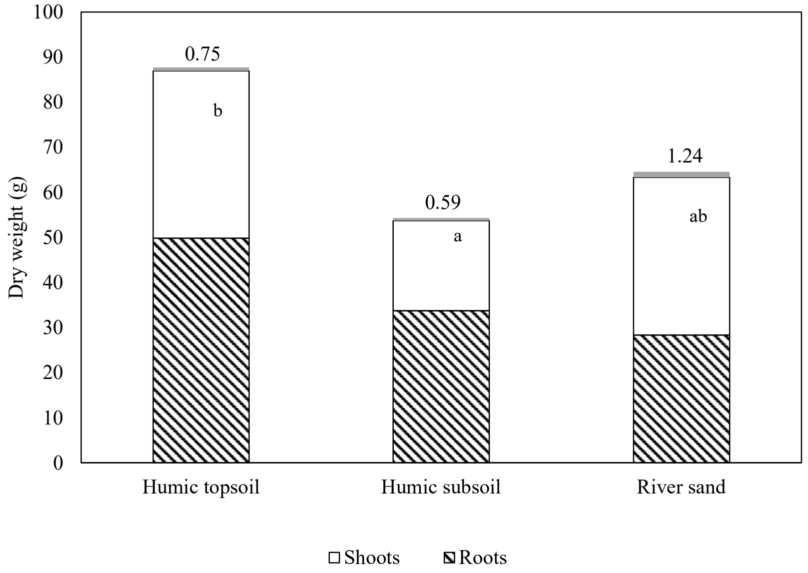

Figure 2. Shoot to root ratio under unfertilised conditions in humic topsoil, humic subsoil, and river sand. Letters represent statistical differences at *P* < 0.05 based on the *t*-test in shoots. There are statistical differences between different alphabets.

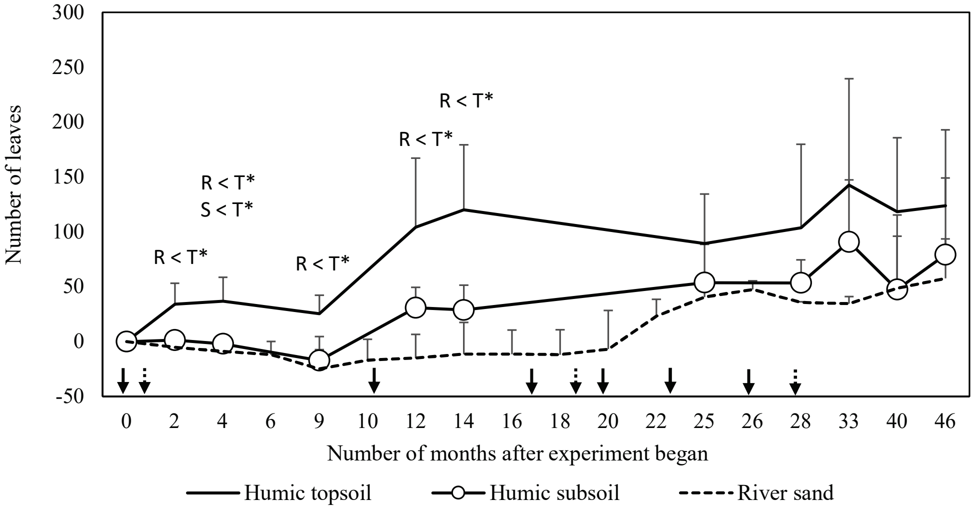

Figure 3. Number of leaves under unfertilised conditions in humic topsoil (line), humic subsoil (line with white circle marker), and river sand (dotted line). Line arrows indicate the fertilisation date for the river sand. The dotted line arrows indicate the fertilisation date for both humic topsoil and subsoil. Letters represent statistical differences at ****P* < 0.05 and *****P* < 0.01 among R (river sand), S (humic subsoil), and T (humic topsoil) based on the *t*-test. Vertical lines indicate standard deviation.

The dry weight of roots was lower than for shoots in river sand (T/R ratio = 1.24). Conversely, the dry weight of the shoots was lower than roots in humic subsoil (T/R ratio 0.59) or topsoil (T/R ratio 0.75).

Number of Leaves

The number of leaves under unfertilised conditions increased beyond 100 in humic topsoil and 50 in both humic subsoil and river sand (Figure 3). The highest number of leaves was found in humic topsoil, followed by humic subsoil, and finally river sand. The number of leaves in the humic subsoil or river sand was significantly lower than for humic topsoil ($P < 0.05$, at 2, 4, 9, 12, and 14 months).

Tree Height

The greatest tree height was observed in humic topsoil, followed by humic subsoil and river sand at 2, 4, 8, 12, and 14 months ($P < 0.05$) after the experiments began (Figure 4).

Main Trunk Diameter Close to the Ground (MTD)

The largest MTD was in the humic topsoil, followed by those in the humic subsoil and river sand. Significant differences were observed after 8 months of the experiment: humic subsoil < humic topsoil ($P < 0.05$) (Figure 5).

Soil and Plant Analyser Development (SPAD) Value

The average SPAD value was 26.0, 24.0, and 22.0 in humic topsoil, humic subsoil, and river sand, respectively: river sand < humic subsoil; river sand < humic topsoil (significance at $P < 0.05$). However, no differences were observed between humic topsoil and humic subsoil (Figure 6).

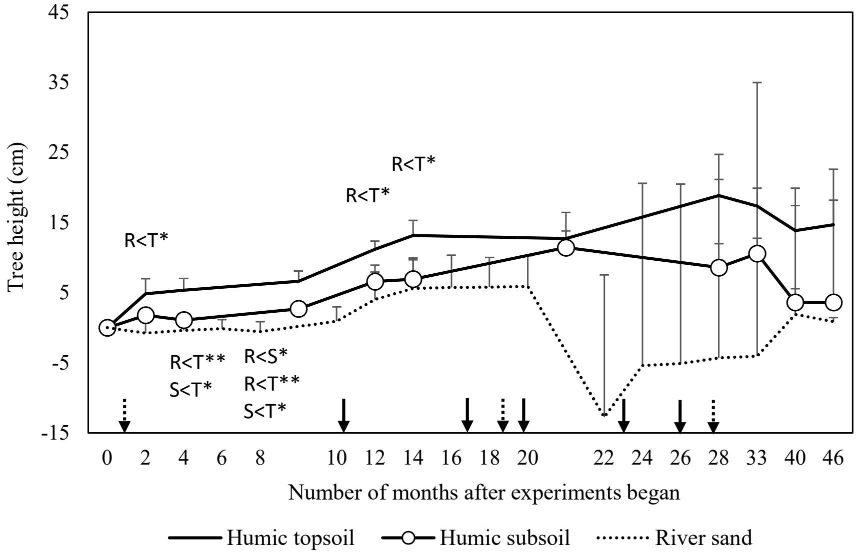

Figure 4. Tree height under unfertilised conditions in humic topsoil (line), humic subsoil (line with white circle marker), and river sand (dotted line). Line arrows indicate the fertilisation date for the river sand. The dotted line arrows indicate the fertilisation date for both humic topsoil and subsoil. Letters represent statistical differences at *P < 0.05 and **P < 0.01 among R (river sand), S (humic subsoil), and T (humic topsoil) based on the *t*-test. Vertical lines indicate standard deviation.

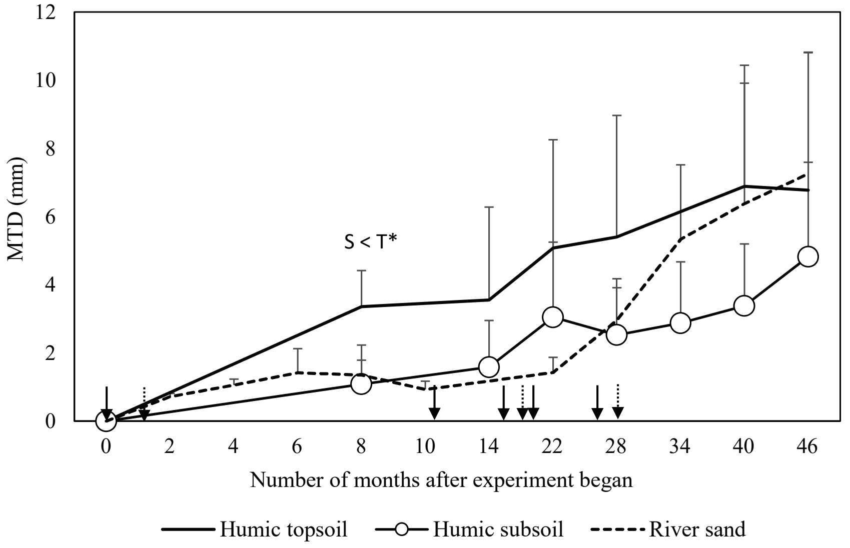

Figure 5. Main trunk diameter close to the ground (MTD) under unfertilised conditions in humic topsoil (line), humic subsoil (line with white circle marker), and river sand (dotted line). Line arrows indicate the fertilisation date for the river sand. The dotted line arrows indicate the fertilisation date for both humic topsoil and subsoil. Letters represent statistical differences at *P < 0.05 and **P < 0.01 among R (river sand), S (humic subsoil), and T (humic topsoil) based on the *t*-test. Vertical lines indicate standard deviation.

Length of First Branch

The length of the first branch showed significant differences ($P < 0.01$) in humic topsoil > river sand and humic topsoil > humic subsoil at 4, 9, 14, 26, 33, and 40 months after the start of the experiment. However, there was no significant difference between humic subsoil and river sand (Figure 7).

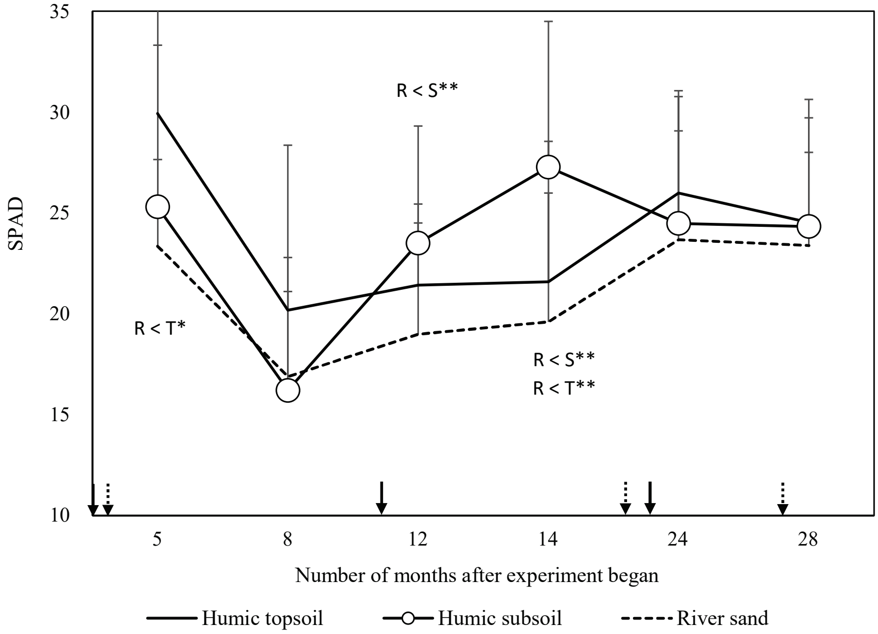

Figure 6. SPAD value under unfertilised conditions in humic topsoil (line), humic subsoil (line with white circle marker), and river sand (dotted line). Line arrows indicate the fertilisation date for the river sand. The dotted line arrows indicate the fertilisation date for both humic topsoil and subsoil. Letters represent statistical differences at *$P < 0.05$ and **$P < 0.01$ among R (river sand), S (humic subsoil), and T (humic topsoil) based on the *t*-test. Vertical lines indicate standard deviation.

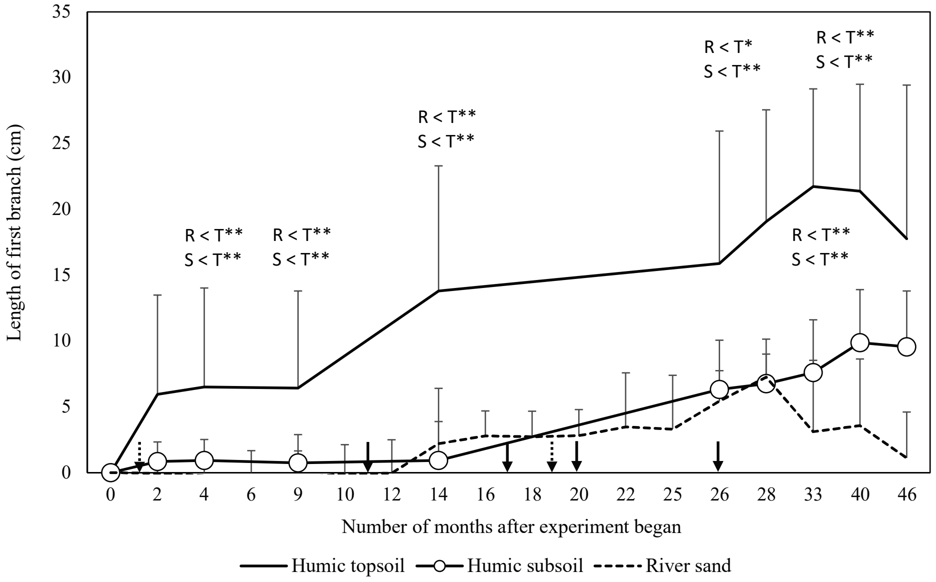

Figure 7. Length of first branch under unfertilised conditions in humic topsoil (line), humic subsoil (line with white circle marker), and river sand (dotted line). Line arrows indicate the fertilisation date for the river sand. The dotted line arrows indicate the fertilisation date for both humic topsoil and subsoil. Letters represent statistical differences at *$P < 0.05$ and **$P < 0.01$ among R (river sand), S (humic subsoil), and T (humic topsoil) based on the *t*-test. Vertical lines indicate standard deviation.

Number of First Branches and Diameter at the Base of the First Branch (DBF)

There were no significant differences in the DBF or number of first branches. However, the number of first branches was in the order humic topsoil > humic subsoil > river sand. The DBF ranked as follows: humic topsoil > river sand > humic subsoil (Figures 8 and 9).

Leaf Length and Width

Leaf length and width was greater in humic topsoil than in humic subsoil and river sand. Length × width of leaf and leaf length were greater in humic topsoil than in humic subsoil. Leaf width was greater in humic topsoil than in humic subsoil or river sand ($P < 0.05$) (Figure 10).

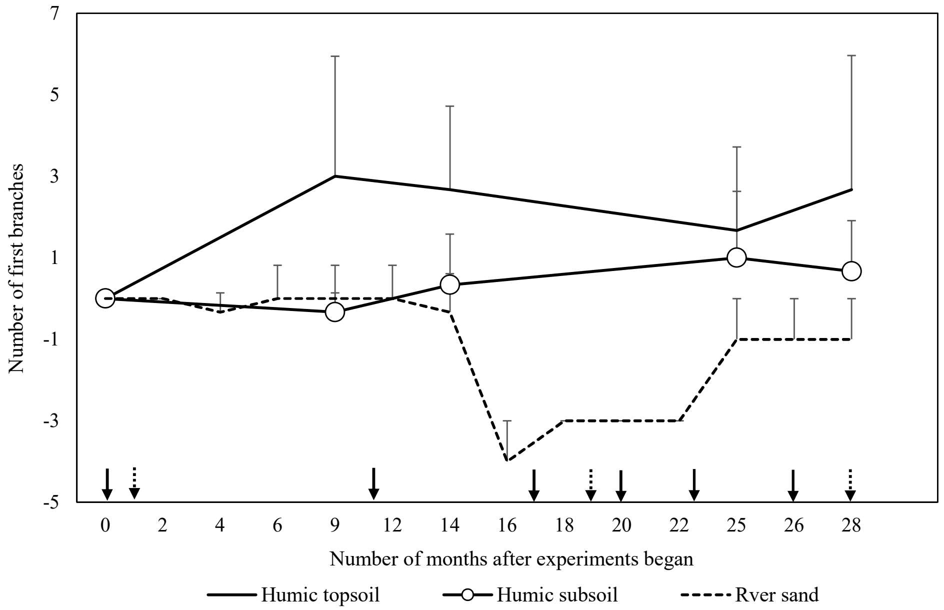

Figure 8. Number of first branches under unfertilised conditions in humic topsoil (line), humic subsoil (line with white circle marker), and river sand (dotted line). Line arrows indicate the fertilisation date for the river sand. The dotted line arrows indicate the fertilisation date for both humic topsoil and subsoil.

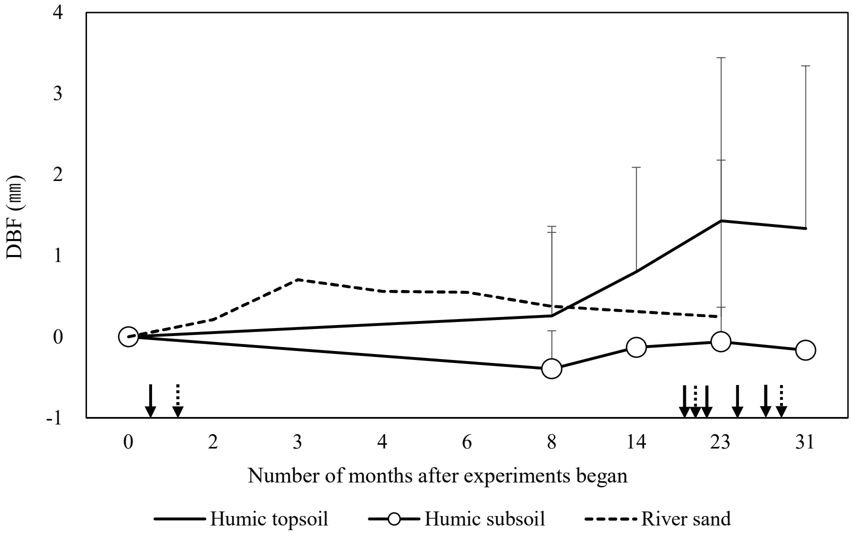

Figure 9. DBF under unfertilised conditions in humic topsoil (line), humic subsoil (line with white circle marker), and river sand (dotted line). Line arrows indicate the fertilisation date for the river sand. The dotted line arrows indicate the fertilisation date for both humic topsoil and subsoil.

DISCUSSION

Individual Impact of N in Humic Topsoil, Humic Subsoil, and River Sand

As shown in Table 6, individual P, K, and Ca applications had no impact in humic topsoil, humic subsoil, or river sand. Individual N addition affected *C. sieboldii* growth in humic topsoil with impacts on dry weight of shoots and roots, dry weight of shoots, and SPAD. Individual N had impacts in humic subsoil on dry weight of shoots and roots, dry weight of shoots, number of leaves, tree height, MTD, SPAD, and DBF. In river sand, individual N had no impacts on any measurement features.

Compound Nutrients Including N in Humic Topsoil, Humic Subsoil, and River Sand

As shown in Table 6, compound nutrients in humic topsoil had impacts on all measurements, except tree height, number of first branches, and length of first branch in NKCa and NPCa, on tree height and number of first branches for NPK, and for dry weight of roots and tree height with NPKCa. In humic subsoil, compound nutrients impacted on all measurements, except for tree height and number of first branches on NKCa, number of first branches and DBF for NPCa, number of first branches for NPK, and dry weight of roots for NPKCa. In river sand, compound nutrients had impacts, including on the number of leaves with NKCa, NPCa, NPK, and NPKCa, dry weight of shoots and roots, dry weight of shoots for NPCa and NPK, dry weight of roots for NPK, and SPAD with NKCa.

Comparison of the Effect Between Individual N and Compound Nutrients, Including N

Individual P, K, and Ca had no impacts in humic topsoil, humic subsoil, or river sand. However, adding P, K, and/or Ca with N increased the values of shoots and/or roots, and number of leaves and SPAD compared to unfertilised, low-nutrient river sand (Table 2). No impact was observed in river sand with N fertilisation alone, but combined fertilisation did affect growth. On the other hand, N alone had impacts in humic topsoil and subsoil, perhaps because they both contain more PO_4^{3-} and Ca^{2+} than river sand (Table 2). With N applied alone to humic topsoil and subsoil (relatively high in P and Ca), the impact on growth was similar to combined fertilisation.

NPCa and NPK gave higher values than individual N in dry weight of shoots and roots and dry weight of

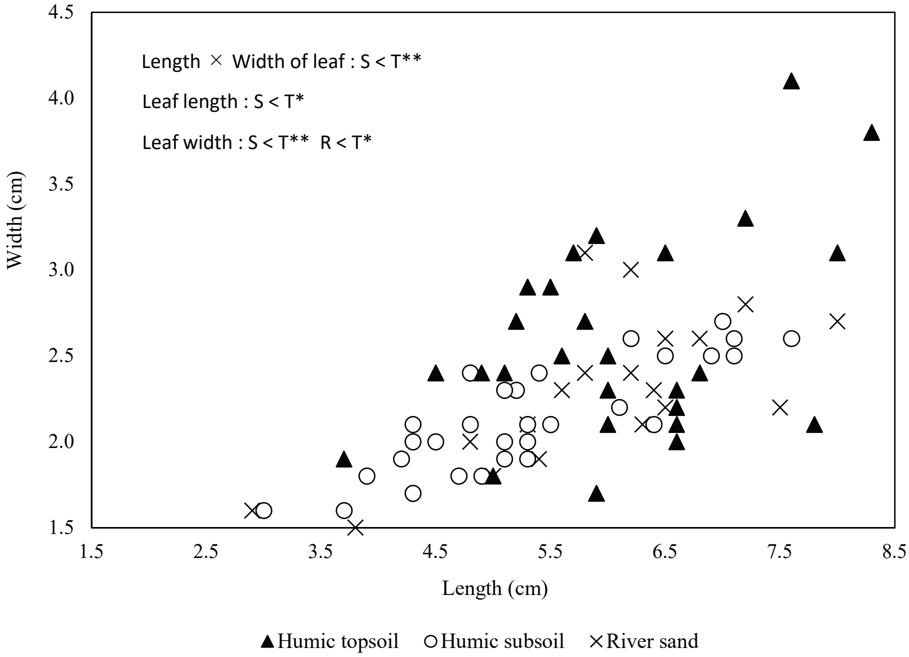

Figure 10. Leaf length and width under unfertilised conditions in humic topsoil (black triangle), humic subsoil (white circle), and river sand (cross). Values represent the average of 10 leaves. There are significant differences ($P < 0.05$) between humic topsoil > humic subsoil in leaf length and length × width of leaf; and humic topsoil > humic subsoil and river sand in leaf width. Letters represent statistical differences at *$P < 0.05$ and **$P < 0.01$ among R (river sand), S (humic subsoil), and T (humic topsoil) based on the *t*-test.

Table 6. Summary of differential growth performance of the fertiliser treatments vis-à-vis different growth media. ◎: Statistically significant individual impact ($P < 0.05$). ○: Statistically significant compound impact ($P < 0.05$). +: The compound nutrient value was higher than that of the individual N. The statistical analysis was conducted using Tukey's test. N (nitrogen); P (phosphorus); K (potassium); Ca (calcium); MTD (main trunk diameter close to the ground); SPAD (soil and plant analyser development); DBF (diameter at the base of the first branch).

	Individual impact difference from unfertilised and NPKCa				Compound impact difference from unfertilised					Compound impact difference from N				
	N	P	K	Ca	PKCa	NKCa	NPCa	NPK	NPKCa	PKCa	NKCa	NPCa	NPK	NPKCa
Humic topsoil														
Dry weight of shoots and roots	◎					○	○	○	○		+	+	+	
Dry weight of shoots	◎					○	○	○	○		+	+	+	+
Dry weight of roots						○	○	○				+		
Number of leaves						○	○	○	○		+	+	+	+
Tree height														+
MTD						○	○	○	○		+	+	+	+
SPAD	◎					○	○	○	○		+	+	+	+
Number of first branches									○			+	+	+
DBF						○	○	○	○		+	+	+	○
Length of first branch								○	○		+		+	+
Humic subsoil														
Dry weight of shoots and roots	◎					○	○	○	○			+		
Dry weight of shoots	◎					○	○	○	○			+		
Dry weight of roots						○	○	○				+		
Number of leaves	◎					○	○	○	○		+	+	○	+
Tree height	◎						○	○	○			+	+	+
MTD	◎					○	○	○	○		+	+	+	+
SPAD	◎					○	○	○	○					+
Number of first branches									○					+
DBF	◎					○		○	○				+	+
Length of first branch						○	○	○	○		+	+	+	+
River sand														
Dry weight of shoots and roots							○	○		+	+	○	○	+
Dry weight of shoots							○	○		+	+	○	○	+
Dry weight of roots								○		+	+	+	+	+
Number of leaves						○	○	○	○		+	+	+	+
Tree height												+	+	+
MTD												+	+	+
SPAD						○					+			
Number of first branches											+	+	+	+
DBF												+	+	
Length of first branch												+	+	+

shoots in river sand. Moreover, NPKCa resulted in higher DBF than individual N in humic topsoil. NPK showed a higher value for the number of leaves than individual N in humic subsoil.

Nitrogen, being the most important macronutrient for crops with individual impacts usually high (Nie et al. 2009), was found to influence *C. sieboldii* growth. Compound fertilisers containing N had greater effect than single N fertilisers, and this was particularly true in the river sand treatments, probably because of their inherent low levels of available P and Ca. Compound nutrient impacts were not necessarily greater than those of individual fertiliser applications but occasionally produced higher impacts (Armson 1977; Hatano 1991).

Difference in the Growth Between Humic Topsoil, Humic Subsoil, and River Sand

The results showed that *C. sieboldii* growth differed between humic topsoil and subsoil. The highest dry weight was observed in humic topsoil, followed by humic subsoil, and river sand. The T/R ratio especially was highest in river sand, followed by humic topsoil and subsoil. This means the amount of roots relative to shoots in river sand was less than in humic topsoil and subsoil. The highest number of leaves, SPAD value, tree height, leaf length and width, DBF, MTD, and length of the first branch were all found in humic topsoil. This was followed by humic subsoil and then, lastly, river sand. Overall, *C. sieboldii*, with unfertilised conditions, showed highest growth in humic topsoil, followed by humic subsoil and river sand. The poor growth in river sand was due to the low substrate concentrations of available NO_3^-, NH_4^+, PO_4^{3-}, and Ca^{2+}. The main reasons for the difference between the humic topsoil and subsoil were the C and N concentrations. The C/N ratios measured in humic topsoil and humic subsoil were 13.1 (C: 23.771, N: 1.816) and 11.6 (C: 4.874, N: 0.42), respectively (Table 2). N, C, and P in the humic topsoil were higher, and K was lower than those in the humic subsoil and river sand.

The importance of high C and N content in topsoil is clear from the literature. Humic topsoil is an andoloil that has high humic content and phosphate absorption (Adachi 1973; Hamasaki 2007). The humic content differed between topsoil, subsoil, and river sand (Yamane et al. 1978), and humic acid contains large amounts of N (Berg and McClaugherty 1989). Oak forests, which consist mainly of *Castanopsis cuspidate,* maintained C/N = 20 as litter decomposition progressed (Chairul and Yoneda 2002). The C/N ratio increased to 38.1 and 24.7 as the fallen leaves of *Chamaecyparis obtuse* and *Betula maximowicziana* increased after one year (Kawada 2000). The soil physical properties were demonstrated by the solid-phase ratio: 38.9% to 45.6%; liquid-phase ratio: 47.1% to 47.2%; and gaseous-phase ratio: 7.3% to 14.0%. The soil chemical properties included C: 147.2 g/kg to 162.1 g/kg; N: 11.7 g/kg to 12.7 g/kg; C/N: 12.5 to 13.9; and pH (H_2O): 5.0 to 6.5 in the *C. sieboldii* forest at the Institute for Nature Study in Tokyo (Miyajima et al. 2016).

Kimura and Kunimura (1961) reported that kaki (persimmon, *Diospyros kaki* Thunb.) growth was high in loam (i.e., humic topsoil) but less so in clay or fine-gravel soils. In addition, organic material (oak leaf litter) promoted kaki growth, and similar results were found for *C. sieboldii*.

Impact of Leaf Litter on *Castanopsis sieboldii* Growth Under Field Conditions

This study demonstrated that N and compound nutrients including N affected *C. sieboldii* growth. It is therefore informative to consider the importance of litter in the relevant nutrient cycling. Under field soil conditions, the main source of N is leaf litter, which contains low concentrations of P, K, and Ca, but which is high in C. The fallen leaves of *Quercus serrata,* which belongs to the same family as *C. sieboldii,* contained N: 0.5% to 1.0%; P: 0.06%; K: 0.2% to 0.6%; and Ca: 1.0% to 1.5%. Microelements such as Mg (magnesium), Zn (zinc), Mn (manganese), and Fe (iron) are also present in humus, along with K and Ca (Armson 1977; Berg and McClaugherty 1989). Strojan (1978) measured the concentrations of Ca, K, Mg, N, P, S (sulfur), Cd (cadmium), Cr (chromium), Cu (copper), Fe, Mn, Na (sodium), Ni (nickel), Pb (lead), and Zn in leaf litter. McClaugherty et al. (1985) reported that mineralisation rates correlate with decomposition rates of native dominant foliage litter. According to Kawada (2000), the chemical components of humus were N = 1.56%, 1.83%, and 2.16%; P = 0.045%, 0.054%, and 0.068%; K = 0.73%, 0.18%, and 0.13%; and Ca = 0.67%, 0.76%, and 0.77% in fresh leaves, after 5 months, and after 1 year, respectively.

The growth of *C. sieboldii* under different humic contents and C-N ratios in the soil was compared, and whilst humic topsoil and subsoil ratios can be similar, humic content varies with the amount of leaf litter. However, these experiments were also performed with river sand as a control with contrasting soil physical properties and low nutrient content. Watanabe and Maruta (1992) reported that at sites where litter was artificially removed, surface soil had less total C and N than otherwise and was harder. Consequently, tree growth was reduced. Soil hardness, porosity, total C, total N, EC (electric conductivity), and exchangeable bases (Ca, Mg, and K) resulted in major differences between managed and abandoned secondary forests (Tsuji and Hoshino 1992).

Based on these results, humus containing compound nutrients (primarily those based on N, P, K, and Ca, and micronutrients) improves *C. sieboldii* growth. Plant leaves and branches produce litter, from which humus and soil organic matter develop and release nutrients (Cui et al. 2022). A major component of humus is N (Dincher et al. 2020; Matkala et al. 2020), and in a natural soil, most available plant N is derived from soil organic matter (Strong and Mason 1999). Soil N mineralisation is positively correlated with litter production, and N is returned to the soil via the litter. Soil N mineralisation is negatively correlated with litter C:N and C:P ratios (Manzoni et al. 2010). It is argued that N derived from the humus promotes *C. sieboldii* growth.

However, soil nutrients, especially available N and P, are low in many urban soils and particularly those under street trees (Schaffert et al. 2022), with low N and C levels also reported (e.g., Zhu et al. 2017; Salomon et al. 2020). Future investigations should therefore address effects of humus content and leaf litter on *C. sieboldii* growth.

CONCLUSIONS

Three main research results were found: (1) *Castanopsis sieboldii* seedling growth under controlled experimental conditions was shown to be influenced by the specific additions of macronutrients alone or in combination. In some cases, growth was facilitated and in others it was restricted. Nitrogen applications enhanced growth except where availability of P or K were limiting; (2) the effects of nutrient additions varied significantly between typical soil types from urban areas where *C. sieboldii* is found, with humic topsoil the most favourable and river sand the least; (3) rigorous interrogation of the results from long-term pot experiments generated key insights into the underlying factors determining *C. sieboldii* growth in the field.

Soil physical properties, especially the soil gaseous-phase ratio, significantly influence the growth of *C. sieboldii*, and these giant trees normally exhibit low tolerance of stagnant conditions. However, some are found in low-lying or reclaimed lands where the water is often stagnant and soils are anaerobic. This survival may be due to the soil physical properties at such locations for some reason being favourable or at least tolerable. Moreover, from this study of fertiliser experiments in soils with different humic contents, compound N, P, K, Ca, and humus are important factors in the growth of *C. sieboldii*. Available nitrogen can boost growth, but the impacts are restricted if the soil is low in nutrients (such as river sand) and there is no added P, K, or Ca. Such information can help develop effective planting strategies and can enhance the introduction, conservation, and associated management of native tree species in urban areas.

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