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ORIGINAL ARTICLE

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Inorganic elements in typical Japanese trees for woody biomass fuel

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Abstract The inorganic element contents of trees were measured to evaluate the safety of using wood biomass as thermal power generation fuel. Twelve species of typical conifer trees and 17 species of typical broad-leaved trees in Japan plus 9 species of commonly imported trees were selected and analyzed for the main inorganic elements and several trace elements that are potentially harmful in combustion ash. The ash content in bark, especially in the inner bark, was higher than that in wood, but the highest concentration was in the leaves. In almost all parts of the trees, the order of inorganic element concentration was calcium ≥ potassium ≥ magnesium ≥ sulfur ≥ phosphorous. Among the trace elements, the boron content was high and the mercury content was recorded as being high in conifer bark.

Key words Inorganic elements · Woody biomass · ICP · Ash content · Concentration distribution

Introduction

Biomass energy is a key driver of sustainable social development. The reduction of CO_2 emissions and fossil fuel exhaust poses a serious challenge for power plants. Therefore, biomass energy is much anticipated as a renewable energy source. Woody biomass is the most available resource for power generation fuel, because both the actual amount and the potential amount can be determined.

The ideal approach to introducing biomass energy is one in which biomass resources are recycled without exhausting waste. For woody biomass combustion plants, the available application of woody ash must also be considered. If in the future, woody biomass resources are used as power generation fuel instead of coal, woody ash will become as significant a problem as coal ash.

In the case of coal ash, the leaching of trace elements, e.g., arsenic, selenium, and boron, has been identified.[1–5] Leaching suppression technology has been developed as a countermeasure against the leaching of trace elements from coal ash when the limits stipulated by Japan's Environmental Quality Standards for Soil Contamination are exceeded. The inorganic element content of ash is small for wood, which is mainly composed of cellulose and lignin. On the other hand, all plants, including trees, originally contain some heavy metals, even if the quantities are small. It must be confirmed whether these trace elements are leached from woody ash. However, information on inorganic elements in not only woody ash but also in wood has not yet been summarized, although there is a series of notable studies by Okada and colleagues[6,7] who used instrumental neutron activation analysis to determine the radial distribution of the main inorganic elements in tree stems. The data on elemental concentrations in plant leaves were only recently officially announced.[8]

The first goal of this study was to systematically summarize the data on inorganic elements contained in typical Japanese wood. We assessed the methodology for determining the inorganic element content of wood and deduced the concentrations in conifer trees (softwood) and broad-leaved trees (hardwood) in order to discuss their potential usage for power generation and any possible associated environmental problems.

Materials and methods

Wood from 12 species of typical conifer trees and 17 species of typical broad-leaved trees in Japan and 9 species of commonly imported trees were analyzed. The species of trees

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Part of this article was presented at the 57th Annual Meeting of the Japan Wood Research Society, Hiroshima, Japan, and at the 58th Annual Meeting of the Japan Wood Research Society, Tsukuba, Japan for the wood samples are detailed in the Appendix. Most samples were provided from specimens possessed by the Forestry and Forest Products Research Institute. Some of the samples were supplied from the local area.

After being washed with distilled water, the collected wood blocks were dried using a drying oven at 80°C for more than 1 week. The wood blocks were then separated into bark and sapwood or heartwood, and thin wood pieces were shaved off. These wood pieces were dried using a drying oven for 1 week. This condition was considered the absolute dryness weight and the weight of the wood pieces was measured. A ceramic knife was used to shave off the wood pieces in order to avoid contamination by metal elements.

The amount of inorganic elements present in the samples was analyzed mainly by inductively coupled plasma emission spectrometry (ICP; Seiko Instruments SPS5000), and a sealed polytetrafluoroethylene vessel was used for the applied acid decomposition method.[9,10] The acid decomposition liquid was prepared as follows. A wood sample (0.15 g) was measured in the vessel and the acid mixture (HNO_3 : HF = 1 : 1) was added. The vessel was set in a pressure container made of stainless steel and treated at 140°C for 4 h. Here, arsenic, selenium, and antimony were dealt with by hydrogenation.[11,12] Furthermore, mercury was analyzed using the gold-amalgam method.[13]

Qualitative analysis of cedar was carried out for 42 elements, and 20 of these elements (B, Na, Mg, Al, Si, P, S, K, Ca, Ti, Mn, Fe, Cu, Zn, As, Se, Sr, Sb, Ba, Hg) were determined for quantitative analysis. Trace elements potentially harmful in combustion ash were added to the list of elements to be analyzed, even though they were not detected during qualitative analysis.

Results and discussion

Accuracy of analysis

For the measurement of inorganic elements in this study, general-purpose ICP was used, and acid extraction using mixed nitric acid and fluoric acid was adopted for determination of the silicon content. The glass parts in the analyzer had to be replaced with parts made of Teflon because fluoric acid damages glass. There were concerns that Teflon's low wetting characteristics might have a negative influence on the homogeneous flow of the sample solution in the analyzer, rendering some elements not suitable for analysis by ICP. We therefore assessed the analysis accuracy at the outset.

Apple leaves[14] and pine needles[15] provided by the National Institute of Standards and Technology (NIST) were selected to provide a comparison, and extraction liquid was obtained using two kinds of acid: mixed acid and nitric acid.

The analysis results are shown in Table 1. These data require careful consideration because calcium, potassium, and magnesium were the main inorganic elements contained in the plant. However, alkali metals and alkaline earth metals are not considered suitable for analysis by ICP, as shown in Table 1. As for calcium, extraction by fluoric acid is especially difficult in high concentration. In the case of the analysis of inorganic elements of wood ash, some deposition particles appeared in the mixed-acid extraction liquid. X-ray diffraction analysis (Rigaku RIX3100, RINT TTR III) revealed that the deposition particles were calcium fluoride. It is considered that extraction with fluoric acid is not a suitable method for samples with high calcium content. In this study, all elements except for the silicon were also measured for confirmation by nitric-acid extraction, even though there is a much smaller amount of calcium in trees compared to that in ashes. From Table 1, phosphorus is another element not suitable for extraction with fluoric acid. Phosphorus levels showed a tendency to be greatly overestimated, even though many of the elements were determined as being present at levels less than the certified values. For the measurement of inorganic elements in the trees, the characteristics of ICP analysis are particularly useful, and the analysis results must be taken into consideration.

Ash content was measured following the protocol detailed by the Japan Wood Research Society,[16] i.e., the ash

Table 1. Comparison of measured values with the certified values

Element	Apple leaves (NIST_1515)			Pine needless (NIST_1575a)		
	Certified value	Measured value		Certified value	Measured value	
		HNO_3 + HF	HNO_3		HNO_3 + HF	HNO_3
Calcium (%)	1.526 ± 0.015	1.321	1.683	0.25 ± 0.01	0.22	0.25
Magnesium (%)	0.271 ± 0.008	0.262	0.275	0.106 ± 0.017	0.103	
Potassium (%)	1.61 ± 0.02	1.44	1.14	0.417 ± 0.007	0.392	0.328
Phosphorus (%)	0.159 ± 0.011	0.187	0.159	0.107 ± 0.008	0.115	0.106
Aluminum (mg/kg)	286 ± 9	236	293	580 ± 30	580	549
Barium (mg/kg)	49 ± 2	32	49	6.0 ± 0.2	5.7	9.4
Boron (mg/kg)	27 ± 2	27	30	9.6 ± 0.2	5.7	11
Iron (mg/kg)	83 ± 5			46 ± 2	46	44
Mercury (mg/kg)	0.044 ± 0.004	0.044		0.0399 ± 0.0007	0.037	
Manganese (mg/kg)	54 ± 3	51	49	488 ± 12		
Zinc (mg/kg)	12.5 ± 0.3	14.1	11.5	38 ± 2	51	38

Measured values show the mean of two measurements
Blank indicates less than the limit of quantitation (LOQ)

Table 2. Ash content in typical tree samples

Sample	Ash content (%)
Cryptomeria japonica D. Don	
Bark	2.9
Wood	0.28
Leaf	5.1
Pinus densiflora	
Bark	1.7
Wood	0.16
Leaf	2.6
Castanea crenata	
Bark	(5.2)
Wood	0.16
Quercus serrata	
Bark	(2.5)
Wood	1.0

Values are the average of two measurements

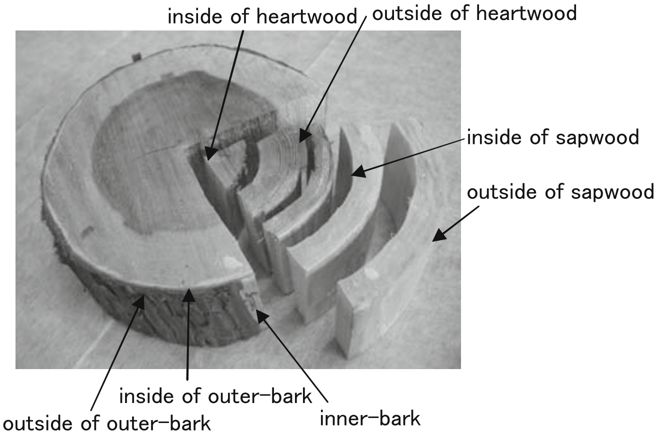

Fig. 1. Photograph of the wood disc samples used for the analysis

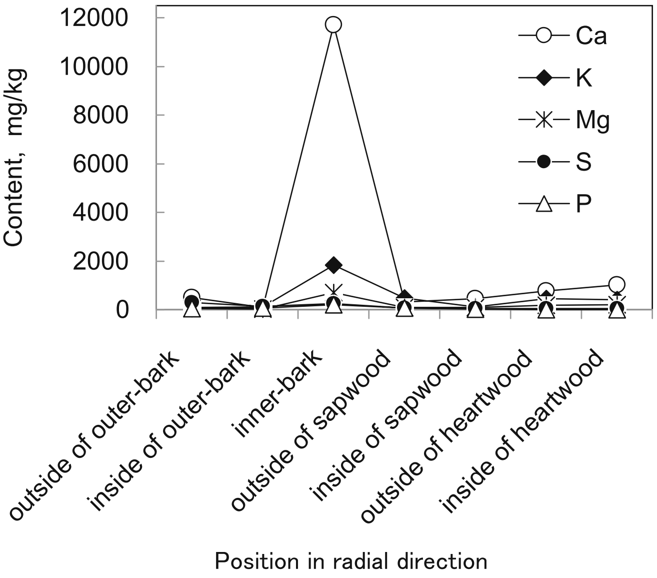

Fig. 2. Radial distribution of inorganic element concentrations

content was estimated by the ratio of the absolute dry weight of a wood sample and the ash weight, which was obtained from heat treatment:

$$A = W/S \times 100$$

where A is the ash content, W is the measurement of ash weight, and S is the measurement of the absolute dry weight of the wood sample.

Measurement of ash content

Because the main constituents of trees are cellulose and lignin, and because the ash content of trees is only about 1%, there has been little study of ash content until now. The appearance of the bark and wood is very different and their chemical characteristics are likely also to be different. In particular, there is very little data on bark because it has limited practical value. Consequently, we measured the ash content of bark and then of wood. For the conifers, measurement of the ash content of the leaves was also carried out.

The results of the ash content measurements are shown in Table 2. The ash contents of *Cryptomeria japonica* and *Pinus densiflora* leaves are also shown in the table as a reference. As for the chemical analysis of trees, there are marked variations among individual trees. Therefore, these experimental results apply only to this experimental sample. We learned the following from the measurement results: ash content was higher in the bark than in the wood, but the highest ash content was in the leaves. Ash content was lower in the wood of conifer trees. The quantity of ash differed between the bark and the wood. From the above results, it is considered suitable to separate the wood from the bark and to analyze both parts for the inorganic element contents of the trees.

Radial and vertical distribution of inorganic elements contained in wood

Radial and vertical distributions of inorganic elements were determined as a pre-examination process to determine the dependence on the sampling point of the analysis results. Test pieces were taken from an individual *Cryptomeria japonica* tree that was about 100 years old and had a diameter at breast height of around 20 cm; it had been cut down in Chiba Prefecture in 2006. As shown in Fig. 1, a wood disk from a height of 120 cm was divided into seven parts for analysis: the outside of the outer bark (surface), the inside of the outer bark, inner bark including cambium, outside of the sapwood, inside of the sapwood, outside of the heartwood, and inside of the heartwood (center).

The highest concentrations were found for calcium, potassium, magnesium, sulfur, and phosphorous, and the concentration distribution of these elements in the wood is shown in Fig. 2. Inorganic elements were found at higher concentrations in the bark compared to those in the wood parts. Especially, the inner bark had the highest amounts of inorganic elements among the bark samples. The high inorganic element concentration of the inner bark is possibly due to the high number of living cells.[17] On the other hand,

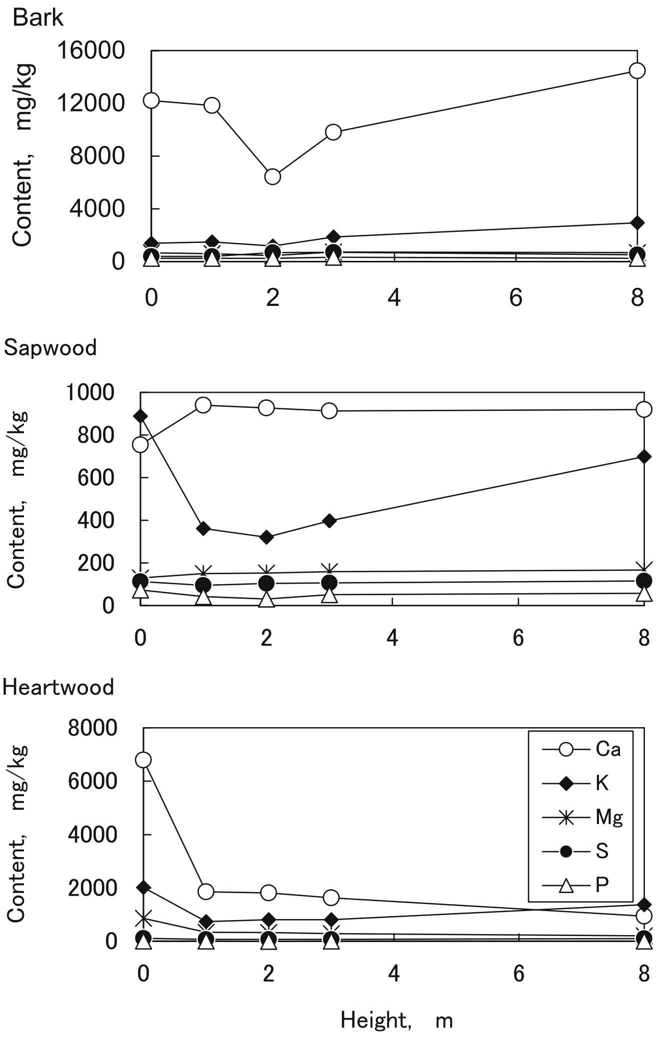

Fig. 3. Vertical distribution of inorganic element concentrations

the concentrations tended to decrease in the sapwood, and did not significantly change in the heartwood. In almost all parts of the tree, the order of inorganic concentration was calcium ≥ potassium ≥ magnesium ≥ sulfur ≥ phosphorous.

The vertical distribution of the concentration was also examined. Wood discs (1 cm thick) were cut from a 10-m-high tree at 0, 1, 2, 3, and 8 m from the ground. Each wood disk was divided into bark, sapwood, and heartwood and was then analyzed. The analysis results are shown in Fig. 3. The sapwood and heartwood generally showed no marked difference in concentration distribution, except that the potassium concentration was high in samples taken at a height of 0 and 8 m. At the middle height from 1 to 3 m, the concentration distribution showed a similar trend. On the other hand, although the concentration in the bark varied for each height, the values were expected to be influenced by atmospheric deposition. Based on the pre-examination findings, the following preparation method of wood samples was adopted in this study: a wood disk was cut at a breast height of 120 cm, divided into bark and wood parts, and the test pieces were shaved off.

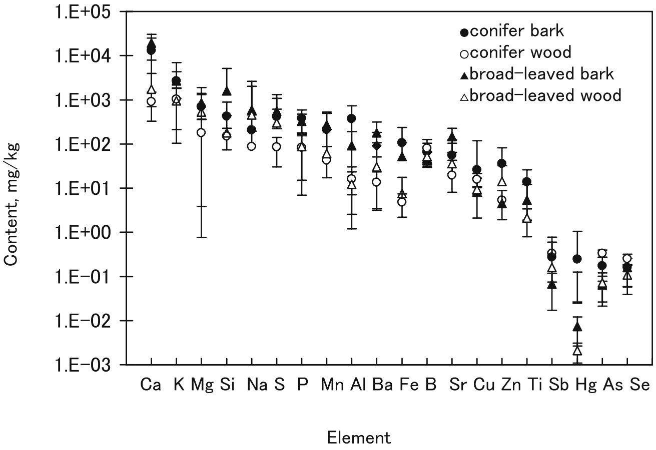

Fig. 4. Summary diagram of the inorganic element content of wood and bark

Data on inorganic elements in trees

Next, the inorganic element contents of the trees were measured. The measured concentrations of the tree samples are given in the Appendix, and the ranges of the measured values are summarized in Fig. 4. Twelve kinds of conifer trees provided 27 wood samples and 34 bark samples, and 17 kinds of broad-leaved trees provided 37 wood samples and 55 bark samples; the average values and standard deviations are shown in Fig. 4. For the sake of convenience, *Ginkgo biloba* was classified among the conifer trees.

All targeted elements were observed to be present in the ash, and calcium and potassium were found to have the highest concentrations among all samples. The concentrations of inorganic elements were confirmed to be generally higher in the bark than in the wood. In this study, the concentration of silicon and sodium was highest in the bark of broad-leaved trees. The leaching of boron from coal ash has been established;[1,2] in conifer bark, boron levels as high as 100 mg/kg were recorded. High mercury levels were also recorded in conifer bark. These results provide enough data to grasp the approximate inorganic element contents, although the standard deviation values are large due to the difference in individual chemical concentrations among trees.

Usage of woody biomass and ash

In the results mentioned above, the inner bark had the highest levels of inorganic elements. As bark can be manufactured into bark pellets and used as fuel for boilers and stoves, it is important to consider that the ash concentration of bark is ten times higher than that of sapwood and heartwood.

The leaching of trace elements can cause a problem if woody ash is handled in addition to the coal ash currently exhausted from thermal power plants. Trace elements regulated by Japan's Environmental Quality Standards for Soil Contamination include boron, arsenic, and selenium. As shown in Fig. 4, significant quantities of boron are contained in wood; regardless of the differences between conifer and broadleaved trees or between bark and sapwood, boron concentrations were consistently high. Although woody ash also contains high concentrations of calcium, potassium, and magnesium, which makes it useful as a soil improving agent, the leaching of boron from woody ash requires attention.

Certain amounts of mercury, arsenic, and selenium were detected, as were other trace elements. A high concentration was found mainly in conifer trees. These elements are volatile and will be released into the atmosphere or adsorbed by the fly ash during combustion. The behavior of inorganic elements under combustion, e.g., diffusion into the atmosphere, concentration to ash, or adsorption by fly ash, depends on the combustion conditions. Environmental countermeasures corresponding to usage must be taken when woody biomass is used as a combustion fuel. On the other hand, several new energy crops such as *Salix*, which accumulate heavy metals from the soil, contain significantly higher concentrations of cadmium and zinc.[18,19] In the case of wood, the concentration of these heavy metals was low or not detected.

Conclusions

We measured the inorganic element contents of trees in order to evaluate the safety of using wood biomass as fuel for thermal power generation. The analysis accuracy was not satisfactory because ICP provided poor analysis of alkali metals and alkaline earth metals and because fluoric acid was used to measure silicon. Furthermore, we did not examine the reproducibility of measured values. It was clear from the beginning that the concentration distribution in the trees would differ greatly according to the type of tree, the growth area, and sampling position, among others.

This article provides useful information for grasping the approximate inorganic element contents based on the classification of bark and wood from conifer and broad-leaved trees. The measured values, the characteristics of the measurement equipment, and the concentration distribution in the trees are presented. These considerations are useful for correctly understanding the analysis results. Moreover, the environmental concerns about the presence of trace elements in wood biomass used as fuel for thermal power generation were explained. We carefully consider the environmental impact of using woody biomass as fuel or using woody ash, although such safety issues have not been discussed extensively to date. This new information will provide important data points for discussing the atmospheric diffusion or fly-ash concentration of chemical materials from woody biomass combustion plants in the future.

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Appendix Data on inorganic elements in typical Japanese wood

Name	Collected place	Collected year	Part	Concentration (mg/kg)					
				Al	Ba	Ca	Cu	Fe	K
Domestic species									
Ginkgo biloba	Hokkaido	2004	Bark	120	100	52 000	4.2	110	20 000
			Sapwood	34	11	1 000	–	–	610
			Heartwood	16	14	1 600	–	–	610
	Ishikawa	1991	Bark	220	110	4 800	6.8	210	14 000
			Wood	15	11	2 900	(0.39)	–	1 100
Larix kaempferi	Yamanashi	2000	Bark	700	36	2 100	6.8	430	850
			Wood	6.1	7.6	380	16	4.2	360
	Toyama	2004	Bark	200	43	1 500	18	57	1 000
			Sapwood	5.8	8.7	270	16	3.1	650
			Heartwood	12	–	91	15	–	160
	Nagano	2006	Bark	870	61	12 000	3.8	380	1 900
			Wood	10	6.3	810	–	1.8	370
Pinus densiflora	Okinawa	1986	Bark	1200	71	18 000	–	35	2 100
			Wood	26	10	1 000	–	–	600
	Mie	1994	Bark	450	24	4 200	3.4	62	880
			Wood	14	9.7	770	–	–	270
	Nagano	2006	Bark	390	110	3 800	–	190	2 800
			Sapwood	14	17	480	–	–	580
			Heartwood	6.7	9.1	130	–	–	130
Pinus thunbergii	Okinawa	1986	Bark	1200	110	18 000	3.8	39	2 900
			Wood	71	9.5	860	15	–	760
	Mie	1994	Bark	960	68	13 000	19	39	1 500
			Wood	39	13	1 100	16	–	450
Abies firma	Aichi	2002	Bark	180	33	6 300	17	5.3	2 800
			Wood	30	8.5	720	16	–	290
	Gunma	2003	Bark	61	64	5 800	17	7.9	1 300
			Wood	15	8.9	770	16	–	1 200
Abies sachalinensis	Hokkaido	1996	Bark	150	300	16 000	4.7	95	4 000
			Wood	7.1	25	1 100	16	–	3 300
	Hokkaido	1999	Bark	110	290	8 600	3.5	27	1 500
			Wood	6.1	50	760	16	–	1 400
Picea jezoensis	Hokkaido	2001	Bark	58	320	9 500	4.6	16	450
			Wood	33	33	820	15	–	1 600
	Hokkaido	2003	Bark	14	120	11 000	3.1	3.6	250
			Wood	9.3	31	1 100	15	–	2 500
Picea jezoensis var. *hondoensis*	Nagano	1951	Bark	37	250	12 000	6.3	26	270
			Wood	3.9	18	920	15	–	2 600
	Gunma	2003	Bark	140	94	4 000	4.6	59	190
			Sapwood	9.3	11	480	16	–	880
			Heartwood	4.5	6.8	160	15	–	1 000
Tsuga sieboldii	Saitama	1950	Bark	660	72	12 000	7.7	120	1 600
			Wood	21	8.5	500	34	8.2	1 100
	Aichi	2002	Bark	470	10	5 900	3.3	25	570
			Wood	26	4.3	560	16	–	1 200
Cryptomeria japonica	Kumamoto	2005	Bark	910	55	13 000	480	460	1 100
			Sapwood	16	14	1 200	–	3.7	370
			Heartwood	8.4	17	1 800	0.55	–	540
	Chiba	2007	Bark	240	7.1	4 700	4.6	240	590
			Sapwood	5.2	–	1 300	–	–	1 900
			Heartwood	11	7.4	930	–	9.3	2 000
	Akita	1991	Bark	72	41	7 500	3.7	37	1 400
			Sapwood	19	–	820	–	–	1 100
			Heartwood	4.0	5.4	2 400	–	–	3 100
Chamaecyparis obtusa	Hokkaido	2000	Bark	360	21	12 000	17	58	190
			Wood	4.5	–	470	15	–	220
	Shimane	2005	Bark	85	39	10 000	3.3	50	570
			Wood	34	5.2	550	16	–	1 100
Thujopsis dolabrata	Tochigi	1999	Bark	30	33	46 000	4.0	12	2 700
			Wood	10	4.1	1 000	–	–	560
	–	–	Bark	130	7.1	36 000	4.6	100	4 400
			Wood	6.3	–	1 400	–	3.2	520
Populus sieboldii	Toyama	2004	Bark	77	380	30 000	4.2	42	3 500
			Wood	7.5	22	830	–	–	580
	Gifu	2005	Bark	72	350	11 000	3.7	51	3 400
			Sapwood	9.4	37	800	–	–	400

Mg	Mn	Na	P	S	Si	Sr	Ti	Zn	As	B	Hg	Sb	Se
2 700	8.8	460	640	840	300	210	2.9	17	(0.078)	63	0.012	(0.087)	–
270	–	50	190	170	–	10	–	–	(0.031)	83	0.001	–	–
330	–	52	95	180	–	13	–	–	(0.048)	67	0.002	–	–
2 700	20.0	1000	470	900	2 100	140	8.3	23	(0.15)	72	0.025	(0.094)	–
200	–	100	140	140	–	13	–	–	(0.023)	57	0.002	–	–
150	79	110	350	260	530	22	36	5.0	(0.21)	140	0.053	(0.21)	(0.08)
41	22	32	86	53	160	6.0	–	–	(0.23)	56	0.001	0.23	(0.070)
160	95	120	350	210	480	20	–	9.4	(0.22)	180	0.011	0.46	(0.070)
49	17	29	180	72	210	5.5	–	–	(0.070)	71	0.001	–	(0.050)
16	–	25	30	45	210	69	–	–	–	220	0.002	–	–
760	60	53	380	290	410	61	31	18	(0.19)	–	0.007	0.32	(0.055)
110	12	8.3	61	55	(26)	8.9	–	4.5	(0.060)	–	–	0.25	(0.083)
1 500	210	400	780	460	410	100	–	36	(0.080)	47	0.018	(0.030)	(0.040)
250	44	110	140	140	180	11	–	5.1	(0.060)	74	0.002	–	(0.15)
470	26	110	130	230	390	27	–	14	(0.050)	–	0.025	0.32	(0.080)
140	19	55	220	46	210	9.1	–	7.4	(0.060)	86	0.001	(0.010)	(0.060)
520	370	44	540	250	280	53	17	3.4	(0.067)	47	0.005	0.14	–
130	47	36	210	150	42	9.2	(0.33)	(2.1)	(0.14)	35	–	0.35	(0.004)
35	5.4	28	4.1	34	31	4.4	–	(0.31)	(0.18)	37	–	0.18	(0.083)
2 000	200	580	770	540	330	130	–	40	(0.070)	69	0.023	(0.020)	0.24
270	36	70	150	150	200	9.8	–	3.6	(0.080)	45	0.002	(0.020)	0.19
900	210	170	200	280	330	58	–	25	(0.080)	53	0.026	(0.050)	(0.030)
250	84	35	210	50	120	8.4	–	7.0	(0.060)	39	0.002	(0.040)	(0.16)
270	210	38	310	260	110	19	–	8.5	(0.19)	33	0.005	(0.12)	0.23
55	12	290	170	85	130	69	–	2.3	0.41	54	0.001	1.1	0.24
340	77	39	340	270	140	61	–	14	(0.27)	32	0.007	(0.15)	0.25
56	4.8	38	91	77	150	12	–	1.6	(0.23)	69	–	0.39	0.26
740	1200	180	910	460	1 000	44	5.9	62	(0.070)	71	0.009	–	0.26
390	140	110	48	72	98	4.4	–	–	(0.070)	160	0.001	–	(0.070)
380	740	74	320	320	290	35	–	33	(0.070)	–	0.014	(0.010)	(0.040)
220	92	120	11	39	140	4.5	–	–	(0.060)	140	–	(0.010)	(0.13)
350	200	110	270	300	130	58	–	130	(0.27)	71	0.024	(0.10)	–
51	35	25	17	32	88	7.6	–	8.4	(0.21)	44	0.004	(0.080)	(0.10)
520	410	84	470	290	140	130	–	200	(0.20)	120	0.002	(0.10)	0.35
67	37	580	14	28	110	11	–	11	(0.16)	67	0.018	(0.080)	(0.16)
390	640	72	320	640	190	39	–	100	0.45	32	1.3	0.59	0.4
72	150	21	5.0	34	170	3.7	–	6.3	(0.21)	32	0.059	(0.15)	(0.12)
240	400	41	180	230	570	8.0	4.0	95	(0.28)	38	0.014	0.26	0.19
54	140	16	100	74	200	68	–	13	0.34	72	0.002	(0.15)	(0.11)
14	32	9.7	6.4	35	180	67	–	5.6	(0.29)	36	0.003	(0.15)	0.38
380	240	66	330	620	530	50	7.7	6.9	(0.24)	39	4.2	0.21	(0.080)
130	33	23	81	260	450	4.0	–	–	(0.21)	38	0.56	(0.15)	(0.060)
220	85	58	230	310	89	12	–	6.3	(0.25)	51	0.014	2.7	(0.070)
72	11	47	70	67	130	69	–	–	(0.24)	94	0.001	(0.12)	(0.050)
427	20	240	300	710	1 600	25	30	17	(0.12)	70	0.052	(0.090)	0.24
81	4.7	64	48	88	130	12	–	–	(0.08)	85	0.005	(0.010)	(0.090)
250	–	88	6.6	51	130	11	–	1.5	–	–	0.003	0.27	(0.15)
630	6.4	840	200	470	–	6.6	15	10	(0.18)	42	0.025	0.16	(0.11)
360	–	220	67	170	–	4.1	–	–	0.25	–	0.007	0.18	(0.051)
420	–	130	6.1	55	–	6.1	–	5.4	(0.17)	84	0.004	0.17	(0.068)
600	5.8	260	170	370	170	16	–	6.9	(0.070)	41	0.022	(0.020)	(0.12)
230	–	190	180	150	150	7.9	–	–	(0.060)	170	0.006	–	(0.070)
970	–	150	43	92	160	14	–	–	(0.060)	–	–	–	(0.10)
220	12	120	100	320	170	18	–	26	(0.24)	79	0.032	0.19	–
140	4.0	13	9.8	50	61	71	–	–	(0.22)	–	0.004	(0.15)	0.18
310	20	140	150	330	210	34	–	24	(0.28)	36	0.024	0.19	0.22
110	5.9	5.9	7.0	41	87	8.2	–	–	(0.19)	–	0.002	0.22	0.27
100	–	71	300	380	170	43	3.4	11	–	–	0.020	–	–
35	–	22	92	49	–	6.6	–	–	–	–	0.002	–	–
1 000	8.4	190	720	780	60	81	5.3	38	–	61	0.72	–	–
210	–	170	65	53	–	13	–	–	–	46	0.013	–	–
1 200	79	97	500	590	93	190	1.4	160	–	42	0.007	(0.005)	–
90	8.9	18	110	36	(25)	8.4	–	7.7	–	54	–	–	–
1 300	400	55	650	500	78	120	(0.90)	200	–	44	0.008	–	–
200	48	25	47	31	(19)	11	–	15	–	40	–	–	(0.001)

Appendix *Continued*

Name	Collected place	Collected year	Part	Concentration (mg/kg)					
				Al	Ba	Ca	Cu	Fe	K
			Heartwood	11	91	2 700	–	–	530
Betula platyphylla var. *japonica*	Ibaraki	2003	Bark	10	150	9 400	(1.2)	4.0	1 500
			Wood	2.4	15	340	–	–	330
	Gifu	2005	Bark	12	110	6 800	–	8.3	1 100
			Sapwood	2.3	12	470	–	–	390
	Nagano	2006	Bark	50	230	25 000	5.3	24	2 000
			Sapwood	7.5	19	770	–	3.0	520
			Heartwood	13	56	3 100	(0.43)	3.6	380
Fagus crenata	Gunma	1981	Bark	76	170	30 000	3.0	51	4 200
			Wood	6.1	9.5	1 400	–	–	1 000
	Gifu	1993	Bark	51	280	41 000	4.7	27	3 600
			Wood	3.9	14	730	–	–	490
Quercus acutissima	Okayama	2000	Bark	31	81	26 000	–	15	1 500
			Wood	12	16	910	–	–	1 000
	Nagasaki	2002	Bark	100	70	14 000	5.0	57	1 200
			Wood	14	14.0	670	–	–	730
Quercus crispula	Gifu	1993	Bark	51	180	14 000	3.1	25	2 500
			Wood	8.5	14	270	–	3.1	710
	Aichi	2002	Bark	29	75	26 000	4.4	12	1 900
			Sapwood	3.5	7.4	650	–	3	630
			Heartwood	7.5	12	1 900	–	–	1 500
Quercus serrata	Mie	1994	Bark	57	220	16 000	3.1	36	1 800
			Sapwood	4.1	36	1 000	–	–	680
			Heartwood	11	22	500	–	–	520
	Kouchi	2003	Bark	360	360	25 000	3.7	180	1 600
			Wood	4.0	42	2 200	–	–	1 000
	Niigata	2007	Bark	160	22	28 000	4.4	98	1 300
			Sapwood	6.0	3.700	2 600	–	35	1 400
			Heartwood	5.2	6.600	4 100	–	–	2 000
Quercus acuta	Chiba	1995	Bark	180	130	30 000	6.1	130	3 400
			Wood	4.1	10	2 400	–	–	2 200
	Mie	2001	Bark	39	400	13 000	3.2	21	2 500
			Wood	3.6	42	1 000	–	–	1 500
Castanea crenata	Nagasaki	2002	Bark	250	360	20 000	4.1	44	3 200
			Sapwood	20	16	150	–	1.2	380
			Heartwood	11	18	310	–	–	950
	Kyoto	2006	Bark	67	340	28 000	–	12	2 100
			Sapwood	16	26	630	–	–	960
			Heartwood	11	19	180	–	–	290
	Chiba	2007	Bark	110	60	33 000	(0.97)	37	1 100
			Wood	7.5	6.9	420	–	–	290
Zelkova serrata	Iwate	2002	Bark	12	130	46 000	–	9.0	2 800
			Sapwood	5.6	21	3 500	–	–	1 700
			Heartwood	3.6	19	1 800	–	–	2 000
	Toyama	2004	Bark	45	45	43 000	–	29	2 800
			Wood	5.5	7.6	3 800	–	–	2 700
Magnolia obovata	Miyazaki	1997	Bark	40	23	6 000	4.6	11	1 800
			Sapwood	30	4.9	610	(0.11)	–	510
			Heartwood	21	5.8	510	–	–	100
	Shimane	2005	Bark	28	40	5 800	(1.7)	15	1 200
			Sapwood	8.4	7.5	610	–	–	590
			Heartwood	6.3	6.4	270	–	–	93
Cinnamomum camphora	Kagoshima	1996	Bark	150	21	28 000	3.8	14	4 600
			Sapwood	14	–	930	–	–	1 500
			Heartwood	15	5.8	2 100	–	3.5	5 300
	Miyazaki	2004	Bark	250	37	34 000	4.7	8.7	4 800
			Sapwood	6.2	–	820	–	–	1 200
			Heartwood	15	5.6	3 600	–	–	1 300
Prunus sargentii	Okayama	2000	Bark	180	180	10 000	4.6	120	2 100
			Sapwood	11.0	12	730	0.14	–	1 300
			Heartwood	12	22	1 200	–	–	260
	Mie	2001	Bark	71	520	10 000	3.1	42	1 400
			Sapwood	31	41	760	–	–	940
			Heartwood	11	42	1 000	–	–	280
Acer mono	Kyoto	1991	Bark	26	260	6 800	10.0	15.0	5 500
			Sapwood	12	12	1 400	–	–	540
			Heartwood	4.9	16	1 500	–	–	750

Mg	Mn	Na	P	S	Si	Sr	Ti	Zn	As	B	Hg	Sb	Se
500	150	50	16	60	(21)	25	–	73	–	36	–	–	(0.021)
370	150	36	190	180	–	47	–	140	(0.001)	32	0.003	(0.004)	0.4
79	26	12	89	43	(5.6)	(15)	4.3	25	(0.050)	43	0.002	(0.36)	(0.042)
360	220	31	260	260	–	87	–	170	(0.054)	42	0.003	(0.040)	(0.23)
75	23	26	64	45	(4.3)	8.6	–	15	(0.034)	50	0.001	(0.004)	(0.059)
610	66	44	410	320	37	260	–	140	–	46	0.003	–	–
210	22	17	110	53	–	7.6	–	14	–	40	0.001	–	–
480	45	83	35	60	–	24	–	21	–	53	0.003	–	–
740	240	89	260	420	3400	150	3.1	13	(0.065)	54	0.009	–	(0.16)
190	36	33	63	84	50	8.2	–	4.7	–	–	0.002	–	(0.20)
590	560	140	350	450	430	200	0.92	16	–	93	0.009	–	(0.20)
380	52	28	32	50	(25)	5.8	0.41	17	–	–	–	–	(0.18)
420	190	47	110	190	33	120	–	3.0	(0.081)	19	0.008	(0.086)	(0.26)
170	43	35	38	82	(18)	5.4	–	(3.2)	(0.091)	43	0.002	((0.10)	(0.11)
520	570	68	160	230	120	73	3.0	37	(0.074)	19	0.005	(0.095)	(0.075)
190	57	160	72	200	(20)	–	–	–	(0.077)	40	–	(0.092)	(0.13)
690	290	93	220	360	(25)	87	–	6.3	–	61	0.008	–	(0.18)
43	17	36	15	55	(21)	(15)	–	–	–	43	–	–	(0.18)
610	95	63	180	290	50	98	1.8	3.8	–	34	0.015	–	(0.34)
83	11	13	130	92	(24)	3.3	–	–	–	42	0.001	–	(0.15)
13	2.6	39	11	70	47	6.4	–	–	–	45	0.002	–	–
460	300	120	180	250	96	180	2.2	4.5	(0.078)	–	0.010	0.15	(0.26)
120	95	64	51	77	(16)	11	–	–	(0.093)	36	0.001	(0.14)	(0.090)
7.4	7.1	48	9.9	55	(22)	7.6	–	–	(0.087)	36	0.002	(0.067)	(0.17)
640	400	83	160	230	1200	360	29	4.2	(0.10)	43	0.010	(0.14)	(0.26)
140	49	14	51	78	(24)	35	–	–	(0.093)	–	0.002	(0.099)	(0.19)
740	210	50	170	340	170	92	6.5	11	(0.038)	79	0.004	(0.16)	–
160	22	25	95.0	150	170.0	9.6	–	–	(0.094)	53	0.002	(0.050)	–
360	25.0	15	6.2	100	–	14.0	–	–	(0.011)	–	0.003	(0.033)	–
680	510	170	290	450	210	85	6.0	6.7	–	46	0.019	(0.019)	(0.017)
190	21	42	100	110	(23)	7.4	–	–	–	–	0.001	–	–
630	1100	43	240	250	53	160	(1.0)	4.7	–	7.8	0.019	–	(0.16)
220	110	22	70	62	(53)	10	–	3.2	–	37	0.003	–	(0.13)
2300	690	120	380	450	97	180	1.9	70	(0.095)	61	0.002	(0.11)	(0.19)
85	12	99	38	82	(20)	3.5	–	–	(0.060)	56	–	0.16	(0.15)
79	19	81	19	88	(23)	3.3	–	4.1	(0.075)	(3.6)	0.006	(0.083)	(0.13)
1800	560	73	410	290	50	170	2.9	130	(0.093)	38	0.004	(0.11)	(0.16)
300	54	68	290	120	(22)	5.9	–	(1.3)	(0.086)	47	–	(0.079)	(0.080)
29	9.9	56	(19)	40	(18)	(14)	–	(1.1)	(0.082)	47	0.002	(0.071)	(0.084)
1200	50	92	140	230	71	110	–	6.4	(0.083)	79	0.009	(0.075)	(0.030)
110	5.2	27	5.6	55	–	15	–	–	(0.015)	–	0.004	(0.042)	(0.009)
620	40	84	380	270	3200	310	–	5.0	–	59	0.002	(0.022)	–
240	5.4	43	130	75	120	28	1.6	7.1	–	45	–	–	–
240	–	40	18	60	49	16	2.0	–	–	44	0.001	–	–
650	8.2	64	300	320	45	280	(0.46)	3.4	–	51	0.004	–	–
390	–	31	260	140	(27)	29	–	–	–	–	–	–	–
540	89	–	390	400	11000	53	–	3.6		50	0.003	(0.003)	(0.025)
120	11	42	96	84	–	7.4	–	–		69	0.001	–	–
7.1	10	–	(10)	76	890	6.6	–	–		41	0.001	(0.016)	–
390	340	7.2	98	320	15000	62	–	3.1		37	0.003	–	–
160	47	43	34	46	–	8.0	–	(3.0)		79	–	–	–
9.0	15	31	(23)	62	–	5.7	–	7.5		64	0.003	–	–
690	110	180	240	280	61	110	(0.23)	4.4	(0.086)	42	0.005	(0.027)	(0.18)
1500	970	37	73	110	(22)	5.1	–	–	(0.080)	75	0.001	(0.028)	(0.16)
3000	17	300	12	69	(12)	10	–	–	(0.046)	63	–	(0.025)	(0.10)
1100	100	290	280	400	(14)	120	–	4.6	(0.060)	33	0.004	(0.018)	(0.15)
590	4.3	59	79	130	(11)	5.5	–	–	(0.076)	41	–	(0.003)	(0.20)
1100	11	53	11	90	(12)	16	–	3.8	(0.096)	38	–	(0.022)	(0.15)
420	350	38	300	290	260	130	(0.21)	8.7	(0.056)	51	0.006	(0.017)	(0.014)
130	14	360	160	49	–	10	–	–	–	41	–	(0.008)	–
100	44	5.7	6.8	13	–	17	–	–	–	46	–	–	(0.011)
1000	410	110	190	210	(8.7)	110	–	27	0.021	–	0.006	(0.017)	–
340	43	50	57	18	–	7.6	–	–		89	–	(0.008)	(0.015)
350	120	5.2	11	19	–	16	–	–		51	–	–	–
1300	820	210	690	810	(26)	260	(0.42)	70	(0.006)	57	0.013	–	(0.18)
360	36	15	100	69	(10	15	–	4.9	(0.022)	39	–	–	(0.10)
330	40	33	35	70	(14)	15	1.2	4.1	(0.016)	59	–	(0.010)	(0.15)

Appendix *Continued*

Name	Collected place	Collected year	Part	Concentration (mg/kg)					
				Al	Ba	Ca	Cu	Fe	K
	Miyazaki	1997	Bark	460	110	22 000	7.0	260	2 200
			Sapwood	12	7.1	1 800	–	–	540
			Heartwood	15	530	15 000	–	–	2 900
Aesculus turbinata	Toyama	2004	Bark	19	270	20 000	5.0	14	2 800
			Wood	7.1	31	1 400	–	8.5	780
	Gifu	1993	Bark	55	78	12 000	7.6	42	3 800
			Wood	12	12	1400	–	–	410
Tilia japonica	Miyazaki	2004	Bark	33	56	7 700	3.1	16	3 600
			Wood	11	11	1 300	–	–	530
	Ishikawa	1982	Bark	42	160	10 000	3.6	27	5 500
			Wood	12	20	830	–	–	1 200
Bruguiera gymnorrhiza	Iriomote-shima	1992	Bark	64	–	16 000	–	62	450
			Sapwood	15	–	5 600	–	–	410
			Heartwood	46	3.8	5 200	–	11	620
	Amami	2002	Bark	220	–	20 000	–	120	1 400
			Sapwood	13	3.5	1 500	–	–	1 000
			Heartwood	65	–	5 000	–	–	1 000
Paulownia tomentosa	Kagoshima	2006	Bark	97	83	3 800	12	84	8 600
			Wood	13	21	490	10	–	450
	Kyoto	2006	Bark	36	31	5 500	10	21	5 300
			Wood	26	8.6	340	18	4.0	340
Foreign species									
Picea engelmannii	USA	1963	Wood	16	50	1 300	–	–	340
	Canada	1959	Wood	30	–	1 500	–	–	340
Tsuga heterophylla Sarg.	Canada	1976	Wood	23	–	1 600	–	–	140
	USA	1961	Wood	65	–	1 000	–	–	480
Pseudotsuga menziesii	Netherlands	1985	Wood	5.7	4.3	190	–	–	150
	USA	1987	Wood	21	11	100	–	–	72
	Japan	1996	Wood	8.6	8.9	400	–	–	240
Alnus rubra	Canada	1959	Wood	25	–	710	–	–	330
	Canada	1976	Wood	7.2	7.4	770	–	–	460
Fagus grandifolia	USA	2001	Wood	27	22	1 100	–	4.2	730
	Canada	1976	Wood	24	25	850	–	3.1	650
Dipterocarpus spp.	Malaysia	–	Wood	8.4	–	140	–	–	340
	Kalimantan	1967	Wood	6.8	7.9	51	(0.39)	–	72
Dryobalanops spp.	Malaysia	–	Wood	14	5.3	35	–	–	70
	Borneo	–	Wood	12	7.3	360	–	–	290
Shorea sect. *Shorea* spp.	Borneo	–	Wood	11	13	5 400	–	–	250
	–	–	Wood	35	–	1 100	–	–	390
Shorea negrosensis	Philippines	1969	Wood	7.2	7.0	210	–	–	480
	Philippines	–	Wood	20	13	140	–	–	100

Measurement values show the mean of multiple measurements ($n = 2$ measurements)
A dash represents less than the limit of quantitation (LOQ)
Values in parentheses indicate that it was lower than the LOQ by the dilution rate

Mg	Mn	Na	P	S	Si	Sr	Ti	Zn	As	B	Hg	Sb	Se
660	160	89	390	510	800	110	15	52	(0.078)	41	0.017	(0.10)	(0.24)
170	9.2	8.6	70	71	(12)	12	–	(0.71)	(0.019)	35	–	(0.016)	(0.046)
10 000	550	83	130	66	150	540	–	24	(0.092)	–	–	(0.004)	(0.26)
520	67	98	440	330	38	140	–	(3.7)	–	43	0.005	–	(0.016)
220	12	42	120	54	(23)	12	–	(0.60)	–	54	–	(0.020)	(0.047)
680	87	96	540	360	80	81	2.2	14	–	56	0.013	–	–
200	11	38	55	33	(20)	11	–	(0.34)	–	57	–	–	–
530	90	45	520	460	3 100	75	3.2	4.5	–	44	0.005	–	(0.059)
140	11	48	97	83	38	13	3.1	–	–	46	–	(0.002)	–
1 500	140	320	440	630	38	110	2.0	15	–	58	0.003	–	–
320	20	79	110	110	98	11	–	18	–	48	–	–	–
1 000	5.5	5900	210	3000	–	250	–	4.5	(0.16)	12	0.008	–	(0.027)
880	3.1	5400	260	2500	–	74	–	–	(0.28)	44	–	–	(0.001)
910	–	1100	130	2200	–	73	–	–	(0.096)	92	0.003	–	–
2 200	38	11000	500	4100	–	280	–	3.4	(0.030)	49	0.002	–	–
670	7.8	6700	370	2400	–	26	–	–	(0.025)	80	–	–	–
2 000	–	7900	260	4200	–	260	–	–	(0.065)	–	–	–	–
820	19	180	410	630	150	72	3.6	38	(0.068)	41	0.007	(0.15)	–
52	–	31	63	50	–	13	–	5.2	(0.062)	55	–	(0.064)	–
820	110	90	300	480	–	41	–	58	(0.025)	41	0.005	(0.092)	–
42	–	37	17	46	–	17	–	8.6	–	63	–	(0.066)	–
98	63	(2.0)	(37)	37	–	10	–	8.3	(0.047)	70	0.050	(0.004)	–
180	–	48	(15)	35	–	11	–	–	(0.018)	230	0.070	(0.008)	–
160	84	78	(31)	53	–	15	–	–	(0.003)	48	0.091	–	–
110	99	70	54	100	–	13	–	(0.070)	(0.058)	130	3.7	–	–
28	8.5	65	(22)	60	–	13	–	–	(0.19)	77	0.610	–	–
3.3	–	63.0	(12)	57	–	13	–	–	–	80	0.005	–	–
70	17.0	3.8	59	43	–	6.1	–	(0.48)	(0.079)	80	0.005	–	–
180	9.5	280	36	220	–	4.3	–	–	(0.035)	78	0.070	–	–
230	22.0	46	46	120	–	7.7	–	–	(0.034)	62	0.005	–	–
170	140	870	(25)	100	–	4.8	–	4.8	(0.070)	41	0.008	–	–
250	37	–	(23)	77	–	5.0	–	3.8	(0.093)	58	0.004	–	–
260	3.8	240	(10)	49	–	3.3	–	14	(0.046)	48	0.001	(0.15)	–
14	–	58	(2.4)	60	–	13	–	–	(0.049)	48	0.068	(0.069)	–
5.9	–	42	(10)	43	2 600	14	–	–	(0.042)	55	0.003	(0.020)	–
160	–	210	(14)	72	4 600	5.3	–	–	(0.14)	56	0.100	1.0	–
1 300	110	670	39	110	–	68	–	–	(0.055)	58	0.045	(0.019)	–
310	67	59	(13)	59	–	13	–	4.7	(0.16)	62	0.002	(0.022)	–
630	10	2300	(9.1)	210	–	5.0	–	–	(0.036)	64	0.013	–	–
5.3	–	130	(4.9)	50	–	14	–	–	(0.060)	55	0.041	–	–