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Predicting wood density of growth increments of Douglas-fir stands in New Zealand

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Abstract

Background: Douglas-fir comprises 6% of New Zealand's planted forest area and contributes to the national carbon sequestration estimate. Carbon stock changes in Douglas-fir stem wood can be calculated by multiplying the increment in stem volume under bark by the density of the growth sheath and the carbon fraction. This paper describes a new model developed to predict variation in wood density of Douglas-fir growth sheaths from known wood density drivers.

Methods: Datasets used to parameterise the wood density model contained: (1) mean breast height (1.4 m above ground) outerwood (based on 50 mm long cores) density of 30 trees per stand from 32 semi-mature and mature stands with soil and climate data, for predicting wood basic density from environmental factors; (2) basic density of wood samples taken at breast height and at regular height intervals along the stem of 75 trees from 10 stands, for predicting the weighted mean wood basic density of pre-defined growth sheaths; and (3) breast height pith-to-bark radial density profiles based on 500 trees from 47 stands, for predicting wood density of individual annual growth rings at breast height. Linear and non-linear mixed models were developed using these data to explain the variation in wood density of growth sheaths.

Results: Breast height outerwood density was positively related to mean annual air temperature and negatively related to soil nitrogen fertility. This environmental model jointly explaining 83% of the variation in wood basic density at breast height of ring 30 from the pith. The radial pattern of wood density variation of annual growth rings at breast height was calibrated to a site using predictions from the environmental model. The ratio of growth sheath density to breast height ring density was applied to the predicted density of annual growth rings at breast height. This ratio decreased from 1.05 close to the pith to 0.95 in outerwood rings of mature trees, with ring number from pith explaining 49% of the variation in this ratio.

Conclusions: A wood density model that incorporates the important drivers of variation in density of stem wood growth sheaths in New Zealand-grown Douglas-fir will improve the accuracy of carbon stock and stock change estimates in NZ's planted forest estate. The new wood density model has been linked to the Forest Carbon Predictor which predicts carbon stocks in live and dead biomass pools from inventory plot measurements, site mean annual temperature, and soil nitrogen fertility information.

Keywords: Stand carbon, Wood density, *Pseudotsuga menziesii*, Models, Site factors, Soil fertility

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Background

Carbon stocks and stock changes in New Zealand's exotic plantation forest area are estimated in order to meet international reporting commitments under the United Nations Framework Convention on Climate Change and the Kyoto Protocol (IPCC 2003). Assessments of the regional performance of a wide range of exotic tree species planted in New Zealand (Beekhuis and Will 1965) revealed that *Pinus radiata* D. Don (radiata pine) performs well in most districts that are free of snow, which explains why this species is widely planted throughout New Zealand and currently comprises approximately 90% of NZ's exotic plantation forest area of 1.7 million ha. In contrast, *Pseudotsuga menziesii* (Mirb.) Franco (Douglas-fir), which currently comprises approximately only 6% (NEFD 2016), performs best in southern and higher elevation areas where cold temperatures reduce the impact of needle diseases (Stone et al. 2007) on growth. Carbon stocks and stock changes over time are estimated for these species using yield tables derived from an inventory plot-based modelling system called the Forest Carbon Predictor (FCP). The FCP links stem gross and net annual volume increment predictions with estimates of wood density of annual growth sheaths (Beets et al. 2011). For radiata pine, growth sheath density is modelled as a function of site mean annual temperature, soil nitrogen fertility, and stocking (Beets et al. (2007)). A growth sheath density model has not been developed for Douglas-fir. However, components of the model developed to predict the density of Douglas-fir log sections in relation to timber performance (Kimberley et al. 2017) are applicable for the estimation of carbon stock changes over time. This paper describes a model developed to predict variation in wood density of Douglas-fir growth sheaths from known drivers of wood density in New Zealand, identified previously by Kimberley et al. (2017), utilising a combination of new and existing sub-models.

Wood density varies in relation to site mean annual temperature, soil nitrogen fertility, and silvicultural management factors (stocking/thinning), both in radiata pine and Douglas-fir (Erickson and Lambert 1958; Jozsa and Brix 1989; Brix 1993; Beets et al. 2007; Kantavichai et al. 2010; Kimberley et al. 2017). Nitrogen fertiliser trials provide direct evidence linking wood density to nitrogen supply. These trials show that fertiliser applications ephemeraly increase foliar nitrogen and reduce wood density of growth rings formed that year (Beets et al. 2001; Jozsa and Brix 1989). By inference, the reduction in wood density with increasing nitrogen fertility of a site, as reflected by the soil carbon (C) nitrogen (N) ratio, $C/(N - 0.014)$ (Beets et al. 2007), can be ascribed to elevated foliar nitrogen.

Wood density also varies radially and longitudinally within stems. Unlike radiata pine, where wood density increases from pith to bark, Douglas-fir wood density

initially decreases in the first 5–7 rings from the pith and then increases beyond ring 10 until attaining a maximum value at around ring 30 from the pith (Jozsa and Brix 1989; Kimberley et al. 2017). Wood density is relatively high near the pith because the density of the early wood is high near the pith in Douglas-fir (Harris and Orman 1958). This radial pattern is evident in Douglas-fir irrespective of height up the stem (Jozsa and Brix 1989).

In this paper, we describe the datasets and model developed to predict variation in wood density of annual growth sheaths from site information.

Methods

Data collection and modelling approach

The data requirements and steps used to model the density of growth sheaths laid down annually in Douglas-fir stands largely follow those developed for radiata pine (Beets et al. 2007). The data and modelling are briefly described here and in detail below.

Firstly, breast height (1.4 m) mean outerwood density was measured in stands sampled across a wide range of sites throughout New Zealand with climate and soil nitrogen fertility information. Outerwood density varies with age but is more-or-less constant from around ring age 30 years. Hence, for modelling purposes, the mean breast height outerwood density of a stand was corrected to growth ring 30 from pith, D_{30} , which we refer to as the reference density. The stands sampled for sub-model 1 (described below) ranged in age from 19 to 52 years (with a mean age of 35 years), and hence extrapolation was required to predict the density of the 30th ring of some stands. Given the ages of the stands sampled, less extrapolation is required to remove age effects using ring 30 as the reference age compared to ring 40, which was used by Kimberley et al. (2017). Sub-model 1 uses site mean annual temperature and soil nitrogen fertility as inputs and outputs the reference density.

Secondly, historical data on breast height pith-to-bark density profiles from mature trees sampled from a wide range of sites throughout New Zealand had already been incorporated in a model for predicting the variation in ring density from pith-to-bark (Kimberley et al. 2017). This model, which we refer to as sub-model 2, has two purposes: to predict the reference density used to parameterise sub-model 1 and to provide pith-to-bark density trajectories. Hence, sub-models 1 and 2 allow for the effects of site factors and tree age on breast height density changes at breast height.

Thirdly, the mean wood density of growth sheaths laid down over the entire length of the stem was determined from disc samples cut at fixed intervals along the stems of trees sampled from a number of sites and stand ages. For each growth sheath, the density of the

corresponding growth ring at breast height was also determined. The ratio of sheath density to the breast height density was calculated for all growth sheaths of each tree. Sub-model 3 predicts the ratios as a function of breast height ring number from pith. The density of annual growth sheaths are obtained for each site by apply the ratios predicted by sub-model 3 to the site-adjusted pith-to-bark density predictions from sub-models 1 and 2.

Development of sub-models

The density of annual growth sheaths is modelled by combining predictions from the above three sub-models, as follows:

1. Sub-model 1 predicts breast height density of the reference ring (30th ring from the pith), using environmental data as input. The density of the reference ring was predicted from the outerwood density measurements of each stand using sub-model 2, and these predicted values used to parameterise sub-model 1.
2. Sub-model 2 predicts wood density of annual growth rings at breast height, numbered from pith to bark. This model was developed in a previous study (Kimberley et al. 2017). Breast height pith-to-bark ring density trajectories are derived from density predicted at the reference ring (D_{30}) from the temperature and soil fertility from sub-model 1.
3. Sub-model 3 predicts wood density of any stem annual growth sheath given the ring age, by applying the predicted ratio of the sheath density/breast height ring density to the site and age adjusted predictions of breast height density of that growth ring predicted by sub-models 1 and 2.

Data requirements for each sub-model

Site effects on breast height outerwood density for parameterising sub-model 1

Sub-model 1 was developed using breast height outerwood density data from 32 stands surveyed in 2011 (Table 1). These stands were growing at sites selected to cover the spatial distribution and site fertility of Douglas-fir across New Zealand. Outerwood density at these sites ranged from 333 to 526 kg/m³ with a mean of 433 kg/m³ (Table 2) and were similar in density to data in the national wood density database, which contains data from 312 stands ranging in outerwood density from 319 to 532 kg/m³, with a mean of 427 kg/m³ (Kimberley et al. 2017). Because breast height wood density varies considerably from pith to bark (Kimberley et al. 2017), only stands aged 19 years or older were included (Table 1). One outerwood density core was taken at 1.4 m height from 30 live dominant and co-

dominant trees within each stand. Small trees were excluded because volume increment per hectare largely reflects the growth rate of larger trees within a stand. Each core was trimmed to give a 50-mm-long sample of outerwood from immediately under the bark. The number of annual growth rings within each 50-mm-long core sample was recorded and its basic density determined using the maximum moisture content method (Smith 1954).

Data for each stand, including mean ring number from pith, the measured outerwood density, the predicted breast height wood density of ring 30 from pith (reference ring), and site variables are given in Table 2. The mean number of rings at breast height was calculated for each site by subtracting breast height age (the number of years required for trees to grow to breast height, 1.4 m) from stand age. Breast height age was estimated for each stand from site index using a national height/age function for Douglas-fir and ranged from 1.2 to 5.2 years and averaged 2.9 years. The mean ring number from pith of the outerwood core samples was calculated by subtracting half the mean number of rings per core from the mean number of rings at breast height. Because the stands varied in age (Table 1), breast height outerwood density measurements were corrected to ring 30 from pith. This was achieved using sub-model 2, the breast height radial density model described in Kimberley et al. (2017) and is described in the 'Appendix' section.

Depending on the site, either 20 or 30 0–5 cm mineral soil cores were collected systematically from throughout the stand with a Hoffer tube sampler. These soil core samples were bulked and air-dried, and the fine earth fraction (<2 mm), and carbon and nitrogen analysed using a Leco CNS-2000 furnace (LECO Corp., St Joseph, MI, USA). Site mean annual air temperature was estimated from the National Institute of Water and Atmospheric Research (NIWA) climate surfaces.

Breast height pith-to-bark density profiles and density of the 30th ring from pith for parameterising sub-model 2

Sub-model 2 was developed from breast height pith-to-bark radial wood density core data, which were compiled and published by Kimberley et al. (2017). The 5-mm-diameter core samples were available for approximately 500 trees from 47 stands. Cores were Soxhlet extracted with methanol to remove extractives and resin, a strip milled from each core, and the strips scanned using the X-ray densitometer at Scion (Cown and Clement 1983).

Density of stem wood growth sheaths and of the corresponding rings at breast height for parameterising sub-model 3

Sub-model 3 was developed using wood density data from eight stands, six of which ranged in age from 9 to 31 years (Table 3). Stand attributes determined at these

Table 1 Location and age of Douglas-fir stands sampled in a national wood density survey used to develop sub-model 1

Site number	Location or forest	Stand age (years)	Latitude (°S)	Longitude (°E)	Elevation (m)	Stocking (stems/ha)
1	Arrowtown	27	44.94	168.77	495	450
2	Ribbonwood	28	44.38	169.82	650	500
3	Glenfoyle	30	44.72	169.33	400	633
4	Castledowns	26	45.85	168.20	500	490
5	Tokoiti	24	46.16	169.97	70	463
6	Gwavas	52	39.71	176.37	486	558
7	Dusky	27	45.85	169.12	300	490
8	Te Wera	42	39.19	174.63	214	580
9	Whakarewarewa	28	38.21	176.27	420	650
10	Berwick	30	45.87	170.02	530	490
11	Kinleith	52	38.38	175.87	443	537
12	Rotoehu	39	37.98	176.52	266	433
13	Kaingaroa	52	38.45	176.60	438	537
14	Rotoehu	52	37.91	176.58	91	550
15	Hanmer	27	42.53	172.91	520	490
16	Wairoa	31	38.98	177.56	350	488
17	Kaingaroa	28	38.89	176.29	780	500
18	Rankleburn	52	45.99	169.42	150	176
19	Kaingaroa	20	38.38	176.71	255	533
20	Craigieburn	32	43.15	171.73	800	500
21	St Arnaud	28	41.76	172.79	560	575
22	Tauhara	23	38.70	176.23	550	633
23	BurntFace6	44	43.04	171.64	1080	650
24	BurntFace1	46	43.04	171.63	800	520
25	BurntFace5	46	43.04	171.63	960	640
26	BurntFace3	46	43.04	171.63	850	680
27	North Bank	29	41.47	173.67	200	700
28	Golden Downs	52	41.46	172.91	413	638
29	Kaingaroa	21	38.88	176.29	790	1375
30	Forest Creek	19	43.69	170.88	737	1080
31	Kaingaroa	28	38.34	176.39	367	800
32	Whakarewarewa	31	38.21	176.28	440	717

six stands were based on a 0.04-ha sample plot installed at each site. Diameter at breast height of all trees in the plot and the height of a random sample of no less than 20 dominant or co-dominant trees were measured. Eight to 10 dominant or co-dominant trees per plot were selected across the dbh range and felled, individual tree biomass measured, and stand biomass determined (Beets, P.N., Oliver, G.R., Pearce, S.H., Kimberley, M.O., Henley, D. G., & Meason, D.F. Species-specific adjustment function for the Forest Carbon Predictor. *New Zealand Journal of Forestry Science* (submitted)). Disc sampling points were marked at pre-determined height intervals along each stem, starting nominally at the base (0.15 m height) and

thereafter at either 1 m (9- and 10-year-old stands), 2 m (19- and 21-year-old stands), or 3 m (28 and 31-year-old stands) intervals along the stem to the top of the tree. A 5-cm-thick disc sample was cut at each stem sample height (except the base, where a 2.5-cm-thick disc was taken to ensure appropriate weighting of samples when calculating sheath density).

Wood density of growth sheaths was determined from sector samples. Two 40° opposing sectors were cut from each disc, and each sector divided into ring groups comprised of either two ring (in the 9- and 10-year-old trees) or five ring groups (trees older than 10 years). The density of wood samples was determined following standard

Table 2 Outerwood basic density of 50-mm core samples, mean ring number from pith, predicted basic density of ring 30 from pith, and environmental variables at 32 Douglas-fir sites used to develop sub-model 1

Site number	Mean ring number from pith	Measured outerwood density (kg m ⁻³)	Predicted wood density of reference ring (ring 30 from pith) (kg m ⁻³)	Mean annual temperature (°C)	Soil C (%)	Soil N (%)	Soil C/(N – 0.014)
1	19.2	384	399	8.9	2.53	0.200	13.6
2	20.1	386	398	7.9	4.36	0.307	14.9
3	21.8	393	399	10.3	3.09	0.214	15.5
4	18.8	319	333	7.8	5.57	0.380	15.2
5	16.9	408	430	10.1	3.56	0.235	16.1
6	36.8	426	423	10.9	11.56	0.749	15.7
7	18.1	381	397	9.6	5.46	0.342	16.6
8	27.4	491	491	12.0	13.15	0.757	17.7
9	15.8	493	526	12.2	6.14	0.352	18.2
10	21.8	369	376	8.1	5.17	0.295	18.4
11	42.1	444	440	11.7	10.85	0.612	18.1
12	29.2	489	489	12.5	4.64	0.262	18.7
13	40.3	454	450	11.5	5.99	0.334	18.7
14	38.1	497	494	13.3	6.51	0.361	18.8
15	19.9	406	420	9.8	1.99	0.107	21.4
16	24.2	461	466	11.3	3.12	0.166	20.5
17	19.6	421	437	9.5	5.18	0.262	20.9
18	43.3	420	415	9.8	5.61	0.279	21.2
19	14.3	446	482	12.9	4.43	0.217	21.8
20	23.3	369	372	8.3	4.25	0.205	22.3
21	20.6	411	422	9.4	4.94	0.230	22.9
22	15.9	419	447	10.8	6.70	0.290	24.3
23	31.3	366	361	7.3	11.09	0.452	25.3
24	34.7	420	415	7.9	3.57	0.144	27.5
25	34.1	401	396	7.6	4.15	0.166	27.3
26	34.4	418	413	7.6	4.19	0.156	29.5
27	21.1	485	495	11.6	3.38	0.117	32.8
28	39.5	505	501	10.4	3.79	0.129	33.0
29	12.8	373	412	9.3	6.86	0.322	22.3
30	13.6	362	403	8.2	3.99	0.234	18.1
31	23.7	488	493	11.9	6.25	0.328	19.9
32	26.5	462	463	12.0	8.04	0.424	19.6

methods (Cown et al. 1991). Briefly, this involved measuring the volume of each wood sample using water displacement and its oven dry weight following drying at 105° C. Growth sheath density was calculated by dividing the total dry weight of sector samples representing each ring group by the corresponding volume of the sector samples.

In addition to the six stands with biomass measurements, data from two mature Douglas-fir stands sampled in a wood properties study in 1993 were included to extend the age range available for analysis. Disc samples were cut at 5-m intervals along the stem from 11 trees in a 33-year-old stand at Waiotapu and 14 trees from a 59-year-old stand in Waimahia. Measurements of ring width and wood density were obtained using X-ray densitometry

of strips cut from discs at Scion (Cown and Clement 1983), as in sub-model 2. Breast height measurements of outerwood density were obtained using 50-mm-long cores. The density of growth sheaths was represented by the number of rings in the breast height outerwood cores (the outer 10 rings at Waiotapu and outer 21 rings at Waimahia). Mean density of the growth sheath was calculated as a weighted average of the required rings across all disc heights, weighted by ring area.

The calculated ratios of sheath density to breast height ring density for sub-model 3 were based on trees sampled from juvenile and mature stands because sub-model 3 is intended to be applied to stands of any age.

Table 3 Stand attributes, site characteristics, and wood density in Douglas-fir stands used to develop sub-model 3

Attribute	Units	Gowan Hill 10 years	Kaingaroa 21 years	Forest Creek 9 years	Forest Creek 19 years	Kaingaroa 28 years	Whakarewarewa 31 years
Year planted		1998	1985	2000	1990	1982	1979
Initial stocking	Stems/ha	1600	1450	1419	1372	1666	2000
Stand age	Years	10	21	9	19	28	31
Live stocking at assessment age	Stems/ha	1186	1250	1419	1051	800	717
Basal area	m ² /ha	24.8	52.6	12.0	37.9	55.5	46.7
Mean top height	m	8.4	15.5	6.5	14.7	25.6	26.2
Average ring age of outerwood	years	7.5	15.5	6.5	16.5	25.5	28.5
Breast height wood density of outer 5 rings of plot trees (and sample size)	kg/m ³	336 (20)	373 (20)*	388 (36)	362 (23)	488 (8)	462 (35)
Elevation	m	254	790	786	737	367	440
Mean annual temperature	°C	9.8	9.4	8.0	8.2	11.9	12.0
C (0–5 cm soil)	%	5.6	6.9	5.3	4.0	6.3	8.0
N (0–5 cm soil)	%	0.41	0.32	0.37	0.23	0.33	0.42
C/(N – 0.014)		14.1	22.3	14.9	18.1	19.9	19.6

*Mean of 50-mm cores with average ring age of outerwood based on diameter increment of the 10 biomass trees

Statistical analysis

Sub-model 1

Pearson correlation and partial correlation coefficients between measured breast height density of outerwood (D_{ow}) and site mean annual temperature, MAT, soil nitrogen fertility index, $C/(N - 0.014)$ (following Beets et al. 2007), and ring number from pith, R , were calculated using the CORR procedure in SAS Version 9.3. Correlations using the predicted breast height density of ring 30 from pith (D_{30}) were also examined to determine whether this variable eliminated any age-related correlation. The following multiple linear regression model was then fitted using the SAS GLM procedure for predicting D_{30} from mean annual temperature and soil C/(N – 0.014) ratio:

$$\text{Sub-model 1: } D_{30i} = a1 + b1 \times MAT_i + c1 \times C\%/(N\% - 0.014)_i + e_i \quad (1)$$

where D_{30i} is breast height wood density at ring 30 from pith (kg m⁻³) for site i , derived using sub-model 2 from outerwood density measurements, MAT_i is mean annual temperature for stand i , the adjusted C:N ratio, $C/(N - 0.014)$, is based on C and N in the upper 5 cm of mineral soil, $a1$, $b1$, and $c1$ are regression coefficients, and e_i is the error term assumed to be independently and identically, normally distributed with mean zero. The model was tested to determine whether significant differences in the relationship in either intercept or slope parameters existed between North and South Island stands and between stands planted prior to and after 1990.

Sub-model 2

The development of sub-model 2 is fully described in Kimberley et al. (2017). For our purposes, sub-model 2 was initially used to adjust the breast height outerwood density measurements of stands used to parameterise sub-model 1 to the 30th growth ring from the pith. This adjustment was necessary to remove the effects of stand age on outerwood density measurements. The main use of sub-model 2 is to predict breast pith-to-bark ring density profiles, after taking into account the site determined predictions of outerwood density (30th ring from pith) from sub-model 1, as described in the 'Appendix' section.

Sub-model 3

A mixed model was used to predict the ratio of growth sheath to breast height wood density as a function of breast height ring from pith, fitted using the SAS MIXED procedure. Various transformations of the independent variable were tested for inclusion in the model including untransformed (linear), square root, and log. The square root transformation provided the best fit and was therefore chosen for the final model which was of the following form:

$$\text{Sub-model 3: } (DS_R/D_R)_{ij} = a3 + b3 \times \sqrt{R_{ij}} + s_i + e_{ij} \quad (2)$$

where $(DS_R/D_R)_{ij}$ is the ratio of sheath density to breast height density for sheath j in stand i , R_{ij} is breast height ring-from-pith, $a3$ and $b3$ are model coefficients, s_i is a random error term representing stand i , and e_{ij} is the residual error term with both error terms assumed to be

independently and identically, normally distributed with mean zero.

Results

Sub-model 1—prediction of breast height wood density of ring 30 from pith from site variables

Measured breast height density of outerwood, D_{ow} , was strongly positively correlated with mean annual temperature ($r = 0.82$) and weakly correlated with stand age ($r = 0.36$) (Table 4). Moreover, D_{ow} was significantly correlated with soil C/(N - 0.014) only after accounting for temperature and age effects, with a partial correlation of 0.62 (Table 4). Defining outerwood density as the predicted density of ring 30 from pith, D_{30} (the reference ring), using the pith-to-bark density profile model described in Kimberley et al. (2017), eliminated stand age effects. Relationships between breast height wood density at ring 30 from pith and mean annual temperature and soil C/(N - 0.014) are shown in Fig. 1.

The regression model that predicts wood density at breast height in ring 30 from pith from mean annual temperature and the adjusted soil C:N ratio (i.e. C/(N - 0.014) explained 83% of the variation in density. Parameter estimates are given in Table 5. Tests were made to determine whether separate intercept or slope parameters were required for North and South Islands, or for stands planted before and after 1990, but no significance differences in the relationship were found for these factors.

Sub-model 2—breast height pith-to-bark radial density data

While already published in Kimberley et al. (2017), for completeness, the functions are also provided in the ‘Appendix’ section of our paper, which describes firstly how D_{30} is derived when parameterising sub-model 1, and secondly how breast height pith-to-bark ring density predictions are adjusted using sub-model 2 for the

Table 4 Correlations between Douglas-fir basic wood density, temperature (MAT), soil C/(N - 0.014), and ring number (R), based from 32 sites throughout New Zealand. The wood density variables analysed include the measured breast height outerwood density (D_{ow}) and predicted outerwood density of ring 30 from pith (D_{30}). The table shows wood density Pearson correlations (r) with each variable and partial correlations with each variable adjusted for the other two variables (partial r)

Variable	D_{ow}		D_{30}	
	r	Partial r	r	Partial r
MAT	0.82**	0.90**	0.85**	0.91**
C/(N - 0.014)	0.26	0.62**	0.21	0.64**
R	0.36*	0.40*	0.11	-0.16

Statistical significance indicated by * ($p < 0.05$) and ** ($p < 0.01$)

effects of site factors which are predicted using sub-model 1.

Sub-model 3—ratios for predicting the density of growth sheaths from breast height ring density

The mean basic density of wood laid down in growth sheaths over the entire stem and at breast height of defined groups of rings are summarised for each stand in Table 6. The ratio of wood density of the growth sheath to the breast height density was greater than one for the inner 10 rings from pith, but less than one beyond ring 10 (Fig. 2).

The regression model represented by Eq. 2 predicts the growth sheath density/breast height ring density ratio from the breast height ring number from pith. This model explained 49% of the variation in the ratio. Parameter estimates for sub-model 3 (Eq. 2) are given in Table 7.

Discussion

Studies of regional differences in Douglas-fir wood density have identified elevation, temperature, rainfall, soil, and silvicultural factors as drivers of wood density in New Zealand and elsewhere (Erickson and Lambert 1958; Jozsa and Brix 1989; Brix 1993; Beets et al. 2001; Kantavichai et al. 2010; Kimberley et al. 2017). Two important environmental drivers influencing wood density variation in New Zealand-grown Douglas-fir and radiata pine are mean annual temperature and nitrogen fertility of the site, while stocking/thinning has a small effect on density (Kimberley et al. 2017). The importance of nitrogen supply on wood density was clearly demonstrated for radiata pine growing on nitrogen-deficient coastal dunes, where nitrogen inputs from mineral fertiliser applications and legumes decreased wood density and latewood percent (Beets et al. 2001). The influence of temperature on density was more evident in overseas studies than in New Zealand, where historic surveys of breast height outerwood density did not find a relationship with temperature. This unexpected result was previously ascribed to confounding owing to seedlot differences in density, as discussed by Kimberley et al. (2017). The most recent compilation and analysis has clearly shown that temperature is the main climatic factor determining outerwood density variation in New Zealand, and that the fertility of the site is also relevant (Kimberley et al. 2017).

The effect of nitrogen fertility on density, reported in Kimberley et al. (2017), was based on 18 sites, all of which were located in the South Island of New Zealand. Our analysis of the effect of soil fertility on outerwood density, which includes an allowance for stand age effects on outerwood density using D_{30} , is based on 32 widely dispersed sites throughout both islands of New Zealand.

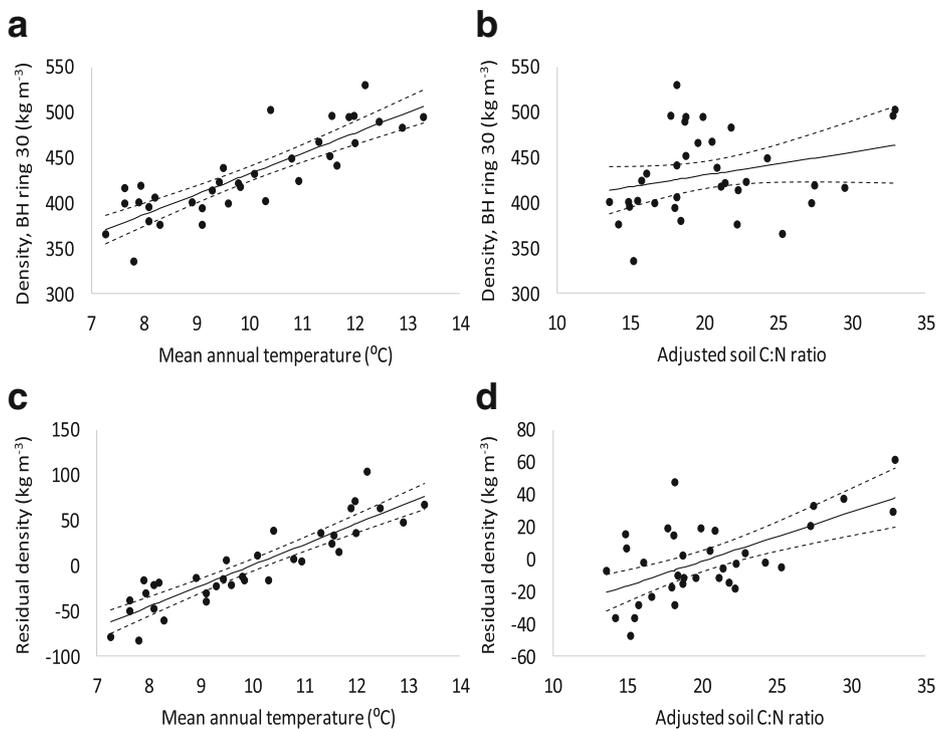


Fig. 1 Relationships between the predicted breast height wood density of ring 30 from pith and temperature and adjusted soil C:N ratio (i.e. $C/(N - 0.014)$). **a** Wood density vs mean annual temperature. **b** Wood density vs adjusted soil C:N ratio. **c** residuals from wood density = $a + b \times$ (adjusted soil C:N ratio) regression vs mean annual temperature. **d** Residuals from wood density = $a + b \times$ (mean annual temperature) regression vs adjusted soil C:N ratio

Analysis of this more comprehensive dataset indicates that the difference in mean density between the North and South Islands, reported in Kimberley et al. (2017), was likely a result of differences in site fertility. The new model incorporates the effects of temperature and nitrogen fertility on wood density and can therefore be confidently applied to Douglas-fir stands growing throughout New Zealand.

The wood density of annual growth sheaths is predicted by multiplying the growth ring density at breast height by the ratio of sheath density/breast height density of the corresponding growth ring. This ratio is moderately stable, although it declined, on average, from 1.05 to 0.95 with increasing ring age. The ratio exceeds 1.0 in small trees and

in rings near the pith of mature trees, when proportionally more of the wood of the corresponding growth sheath is below breast height. Conversely, the ratio averages 0.95 in the outer growth rings of mature trees when proportionally more of the wood of a growth sheath is above breast height. Clearly, wood density within a growth sheath decreases with height up the stem. This conclusion is supported by the finding that wood density of log sections decreases with height (Kimberley et al. 2017).

The wood density model is intended to be applied to stands that are not being fertilised. The adjusted soil C/N ratio reflects the effects of land use history differences on soil nitrogen fertility and hence on wood density. Use of this model therefore implies that all rings from pith-to-bark have low density if the outerwood density is low, or conversely, that all rings will have a high density if the outerwood density is high. This site-determined pattern is clearly evident in the within-tree density trends illustrated in Kimberley et al. (2017). In contrast, fertilised stands exhibit an ephemeral reduction in wood density of between 5 and 16%, which persists as long as foliar N levels are elevated in response to fertilisation (Jozsa and Brix 1989; Erickson and Lambert 1958; Erickson and Harrison 1974). Given the generally ephemeral nature of foliar responses to fertiliser additions, applying the new

Table 5 Parameter estimates for sub-model 1. The model predicts breast height wood density in ring 30 from pith (D_{30}) from mean annual temperature (MAT) and soil $C/(N - 0.014)$, and was fitted to Douglas-fir data from 32 sites throughout New Zealand. The model $R^2 = 0.83$ and root mean square error = 19.7 kg m^{-3}

Parameter	Estimate	Std. error	t value	p value
a1	136.5	24.0	5.05	< 0.0001
b1	23.3	2.0	11.56	< 0.0001
c1	3.09	0.72	4.29	< 0.0001

Table 6 Mean basic density at breast height and mean basic density of growth sheaths for given groups of rings (counted from bark), and the sheath/breast height (BH) density ratio for eight Douglas-fir stands in New Zealand

Site and stand age of biomass trees (N is sample size)	Rings from bark	Mean ring from pith	Sheath density	BH density	Sheath/BH density ratio
Forest Creek age 9 years (N = 8)	1–3	6	373	350	1.068
	4–8	3	401	415	0.960
Forest Creek age 19 years (N = 8)	1–5	14	370	373	0.999
	6–10	9	356	349	1.026
	11–17	4	418	419	0.993
Gowan Hill age 10 years (N = 8)	1–2	7	370	344	1.082
	3–4	5	355	330	1.078
	5–6	3	403	370	1.093
	7–10	1	408	400	1.020
Kaingaroa age 21 years (N = 10)	1–5	16	399	442	0.906
	6–10	11	362	367	0.988
	11–17	6	366	374	0.983
Kaingaroa age 28 years (N = 8)	1–5	24	472	488	0.969
	6–10	19	445	456	0.976
	11–15	14	463	463	1.004
	16–20	9	411	399	1.033
	21–30	4	450	439	1.036
Whakarewarewa age 31 years (N = 8)	1–5	27	453	485	0.938
	6–10	22	413	436	0.950
	11–15	17	417	444	0.939
	16–20	12	398	398	1.002
	21–25	7	430	397	1.081
26–30	2	460	423	1.087	
Waiotapu age 33 years (N = 11)	1–10	26	383	403	0.950
Waimahia age 59 years (N = 14)	1–20	47	434	469	0.925

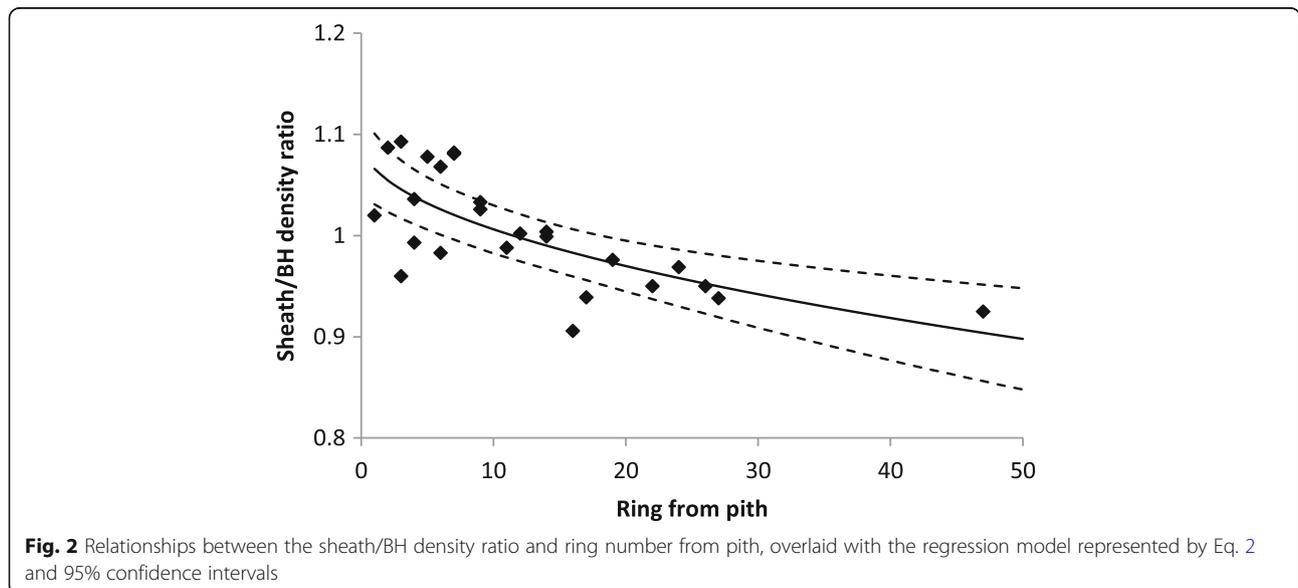


Fig. 2 Relationships between the sheath/BH density ratio and ring number from pith, overlaid with the regression model represented by Eq. 2 and 95% confidence intervals

Table 7 Parameter estimates for sub-model 3. The model predicts the sheath to breast height wood density ratio as a function of breast height ring number from pith, and was fitted to Douglas-fir data from eight sites in New Zealand. The model $R^2 = 0.49$

Parameter	Estimate	Std. error	t value	p value
a_3	1.094	0.021	51.15	< 0.0001
b_3	-0.0277	0.0059	-4.67	0.042

wood density model, which was developed using data from unfertilised stands, to fertilised stands is unlikely to lead to significant prediction errors.

The new Douglas-fir density model is similar to the growth sheath density model developed for radiata pine (Beets et al. 2007), where wood density is also modelled as a function of ring age, site mean annual temperature, and nitrogen fertility. As in radiata pine, diameter growth rate significantly influences ring density in Douglas-fir; however, this effect was materially unimportant, in carbon stock terms, although statistically significant in Douglas-fir (Kimberley et al. 2017), and hence was excluded from the model. The new wood density model for Douglas-fir replaces a preliminary version of the model in the FCP that overestimated wood density by approximately 5%. In the FCP, stem volume increment predictions from the 500 Index growth model (Knowles 2005) are multiplied by the density of the corresponding 'growth sheaths' to give annual stem wood dry matter increments in Douglas-fir¹. Stem dry matter increments are expanded to total dry matter in live and dead organic matter pools using C_Change (Beets et al. 1999).

Conclusion

This study has shown that site mean annual temperature and soil nitrogen fertility are important environmental drivers of variation in stem wood density of Douglas-fir in New Zealand. The new wood density model has been linked to the Forest Carbon Predictor, which uses site mean annual temperature, soil nitrogen fertility data, and tree measurements from national inventory plots to improve the accuracy of carbon stock estimates for New Zealand's planted forest estate.

Endnotes

¹Beets, P.N., Oliver, G.R., Pearce, S.H., Kimberley, M.O., Henley, D. G., & Meason, D.F. Species-specific adjustment function for the Forest Carbon Predictor. *New Zealand Journal of Forestry Science* (submitted).

Appendix

Estimation of basic wood density at breast height in ring 30 from pith in New Zealand Douglas-fir

Sub-model 2 was applied for two distinct modelling purposes:

1. Equations 3 and 4, described in Kimberley et al. (2017), can be used to predict basic wood density at breast height (D_R) as a function of ring number from pith (R):

$$D_R = a + (b-R)/(c + d \times \exp(Rf)) + (1-g \times \exp(-Rh)) \times L \quad (3)$$

Parameters are given in Table 8 in the 'Appendix' section. The pith-to-bark density profile provided by sub-model 2 is calibrated to a site using the parameter L . To predict D_R at D_{30} (the outerwood density predicted using sub-model 1 in this paper), L is calculated using:

$$L = D_{30} - (a + (b-30)/(c + d \times \exp(30f)))/(1-g \times \exp(-30h)) \quad (4)$$

2. This approach can also be used to estimate L from an outerwood density measurement (D_{core}) of a stand, and was used in the current study to predict D_{30} for each of the sites used to develop sub-model 1. In this case, values of L_R are calculated for each ring R in the core using:

$$L_R = D_{\text{core}} - (a + (b-R)/(c + d \times \exp(Rf)))/(1-g \times \exp(-Rh)) \quad (5)$$

The L_R are averaged over all rings in the core to give L which is used in Eq. 3 to predict D_{30} .

Table 8 Parameter values used in sub-model 2 (from Table 7, Kimberley et al. 2017)

Parameter	Value
a	432.6
b	1.22
c	0.0235
d	0.0125
f	0.221
g	0.814
h	0.258

Abbreviations

a, b, c, d, f, g, h : Sub-model 2 coefficients (see Appendix); $a1, b1, c1$: Sub-model 1 coefficients; $a3, b3$: Sub-model 3 coefficients; BH: Breast height; C: Carbon; $C/(N - 0.014)$: Adjusted carbon to nitrogen ratio; D_{30} : Breast height wood density at ring 30 from pith; D_{ow} : Breast height density of outerwood; D_R : Breast height wood density at ring R from pith; DS_R : Wood density of growth Sheath at ring R from pith; FCP: Forest Carbon Predictor; i : The i^{th} stand; IPCC: Intergovernmental Panel on Climate Change; j : The j^{th} growth sheath; MAT: Mean annual temperature; N: Nitrogen; NEFD: National Exotic Forest Description; NIWA: National Institute of Water and Atmosphere Research; R : Ring number from pith at breast height; s, e : Model error terms

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Availability of data and materials

Please contact author for data requests.

Authors' contributions

PNB developed the concept for this manuscript and was the primary author. MOK developed the modelling approach, undertook the data analysis, and contributed to writing the paper. GRO and SHP undertook the biomass sampling and sample processing and contributed to writing the paper. All authors read and approved the final version of the manuscript.

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Ethics approval and consent to participate

Not applicable

Competing interests

The authors declare that they have no competing interests.

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