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Original Article

Exposure Determinants of Wood Dust, Microbial Components, Resin Acids and Terpenes in the Saw- and Planer Mill Industry

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Abstract

Objectives: Sawmill workers have an increased risk of adverse respiratory outcomes, but knowledge about exposure–response relationships is incomplete. The objective of this study was to assess exposure determinants of dust, microbial components, resin acids, and terpenes in sawmills processing pine and spruce, to guide the development of department and task-based exposure prediction models.

Methods: 2474 full-shift repeated personal airborne measurements of dust, resin acids, fungal spores and fragments, endotoxins, mono-, and sesquiterpenes were conducted in 10 departments of 11 saw- and planer mills in Norway in 2013–2016. Department and task-based exposure determinants were identified and geometric mean ratios (GMRs) estimated using mixed model regression. The effects of season and wood type were also studied.

Results: The exposure ratio of individual components was similar in many of the departments. Nonetheless, the highest microbial and monoterpene exposure (expressed per hour) were estimated in the green part of the sawmills: endotoxins [GMR (95% confidence interval) 1.2 (1.0–1.3)], fungal spores [1.1 (1.0–1.2)], and monoterpenes [1.3 (1.1–1.4)]. The highest resin acid GMR was estimated in the dry part of the sawmills [1.4 (1.2–1.5)]. Season and wood type had a large effect on the estimated exposure. In particular, summer and spruce were strong determinants of increased exposure to endotoxin (GMRs [4.6 (3.5–6.2)] and [2.0 (1.4–3.0)], respectively) and fungal spores (GMRs [2.2 (1.7–2.8)] and [1.5 (1.0–2.1)], respectively). Pine was a strong determinant for increased exposure to

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both resin acid and monoterpenes. Work as a boilerman was associated with moderate to relatively high exposure to all components [1.0–1.4 (0.8–2.0)], although the estimates were based on 13–15 samples only. Cleaning in the saw, planer, and sorting of dry timber departments was associated with high exposure estimates for several components, whereas work with transportation and stock/finished goods were associated with low exposure estimates for all components. The department-based models explained 21–61% of the total exposure variances, 0–90% of the between worker (BW) variance, and 1–36% of the within worker (WW) variances. The task-based models explained 22–62% of the total variance, 0–91% of the BW variance, and 0–33% of the WW variance.

Conclusions: Exposure determinants in sawmills including department, task, season, and wood type differed for individual components, and explained a relatively large proportion of the total variances. Application of department/task-based exposure prediction models for specific exposures will therefore likely improve the assessment of exposure–response associations.

Keywords: BW and WW variance; endotoxin; exposure prediction model; fungal fragments; fungal spores; mixed model; season; task-based and department-based

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Introduction

Sawmill workers are exposed to wood dust that may cause nasal and sinonasal cancers (IARC, 2012) and possibly lung cancer (Barcenas *et al.*, 2005; Jayaprakash *et al.*, 2008) as well as non-malignant respiratory health effects including asthma. They are also exposed to micro-organisms, bacterial endotoxins, resin acids (diterpenes), and vapours containing terpenes, but associations with these exposures and respiratory health have not often been studied. Nonetheless, some evidence exists for an association with monoterpenes and irritation of the eyes, mouth and throat, chest tightness, reduced lung function, increased bronchial hyperactivity, and airway inflammation (Hedenstierna *et al.*, 1983; Johard *et al.*, 1993; Dahlqvist and Ulfvarson, 1994; Eriksson *et al.*, 1996). Also, abietic acid (produced mainly by pine trees and other conifers) has been associated with allergic sensitization, respiratory symptoms and asthma (Ayars *et al.*, 1989; Hessel *et al.*, 1995; Demers *et al.*, 1997); and exposure to fungal spores has been linked to respiratory symptoms and allergic alveolitis (Wimander and Belin, 1980; Eduard *et al.*, 1992, 1993; Halpin *et al.*, 1994a,b).

Despite complex exposures, involving wood dust and multiple wood-associated chemicals and organisms, with each potentially able to contribute to adverse respiratory health, most studies continue to measure only wood dust. As a result, significant knowledge gaps remain both in terms of what workers are exposed to, and how these exposures either individually or in combination, affect respiratory health. We have recently reported on these exposures in sawmill workers in Norway and found that the occupational exposure limit (OEL) of 2 mg m^{-3} for wood dust from Nordic species except beech and oak (total dust), and the recommended OELs of 90 EU m^{-3} for inhalable endotoxin and 1×10^5 fungal spores m^{-3} were exceeded in a proportion of workers (1%, 7.5%, and 38%, respectively) (Straumfors *et al.*, 2018), suggesting that at least some of these exposures may contribute to adverse health effects in this industry.

The present study assessed exposure determinants of dust, endotoxins, fungal spores and fragments, terpenes, and resin acids in 11 saw- and planer mills, processing pine and spruce. The study is part of a large longitudinal study on respiratory health of Norwegian sawmill workers. The aim was to guide the development of department-based and task-based exposure prediction models that can be used to study exposure–response relationships in large-scale epidemiological studies in the sawmill industry.

Methods

Study design

In the period 2013–2016 we conducted multiple and repeated airborne exposure measurements in 205 workers from 11 large- and medium-sized industrial sawmills, sorting and planing companies in Norway that processed spruce (*Picea abies*) and/or pine (*Pinus sylvestris*) (Table 1). The companies were recruited from the two largest actors in the Norwegian wood industry and from independent sawmill companies, and the selection was based on size, location and wood type. Small private sawmills connected to farms were not included. Workers were selected among all departments for each shift at each sawmill. The sampling logistics allowed measurements of 14 workers per shift, and were restricted by the available sampling equipment and the amount of sampling equipment possible to put on each

Table 1. Sampling overview of the multiple repeated exposure measurements of sawmill workers.

Exposure component	Number of measurements	Group variables			Number of observations per group variable		
		Companies	Workers	Sample period	Companies	Workers	Sample period
Dust	501	11	205	262	46 (37–58)	2.4 (1–6)	1.9 (1–2)
Endotoxin	481	11	199	252	44 (37–51)	2.4 (1–4)	1.9 (1–2)
Fungal spores	476	11	194	249	43 (34–51)	2.5 (1–4)	1.9 (1–2)
Resin acids	502	11	205	262	46 (37–58)	2.4 (1–6)	1.9 (1–2)
Monoterpenes	387	11	166	203	35 (16–50)	2.3 (1–4)	1.9 (1–2)
Fungal fragments	69	2	30	36	35	2.3 (1–4)	1.9 (1–2)
Sesquiterpenes	58	11	42	45	5 (2–13)	1.4 (1–4)	1.3 (1–2)

worker. The exposures were measured on 2 consecutive days for each worker (first sample period), and repeated on 2 consecutive days in the following season (second sampling period) to include both summer and winter season. This resulted in the collection of 2029 personal thoracic aerosol samples and 445 personal samples of volatile compounds. A schematic illustration of the industrial process and the associated job groups, as well as a description of the work conducted in each job group have been published previously (Straumfors *et al.*, 2018). Information of job group, task, and work duration was collected by questionnaires after each measurement. From this, 29 tasks were specified across 10 different job groups/departments (Table 2).

Exposure measurements and laboratory analyses

The sampling and analyses of dust, resin acids, endotoxin, fungal particles, and terpenes were performed as described in detail previously (Straumfors *et al.*, 2018). In short, full-shift (duration 170–642 min, median 513 min) personal thoracic aerosol samples were collected using BGI GK2.69 cyclones (BGI Inc., Waltham, MA, USA) mounted with Millipore 37 mm sampling cassettes (Merck Life Sciences, Darmstadt, Germany) at a flow rate of 1.6 l min^{-1}. Monoterpenes were collected using Anasorb CSC charcoal tubes (SKC Cat. no. 226-01) (SKC Ltd, Dorset, UK), and sesquiterpenes were trapped on Tenax TA sorbent tubes (Markes Int., Ltd, Llantrisant, RCT, UK), both at a flow rate of 50 ml min^{-1}. Dust weights were determined using a microbalance (Sartorius AG MC5, Göttingen, Germany). Resin acids were analysed using liquid chromatography with mass spectrometric (MS) detection and atmospheric pressure chemical ionization in negative mode. Endotoxins were analysed using the kinetic Limulus amoebocyte lysate assay (Lonza Ltd, Basel, Switzerland). Fungal particles were analysed by field emission scanning electron microscopy. Monoterpenes were analysed by gas chromatography (GC) with flame ionization detection (Agilent Technologies, Santa Clara, CA, USA) and sesquiterpenes by thermal desorption–GC–MS (Markes Int., Ltd, Llantrisant, RCT, UK and Agilent Technologies, Santa Clara, CA, USA).

Data analyses

We recently showed that the individual components within the broader groups of resin acids, monoterpenes, sesquiterpenes, and fungal fragments were strongly correlated (Straumfors *et al.*, 2018). The summed concentrations of the individual components within each of these groups were

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Table 2. Description of tasks by departments in the Norwegian sawmill industry.

Tasks by department	Task description
Saw	
Control room	Remote operation of the saw from enclosed control room
Cleaning	Cleaning with broom or compressed air during production stops or in the end of the shift
Out in the production	Trouble shooting, handling stuck timber, *etc*.
Sorting of green timber	
Control room	Quality sorting of undried, cut timber by remote operation in enclosed control room. Remote use of docking saw
Cleaning	Cleaning with broom or compressed air during production stops or in the end of the shift
Filleting	Operator post were sorted timber of a certain dimension and quality were piled with fillets between the layers to enable air passing between the planks
Sorting	Quality sorting undried, cut timber and use of docking saw either manually by sitting or standing beside the timber transportation belt, or by joystick operation sitting in an elevated, but unprotected chair beside the transportation belt
Kiln drying	
Forklift	Transporting piles of timber sorted by dimension and quality in and out of the kiln drier
Operational control	Programming and operating the kiln dryer
Various kiln dryer tasks	Checking timber humidity, trouble shooting
Sorting of dry timber	
Sorting	Manual quality sorting of dried timber
Strapping and wrapping	Labelling, strapping and wrapping sorted timber
Cleaning	Cleaning production areas with broom or compressed air during production stops or in the end of the day
Planing	
Cleaning	Cleaning planers and production area with broom or compressed air
Control planer	Control position for the planer
Control saw	Control position for the saw, cutting and profiling timber
Strapping and wrapping	Labelling, strapping and wrapping of planed timber
Timber feed and resaw	Removing spots and weaknesses from the timber before feeding the planer with dried timber
Sorting	Sorting of planed timber
Stock/finished goods	Despatching, picking of materials for customers, use of wrapping machine and forklift
Maintenance	All kinds of repairs and maintenance work all over the sawmill and in the workshop
Transport	
Green timber	Transport of logs the storage yard to debarking machine with log dumpers and cut undried timber with forklift
Dry timber	Transport of dry timber with forklift
Wood chips, splinter and bark	Transport with truck or dumper
Various other transport	Transport of other materials related to sawmilling in the yard
Boilerman	Fuelling kiln, cleaning kiln
Timber roof trusses	
Docking saw	Cutting dried timber to fit for assembly into trusses
Assembly	Assembly of roof trusses parts
Forklift	Transport of dried timber and finished trusses

therefore used in this study. Samples with values below the limit of detection (LOD) were replaced with the respective LOD/$\sqrt{2}$ and adjusted for air volume (gravimetric analyses) and dilution (endotoxin). Samples with no observed spores were replaced by the LOD and adjusted for air volume. The exposure data were skewed and approximated a log-normal

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distribution, so we used ln-transformed values and present geometric means (GMs) with geometric standard deviations (GSDs). In addition to presenting overall GMs and GSDs we also present GMs adjusted for random effects (GM_{ADJ}), and GSDs expressing the standard deviations between companies (GSD_{BC}), between workers (GSD_{BW}), and within workers (GSD_{WW}) using pure random effects models.

To assess the effect of tasks, departments, season, and wood types on exposure we used mixed model regression using the mixed command in STATA with three levels: (i) sample period nested in; (ii) workers nested in; and (iii) companies as random effects. Season, wood type, and either task-durations or department-time were included as fixed effect variables. Since workers were typically conducting multiple tasks on the same day, and sometimes in several departments during a shift, variables for all tasks or all departments were always included in the models. The variables were time-weighted by hours; i.e. the duration of each task or time spent in each department was included. Interactions between season and/or wood type and the variables for department-time were also tested. The influence of adding fixed effect variables and interaction terms into the model was tested by likelihood ratio (LR) test using the maximum likelihood function with a P-level ≤0.05 considered statistically significant. Model selection was supported by the minimum Akaike's information criterion (AIC) score of the models tested. The restricted maximum likelihood algorithm and Satterthwaite approximations to the degrees of freedom were used to fit the mixed models, and estimate P-values and variance components. An independent covariance structure for the random effects was assumed. The effects of department-time and task-duration were expressed as geometric mean ratios (GMRs, exposure per hour). GMs and GMRs with 95% confidence intervals were calculated by taking the inverse logarithm of the regression coefficients and the 95% confidence intervals. A P-level ≤0.05 was considered statistically significant. Simpler one- and two-level models were used for fungal fragments and sesquiterpenes because of the more limited number of observations. Department-time was grouped into (i) green departments (saw + sorting of green timber); (ii) dry departments (kiln drying + sorting of dry timber + planing); and (iii) other departments (stock finished goods maintenance + transport + boilerman) and included as fixed variables. Person ID nested in Company ID was included as random variables for sesquiterpenes. Company ID was omitted from the fungal fragment model since fungal fragments were analysed in only two companies, and Person ID was the only random variable for this model. Exposure levels of different combinations of determinants can be computed from the models as follows:

$$E = \text{GM} \times \text{GMR}_{\text{determinant 1}} \times \text{GMR}_{\text{determinant 2}} \times \text{GMR}_{\text{determinant } n}$$

where E = exposure, GM is the model intercept, and $\text{GMR}_{\text{determinant 1}}$ and $\text{GMR}_{\text{determinant 2}}$ are the GMR for determinants 1 and 2, respectively.

To quantify the contribution of the fixed effects to the between company (BC), between workers (BW), and within workers (WW) variance components, values of the various components obtained from the mixed models were compared with those from a pure random effects model. The percentage of the variances that could be explained by the fixed effect variables was calculated as follows: $(\text{var}_{\text{random}} - \text{var}_{\text{mixed}})/\text{var}_{\text{random}} \times 100\%$. The 2 consecutive sampling days in each season constituted the sampling periods that were included as random effect, nested in worker in the mixed models. Hence, the WW variance component was split in a 'between sampling periods component' (WW_{BSP}) and a 'within sample periods component' (WW_{WSP}). The covariance structure obtained with this model is a compound symmetry structure. The variance inflation factors indicated no serious collinearity problems between the different department time and different task durations. No variance component analyses were conducted for fungal fragments and sesquiterpenes due to the relatively small number of samples for these exposures.

The IBM SPSS statistics 25 (IBM, North Castle, NY, USA) and STATA/SE 15.1 (StataCorp LP, College Station, TX, USA) were used for the statistical analyses.

Results

General exposure and variances

The general GM exposures were 0.09 mg m^{-3} thoracic dust, 2.5 EU m^{-3} endotoxin, 4 × 10^4 m^{-3} fungal spores, 1.6 µg m^{-3} resin acids, 1.1 mg m^{-3} monoterpenes, 20 × 10^4 m^{-3} fungal fragments, and 40 µg m^{-3} sesquiterpenes (Table 3). The geometric standard deviation (GSD_{OBS}) of dust exposure was 2.6, and a moderate GSD within workers (GSD_{WW} = 1.8) and between workers (GSD_{BW} = 2.0), while the GSD between companies (GSD_{BC} = 1.4) was low (Table 3). The GSDs of the other exposure components were considerably greater. In particular, the GSD_{OBS} for endotoxin, fungal spores, and fragments was between 3.2 and 4.9, with similarly high GSD_{WW}. The GSDs of the terpene and resin acid exposures were particularly high (GSD_{OBS} 4.1–7.8), with the largest GSD_{BW} (5.5 and 4.0, respectively). The GSD_{BC} was relatively small for all components. To be able to generalize analyses across companies, Company ID was included as a random variable in all subsequent analyses.

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Table 3. GM exposure and standard deviations in the saw-, sorting, and planer mill industry.

Component	*N*	*N* < LOD	AM	GM_{OBS}	GSD_{OBS}	GM_{ADJ}	GSD_{BC}	GSD_{BW}	GSD_{WW}
Dust (mg m^{-3})	501	53	0.20	0.09	2.61	0.09	1.38	2.02	1.85
Endotoxin (EU m^{-3})	481	124	15.0	2.50	4.94	2.50	1.59	2.32	3.59
Fungal spores (spores m^{-3})	476	77	12.5×10^4	4×10^4	4.19	4×10^4	1.43	2.32	3.01
Fungal fragments (fragments m^{-3})	69	-	36×10^4	20×10^4	3.23	21×10^4	-	1.73	2.82
Resin acids (µg m^{-3})	502	0	7.93	1.56	5.52	1.37	1.68	4.01	2.50
Monoterpenes (mg m^{-3})	387	0	0.87	1.11	7.75	1.02	2.13	5.46	2.45
Sesquiterpenes (µg m^{-3})	58	0	92	40	4.08	41	2.23	2.84	2.01

GM_{OBS}: geometric mean of the observed values; GSD_{OBS} geometric standard deviation of the observed values; GM_{ADJ}: GM adjusted for random effects; GSD_{BC}: geometric standard deviation of the mean between companies; GSD_{BW}: geometric standard deviation of the mean between workers; GSD_{WW}: geometric standard deviation of the mean within workers; Company ID: 11 groups, Person ID: 205 groups; -: no GSD, only two companies; LOD: limit of detection.

Department-based exposure models and influence of season and wood type

The mean dust exposure per hour was similar in all departments, although somewhat higher for the boilerman group (GMR 1.26), and lower for the stock/finished goods workers (Table 4). Significant interaction effects were observed between wood types and planing, stock/finished goods, and maintenance, but the magnitude of the effects was relatively small. Using the estimates presented in Table 4, dust exposures never exceeded 2 mg m^{-3} for any of the workers even after a full 8 h workshift (data not shown).

Mean endotoxin exposure was generally low (Table 3) and similar in several departments (Table 4). Summer and processing spruce were strong to moderate determinants for increased endotoxin exposure (GMR 4.6 and 2.0), but there was significant interaction between spruce processing and maintenance, and spruce processing and the boilerman group resulting in reduced endotoxin exposure estimates (Table 4). According to these estimates, the endotoxin exposure did not exceed the 90 EU m^{-3} recommended inhalable exposure limit in any of the departments even after a full 8 h shift (data not shown).

Mean fungal spore exposures were also relatively low (Table 3) and similar between most departments (Table 4). The highest GMR was 1.07 in the saw and the sorting of dry timber department, whereas the lowest exposure was in the roof timber trusses department (GMR 0.66) (Table 4). Summer and processing spruce were associated with increased fungal spore exposure (GMR 2.16 and 1.45).

Resin acid exposure was highest in the sorting of dry timber department (GMR 1.35), but exposures were also higher in the planing department (GMR 1.17) compared with other departments. The strongest determinant for resin acid exposure was the processing of pine, resulting in more than twice the exposure compared to processing spruce (GMR 0.44 for spruce). The exposure was lower in summer for some of the job groups as shown by interactions between summer and the saw (GMR 0.91), kiln dryer (GMR 0.74), sorting of dry timber (GMR 0.86), planing (GMR 0.88), and maintenance (GMR 0.86) departments, respectively (Table 4).

Monoterpene exposure was highest in the saw (GMR 1.25) and the sorting of green timber (GMR 1.15) departments, whereas processing pine wood resulted in four times higher monoterpene exposure than processing spruce (GMR 0.25 for spruce) and exposure was nearly twice as when processing mixture of pine and spruce (GMR 0.57) (Table 4). Stock/finished goods, transport, and production of timber roof trusses were the lowest exposed job groups for all components (Table 4).

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Table 4. Mixed models showing GMRs of exposures by department, season and wood type.

Determinants	Dust (mg m⁻³) × h⁻¹		Endotoxin (EU m⁻³) × h⁻¹		Fungal spores (×10⁴/m³) × h⁻¹		Resin acids (µg m⁻³) × h⁻¹		Monoterpenes (mg m⁻³) × h⁻¹	
	N	GMR ($CI_{95\%}$)	*N*	GMR ($CI_{95\%}$)	*N*	GMR ($CI_{95\%}$)	*N*	GMR ($CI_{95\%}$)	*N*	GMR ($CI_{95\%}$)
GM[a]	501	0.12 (0.07;0.20)	481	0.77 (0.33; 1.78)	476	2.27 (1.05; 4.91)	502	1.78 (0.91; 3.49)	387	3.83 (1.63; 8.98)
Department										
Saw	101	0.98 (0.91; 1.05)	91	**1.16 (1.04; 1.29)**	93	1.07 (0.96; 1.18)	102	1.08 (0.98; 1.20)	67	**1.25 (1.11; 1.40)**
Sorting of green timber	120	0.95 (0.89; 1.02)	108	1.06 (0.95; 1.17)	108	0.99 (0.90; 1.10)	120	1.04 (0.95; 1.13)	85	**1.15 (1.03; 1.29)**
Kiln drying	38	0.98 (0.89; 1.08)	38	0.93 (0.80; 1.08)	35	0.98 (0.85; 1.14)	38	0.91 (0.79; 1.03)	34	0.91 (0.78; 1.06)
Sorting of dry timber	122	1.03 (0.97; 1.10)	114	1.02 (0.92; 1.13)	122	1.07 (0.97; 1.17)	123	**1.35 (1.24; 1.48)**	100	**0.81 (0.72; 0.90)**
Planing	90	0.94 (0.86; 1.02)	89	0.96 (0.87; 1.07)	83	1.01 (0.91; 1.12)	89	**1.17 (1.06; 1.30)**	60	0.99 (0.88; 1.12)
Stock/finished goods	32	**0.78 (0.69; 0.89)**	33	0.88 (0.77; 1.01)	31	**0.86 (0.76; 0.98)**	33	**0.79 (0.71; 0.89)**	27	**0.70 (0.61; 0.81)**
Maintenance	73	1.02 (0.94; 1.11)	73	1.03 (1.00; 1.28)	75	0.98 (0.87; 1.09)	74	1.07 (0.96; 1.19)	66	0.98 (0.87; 1.11)
Transport	67	**0.90 (0.84; 0.97)**	68	0.90 (0.81; 1.00)	66	**0.87 (0.79; 0.97)**	68	**0.77 (0.70; 0.84)**	58	**0.77 (0.69; 0.87)**
Boilerman	15	**1.26 (1.07; 1.49)**	15	**1.44 (1.05; 1.97)**	13	1.02 (0.79; 1.32)	15	1.10 (0.88; 1.36)	13	1.04 (0.81; 1.34)
Timber roof trusses	6	0.96 (0.85; 1.10)	6	**0.81 (0.67; 0.98)**	6	**0.66 (0.55; 0.79)**	6	**0.71 (0.60; 0.84)**	4	**0.68 (0.53; 0.86)**
Season										
Winter (ref)	277	1	255	1	254	1	277	1	235	1
Summer	224	0.87 (0.75; 1.01)	226	**4.64 (3.51; 6.15)**	222	**2.16 (1.69; 2.76)**	225	1.08 (0.74; 1.59)	152	0.97 (0.70; 1.35)
Wood type										
Pine (ref)	166	1	152	1	154	1	166	1	137	1
Spruce	249	0.79 (0.61; 1.02)	248	**2.01 (1.35; 2.98)**	246	**1.45 (1.02; 2.08)**	250	**0.44 (0.33; 0.59)**	182	**0.25 (0.70; 1.35)**
Pine and spruce	86	0.79 (0.59; 1.06)	81	**1.60 (1.08; 2.36)**	76	1.22 (0.83; 1.80)	86	0.85 (0.63; 1.16)	68	**0.57 (0.39; 0.84)**
Interactions										
Saw # summer		-		-		-		0.91 (0.83; 1.01)		-
Kiln dryer # summer		-		-		-		**0.74 (0.61; 0.89)**		-
Sorting of dry timber # summer		-		-		-		**0.86 (0.80; 0.92)**		-
Planing # summer		-		-		-		**0.88 (0.81; 0.96)**		-
Planing # spruce		1.05 (0.98; 1.12)		-		-		-		-
Planing # pine and spruce		**1.09 (1.02; 1.17)**		-		-		-		-
Stock/finished goods # spruce		**1.21 (1.05; 1.40)**		-		-		-		-
Stock/finished goods # pine and spruce		1.14 (0.99; 1.31)		-		-		-		-
Maintenance # summer		-		**0.83 (0.74; 0.93)**		-		**0.86 (0.78; 0.95)**		-
Maintenance # Spruce		**1.10 (1.01; 1.19)**		-				-		-
Maintenance # pine and Spruce		1.10 (0.99; 1.21)		-		-		-		-
Boilerman # spruce		-		**0.58 (0.38; 0.88)**		-		-		-
Boilerman # pine and spruce		-		0.01 (0.00;1.28)		-		-		-

GMR ($CI_{95\%}$): geometric mean ratio of exposure (95% confidence interval of the GMR); bold numbers means *P*-value ≤0.05. GMR represents exposure per hour. *N* is the number of samples that is included in each category. Several categories may be included in the same measurement, so the categories are not necessarily exclusive. - means no data, variable omitted from model.

[a]Expected GM exposure for workers that worked in a 'weighted' mix of departments, GM = exp(constant).

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Table 5. Mixed models showing GMRs of exposure to fungal fragments[e] and sesquiterpenes.[f]

Determinants		Fungal fragments ($\times 10^4$/m^3) $\times$ h^{-1}		Sesquiterpenes (μg m^{-3}) $\times$ h^{-1}
	N	GMR ($CI_{95\%}$)	*N*	GMR ($CI_{95\%}$)
GM[a]	69	5.46 (0.85;35.06)	58	31.53 (2.26; 439.64)
Department				
Green departments[b]	42	1.11 (0.88; 1.41)	55	1.12 (0.80; 1.55)
Dry departments[c]	42	1.14 (0.89; 1.44)	22	0.94 (0.66; 1.34)
Other departments[d]	8	1.17 (0.82; 1.66)	10	0.87 (0.56; 1.36)
Season				
Winter (ref)	36	1		-
Summer	33	**2.52 (1.43; 4.44)**		-

GMR ($CI_{95\%}$): geometric mean ratio of exposure (95% confidence interval of the GMR); bold numbers means *P*-value ≤0.05. GMR represents exposure per hour.
N is the number of samples that is included in each category. Several categories may be included in the same measurement, so the categories are not necessarily exclusive.
- means no data, variable omitted from model.
[a]Expected geometric mean (GM)exposure for workers that worked in a 'weighted' mix of departments, GM = exp(constant).
[b]Green departments denotes the saw department and sorting of green timber grouped together.
[c]Dry departments denotes kiln drying, sorting of dry timber and planing grouped together.
[d]Other departments denotes stock finished goods, maintenance, transport and boilerman grouped together.
[e]Person ID was the only random variable in fungal fragments model.
[f]Random variables in sesquiterpene model were Company ID and Person ID.

The exposure estimate for fungal fragments was similar in the grouped departments of green, dry, and other departments (Table 5), but summer was a strong determinant for increased exposure (GMR 2.5) (Table 5). The exposure estimate for sesquiterpenes was also similar in the three grouped categories, but was somewhat higher in the green departments (Table 5). Season had no effect on sesquiterpene exposure. Wood type did not influence the exposure estimates for fungal fragment nor for sesquiterpenes.

Task-based exposure models and influence of season and wood type

Further exposure models were considered by including task-duration in hours by department (Table 6). Dust exposure was highest for boilerman (GMR 1.31), for various kiln dryer tasks (GMR 1.25), for cleaning in the sorting of dry timber department (GMR 1.15), and for cleaning in the planing department (GMR 1.12). The differences between tasks ranged from GMR 0.85–1.31 for all tasks with greater than 8 observations.

The endotoxin exposure estimates (expressed per hour) were similar across several different tasks, although they were somewhat higher for cleaning in the department where dry timber was sorted (GMR 1.51), for various kiln dryer tasks (GMR 1.44), and for cleaning and being out in the production in the saw department (GMR 1.20 and 1.25, respectively). Transport operations were associated with lower exposures (GMRs 0.62–0.93). Exposure was higher in summer (GMR 3.82), and when processing spruce (GMR 1.89) (Table 6).

Fungal spore exposure was highest at the control saw operator post in the planer department (GMR 1.76) and when cleaning in the department where dry timber was sorted (GMR 1.50). The control planer operator post in the planer department and cleaning in the saw department were also associated with higher exposure estimates (GMR 1.17 and 1.15, respectively). In contrast, cleaning in the department where green timber were sorted was associated with less exposure (GMR 0.67, Table 6). The exposure was higher in summer (GMR 2.05), and when processing spruce (GMR 1.45) (Table 6).

The GMRs of resin acids were highest for tasks in the sorting of dry timber department (GMRs 1.19–1.41) and several tasks in the planing department (GMRs up to 1.16), and for cleaning in the saw department (GMR 1.19) (Table 6). Operating a forklift and tasks involved in operational control related to kiln drying as well as transport of green or dry timber were associated with the lowest exposure estimates (GMR 0.39–0.78). The exposure was approximately twice as high in winter (GMR 1.0, reference) as in summer (GMR 0.53), and lower for spruce (GMR 0.43) compared to pine (GMR 1.0, reference).

Monoterpene exposures were elevated for most tasks in the saw and in the sorting of green timber

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department (GMR 1.01–1.46), whereas the estimates for the dry departments were, with some exceptions, mostly lower (GMR 0.77–1.06) (Table 6). The exposure for monoterpenes was highest when processing pine, whereas lower estimates were found for processing spruce or a mixture of pine and spruce (GMR 0.26 and 0.59, respectively).

The inclusion of season did not improve the regression model for monoterpenes, and inclusion of wood species did not improve the model for wood dust (LR test >0.05). Nonetheless, they were included for equal comparison with the models of the other exposure components.

Example calculations of exposure estimates using modelled exposure determinants

An example calculation of exposure estimates using the *department-based model* is shown as follows: Resin acid exposure of a full shift in the sorting of dry timber department, in summer, when processing spruce:

$$E = GM \times (GMR_{\text{sorting of dry timber department}})^{8h} \times GMR_{\text{summer}} \times GMR_{\text{spruce}} \times (GMR_{\text{sorting of dry timber\#summer}})^{8h}$$
$$E = 1.78 \times 1.35^{8} \times 1.08 \times 0.44 \times 0.86^{8} = 2.80\ \mu\,\text{g}\,\text{m}^{-3} \quad (1)$$

An example calculation of estimates using the *task-based models* may be shown as follows:

Resin acid exposure, 2 h strapping and wrapping and 3 h sorting in the sorting of dry timber department, 1 h transport of dry timber, and 1 h various other transport, in winter, when processing pine:

$$E = GM \times (GMR_{\text{strapping av wrapping/SDT}})^{2\,h} \times (GMR_{\text{sorting/SDT}})^{3\,h} \times (GMR_{\text{dry timber/transport}})^{1\,h} \times (GMR_{\text{various/transport}})^{1\,h} \times GMR_{\text{winter}} \times GMR_{\text{pine}}$$
$$E = 2.77 \times 1.28^{2} \times 1.19^{3} \times 0.76^{1} \times 1.37^{1} \times 1\,(\text{reference group}) \times 1\,(\text{reference group}) = 7.96\ \mu\,\text{g}\,\text{m}^{-3} \quad (2)$$

Explained variances

The BC variance of the random models was low for all components, and the fixed effects of neither the department-based nor the task-based models explained much of the endotoxin or the fungal spore exposure variance BC. However, 21–79% of the BC variance of the other components was explained (Table 7). The fixed effects of the models of the main components (dust, endotoxin, fungal spores, resin acid, and monoterpenes) explained 21–61% of the total variance, which was mostly attributable to BW variance (up to 91%), except for endotoxin (Table 7). The BW variance of endotoxin was small regardless of the model used. The fixed effects explained the within worker (WW_{TOT}) variance to a variable extent, from marginal for monoterpenes (0–1%) to relatively high for endotoxins and resin acids (24–36%). Fixed effects explained mainly the WW_{BSP} variance (12–73%) and not the WW_{WSP} variance (0–5%). The variances explained by the task-based models were similar to the variances explained by the department-based models.

Discussion

Determinants of exposure to wood dust, microbial components, resin acids, and terpenes were individually assessed by mixed model regression of job groups/departments, tasks, season, and wood type. This represents the most detailed exposure determinants study conducted in the sawmill industry to date and showed several differences and similarities in exposure determinants for the individual components. The models resulting from this study allow the development of detailed exposure prediction models for use in epidemiological exposure–response studies in the saw-, sorting-, and planer mill industry. The identified determinants may be useful in qualitative exposure assessments in similar sawmills and for designing measurement programs.

The most important determinants for high dust exposure were work as a boilerman, work with various kiln dryer tasks, and cleaning in the departments for planing and sorting of dry timber, respectively. The boilermans' tasks included feeding the heater, sometimes with dusty wood splinters, and cleaning the heater, that would give soot exposure, measured as dust mass in this study.

The department-based models of endotoxin indicated similar exposure across departments, except for the saw department and the boilerman that had higher estimates. However, providing more information of the work, the task-based models of endotoxin indicated that cleaning represented higher exposure intensity than other tasks in the sorting of dry timber department, that and that all tasks in the saw department had GMR greater than 1. Although exposure estimates for kiln drying were not significantly different than most other departments in the department-based model, the task-based model showed that various kiln dryer tasks were associated with considerably high exposure, whereas working with a forklift was associated with considerably reduced exposure. This shows the importance of the extra information the task-based models are providing in occupational exposure assessments.

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Table 6. Mixed models showing GMRs of exposures by task, season and wood type.

Determinants		Dust (mg m⁻³)		Endotoxin (EU m⁻³)		Fungal spores (×10⁴ /m³)		Resin acids (µg m⁻³)		Monoterpenes (mg m⁻³)
Tasks by department	*N*	GMR ($CI_{95\%}$)	*N*	GMR ($CI_{95\%}$)	*N*	GMR ($CI_{95\%}$)	*N*	GMR ($CI_{95\%}$)	*N*	GMR ($CI_{95\%}$)
GM[a]		0.11 (0.06; 0.18)		1.05 (0.44; 2.47)		2.56 (1.20; 5.46)		2.77 (1.44; 5.35)		4.37 (1.83;10.4)
Saw	101		91		93		102		67	
Control room	80	0.94 (0.86; 1.03)	69	1.06 (0.92; 1.22)	70	1.02 (0.89; 1.16)	80	0.96 (0.85; 1.07)	51	**1.22 (1.03; 1.44)**
Cleaning	55	1.04 (0.92; 1.17)	47	1.20 (0.99; 1.46)	49	1.14 (0.94; 1.39)	55	**1.19 (1.01; 1.39)**	36	**1.31 (1.04; 1.64)**
Out in the production	65	1.00 (0.88; 1.13)	58	**1.25 (1.02; 1.53)**	62	1.07 (0.90; 1.27)	66	1.05 (0.90; 1.24)	47	1.16 (0.93; 1.44)
Sorting of green timber	120		108		108		120		85	
Control room	8	0.95 (0.74; 1.23)	8	0.89 (0.59; 1.37)	6	1.04 (0.69; 1.59)	8	0.97 (0.68; 1.37)	4	1.49 (0.9; 2.46)
Cleaning	14	1.01 (0.79; 1.29)	14	0.81 (0.56; 1.18)	18	**0.67 (0.49; 0.92)**	14	0.98 (0.72; 1.34)	11	1.01 (0.69; 1.48)
Filleting	63	0.94 (0.87; 1.01)	52	1.02 (0.90; 1.15)	53	0.97 (0.87; 1.09)	63	0.98 (0.89; 1.09)	50	1.09 (0.95; 1.25)
Sorting	78	0.97 (0.90; 1.05)	68	1.07 (0.95; 1.21)	65	1.05 (0.93; 1.19)	78	1.04 (0.94; 1.15)	54	**1.16 (1.01; 1.34)**
Kiln drying	38		38		35		38		34	
Forklift	20	0.90 (0.79; 1.04)	20	**0.76 (0.61; 0.96)**	18	1.04 (0.84; 1.29)	20	**0.69 (0.57; 0.83)**	18	0.82 (0.65; 1.03)
Operational control	26	0.92 (0.78; 1.09)	26	0.8 (0.60; 1.05)	23	0.98 (0.75; 1.28)	26	**0.77 (0.61; 0.96)**	24	0.84 (0.64; 1.10)
Various kiln dryer tasks	10	1.25 (0.97; 1.60)	10	1.44 (0.95; 2.19)	9	0.76 (0.50; 1.14)	10	1.26 (0.89; 1.79)	10	1.08 (0.75; 1.56)
Sorting of dry timber	122		114		122		123		100	
Sorting	87	1.01 (0.94; 1.09)	83	0.96 (0.86; 1.08)	91	1.01 (0.91; 1.13)	88	**1.19 (1.08; 1.31)**	73	**0.77 (0.68; 0.87)**
Strapping and wrapping	77	1.04 (0.97; 1.11)	74	0.99 (0.88; 1.11)	80	1.06 (0.95; 1.17)	78	**1.28 (1.16; 1.40)**	67	**0.81 (0.71; 0.91)**
Cleaning	42	1.15 (0.93; 1.44)	42	**1.51 (1.06; 2.17)**	45	**1.5 (1.09; 2.09)**	42	**1.41 (1.05; 1.90)**	39	0.78 (0.54; 1.13)
Planing	90		89		83		89		60	
Cleaning	39	1.12 (0.97; 1.28)	38	0.98 (0.78; 1.23)	31	1.03 (0.76; 1.39)	39	1.14 (0.95; 1.38)	24	0.86 (0.66; 1.13)
Control planer	30	1.05 (0.91; 1.22)	30	0.89 (0.71; 1.13)	22	1.17 (0.86; 1.58)	30	1.08 (0.89; 1.32)	17	0.99 (0.70; 1.40)
Control saw	18	0.91 (0.77; 1.07)	18	1.05 (0.81; 1.37)	11	**1.76 (1.16; 2.67)**	18	1.16 (0.93; 1.44)	8	1.05 (0.59; 1.88)
Strapping and wrapping	35	0.95 (0.87; 1.04)	35	0.94 (0.82; 1.08)	36	0.92 (0.81; 1.05)	34	0.99 (0.89; 1.12)	23	**0.84 (0.72; 0.99)**
Timber feed and resaw	46	1.01 (0.93; 1.10)	46	0.98 (0.85; 1.12)	40	1.01 (0.88; 1.16)	46	**1.13 (1.01; 1.26)**	27	1.06 (0.90; 1.24)
Sorting	42	0.97 (0.89; 1.07)	42	0.92 (0.79; 1.07)	40	0.98 (0.85; 1.13)	42	**1.15 (1.01; 1.30)**	27	1.03 (0.87; 1.21)
Stock/finished goods	32	**0.88 (0.81; 0.96)**	33	**0.87 (0.76; 0.99)**	31	**0.85 (0.75; 0.96)**	33	**0.78 (0.70; 0.88)**	27	**0.69 (0.60; 0.80)**
Maintenance	73	**1.08 (1.00; 1.16)**	73	1.01 (0.9; 1.14)	75	0.96 (0.86; 1.07)	74	0.98 (0.89; 1.08)	66	0.96 (0.85; 1.08)
Transport	67		68		66		68		58	
Green timber	35	**0.85 (0.79; 0.92)**	35	**0.87 (0.77; 0.98)**	36	**0.85 (0.76; 0.95)**	35	**0.73 (0.66; 0.81)**	31	**0.77 (0.68; 0.88)**
Dry timber	25	0.99 (0.91; 1.08)	25	0.89 (0.77; 1.01)	21	**0.85 (0.75; 0.97)**	25	**0.76 (0.68; 0.85)**	21	**0.71 (0.61; 0.82)**
Wood chips, splinter and bark	18	1.01 (0.84; 1.21)	19	0.93 (0.7; 1.23)	18	1.07 (0.82; 1.40)	19	**0.78 (0.62; 0.99)**	17	0.96 (0.73; 1.25)
Various other transport	4	0.77 (0.41; 1.45)	4	0.62 (0.23; 1.66)	2	0.38 (0.07; 1.93)	4	1.37 (0.61; 3.08)	2	2.50 (0.59; 10.6)
Boilerman	15	**1.31 (1.11; 1.55)**	15	1.10 (0.86; 1.40)	13	1.00 (0.78; 1.28)	15	1.09 (0.88; 1.34)	13	1.03 (0.80; 1.32)
Timber roof trusses	6		6		6		6		4	

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Table 6. Continued

Determinants	Dust (mg m^{-3})		Endotoxin (EU m^{-3})		Fungal spores (×10^4 /m^3)		Resin acids (µg m^{-3})		Monoterpenes (mg m^{-3})	
Tasks by department	N	GMR (CI$_{95\%}$)	N	GMR (CI$_{95\%}$)	N	GMR (CI$_{95\%}$)	N	GMR (CI$_{95\%}$)	N	GMR (CI$_{95\%}$)
Docking saw	2	1.04 (0.83; 1.31)	2	0.99 (0.70; 1.39)	4	0.64 (0.52; 0.80)	2	1.00 (0.75; 1.34)	2	0.66 (0.46; 0.93)
Assembly	4	0.93 (0.80; 1.08)	4	0.75 (0.60; 0.94)	2	0.64 (0.49; 0.84)	4	0.62 (0.52; 0.75)	2	0.63 (0.45; 0.87)
Forklift	1	0.72 (0.15; 3.38)	1	0.44 (0.03; 5.80)	1	3.76 (0.36; 39.2)	1	0.89 (0.10; 7.57)	1	1.04 (0.14; 7.72)
Season										
Winter (ref)	277	1	255	1	254	1	277	1	235	1
Summer	224	0.87 (0.75; 1.01)	226	3.82 (2.90; 5.05)	222	2.05 (1.60; 2.63)	225	0.53 (0.43; 0.66)	152	1.05 (0.74; 1.49)
Wood type										
Pine (ref)	166	1	152	1	154	1	166	1	137	1
Spruce	249	0.95 (0.75; 1.19)	248	1.89 (1.26; 2.85)	246	1.45 (1.02; 2.05)	250	0.47 (0.35; 0.63)	182	0.26 (0.17; 0.40)
Pine and spruce	86	0.95 (0.76; 1.20)	81	1.48 (0.99; 2.21)	76	1.26 (0.85; 1.85)	86	0.79 (0.58; 1.08)	68	0.59 (0.40; 0.88)

GMR (CI$_{95\%}$): geometric mean ratio of exposure (95% confidence interval of the GMR); bold numbers means P-value ≤0.05. GMR represents exposure per hour. N is the number of samples that is included in each category. Several categories may be included in the same measurement, so the categories are not necessarily exclusive.

[a]Expected geometric mean (GM) exposure for workers that worked in a 'weighted' mix of departments, GM = exp(constant).

Similar to endotoxin, the department-based fungal spore model did not show clear differences in exposure intensities between departments, but significant differences between tasks were shown. In particular, controlling the saw in the planing department and cleaning in the sorting of dry timber department were associated with higher exposure estimates. Sorting has previously been shown to represent significantly higher exposure to endotoxins, fungi, and bacteria compared to planing, debarking, and saw tasks grouped together, although the number of samples per site was small in this study (Oppliger *et al.*, 2005). Debarking has previously been identified as an activity with the highest microbial exposure (Duchaine *et al.*, 2000), but this work is now fully automated in Norwegian sawmills, and was therefore not included in the present study. Endotoxin and fungal exposure were highest in summer and when working with spruce. Although we are not aware of any other reports of similar observations, and both spruce and pine have natural resistance against microorganisms (Pearce, 1996), we speculate that spruce may be more prone to fungal infection in warm and humid conditions than pine. However, this observation could also be biased by the fact that more spruce than pine was processed (46% spruce in summer compared with 33% pine, and 54% spruce in winter compared with 33% pine). The effect of season on endotoxin and fungal exposure is most likely explained by warmer temperatures and better growth conditions for microorganisms in summer.

The highest GMR of resin acid was observed for the sorting of dry timber department followed by planing in the department-based model. The task-based model suggested that all tasks within the sorting of dry timber department and several tasks in the planing department represented relatively high exposure intensity, as shown by GMR above 1.19 and 1.13, respectively. An 8 h shift of cleaning in the dry timber department, would, however, in winter and when processing pine, result in four times higher exposure than 8 h of sorting. Although the resin acid exposure in the saw department was not particularly high, according to the task-based model, cleaning in the saw represented equally high exposure as sorting of dry timber. Likewise, the estimate of kiln drying in the department-based model was not particularly high, but an estimate of 1.26 for conducting various kiln drying tasks suggests that this particular task is associated with high resin acid exposure, whereas work with a forklift associated to kiln drying was a determinant of low exposure. In contrast to microbial exposure, pine was the strongest determinant for increased resin acid exposure, associated with exposures more than twice that of spruce. Furthermore, whereas the

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Table 7. Variance components of department-based random and mixed models.

Exposure component		Variance					
		BC	BW	WW_{BSP}	WW_{WSP}	WW_{TOT}	Total variance
Dust	σ^2_{random}	0.10	0.44	0.07	0.35	0.42	0.97
	DEP σ^2_{mixed}	0.08	0.30	0.03	0.35	0.38	0.76
	DEP %	21	32	66	0	11	21
	TASK σ^2_{mixed}	0.08	0.30	0.02	0.35	0.37	0.75
	TASK %	6	31	72	0	13	22
Endotoxin	σ^2_{random}	0.25	0	1.29	1.00	2.29	2.54
	DEP σ^2_{mixed}	0.31	0	0.52	0.95	1.47	1.78
	DEP %	0	0	60	5	36	30
	TASK σ^2_{mixed}	0.32	0.00	0.57	0.97	1.53	1.85
	TASK %	0	98	56	4	33	27
Fungal spores	σ^2_{random}	0.13	0.39	0.56	0.97	1.53	2.06
	DEP σ^2_{mixed}	0.15	0.16	0.27	0.99	1.26	1.58
	DEP %	0	58	52	0	18	23
	TASK σ^2_{mixed}	0.12	0.15	0.26	0.96	1.23	1.50
	TASK %	9	62	53	1	20	27
Resin acids	σ^2_{random}	0.26	1.61	0.46	0.67	1.13	3.00
	DEP σ^2_{mixed}	0.06	0.31	0.12	0.67	0.79	1.17
	DEP %	76	81	73	0	30	61
	TASK σ^2_{mixed}	0.05	0.24	0.18	0.67	0.85	1.14
	TASK %	79	85	60	0	24	62
Monoterpenes	σ^2_{random}	0.56	2.34	0.75	0.56	1.31	4.22
	DEP σ^2_{mixed}	0.25	0.22	0.66	0.64	1.30	1.78
	DEP %	54	90	12	0	1	58
	TASK σ^2_{mixed}	0.29	0.21	0.80	0.57	1.37	1.87
	TASK %	49	91	0	0	0	56

σ^2_{random}: exposure variance of random effects model; DEP σ^2_{mixed}: exposure variance of department-based mixed effects model; DEP %: variance explained by fixed effects in department-based model; TASK σ^2_{mixed}: exposure variance of task-based mixed effects model; TASK %: variance explained by fixed effects in task-based model BC: between company; BW: between worker; WW_{BSP}: within worker variance between sample periods; WW_{WSP}: within worker variance within sample periods; WW_{TOT}: sum of WW_{BSP} and WW_{WSP}.

effect of season was evident by increased resin acid exposure estimates in winter of the task-based models, no general effect of season was identified in the department-based model. However, an interaction between summer and several of the departments reduced the estimates in the department-based model specifically related to interactions with specific job groups.

The highest exposure to monoterpenes was in the saw and the sorting of dry timber departments, as shown by the department-based model. The task-based model suggests that all tasks in these departments contributed to the increased exposure, but the cleaning task and work in the control room were associated with the highest exposure estimates in the saw department. It was surprising that work in the control room also had a high monoterpene estimate. We speculate that the ventilation in the control room might not have been as effective for volatile terpenes as it was for airborne particles. As for resin acids, pine was a strong determinant for increased monoterpene exposure in general, but season had no effect in any of the models.

Different wood types may display different chemical profiles as well as resistance to microbial colonization as shown for terpene and resin acid content in

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different conifers in another study (Demers *et al.*, 2000). Our study, which focussed on two different tree species, also showed that resin acid and monoterpenes exposures were higher when working with pine compared with spruce. This is in agreement with other studies in sawmills (Teschke *et al.*, 1999) and in furniture factories (Hagstrom *et al.*, 2012). In particular, although Teschke and colleagues did not separate samples from work with spruce and pine, they showed that spruce and pine combined resulted in higher exposure than alpine fir and mixed wood types. The observed increase in resin acid exposure in winter may be due to less ventilation from open doors, hatches and windows during winter and dryer air leading to more static charge on airborne particles hindering sedimentation. The reason for not observing the same pattern for monoterpenes, may be that the general ventilation system is more effective for vapours than for particle-bound resin acids.

We believe that the department-based and task-based models are a good basis for the development of exposure prediction models for use in exposure–response studies in this industry in Norway and internationally. However, sawmills processing other wood types may show different profiles and seasonal variation may also differ, depending on latitude and climate. The relationship between wood dust exposure and health effects has been shown to be stronger when dust exposures were assigned based on the workers' jobs, rather than their own exposure measurements, particularly when exposures were estimated using an empirical model of the determinants of exposure (Teschke *et al.*, 2004). From a statistical point of view this supports the use of group-based model estimates for epidemiological studies as they tend to be less affected by exposure misclassification. In addition, stronger associations based on job-based mean exposures may reflect that health effects may not necessarily be associated with dust mass *per se*, but rather with some other exposures that are taken into account by job groups and/or other determinants (Wameling *et al.*, 2000; Teschke *et al.*, 2004). In the present study, we have modelled the exposure to several components in order to be able to study their individual and combined potential to cause respiratory effects in this population in more detail in future epidemiological analyses. The low correlation observed between the measurements of the different components (Straumfors *et al.*, 2018), indicated that this will be possible. However, pairwise correlations of model estimates (linear prediction of the fixed portion of the department models) showed that the correlation between estimates of fungal spores and endotoxins was high (r_p = 0.82) compared with the correlation using measured values (r_p = 0.39). Hence, there is a limitation in the use of estimates of the department-based model of fungal spores and endotoxin in epidemiological analyses of long-term health effects, implicating that one cannot separate the health effects of endotoxins from that of fungal spores. The correlation between department-based estimates of all other components was low, suggesting that the investigation of the exposure–response association with the other exposure components will not have similar limitations.

The observed WW and BW variances of the random models for dust, resin acid, and monoterpenes were similar as previously reported for wood dust, although these studies had fewer measurements (Scheeper *et al.*, 1995; Vinzents *et al.*, 2001). The WW/BW variance ratio has in some studies been used to validate the usefulness of model-based exposure estimates on individual- versus group-based levels (Scheeper *et al.*, 1995; Vinzents *et al.*, 2001; Burdorf and Van Tongeren, 2003). A variance ratio less than 1 indicates large exposure contrasts, and the possibility to obtain exposure estimates of enough precision for individually based risk assessment in epidemiological studies. In contrast, a variance ratio greater than 1, as we observed for all exposure components in both the task-based models and the department-based models, indicates larger difference in exposure between work-shifts (within the same worker) than among workers within the same job groups, and a group-based epidemiological approach may therefore be more appropriate. For the microbial components, this is likely to be related to the relatively fast changes in microbial occurrence due to their being biologically dependent on growth conditions. It further indicates that a group-based risk assessment strategy may give more precise estimates of exposure in both a task-based assessment and a department-based assessment. In general, group-based exposure estimates are likely to be less biased than individually based exposure estimates in epidemiological studies (Loomis and Kromhout, 2004).

As judged by comparison of AICs, task-based models were not better in predicting the exposure ratio than the department-based models, and the exposure variances explained by the fixed effects were similar in the two model types. However, the task-based models do, to a certain extent, provide information on differences in exposure intensity between tasks within a department, which is useful in occupational hygienic assessments. The explained variance for dust exposure in both models (21–22%) was slightly lower than the 26 % explained variance of wood dust previously demonstrated in the furniture industry (Schlunssen *et al.*, 2008; Hagstrom *et al.*, 2012), whereas the explained variance for monoterpene exposure (56–58%) was considerably higher. The latter two studies had, however, not included repeated measurements. The models of Teschke and colleagues explained as much as 61–80% of the ordinary

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least squared variance of inhalable particles, estimated wood dust, resin acids, and monoterpenes, but were based on different statistics and only one sawmill (Teschke *et al.*, 1999).

The determinants in the mixed models explained up to 33% of the WW_{TOT} variance, as shown by a slight reduction of the WW_{TOT} variance from the random to the mixed models, although 1% of the WW_{TOT} variance of monoterpene exposure could be explained by the task-based model and 0% by the department-based model. The BW variances were greatly reduced in the mixed models, with the determinants explaining up to 91% of the BW variances but none of the BW variance of endotoxin exposure. Except for endotoxin and fungal spores, determinants in the models explained the BC variances with fairly high percentages, which suggests that the models are useful for other similar sawmills.

Conclusions

Exposure determinants in sawmills including department, task, season, and wood type differed for individual components, and explained a large proportion of the total variance. Nonetheless, exposure intensity was generally similar in many of the departments, and the time spent and tasks performed in particular departments is therefore critical in terms of exposure risk. Some notable differences were observed, with the highest microbial and monoterpene exposure (expressed per hour) estimated for the green part of the sawmills (where fresh logs are processed), and highest resin acid exposure estimated in the dry part of the sawmills (where kiln-dried timber is processed). Cleaning in the saw, planer, and sorting of dry timber departments was associated with several increased exposure estimates, whereas work with transportation and stock/finished goods was associated with reduced exposure estimates for all components. Boilerman was highly exposed for all components, but estimates were based on 13–15 samples only. Season and wood type had a large effect on the estimated exposure, with summer and spruce being strong determinants of elevated exposure to endotoxin and fungal spores, pine a strong predictor of elevated exposure to both resin acid and monoterpenes, and winter being associated with increased resin acid exposure. Using this information in epidemiological health studies in this industry will likely reduce potential misclassification of exposure potentially resulting in improved assessments of exposure–response relationships. Furthermore, it will allow health effects to be assessed for both the individual components as well as all combined exposures.

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Conflicts of interest

The authors have no conflicts of interest.

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