Respirable Dust and Quartz Exposure from Three South African Farms with Sandy, Sandy Loam, and Clay Soils

ANDREW J. SWANEPOEL1*, HANS KROMHOUT2, ZUBAIR A. JINNAH3, LÜTZEN PORTENGEN2, KEVIN RENTON4, KERRY GARDINER1 and DAVID REES4

1School of Public Health, University of the Witwatersrand Johannesburg, South Africa; 2Institute for Risk Assessment Sciences, University of Utrecht, Utrecht, The Netherlands; 3School of Geosciences, University of the Witwatersrand, Johannesburg, South Africa; 4National Institute for Occupational Health, National Health Laboratory Service and School of Public Health, University of the Witwatersrand, Johannesburg, South Africa

Received 9 November 2010; in final form 9 February 2011; published online 17 June 2011

Objectives: To quantify personal time-weighted average respirable dust and quartz exposure on a sandy, a sandy loam, and a clay soil farm in the Free State and North West provinces of South Africa and to ascertain whether soil type is a determinant of exposure to respirable quartz.

Methods: Three farms, located in the Free State and North West provinces of South Africa, had their soil type confirmed as sandy, sandy loam, and clay; and, from these, a total of 298 respirable dust and respirable quartz measurements were collected between July 2006–November 2009 during periods of major farming operations. Values below the limit of detection (LOD) (22 μg . m⁻³) were estimated using multiple ‘imputation’. Non-parametric tests were used to compare quartz exposure from the three different soil types.

Results: Exposure to respirable quartz occurred on all three farms with the highest individual concentration measured on the sandy soil farm (626 μg . m⁻³). Fifty-seven, 59, and 81% of the measurements on the sandy soil, sandy loam soil, and clay soil farm, respectively, exceeded the American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value (TLV) of 25 μg . m⁻³. Twelve and 13% of respirable quartz concentrations exceeded 100 μg . m⁻³ on the sandy soil and sandy loam soil farms, respectively, but none exceeded this level on the clay soil farm. The proportions of measurements >100 μg . m⁻³ were not significantly different between the sandy and sandy loam soil farms (‘prop.test’; P = 0.65), but both were significantly larger than for the clay soil farm (‘prop.test’; P = 0.0001). The percentage of quartz in respirable dust was determined for all three farms using measurements > the limit of detection. Percentages ranged from 0.5 to 94.4% with no significant difference in the median quartz percentages across the three farms (Kruskal–Wallis test; P = 0.91).

Conclusion: This study demonstrates that there is significant potential for over-exposure to respirable quartz in farming and even clay soil farming may pose a risk. Soil type may determine whether exposure is >100 μg . m⁻³, but the job type and the manner in which the task is performed (e.g. mechanical or manual) may be important determinants of exposure. Identifying quartz exposure determinants (e.g. type of job) and modifiers will be of value to focus implementation of controls of particular importance in developing countries.

Keywords: agriculture; clay; quartz; sand; sand loam; silica; soil types

*Author to whom correspondence should be addressed. Tel: +27-(0)-11-717-2507; fax: +27-(0)-86-553-5885; e-mail: andrew.swanepoel@wits.ac.za
INTRODUCTION

Although silica-associated diseases in agriculture have been reported infrequently (Swanepoel et al., 2010), exposure to respirable crystalline silica (quartz) above occupational exposure limits (OELs) has been demonstrated in farming (Popendorf et al., 1982; Green et al., 1990; Lawson et al., 1995; Molocznik and Zagorski, 1998; Nieuwenhuijzen et al., 1999; Archer et al., 2002; Swanepoel et al., 2010) and has been reviewed recently (Swanepoel et al., 2010). One possible determinant of exposure intensity is the nature of the soil (Stopford and Stopford, 1995a,b; Archer et al., 2002); but the data to quantify the effect of soil type are modest.

Sandy and sandy loam soils (i.e. soils of clay and sand with admixture of decayed vegetable matter) have been found to contain higher levels of quartz in the respirable fraction in parts of eastern North Carolina compared with other North Carolina regions (Archer et al., 2002; Stopford and Stopford, 1995a,b).

In North Carolina, mean quartz percentages in the respirable fraction of sandy soils (29.0 ± 11.1%) were consistently higher than in clay soils (2.17 ± 0.85%) (Stopford and Stopford, 1995a). The mass of respirable quartz particles made up a greater portion of sandy soils (1.02 ± 0.39 %) than clay soils (0.29 ± 0.15%). No airborne measurements were taken to estimate how this difference related to personal exposure during farming activities.

A larger study in the same region compared sandy soils from the sand hills of North Carolina (Stopford and Stopford, 1995b) with sandy loam farms in the coastal plains of North Carolina and clay soils of Piedmont, with similar findings. The respirable fraction of sandy soils averaged 29.0 ± 11.1% [standard deviation (SD) 11.1] versus 15.2% (SD 4.1) in sandy loam soils and 2.2% (SD 0.8) in clay soils. Respirable quartz in sandy soils averaged 1.0% (SD 0.4) versus 0.7% (SD 0.4) in sandy loam soils and 0.3% (SD 0.1) in clay soils; suggesting that, during farm activities, there is potential for greater respirable quartz exposures on sandy or sandy loam soils than clay soils.

Farming in sandy soils has been shown to generate high levels of respirable quartz. In eastern North Carolina, the highest respirable quartz concentration measured in the breathing zone of a worker was 3910 g/m$^3$ (during sweet potato transplanting) with an overall mean concentration of 700±1600 g/m$^3$ in a group of 27 workers (Archer et al., 2002). On a sandy soil farm in South Africa, 18 of 138 respirable quartz measurements (13%) exceeded the South African occupational exposure limit of 100 μg · m$^{-3}$ (Swanepoel et al., 2010).

There are scant data on the potential for exposure to quartz during farming in clay soils. Therefore, the objectives of this study were to determine whether farming activities on a clay soil farm generated time-weighted average (TWA) respirable quartz concentrations above OELs and to test the hypothesis that the level of exposure to respirable quartz follows a declining gradient from sandy to sandy loam soils with less potential for high exposure from clay soils. To achieve these objectives, data were collected from a clay and sandy loam soil farm and previously published data from a sandy soil farm (Swanepoel et al., 2010) were used.

METHODS

Sampling strategy

Geological maps were used to identify sandy, sandy loam, and clay soil regions in South Africa. A farm in each region was selected by means of convenience sampling (i.e. access was granted as the researcher knew the farmers) and all three farms were representative of the region in terms of farming activities and the livestock and crops produced on the farms (which included cattle, maize, wheat, sunflower, water melon, pumpkin, and potatoes). A geologist conducted soil grain size analysis, a standard test to classify soil type (Lewis and McConchie, 1994), on six bulk soil samples from the three farms (shown in Table 1). The farms were located in the Free State and North West provinces and annual rainfall in the provinces averages 400–450 and 300–700 mm, respectively.

The sandy soil farm was situated in the north western part of the Free-State province (being ~1500 ha in size). Twenty people worked on the farm and all workers agreed to participate voluntarily in the study. The sandy loam and clay soil farms were situated in the southern and eastern part of the North West province, respectively. Maize and sunflowers were the most important crops, with the North West province being the major producer of maize in South Africa (Statistics-South Africa, 2002). The sandy loam soil farm and clay soil farm were ~2000 and 800 ha in size with 30 and 15 people working on the farms, respectively. All workers were resident on the farms and did not specialize in one specific task.

The major tasks undertaken on the three farms over the annual farming cycle were identified in conjunction with the farmer and have been described previously for the sandy soil farm (Swanepoel...
et al., 2010). Tasks were selected to be representative of potentially dusty jobs for the sandy soil farm performed by farm workers throughout the study period. Maize was the only product farmed on the clay soil farm; hence, dust and quartz exposure were only measured during maize planting and maize harvesting which occurs for \( \frac{1}{12} \) months of the year. No respiratory protective equipment was said to be or observed to be used and all tractor drivers measured during the study used ‘open-cabbed’ tractors.

Walkthrough inspection

A Southern African Institute of Occupational Hygiene (SAIOH)-registered occupational hygienist performed a walkthrough inspection on each farm prior to personal dust sampling. Workers were observed throughout the shift and detailed information on tasks performed, duration of these tasks, the process i.e. manual versus mechanical and specific work practices were recorded during personal sampling.

Personal dust measurement

The Health and Safety Executive (HSE) Methods for the Determination of Hazardous Substances (MDHS) 14/3 method was used to collect 298 personal breathing zone (PBZ) respirable dust measurements by means of a Higgins–Dewell cyclone using pre-weighted 25- mm polyvinyl chloride filters for the purpose of evaluating respirable dust and quartz exposure of the farm workers (HSE, 2000). A sampling train was set-up with the filter cassette fixed to the lapel of the study participant’s working coat. Gillian battery-operated air-sampling pumps set at a flow rate of 2.2 min\(^{-1}\) were used. PBZ measurements were collected over a period of \( \frac{1}{24} \) h (mean = 460 min, range = 360–520 min); although shift durations varied substantially depending on task and could exceed 12 h. During the sampling period, any unusual occurrences were noted. After sampling, the filters were capped, sealed, and stored in plastic bags until transported for gravimetric and quartz analyses. Two field blanks were taken on each field sampling day and were included in the analyses to assess any contamination of the filter cassettes used. Sampling pumps were calibrated before and after sampling using a Gillibrator bubble flow meter to verify that the air-sampling rate had remained constant (within the 5% variation allowed) throughout the sampling period. If the flow rate was >5% below the initial flow rate, the sample was not included in the analysis. Samples considered to be wet were to have been excluded from analysis, but none was. The filters were equilibrated in an environmentally controlled weighing area for at least 3 h and weighed before and after sampling on a microbalance with a resolution of 10 \( \mu \)g. For each sample, a respirable dust concentration using the difference in filter weight, after adjustment for field blanks, and sampling volume was calculated. The farms were visited nine times over a 36-month period, which summated to 27 days of sampling in total.

Quartz analysis

Weighed filters were sealed in Petri dishes and transported to the National Institute for Occupational Health (NIOH) for quartz analysis using X-ray diffraction (XRD) as specified in the HSE MDHS 101 method (HSE, 2005). The limit of detection (LOD) reported by the NIOH was 22 \( \mu \)g and results were expressed in micrograms per cubic metre.

Classification of soil type

Grain size analysis is a common technique for classifying sediments and soils (Lewis and McConchie, 1994) and was used in this study to classify farm soil by sand and clay content. Two surface soil samples were collected from different actively farmed locations on each of the three farms and transported to the School of Geosciences of the University of the Witwatersrand (Johannesburg, South Africa) for grain size analysis. Samples of 150 g were soaked overnight in water with <1 g of sodium hexametaphosphate added to aid clay deflocculation. Samples were wet-sieved through a 63-\( \mu \)m sieve in order to separate sand from silt and clay. The sand was dried and weighed, while the clay was separated from the silt. The clay-silt suspension was poured into a cylindrical flask filled with water. After \( \frac{1}{24} \) h,
the top 5 cm of suspension (containing only clay-sized particles) was extracted using a pipette. Cylinders were then topped-up with water and the process repeated until the amount of clay left in the solution was negligible. The clay and silt suspensions were then dried and weighed.

**Data analyses**

Descriptive analyses as well as formal hypothesis testing were undertaken using the S-PLUS (version 8.1) and SAS System Software packages (version 9.1). Large proportions of the respirable quartz measurements were below the (LOD) of 22 µg reported by the analytical laboratory: of the 298 respirable quartz measurements, 123 were found to be below the analytical LOD. Consequently, values below the LOD were estimated using the method of multiple imputation as described by Lubin et al. (2004). These imputed values were used to calculate the geometric mean (GM) and geometric standard deviation (GSD) and in the hypothesis testing procedures applied to compare respirable quartz measurements among the three types of soil. Testing for normality showed that both the respirable dust and respirable quartz measurements could best be described as log-normally distributed. To describe measures of central tendency and distribution of the concentrations, GMs, and GSDs were calculated by dividing the respirable quartz concentration by the respirable dust concentration.

Quartz percentages in the respirable fraction of the dust were calculated by the respirable quartz concentration divided by the respirable dust concentration. The respirable dust concentration was determined by the respirable dust concentration divided by the respirable dust concentration. The respirable dust concentration was determined by multiplying the AM of the two sets of observations by the arithmetic mean (AM) of the two sets of observations. The method by Bland and Altman (1999) was applied to the two datasets and is illustrated in Fig. 1 where the differences of the two datasets are viewed against the arithmetic mean (AM) of the two sets of observations within 0.95 limits of agreement. Nineteen of the 20 differences fall well within these limits supporting the results obtained from the formal tests.

**RESULTS**

**Soil type classification**

Average soil grain size analyses for the three farms are presented in Table 1. Based on these results, the three farms under study can be described as sandy soil (sandy percentage = 86%), sandy loam (sandy percentage = 64%), and clay soil (clay percentage = 45%).

**Respirable dust and quartz exposures on a sandy, sandy loam, and a clay soil farm**

Eight-hour TWA respirable dust concentrations for all three farms are shown in Table 2. The respirable dust concentrations differed across the three farms (Kruskal–Wallis test; \( P = 0.006 \)). The median
respirable dust concentrations of the sandy soil and sandy loam soil farms did not differ significantly (Wilcoxon test; \( P = 0.2 \)), but the median concentrations of the sandy soil and sandy loam soil farms were significantly lower than that of the clay soil farm (Wilcoxon test; \( P = 0.002 \) and \( P = 0.001 \), respectively). Nevertheless, the highest individual respirable dust concentration (6.49 mg m\(^{-3}\)) was measured on the sandy soil farm, during wheat planting operations that involved a tractor-drawn machine (planter) driven by an intratracheal tractor driver planting wheat seeds in the soil.

The distributions of respirable dust exposure on the three farms are depicted in Fig. 2. The highest value of 6.49 mg m\(^{-3}\) from the sandy soil farm is omitted from the Figure. In this figure and subsequent box and whisker plots, the bold horizontal line is the median, the box ends are the 25 and 75\% quantiles and the end of the lines from the boxes are the minimum and maximum values, except that outliers are shown as circles.

TWA respirable quartz concentrations for all three farms are shown in Table 3. Imputed data were used to calculate means and SDs and TWA concentrations for comparison with the exposure standards. The clay soil farm had a greater proportion of measurements below the analytical LOD (64\%) and no value exceeded 100 \( \mu g \cdot m^{-3} \). The sandy and sandy loam soil farms were very similar with respect to the distribution of the concentrations; although, the sandy soil farm had the highest concentration measured (626 \( \mu g \cdot m^{-3} \)). For the sandy, sandy loam, and clay soil farm, 12, 13, and 0\% of the respirable quartz measurements exceeded the South African DoL OEL of 100 \( \mu g \cdot m^{-3} \), and substantial proportions of the measurements exceeded the lower standards of the NIOSH and the ACGIH TLV–TWA.

The difference between average respirable quartz concentrations on the clay soil farm and the other two farms was not statistically different (Kruskal–Wallis test; \( P = 0.17 \)). However, comparisons of the percentage measurements exceeding the exposure limits of 100, 50 and 25 \( \mu g \cdot m^{-3} \) showed statistically significant differences among the three farms (prop.test; all \( P \)-values <0.0002). Although the proportions of measurements above the 100 \( \mu g \cdot m^{-3} \) level were not significantly different for the sandy and sandy loam soil farms, both were significantly larger than the clay soil farm (prop.test; all \( P \)-values <0.001). Surprisingly, the clay soil farm had a larger proportion of measurements above the 25 \( \mu g \cdot m^{-3} \) level than the other two farms, but the sandy soil farm had the largest proportion of measurements above the 50 \( \mu g \cdot m^{-3} \) level (prop.test; all \( P \)-values <0.003). Not shown in the table is that for measurements over the 100 \( \mu g \cdot m^{-3} \) level, the median quartz

![Fig. 1. Bland–Altman comparison between the NIOH and HSL of 20 respirable quartz measurements.](https://academic.oup.com/annweh/article-abstract/55/6/634/175391)

<table>
<thead>
<tr>
<th>Farm</th>
<th>( n )</th>
<th>AM</th>
<th>GM</th>
<th>GSD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy soil farm</td>
<td>138</td>
<td>0.68</td>
<td>0.3</td>
<td>3.2</td>
<td>0.02</td>
</tr>
<tr>
<td>Sandy loam soil farm</td>
<td>77</td>
<td>0.46</td>
<td>0.2</td>
<td>2.9</td>
<td>0.03</td>
</tr>
<tr>
<td>Clay soil farm</td>
<td>83</td>
<td>0.73</td>
<td>0.5</td>
<td>2.5</td>
<td>0.06</td>
</tr>
<tr>
<td>Total</td>
<td>298</td>
<td>0.64</td>
<td>0.3</td>
<td>3.0</td>
<td>0.02</td>
</tr>
</tbody>
</table>

To calculate means and SDs and TWA concentrations for comparison with the exposure standards. The clay soil farm had a greater proportion of measurements below the analytical LOD (64\%) and no value exceeded 100 \( \mu g \cdot m^{-3} \). The sandy and sandy loam soil farms were very similar with respect to the distribution of the concentrations; although, the sandy soil farm had the highest concentration measured (626 \( \mu g \cdot m^{-3} \)). For the sandy, sandy loam, and clay soil farm, 12, 13, and 0\% of the respirable quartz measurements exceeded the South African DoL OEL of 100 \( \mu g \cdot m^{-3} \), and substantial proportions of the measurements exceeded the lower standards of the NIOSH and the ACGIH TLV–TWA.

The difference between average respirable quartz concentrations on the clay soil farm and the other two farms was not statistically different (Kruskal–Wallis test; \( P = 0.17 \)). However, comparisons of the percentage measurements exceeding the exposure limits of 100, 50 and 25 \( \mu g \cdot m^{-3} \) showed statistically significant differences among the three farms (prop.test; all \( P \)-values <0.0002). Although the proportions of measurements above the 100 \( \mu g \cdot m^{-3} \) level were not significantly different for the sandy and sandy loam soil farms, both were significantly larger than the clay soil farm (prop.test; all \( P \)-values <0.001). Surprisingly, the clay soil farm had a larger proportion of measurements above the 25 \( \mu g \cdot m^{-3} \) level than the other two farms, but the sandy soil farm had the largest proportion of measurements above the 50 \( \mu g \cdot m^{-3} \) level (prop.test; all \( P \)-values <0.003). Not shown in the table is that for measurements over the 100 \( \mu g \cdot m^{-3} \) level, the median quartz...
concentration of the sandy soil farm exceeded the median quartz concentration of the sandy loam soil farm (median concentrations sandy and clay, respectively 14.3 and 14.0; Wilcoxon test; \( P = 0.0001 \)).

The distributions of respirable quartz exposures on the three farms are depicted in Fig. 3 using imputed data for values less than LOD.

Four large outliers were omitted to enable clearer box plots (specifically 626, 318 and 308 \( \mu g \cdot m^{-3} \) from the sandy soil farm and 413 \( \mu g \cdot m^{-3} \) from the sandy loam soil farm).

Quartz percentages of the respirable dust were determined for all three farms on measurements greater than the LOD and are summarized in Table 4. The percentage respirable quartz varied greatly in respirable dust on all three farms; the highest quartz percentage was found on the sandy soil farm and the average was lowest on the clay soil farm. However, differences between the three farms were not statistically significant (Kruskal–Wallis test; \( P = 0.91 \)).

The distribution of the respirable quartz percentage of the dust on the three farms is depicted in Fig. 4 using imputed data for values less than LOD.

Quartz exposure was measured for two similar occupations on the sandy, sandy loam, and clay soil farms; namely, maize planter operators and maize planter tractor operators and the distributions of the data are depicted in Fig. 5a,b.

Fig. 5a shows lower respirable quartz exposures on the clay soil farm than on sandy soil and sandy loam soil farms for maize planter operators; these differences were statistically significant (Kruskal–Wallis test; \( P < 0.001 \)). Average respirable quartz exposures were not significantly different for maize planter tractor operators (Kruskal–Wallis test; \( P = 0.8 \)), although the highest concentrations were on the sandy soil farm (Fig. 5b).

### Table 3. Eight-hour TWA respirable quartz concentrations (micrograms per cubic metre) on a sandy, sandy loam, and clay soil South African farm

<table>
<thead>
<tr>
<th>Farm</th>
<th>( n )</th>
<th>(&lt;\text{LOD})</th>
<th>AM</th>
<th>GM</th>
<th>GSD</th>
<th>Range</th>
<th>( \geq 100^a )</th>
<th>( \geq 50^b )</th>
<th>( \geq 25^c )</th>
<th>Quartz median</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy soil farm</td>
<td>138</td>
<td>35</td>
<td>53.2</td>
<td>31.7</td>
<td>2.7</td>
<td>(&lt;\text{LOD} – 626)</td>
<td>12</td>
<td>30</td>
<td>57</td>
<td>14.3</td>
</tr>
<tr>
<td>Sandy loam soil</td>
<td>77</td>
<td>27</td>
<td>46.85</td>
<td>31.6</td>
<td>2.3</td>
<td>(&lt;\text{LOD} – 413)</td>
<td>13</td>
<td>22</td>
<td>59</td>
<td>14.0</td>
</tr>
<tr>
<td>Clay soil farm</td>
<td>83</td>
<td>64</td>
<td>33.8</td>
<td>31.1</td>
<td>1.4</td>
<td>(&lt;\text{LOD} – 98)</td>
<td>0</td>
<td>9</td>
<td>81</td>
<td>13.7</td>
</tr>
<tr>
<td>Total</td>
<td>298</td>
<td>41</td>
<td>46.0</td>
<td>31.5</td>
<td>2.3</td>
<td>(&lt;\text{LOD} – 626)</td>
<td>9</td>
<td>22</td>
<td>64</td>
<td>14.0</td>
</tr>
</tbody>
</table>

\( ^a \) Measurements greater or equal to the South African OEL of 100 \( \mu g \cdot m^{-3} \) for respirable quartz.

\( ^b \) Measurements greater or equal to the NIOSH Recommended Exposure Limit of 50 \( \mu g \cdot m^{-3} \) for respirable quartz.

\( ^c \) Measurements greater or equal to the ACGIH TLV of 25 \( \mu g \cdot m^{-3} \) for intratracheal respirable quartz.
This paper describes personal airborne respirable dust and quartz exposures on three geologically different types of farms; namely, a sandy, a sandy loam, and a clay soil farm in South Africa, and determined whether soil type influenced the levels of exposure to respirable quartz. We have shown that quartz exposures above two generally used OELs were found on all of the farms, with similar exposures for the sandy and sandy loam soil farms, whereas the clay soil farm generated a smaller proportion of exposures.

Of particular interest is that no measurements exceeded the South African OEL of 100 µg·m⁻³ on the clay soil farm; but 9% of them were between 50 and 100 µg·m⁻³. However, these differences were not as great as expected. Of particular interest is that no measurements exceeded the South African OEL of 100 µg·m⁻³ on the clay soil farm; but 9% of them were between 50 and 100 µg·m⁻³. However, these differences were not as great as expected. Of particular interest is that no measurements exceeded the South African OEL of 100 µg·m⁻³ on the clay soil farm; but 9% of them were between 50 and 100 µg·m⁻³. Additionally, on each of the three farms, the median quartz exposures were all above the ACGIH TLV of 25 µg·m⁻³ (Fig. 3) suggesting a possible risk of over exposure to quartz even on the clay soil farm. Surprisingly, all the three farms had similar percentages of quartz in respirable dust (Table 4).

Some limitations should be borne in mind. Soil types are a continuum from very sandy to mostly clay and the soil type may vary on an individual farm. The farms studied were probably not optimally distributed along this continuum with the sandy loam soil farm likely towards the sandy end of the spectrum; hence, explaining the similarity in quartz exposures between the sandy and sandy loam soil farms. Also, the clay soil farm may not have been at the extreme for clay soils, so lower quartz exposures may be found in further studies. These results may not reliably define quartz exposure in farming over an annual farming cycle as a multitude of tasks are performed for variable periods using a selection of farming implements. Additionally, some workers may be seasonal or specialize in particular tasks. Furthermore, farming is obviously an outdoor activity and quartz exposures may be affected greatly by weather conditions. A potential explanation for the lower quartz levels on the clay soil farm is that rain or lack of wind reduced dustiness and hence.

**DISCUSSION**

![Box and whisker plot comparing TWA respirable quartz exposures from a sandy, a sandy loam, and a clay soil South African farm.](https://academic.oup.com/annweh/article-abstract/55/6/634/175391)

**Table 4. Respirable quartz percentages (%) of the respirable dust for measurements above the LOD on a sandy soil, a sandy loam soil, and a clay soil South African farm**

<table>
<thead>
<tr>
<th>Farm</th>
<th>n</th>
<th>AM</th>
<th>GM</th>
<th>GSD</th>
<th>Range</th>
<th>%Quartz median</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy soil farm</td>
<td>89</td>
<td>20.0</td>
<td>14.2</td>
<td>2.5</td>
<td>0.5–94.4</td>
<td>14.3</td>
</tr>
<tr>
<td>Sandy loam soil farm</td>
<td>55</td>
<td>20.4</td>
<td>14.4</td>
<td>2.4</td>
<td>1.5–76.0</td>
<td>14.0</td>
</tr>
<tr>
<td>Clay soil farm</td>
<td>30</td>
<td>20.3</td>
<td>13.9</td>
<td>2.5</td>
<td>1.5–72.3</td>
<td>13.7</td>
</tr>
<tr>
<td>Total</td>
<td>174</td>
<td>20.2</td>
<td>14.2</td>
<td>2.5</td>
<td>0.5–94.4</td>
<td>14.0</td>
</tr>
</tbody>
</table>
lowered exposures, but this explanation is not possible as average respirable dust levels were highest on the clay soil farm and thus lower general dustiness on this farm cannot explain the lower quartz levels. Measurement error is a consideration but not to the extent that it would alter the major findings. The NIOH and HSL respirable quartz values did not differ to any significant extent and the same person in the same laboratory (NIOH, Johannesburg, South Africa) performed all the analytical quartz measurements (XRD) for the three farms.

Analysis deviance is a further factor. A substantial proportion of respirable quartz measurements were below the LOD and concentrations were estimated using imputed data, which has consequences (Helsel, 2010). The high percentage of measurements >25 μg · m⁻³ (81%) on the clay soil farm in particular is partially a result of the imputation. Nevertheless, imputed data do not account for the substantial proportions of quartz concentrations >50 μg · m⁻³ found on all three farms.

Although a large number of measurements were collected (298), the lack of a statistically significant difference in respirable quartz exposure in maize planter tractor operators on the different farms may be due to the relatively small number of measurements for this job.

Respirable quartz measurements from the three South African farms ranged from below the LOD to 626 μg · m⁻³ and confirmed a quartz risk as some concentrations exceeded generally accepted occupational exposure limits in all jobs evaluated, even though the majority of respirable dust concentrations were well below 5 mg · m⁻³. The AM respirable dust concentration of the sandy, sandy loam, and clay soil farms were 0.68, 0.46 and 0.73 mg · m⁻³, respectively, and were lower than the overall mean respirable dust concentration of 1.3 ± 2.9 mg · m⁻³ on a sandy soil farm reported by Archer et al. (2002). The GM personal respirable quartz concentrations on the three farms of 31.7, 31.6, and 31.1 μg · m⁻³ reported in our study were also considerably lower than the overall GM of 700 ± 1600 μg · m⁻³ reported during a study in Northern California agriculture (Archer et al., 2002), but the latter study is unlikely to be representative of farming given the very high levels.

Although the highest percentage quartz content in the respirable fraction of the breathing-zone samples was 94.4%, the median percentage levels on the three farms were lower than reported by Stopford and Stopford (1995a,b). The median percentage quartz concentrations of the respirable dust on the sandy soil, sandy loam soil, and clay soil farms were 12.5, 13.5, and 7% compared to 29% observed in North-California agriculture (range 10.5–44.5%) (Stopford and Stopford, 1995a,b).

The relatively small differences in quartz exposures and the lower quartz percentage concentrations in the dust found on the three farms in this study when compared to other studies may be partly due to the tasks included in this exposure assessment. For example, tasks quantified on the sandy soil farm included manual jobs, including pumpkin and watermelon harvesting, which

**Fig. 4.** Box and whisker plot comparing respirable quartz percentages of the respirable dust for measurements above the LOD from a sandy, a sandy loam and a clay soil South African farm.
contributed ~50% of the measurements taken on the farm. Quartz exposures during pumpkin and watermelon handling ranged between 13 and 101 µg · m⁻³ and 12 and 75 µg · m⁻³, respectively. Manual jobs may be less dusty than mechanical processes such as soil preparation (Swanepoel et al., 2010). The exposure assessment on the sandy loam and clay soil farms only included mechanical jobs, which may explain the unexpectedly small differences in quartz exposures among the three farms.

CONCLUSION

Exposure to respirable quartz >25 µg · m⁻³ was convincingly shown on all three farms in this study; and 13 and 12% of exposures on the farms with sandy and sandy loam soils, respectively, were above the South African exposure limit. Soils with a high percentage of crystalline silica (>30%) may cause peak exposures >100 µg · m⁻³ more often than clay soils. These findings support other studies on farms in which the potential for high exposure to respirable quartz exposure has been shown. Seventy nine percent of the quartz measurements exceeded the AGG TLV of 25 µg · m⁻³ during mechanical tasks (i.e. maize planter and tractor drivers) compared to the 39% exceeded during manual tasks (i.e. watermelon harvesting) (Swanepoel et al., 2010). Nevertheless, the published literature on personal airborne exposure to quartz and the relation to soil type is

**Fig. 5.** (a) Box and whisker plot comparing TWA respirable quartz exposures of maize planter operators from a sandy, a sandy loam, and a clay soil farm in South Africa. (b) Box and whisker plot comparing TWA respirable quartz exposures of maize planter tractor operators from a sandy, a sandy loam and a clay soil farm in South Africa.
inadequate to define the quartz risk in agriculture reliably when farming on soils that differ geologically. Additionally, job type and the manner in which the task is performed (e.g. mechanical or manual) may be important determinants of exposure. Consequently, further research is required to quantify quartz exposure with greater accuracy and precision and in the correct fraction; and to identify settings and tasks which place those who work on farms at risk of quartz-associated diseases; in particular: (i) consideration of the relationship between dustiness and quartz exposure; (ii) what level of sand in soil is thought not to produce peak exposures over the commonly used exposure limit of 100 μg · m⁻³; and (iii) an estimate of the lifetime exposure of workers in order to facilitate comparison of risk with observed disease need to be included in further research. Exposure modifiers need to be defined so that controls can be implemented in the most focused and economically viable way—which is of particular importance in developing countries with large numbers of people employed in farming.

FUNDING

University of the Witwatersrand Individual Faculty Research Grant (001-254-8511101-5121105-4526).

REFERENCES

Archer JD, Cooper GS, Reist PC et al. (2002) Exposure to respirable crystalline silica in eastern North Carolina farm workers. AIHA J (Fairfax, Va); 63: 750–5.


