EXPOSURE TO RESPIRABLE CRYSTALLINE SILICA IN CENTRAL SOUTH AFRICAN FARM WORKERS

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A thesis submitted to the Faculty of Health Sciences, University of the Witwatersrand, in fulfillment of the requirements for the degree of Doctor of Philosophy

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DECLARATION

This thesis is submitted in the optional format, approved by the Faculty of Health Sciences, of published work with encompassing introduction and conclusion.

I, Andrew Johnstone Swanepoel, declare that this thesis is my own work, except where acknowledged as otherwise. It is being submitted for the degree of Doctor of Philosophy in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at this or any other university.

Andrew Johnstone Swanepoel

Signed on the 12th day of March, 2012.

DEDICATION

I would like to dedicate this PhD to my parents

Jan Willem Hendrik Swanepoel

and

Cornelia Johanna Swanepoel

And to my wife

Tanya Swanepoel

PUBLICATIONS AND PRESENTATIONS ARISING FROM THIS THESIS

Published papers

1. **Swanepoel AJ**, Rees D, Renton K, Swanepoel CJ, Kromhout H, Gardiner K. Quartz Exposure in Agriculture: Literature Review and South African Survey. *Annals of Occupational Hygiene.* 2010; 54(3): 281–292.
2. **Swanepoel AJ**, Kromhout H, Jinnah Z, Portengen L, Renton K, Gardiner K, Rees D. Respirable dust and quartz exposure from three South African farms with sandy, sandy loam and clay soils. *Annals of Occupational Hygiene.* 2011; 55(6): 634–643.

Submitted papers

1. **Swanepoel AJ**, Swanepoel CJ, Rees D. Determinants and modifiers of quartz exposure in farming (submitted to *Occupational and Environmental Medicine* Aug 2011).
2. **Swanepoel AJ**, Rees D. Silica exposure in South African farming (submitted to *Occupational Health Southern Africa* Aug 2011).

The publishers of the two published scientific reports have given permission for reprinting of the published papers.

International conference presentations

1. **Swanepoel AJ**, Rees D, Renton K, Kromhout H. Exposure to Respirable Crystalline Silica in South African Farm Workers. Inhaled Particle X (IPX) Conference, Sheffield, United Kingdom. 23 – 25 September 2008.

2. **Swanepoel AJ**, Rees D, Renton K, Kromhout H. Quartz exposure on a sandy, a sandy loam and a clay soil farm in South Africa. The eighth International Occupational Hygiene Association (IOHA) Conference, Rome, Italy. 28 September – 2 October 2010.

3. **Swanepoel AJ,** Rees D, Swanepoel CJ. Determinants and modifiers of quartz exposure in farming. 22nd International Conference on Epidemiology in Occupational Health (EPICOH), Oxford, United Kingdom. 7 - 9 September 2011 (presented by Rees D).

Local conference presentations

1. **<u>Swanepoel AJ</u>**, Rees D, Renton K, Kromhout H. Silica exposure in South African agriculture. NIOH Research Forum, Johannesburg, South Africa. 28 September 2009 (presented by Rees D).

2. **<u>Swanepoel AJ</u>**, Rees D, Renton K, Kromhout H. Silica exposure in South African agriculture. Showcasing postgraduate research at Wits, Johannesburg, South Africa. 7 - 8 November 2009 (poster presentation; awarded 1st prize).

3. **<u>Swanepoel AJ</u>**. Exposure to Respirable Crystalline Silica in South African Farm Workers. Interim seminar as part of the Wits, School of Public Health Interdisciplinary Doctoral Programme, Johannesburg, South Africa. 7 December 2009.

4. **<u>Swanepoel AJ</u>**, Rees D, Kromhout H. Quartz exposure on three central South African farms. Safeconex meeting, Johannesburg, South Africa. 17 – 18 September 2010.

5. **<u>Swanepoel AJ</u>**, Rees D, Kromhout H. Quartz exposure on farms in South Africa representing various soil types. Safeconex meeting, Johannesburg South Africa. 17 - 18 September`2010 (poster presentation; awarded 1st prize).

ABSTRACT

Introduction

Personal exposure to respirable crystalline silica (commonly in the form of quartz) causes serious adverse health effects and has been well documented in industries formally known as the 'dusty trades'. Very little information exists on personal quartz exposure in agricultural settings. Silica exposure is an important public health issue particularly in settings of high tuberculosis (TB) and Human Immunodeficiency Virus (HIV) rates. The mineral has contributed to serious epidemics of TB in southern Africa and other low and middle - income regions of the world because of the increased risk of pulmonary tuberculosis in silica exposed workers. It is well known that HIV infection increases the incidence of TB and the risk of tuberculosis in individuals with both HIV and silicosis is larger than the sum of each factor. Globally (especially in resource poor countries), agriculture employs a very large population that may be affected.

Objectives

The objectives of the PhD were to review the published literature on respirable quartz exposure and associated disease in agricultural related settings systematically; to measure personal time weighted average respirable dust and quartz on sandy, sandy loam and clay soil farms in the Free State and North - West provinces of South Africa; to ascertain whether soil type is a determinant of exposure to respirable quartz; to identify additional determinants of quartz exposure in farming; to estimate annual cumulative respirable quartz exposure; and to discuss some occupational health implications and research needs.

Methodology

Published studies on exposure to silica and quartz in agriculture and related settings as well as silica - associated disease in farming were searched systematically through "PubMed"; and, critiqued. 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. These measurements were collected using standard international measurement and analytical methods. Quartz determinations were done using X - ray diffraction by a quality - assured, accredited laboratory, and were verified by a leading external agency.

Respirable quartz values below the limit of detection (22 $\mu g.m^{-3}$) were estimated using multiple imputation. Non - parametric tests were used to compare quartz exposure from the three different soil types. Variables such as soil type, commodity farmed, activity (nature of work done), process (manual vs mechanical), quartz % and weather variables (e.g. wind and humidity during the week prior of and during sampling) were used in bivariate and multiple regression modeling to identify determinants of respirable quartz exposure. Logistic regression was done aiming to identify determinants of respirable quartz greater than 50 $\mu g.m^{-3}$ and to deal with data points below the detection limit without including multiple imputation methods. The annual cumulative exposure was estimated for a typical farm worker on the sandy soil farm using activity - specific measurements and duration of each activity in a year. Particle sizes of respirable dust fraction were determined using laser light scattering.

Results

Literature review

In total, 17 studies were identified: 11 investigated respirable dust and quartz exposure on farms and six quartz related disease in agricultural settings. They provided convincing evidence of a respirable quartz risk on sandy soil farms but scant evidence of associated disease.

Exposure to respirable dust and quartz

Respirable quartz measurements from the three South African farms ranged from not detectable to 626 $\mu g.m^{-3}$ and confirmed the quartz hazard: some concentrations exceeded generally accepted occupational exposure limits in all activities evaluated, even though 278 (93.3 %) of the respirable dust concentrations were well below a commonly used occupational exposure limit of 2 $mg.m^{-3}$. Fifty seven percent, 59% and 81% of the respirable quartz 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 $\mu g.m^{-3}$. Twelve percent and 13% of respirable quartz concentrations exceeded 100 $\mu g.m^{-3}$ on the sandy soil and sandy loam soil farms respectively, but none exceeded this level on the clay soil farm.

Determinants of exposure

The proportions of measurements greater than 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; $p= 0.001$). The percentage of quartz in respirable dust was determined for all three farms using samples of a size such that all measurements were well above the analytical detection limit. Percentages ranged from 0.5 - 94.4% with no significant difference in the median quartz percentages across the three farms (Kruskal - Wallis test; $p = 0.91$).

Bivariate analyses showed that commodity (Kruskal - Wallis test; $p = 0.001$), activity (Kruskal-Wallis test; $p = 0.001$) and process (Wilcoxon test; $p = 0.003$) were associated with respirable quartz concentrations. Multiple linear regression showed that soil type, season, commodity, activity, process, quartz percentage, humidity on the morning of measurement and interactions between activity, respirable dust exposure and quartz percentage were significantly related to respitable quartz exposure. Logistic regression showed that, during univariate analyses, cereal planter operator, increased quartz % in respirable dust, decreased humidity on the day of measurement and increased respirable dust concentration were all significantly associated with quartz levels above 50 µg.m^{-3}. Multivariate analyses showed that cereal planter operator remained a strong determinant of higher level of exposure relative to other activity (OR 3.76 95% CI 1.64 - 8.63). Increased levels of quartz % in respirable dust increased the ORs for exposure above 50 µg.m^{-3}.

Annual cumulative exposure

The estimated annual cumulative exposure of a farm worker exposed at the highest concentration measured for each task exceeded the cumulative exposure had the worker been exposed at 100 µg.m^{-3} by 1.46 times. At median quartz exposures measured for each of the activities done during the year, the chances of exceeding the cumulative exposure if exposed at the South African OEL are small: the ratio of the estimated cumulative exposure indices to occupational exposure limit cumulative exposure = 0.29.

Particle size

The median D50 particle size of the 30 respirable dust samples measured in this study was 5.53 µm with the smallest D50 value reported by the laboratory being 3.39 µm.

Conclusion

Despite its ubiquity, little is known about quartz exposure in the agricultural industry. This thesis not only demonstrates significant potential for overexposure in some settings, it also may be the biggest study of its kind: it is the first study to have measured a large number (298) of personal respirable quartz concentrations across various activities on three farms known to have different soil types. It is also the first study in farming that attempted to relate personal respirable quartz exposures to possible determinants, to consider potential modifiers of quartz exposure and to estimate annual cumulative quartz exposure. The study adds considerably to the evidence that over - exposure to quartz may be a risk in farming and has

identified the need for practical interventions and research gaps. In addition, this study makes it possible to use the detailed analyses of silica exposure determinants in farming in other settings with similar conditions.

Soil type may determine whether exposure is greater than 100 $\mu g.m^{-3}$, 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, which is of particular importance in developing countries. The nature of farming and weather variables may add information about exposure risk and should be included with soil type in future farming exposure assessment studies. Given the large numbers of farm workers possibly exposed to silica and the seriousness of silica - associated diseases, some dust - related occupational health interventions should be considered in South African farming, particularly because during the course of the studies none of the South African farms had medical surveillance programmes in place and few, if any, dust control measures were observed. Practitioners working in farming areas should be aware that silica - associated diseases may occur in farm workers; therefore despite limited evidence for silica associated disease, occupational health interventions appear justified.

No study previously has defined the burden of silica – associated diseases in farming. A starting point may be to perform radiological surveys on long service farm workers (possibly more than 20 years service and performing dusty activities) on a sandy soil farm, as sandy soils are likely to produce the highest silica levels. An effort should also be made to define the duration and intensity of silica exposure in farming over the annual cycle. Lastly, cost -

effective methods to reduce respirable dust and silica exposure in farming should be identified.

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LIST OF ABBREVIATIONS

ACGIH	American Conference of Governmental Industrial Hygienists
AIDS	Acquired Immune Deficiency Syndrome
Al^{3+}	Aluminum
ANOVA	Analysis of Variance
C	Ceiling levels
CE	Cumulative Exposure
CEI	Cumulative Exposure Indices
CEN	European Standardization Committee
CI	Confidence Interval
cm	Centimeter (s)
COPD	Chronic Obstructive Pulmonary Disease
CSIR	Council for Scientific and Industrial Research
D50	50% Diameter
DL	Detection Limit (s)
DME	Department of Minerals and Energy

DMR	Department of Mineral Resources
DoL	Department of Labour
EU	European Union
FAO	Food and Agriculture Organization
g	Gram (s)
GDP	Gross Domestic Product
GM	Geometric Mean
GSD	Geometric Standard Deviation
h	Hour (s)
HIV	Human Immunodeficiency Virus
HSE	Health and Safety Executive
IARC	International Agency for Research on Cancer
IOM	Institute of Occupational Medicine
IR	Infrared
ISO	International Organization for Standardization
ℓ	Litre (s)
LOD	Limit of Detection
m^3	Cubic Metre (s)

mg	milligram
MCE	Mixed Esters of Cellulose
MDAD	Mineral Dust Airways Disease
min	Minute
MLE	Maximum Likelihood Estimation
NHLS	National Health Laboratory Service
NIOH	National Institute for Occupational Health
NIOSH	National Institute for Occupational Safety and Health
NTM	Non - Tuberculous Mycobacterium
OEL	Occupational Exposure Limit (s)
OHSA	Occupational Safety and Health Association
OR	Odds Ratio
PBZ	Personal Breathing Zone
PEL	Permissible Exposure Limit (s)
PM	Particulate Matter
PMF	Progressive Massive Fibrosis
ppm	parts per million
PSA	Particle Size Analysis

PVC	Polyvinyl Chloride
RCS	Respirable Crystalline Silica
REL	Recommended Exposure Limit (s)
RPE	Respiratory Protective Equipment
SANS	South African National Standards
SD	Standard Deviation
SiO_2	Silicon Dioxide
STEL	Short Term Exposure Limit (s)
TB	Tuberculosis
TLV	Threshold Limit Value (s)
TWA	Time - Weighted Average
μm	Micrometer (s)
US	United States
WASP	Workplace Analysis Scheme for Proficiency
XRD	X - Ray Diffraction

AUTHOR CONTRIBUTIONS

As part of the Declaration, contributions of co – authors to each of the published and submitted studies are detailed below:

Chapter 6

Swanepoel AJ, Rees D, Renton K, Swanepoel CJ, Kromhout H, Gardiner K. Quartz Exposure in Agriculture: Literature Review and South African Survey. Annals of Occupational Hygiene. 2010; 54(3): 281–292.

The idea and experimental design was formulated through discussions with David Rees. I carried out all of the exposure assessment procedures and analyzed the data with assistance from Cornelia Swanepoel. David Rees, Hans Kromhout, Kevin Renton and Kerry Gardiner edited the manuscript.

Chapter 7

Swanepoel AJ, Kromhout H, Jinnah Z, Portengen L, Renton K, Gardiner K, Rees D. Respirable dust and quartz exposure from three South African farms with sandy, sandy loam and clay soils. *Annals of Occupational Hygiene.* 2010; 55(6): 634–643.

The idea and experimental design was formulated through discussions with David Rees. I carried out all of the exposure assessments procedures on the farms. The data methodology and analysis were done by me and Lutzen Portengen. David Rees, Hans Kromhout, Kevin Renton and Kerry Gardiner edited the manuscript. Zubair Jinnah conducted all aspects of the soil grain size analysis.

Chapter 8

Swanepoel AJ, Swanepoel CJ, Kromhout H, Rees D. Determinants and potency modifiers of quartz exposure in farming (submitted to *Occupational and Environmental Medicine,* Oct 2011).

The idea and experimental design was formulated through discussions with David Rees. I carried out all of the exposure assessments procedures on the farms. The data methodology and analysis were done by me and Cornelia Swanepoel. David Rees, Cornelia Swanepoel and Hans Kromhout edited the manuscript.

Chapter 9

Swanepoel AJ, Rees D. Silica exposure in South African farming (submitted to *Occupational Health Southern Africa,* Aug 2011).

The idea was formulated through discussions with David Rees. I carried out all of the exposure assessments procedures on the farms. David Rees edited the manuscript.

As supervisor of the candidate, I confirm that he acted as principal investigator on all four studies.

David Rees　　　　　　　　　　Date

CHAPTER 1

General introduction

Exposure to respirable crystalline silica dust (commonly in the form of quartz) is associated with multiple diseases and has been classified as a human carcinogen (IARC, 1997). Silicosis, a fibrotic nodular disease of the lung parenchyma, and silica dust - associated tuberculosis (TB), in particular, are the two diseases that remain high on the list of occupational health priorities in low and middle - income countries. Silicosis and lung cancer still occur in some high - income countries (Rees and Murray, 2007).

Silica exposure is an important public health issue not only because respirable crystalline silica exposure is associated with serious illnesses, including silicosis and lung cancer (IARC, 1997), chronic obstructive pulmonary disease (COPD), autoimmune and renal diseases and increased mortality (Steenland, 2005); but also, because in geographies where there is concomitant TB, silica exposure increases the risk of pulmonary tuberculosis (Hnizdo and Murray, 1998). Silica – associated diseases are of increased concern in poor and middle - income countries (which have more than 70% of the world's population) where there are high HIV infection rates because there is a multiplicative interaction between HIV, silicosis and TB: silicosis in HIV - positive individuals increases the risk of contracting tuberculosis substantially (Corbett *et al.*, 2000; WHO, 2010).

It is therefore not surprising that the International Labour Organization (ILO) and the World Health Organization (WHO) have embarked upon a Global Elimination of Silicosis Campaign (Fedotov, 1997). Previously, silica exposure and its adverse health effects have focused on industries historically known as the "dusty trades," such as heavy construction and sandblasting, mining and quarrying, foundries, and other occupations and industries where silica is used as a raw material or an abrasive (IARC, 1997). Despite this, silica is not widely appreciated as an agricultural occupational hazard. Although the National Institute for Occupational Safety and Health (NIOSH) has noted that farming consistently is the third most frequently mentioned occupation where silicosis was mentioned on a death certificate (NIOSH, 1992), NIOSH did not list agriculture among the top 15 non-mining industries where workers were potentially exposed to quartz (NIOSH, 1991). Furthermore, there has been little regulatory attention paid to this concern internationally and nationally. Some authoritative publications list agriculture as a possible source of quartz exposure (NIOSH, 2002) but many standard reference works do not (Parkes, 1994; Stellman, 1998; Hendrick *et al.*, 2002), even though good studies have shown that some farming activities in certain settings can produce respirable silica levels well above generally accepted safe levels (Nieuwenhuijsen *et al.*, 1999; Archer *et al.*, 2002).

Literature on silica exposure in farming is surprisingly limited and no attempt has been made to summarise the findings of silica exposure studies in this industry despite a large workforce that may be affected. The International Labor Organization (ILO) estimated that agriculture may have the largest labour force globally, estimated at 1.1 billion people (ILO, 2005). In many developing countries, over 80% of the work force may be involved in agriculture (ATS, 1998). Therefore, silica exposure in farming may potentially be a substantial issue globally but not much is known about silica exposures in this industry, hence this PhD.

1.1 Research aims

The main aim of this thesis was to systematically investigate personal exposure to respirable crystalline silica (quartz) during agricultural activities. Quartz exposures were quantified across the ends of the soil spectrum e.g. sandy, sandy loam and clay soils. Because silica exposure in farming may be influenced by several factors, a secondary aim of this thesis was to investigate possible determinants and exposure modifiers of silica exposure during farming.

1.2 Structure of thesis

The PhD is presented in nine parts. In **Chapter 2** I briefly review silica dust, sources of silica exposure, the basis and limitations of international and local silica occupational exposure limits (OEL) as well as silica associated diseases. I also review what is known about silica exposure in the agriculture industry. **Chapter 3** briefly describes all aspects of the methodology followed during this study. **Chapter 4** summarizes the main findings as reported in more detail in Chapters 6 – 9. In **Chapter 5** the results of the study are presented and the main methodological issues experienced during the study are discussed. **Chapters 6 – 9** are publications and submitted work that form the main body of the thesis. In **Chapter 6** I critically review the published literature on respirable dust and silica exposure as well as disease in agriculture. I further describe respirable dust and silica concentrations during farming on a farm in central South African. **Chapter 7** quantifies personal time weighted average (TWA) respirable dust and silica exposures on a sandy, a sandy loam and a clay soil farm in the Free State and North - West provinces of South Africa; and, ascertains whether soil type is a determinant of exposure to respirable silica. In **Chapter 8** possible determinants, if any, of personal exposure to silica during farming are identified and modifiers of silica potency are investigated. In **Chapter 9** the results of the silica exposure assessment are summarized and some implications for the occupational health professional in South Africa are described.

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CHAPTER 2

Background and literature review

This literature review is limited to general issues, covering silica dust and sources of silica exposure, international and local occupational exposure limits (OELs), factors influencing silica potency as well as silica associated diseases. This chapter briefly describes agriculture as a global industry and then describes farming in South Africa. Chapter 4 comprehensively covers silica (quartz) exposure and silicosis in agriculture. This section concludes by reviewing what is known about silica exposure in the agriculture industry and published literature on non – occupational exposure and environmental exposure to quartz are summarized.

2.1 Silica dust and its properties

Importantly, silica is not a single substance (Gulumian, 2007) but is the most abundant surface mineral in the earth's crust (up to 20%) and a major constituent of soils (Madsen *et al.*, 1995). It comprises an atom of silicon and two atoms of oxygen (SiO_2) uncombined with other elements, hence sometimes called 'free silica', i.e., free of other elements (see Figure 1) (Rees and Murray, 2007).

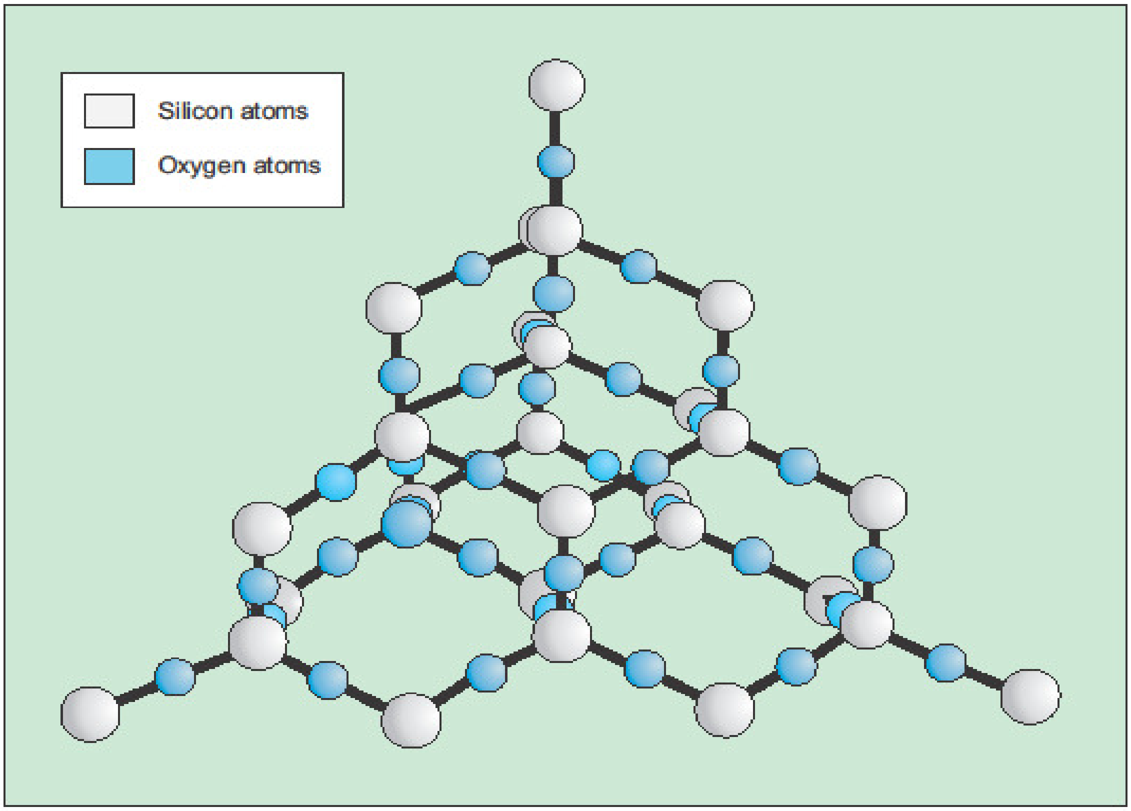

Figure 1. The molecular structure of the quartz polymorph of crystalline silica (SiO_2) (drawn by Roy Hollowday, Graphics unit, University of the Witwatersrand)

Because silicon and oxygen are so abundant, many minerals contain SiO_2 and are usually combined with other elements, often cations. These minerals are known as silicates (rather than silica) and are classified on the basis of how extensively silica is polymerized. The degree of polymerization will in turn determine the resistance to chemical weathering. Silicates are ubiquitous; even the varieties of asbestos are silicates (Lee *et al.*, 2008; Elholm *et al.*, 2010). Free crystalline silica is so common that whenever the surface of the earth is disturbed - for example during mining or when sand, stones or rocks are drilled, moved, crushed or processed - exposures potentially hazardous to a person's health may occur.

Silica polymorphs having the same chemical composition, but different amorphous or crystalline structures, can form in silica - rich environments, usually as a function of temperature and pressure. Silica occurs primarily in a crystalline, but also can occur in a non - crystalline (amorphous) form which is less hazardous than crystalline silica; but heat and pressure can change amorphous silica to crystalline forms. Exposure to changes in temperature and pressure, either natural or synthetic, may cause the crystalline structure to change (Iler, 1979; Klein and Hurlbut, 1993; Hemley *et al.*, 1994; Navrotsky, 1994; IARC, 1997). There are eight natural forms or polymorphs of free crystalline silica (i.e., alpha quartz, beta quartz, tridymite, cristobalite, keatite, coesite, stishovite, and moganite); most quite rare and produced by extreme heat and pressure (Parkes, 1994). Each form of silica is unique in its spacing, lattice structure, and angular relationship of the atoms. By far the most common polymorph is quartz, a constituent of many sands, stones and rocks. Because of this, quartz can sometimes confusingly be used as a synonym for crystalline silica; therefore the term quartz will be used from now on when referring to this particular mineral and silica or repsirable crystalline silica for more general usage. In the health context and throughout the text, “silica or quartz exposure” usually refers to respirable crystalline silica dust, respirable dust being the fine particles, invisible to the naked eye and mostly smaller than 7 microns in diameter.

Cristobalite and tridymite occur naturally but are mostly produced by industrial operations when alpha quartz or amorphous silica is heated (such as foundry processes, calcining of diatomaceous earth, brick and ceramics manufacturing, and silicon carbide production) (NIOSH, 1974; Altieri *et al.*, 1984; Virta, 1993; Weill *et al.*, 1994). Burning of agricultural waste or products such as rice hulls may also cause amorphous silica to become cristobalite

(Rabovsky, 1995; IARC, 1997). The chemical structures of tridymite and cristobalite are closely related: both are based on a hexagonal tetrahedral sheet but with different stacking sequences (Gulumian, 2007). It has been suggested that cristobalite is more toxic than quartz but the evidence for this is limited. To date, no epidemiological evidence exists indicating that cristobalite is more fibrogenic than quartz and the risks of developing silicosis from occupational exposure to quartz and cristobalite are likely to be similar, providing the surrounding circumstances of exposure are similar (Meldrum and Howden, 2002). The other polymorphs (i.e., keatite, coesite, stishovite, and moganite) are rarely or never observed in nature (Ampian and Virta, 1992). Crystalline silica is more active than amorphous silica and within the crystalline silicas, coesite is less active than quartz, cristobalite or tridymite and stishovite is biologically inert (Brieger and Gross, 1966; Brieger and Gross, 1967; Wiessner *et al.*, 1988). Because silica has many polymorphs, it has been argued whether a single regulatory level is protective of health, taking into account all the different polymorphs and the different forms existing within the same polymorph (Gulumian, 2007).

In the crystalline form, silica is resistant to being broken into smaller and smaller sizes, and thus the percentages of silica in bulk samples of materials are often higher than in the fine respirable dust. The percentage of silica in the un-worked raw material may therefore be a misleading measure of risk; the respirable levels of silica need to be determined (Gulumian, 2007).

Workers in a large variety of industries and occupations may be exposed to quartz because of its widespread natural occurrence and the wide uses of the materials and products containing it and will be briefly discussed below.

2.2 Industries associated with silica exposure

A surprisingly large number of industries generate silica dust (Table 1). Many of these industries are traditionally known as the dusty trades (Parks *et al.*, 1999) and the most common exposures occur in mining and mining - related occupations, such as milling ores, quarrying, tunnelling and excavation. Country rock, i.e., the rock in which the mined mineral is located, often determines the quartz risk. Hence, coal mining, for example, is a quartz risk in some mining regions throughout the world.

Other industries with well known quartz risks include ceramics, construction and foundries. NIOSH estimates that at least 1.7 million U.S. workers are potentially exposed to quartz (NIOSH, 1991). In addition, an undetermined portion of the 3.7 million U.S. agricultural workers (Census, 1997) may be exposed to dust containing a significant percentage of respirable quartz (Linch *et al.*, 1998). Virtually any process that involves movement of earth or disturbance of quartz containing products such as masonry, concrete or soil may expose a worker to quartz. In general, though, the greater the mechanical forces applied, the more likely is the generation of respirable dust (Rees and Murray, 2007).

Table 1. Sources of exposure to respirable crystalline silica

Sources of exposure		Comment
General	Moving, drilling, working, processing, crushing or mining sand, stones or rocks	Free silica content in respirable fraction of dust determines risk
Mining and related activities	Mining and milling	Country rock* an important determinant of risk. Gold, coal, tin, copper, mica, uranium, crocidolite, iron, important in some regions
	Small - scale mining	Under-researched, but exposure may be high
	Mining related	Quarrying, tunnelling, excavating, digging wells and boreholes. Country rock and mineral determines risk. Quarrying granite, sandstone, flint, quartzite, shale and slate may produce high levels of quartz. Potency** of silica may be reduced in some clays
Major industrial sources	Foundry Ceramics Glass manufacture	Pottery, tiles, brick and refractory articles
	Furnace masonry	Cutting, grinding, etc., refractory articles
	Construction	Cutting, grinding, etc., concrete, tiles or bricks. Digging foundations
	Stone working and monumental masonry	Making, cutting, abrasive polishing, etc., of tombstones, billiard tables, slate pencils, cladding and surfaces, including granite counter tops
	Abrasive blasting with sand (sandblasting) or siliceous material	Very high exposures common. Usually cleaning or preparation for coating of metal pieces.

Sources of exposure		Comment
Minor industrial sources	Fillers and scourers	Fine silica may be used for fillers in paints, coatings, plastics, rubber, explosives, dental supplies, etc., or in scouring materials (such as cleaning agents and those used for polishing flour) or grinding materials
	Jewellery	Cutting, buffing, etc., semi - precious gems
	Diatomaceous earth	Calcined material contains cristobalite
	Craft work	Stone carvers, sculpture, pottery. Cases unusual unless frequent exposure, e.g., most working days
Less well established sources	Agriculture	High levels of quartz exposure possible in farming sandy soils but silica - associated disease rare
	Non - occupational	Frequent exposure to sand storms

* Country rock = rock hosting the mineral or being mined. Silica content varies from location to location, even within a mine. ** Potency = ability to cause silicosis

Adapted from Rees and Murray, 2007

2.3 Occupational exposure limits (OELs)

Occupational exposure limits (OELs) are occupational standards and are generally established at levels that can be tolerated by most healthy workers occupationally exposed daily over a working lifetime without adverse effects. OELs commonly change over the years as new exposure – response data become available. Importantly, OELs are generally set to protect against critical health conditions. Not all conditions related to the exposure may be considered in setting the OELs; for example, no quartz OEL has especially considered TB.

In general OELs are set for two main purposes: as statutory standards to which enterprises must comply; and as guides to practitioners and others on the level below which health effects will not be expected to occur. Statutory OELs are often influenced by technical feasibility in attaining the standard and cost; hence they are usually higher than predominantly health based guidance OELs, and vary from country to country.

Existing national OELs for quartz, in EU member states and South Africa are presented in Table 2. These are expressed as long - term limits, averaged over an 8 - hour working day (i.e., 8 hour time - weighted averages, TWA) (Cherrie *et al.*, 2011).

Table 2. Occupational exposure limits for respirable crystalline silica (quartz) in EU Member States and South Africa (Note: 0.1 mg = 100 µg)

Country	OEL – long - term ($mg.m^{-3}$) Quartz
Austria	0.15
Belgium	0.1
Bulgaria	0.07
Czech Republic	0.1
Denmark	0.1
Estonia	0.1
Finland	0.2
France	0.1
Germany	As low as reasonably achievable
Greece	0.1
Hungary	0.15
Ireland	0.05
Italy	0.05
Lithuania	0.1
Luxembourg	0.15
Malta	none
Netherlands	0.075
Norway	0.1
Poland	0.3
Portugal	0.05
Romania	0.1
Slovakia	0.1
Slovenia	0.15
South Africa	0.1
Spain	0.1
Sweden	0.1
Switzerland	0.15
UK	0.1

Adapted from Cherrie et al., 2011

The primary sources of OELs globally include the National Institute for Occupational Safety and Health (NIOSH) recommended exposure limits (RELs); the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs); the U.S. Department of Labour's Occupational Safety and Health Association (OHSA) permissible exposure limits (PELs); and occupational exposure OELs from various European countries. Although in the US PELs are legal standards, they do not apply to farms and most agricultural field operations (NIOSH, 2002). TLVs, on the other hand, are not promulgated standards but are consensus exposure guidelines. They are revised periodically and are rarely subject to legal challenges.

Some limitations regarding TLVs have been discussed (Castleman and Ziem, 1988). Nevertheless, TLVs have been, and still are, the most influential OELs in the world.

Considerations in interpreting quartz OELs in the workplace have also been suggested (Rees and Murray, 2007). OELs are mostly 8 - hour standards, but environmental exposure may be for much longer in agriculture and populations often include the young, the elderly and other vulnerable groups. Measurement error is to be anticipated as very small amounts of dust and silica are collected for analysis: respirable quartz OELs are typically at or below 0.1 $mg.m^{-3}$ and these concentrations often are close to detection limits for most laboratories. Some OELs have been greatly reduced in recent times. For example, the ACGIH TLV was 0.1 $mg.m^{-3}$ for respirable quartz in 1999 and 0.025 $mg.m^{-3}$ by 2006. Similarly, in 2002 the South African OEL for quartz was 0.4 $mg.m^{-3}$ and 0.1 $mg.m^{-3}$ by 2008. Many OELs are not protective against silica-associated diseases (Steenland, 2005), especially in resource poor countries with high background levels of TB.

In South Africa, non - mining OELs are published by the Department of Labour (DoL). They were first published in 1995 and are contained in Tables 1 and 2 of the Regulations for Hazardous Chemical Substances under the Occupational Health and Safety Act, Act 85 of 1993 (DoL, 1993). These OELs are enforceable statutory standards in South Africa. Currently, the South African OEL for respirable quartz is 0.1 $mg.m^{-3}$, the NIOSH REL is 0.5 $mg.m^{-3}$ and the ACGIH TLV is 0.025 $mg.m^{-3}$. It is believed that over a 40- or 45-year working lifetime, workers have a significant chance (at least 1 in 100) of developing radiographic silicosis when exposed to quartz levels at the NIOSH REL (NIOSH, 2002).

There is strong epidemiological evidence to support an association between occupational crystalline silica exposure and several diseases such as lung cancer, pulmonary tuberculosis, and chronic obstructive pulmonary disease (COPD) (WHO, 2000). However, there is continuing controversy regarding quantitative exposure - response relationships and further research is needed to determine at which level of silica exposure these disease may occur.

2.4 Potency modifiers of quartz exposure

Although this thesis does not investigate potency modifiers of silica in farming, a number of uncertainties and information gaps exist on whether or not the fibrogenic potency (i.e., ability to cause silicosis) of quartz is variable, and if so, which factors influence its variability. Many chemical and physical factors alter the toxicity and fibrogenicity of silica e.g., modification of surface properties by coating, grinding and metal binding (Wiessner *et al.*, 1988; Shoemaker *et al.*, 1995; Castranova *et al.*, 1997; Duffin *et al.*, 2001). Therefore, crystalline silica and the importance of the chemical's surface chemistry in relation to its pathogenicity have been extensively reviewed (Kriegseis *et al.*, 1987; Fubini *et al.*, 1995; Ding *et al.*, 1999; Fubini *et al.*, 1999; Konecny *et al.*, 2001; Porter *et al.*, 2002; Bruch *et al.*, 2004; Cakmak *et al.*, 2004; Fubini *et al.*, 2004; Governa *et al.*, 2005).

Chemical structure, composition, crystallinity, chirality, dissoloution of elements, particle size and shape, and surface properties of silica polymorphs are some of the mineralogical characteristics that may affect their biological activities (Ebbesen, 1991; Guthrie and Heaney, 1995). The properties of mineral surfaces e.g., interactions between biological fluids and cellular membranes, may determine their toxicity. A number of investigations confirmed that minerals with the same chemical composition and crystal structure have different pathological potentials when their surfaces possess certain desirable properties (Fubini *et al.*, 2004) or when their surfaces are modified by a variety of treatments (Hochella, 1993; Fubini *et al.*, 1995). The mineralogical characteristics of silica polymorphs in relation to their biological activities were recently reviewed and the author concluded that the crystalline structure, the origin of the silica polymorphs, the various surface modifications and the contaminants in silica polymorphs affect the pathogenic potential of silica (Gulumian, 2007).

The United Kingdom's Health and Safety Executive (HSE) reviewed potency factors with regard to their ability to cause silicosis and summarised their conclusions in a respirable crystalline silica potency matrix (Table 3) (HSE, 2002). The most hazardous form is pure crystalline silica with freshly fractured surfaces, which are particularly active in creating or promoting biological effects. Exposure of animals to freshly fractured quartz increased the risk for pulmonary diseases compared to those animals exposed to aged quartz particles (Shoemaker *et al.*, 1995; Ding *et al.*, 1999; Porter *et al.*, 2002). Because of the difference between freshly fractured and aged quartz, it could be hypothesised whether the same regulatory level for quartz is protective enough for all the occupational environments e.g., those that produce fractured quartz compared to those that use aged quartz (Gulumian, 2007).

Table 3. Respirable crystalline silica (RCS) potency matrix

Potency factors	**Comment**	**Relevant exposure situations**
Particle size - dusts of extremely small particle sizes	Enhanced potency compared with exposures to similar mass of larger size respirable particles	High energy abrasive processes and grinding. Silica flour exposure.
Freshly fractured RCS - production of dry freshly cut surfaces of silica	Dry freshly cut surfaces of silica are presented as the "reference point" against which the potency of other forms is compared.	Mechanical processes i.e. drilling, blasting, grinding and all abrasive processes.
Wetting of freshly cut surfaces	Reduced potency compared to dry freshly cut surfaces. The effect of wetting depends on how long the surfaces have been wetted prior to inhalation. Importantly, the result of wetting is also dust suppression rather than potency reduction.	Wet extraction or handling processes.
"Aged" dusts, i.e., dusts that have not been freshly cut	Reduced potency compared to freshly cut or freshly ground dusts.	Handling of dusts after storage.
Aluminium - containing clay minerals - which coat the surfaces of the silica particles	Reduced potency compared to freshly fractured uncoated surfaces. Once surrounding clay coating has been worn off whilst in the lungs, the toxicity of the inhaled quartz particles can be expressed.	Work in the heavy clay industry or in mines extracting low rank coals.

Adapted from HSE, 2002

With time, the activity of free radicals decays, a process referred to as "ageing", which occurs slowly in air, but rapidly (within minutes) in water. This "ageing" process reduces lung damage compared to freshly fractured quartz. Human studies are consistent in that freshly cut surfaces of quartz are more potent than aged surfaces (HSE, 2002). It has been suggested that the use of "wet - processes" help to reduce the reactivity of freshly cut quartz surfaces. This will however depend on the effectiveness of the wetting process as well as the time interval between dust generation and inhalation of the freshly cut quartz. It is, however, unlikely that wet processes could completely reduce the toxicity of freshly cut surfaces in the seconds between generating the dust and the deposition of the dust into the lungs. These are some considerations that should be borne in mind in deciding what regulatory stance to take in particular industrial settings where such processes occur, and when exposure assessment strategies are developed.

Additionally, contaminants associated with quartz change its toxicity; there is experimental, animal and human evidence indicating that the toxic effects of quartz are reduced in the presence of aluminium - containing clay minerals (Donaldson and Borm, 1998; Duffin *et al.*, 2001; Chen *et al.*, 2005). It has been suggested that this is due to the binding of aluminium ions (Al^{3+}) to the surface silanol groups of quartz. This may be a possible explanation for lower risks with exposure to silica in clays (which contain aluminium compounds) than exposure to pure, fresh silica. In addition, contamination with iron has the opposite effect (Castranova *et al.*, 1997; Gulumian *et al.*, 2005).

Interestingly, some evidence exists that the protective effect of aluminium - containing minerals is not permanent (Le Bouffant *et al.*, 1982; Czernichowski *et al.*, 1987; Bolsaitis and Wallace, 1996). In an animal study, the decline in protection was thought to be due to the differential clearance of aluminium and quartz from the lungs (Le Bouffant *et al.*, 1982). A possible explanation suggested was that the quartz was “cleaned” over time, resulting in the quartz particles beginning to express their pathogenic properties. Although human studies are limited, this factor may to a degree explain the progression of pneumoconiosis in some retired workers. Furthermore, it is possible that the health consequences of ceasing co - exposure to quartz and aluminium - containing clay minerals may be greater in some susceptible groups, e.g. younger workers (Le Bouffant *et al.*, 1982). The retained lung burden of quartz has more time to instigate silicosis development in younger workers, compared to those workers exposed to quartz in the presence of aluminium up until retirement age.

In summary, the published literature indicates that, as long as exposure to aluminium - containing minerals found in close geological association with quartz continues, some protection against the toxicity of respirable quartz will occur. However, when personal exposure to these minerals stops the protective effect is likely to wear off. This hypothesis, although based on scant human exposure evidence, should be borne in mind in the design and interpretation of exposure assessments in occupational settings where there may be co - exposure to quartz and to clay minerals.

Besides aluminum – containing clay minerals, aluminum powder has been shown to completely prevent silicosis in animals (Denny *et al.*, 1937; Crombie *et al.*, 1944; Kennedy, 1956). Inhalation experiments with animals using pure quartz dust with and without aluminum powder showed that typical silicosis was produced in about five months in the control animals receiving silica dust alone. However, the addition of 1 % aluminium powder to inhaled silica dust completely prevented the occurrence of silicosis, even after exposure had been prolonged up to 22 months.

Regardless of the type of dust, extremely small particle size enhances quartz potency; smaller particles possess a larger surface area per unit mass compared to larger - sized particles (HSE, 2002). Hence, smaller particle size fractions (very fine dusts) of quartz would be expected to produce more lung damage than equal masses of larger respirable size fractions (HSE, 2002). Limited experimental and epidemiological evidence exists to supports this conclusion and the available epidemiology studies do not directly inform on this issue. Nevertheless, a greater risk of silicosis in workers exposed to very fine particles of respirable quartz exists; therefore it is helpful to bear this consideration in mind when faced with exposure situations and occupations where very fine quartz dust may be generated.

Finally, there remains a number of uncertainties and information gaps relating to modifiers of quartz potency exist. Variations in surface activities of crystalline silica (because of grinding, origin and contaminants, for example) may result in different samples within the same silica polymorphs having different pathogenicities (Castranova *et al.*, 1996; Castranova *et al.*, 1997; IARC, 1997; Cakmak *et al.*, 2004). Additionally, the potential changes in the surface chemistry of crystalline silica following long - term residence in the lungs, and the possible toxicological consequences of such changes, is a particular area of uncertainty. Furthermore, particle size has been mentioned to contribute to the toxicity of quartz, but limited attempts have been made to determine the size causing silicosis.

2.5 Health risks associated with quartz exposure

Exposure to quartz dust causes multiple diseases (Table 4), but silicosis and silica dust - associated TB, in particular, are the two diseases that remain high on the list of occupational health priorities in low and middle - income countries and that still occur in some high - income countries (Rees and Murray, 2007). Quartz is known to be cytotoxic, inflammogenic, fibrogenic and genotoxic / carcinogenic (IARC, 1987; Bank, 1992; Vallyathan *et al.*, 1998; Donaldson and Tran, 2002; Porter *et al.*, 2002). Other diseases associated with silica exposure include lung cancer (Goldsmith *et al.*, 1982; Koskela *et al.*, 1994; Morgan and Reger, 1996; Weill and McDonald, 1996; Hnizdo *et al.*, 1997; Checkoway *et al.*, 1999; Cocco *et al.*, 2001; Steenland *et al.*, 2001; Martinez Gonzalez and Rego Fernandez, 2002; Pelucchi *et al.*, 2006; Erren *et al.*, 2009; Preller *et al.*, 2010; Vida *et al.*, 2010; Cox Jr, 2011; Gamble, 2011), COPD (Hnizdo and Vallyathan, 2003; Rushton, 2007), renal diseases (Goldsmith and Goldsmith, 1993; Kallenberg, 1995; Wilke, 1997) and systemic autoimmune diseases (Parks *et al.*, 1999): rheumatoid arthritis (Sluis-Cremer *et al.*, 1986; Klockars *et al.*, 1987; Steenland, 2005; Stolt *et al.*, 2005), scleroderma (Anandan *et al.*, 1995; McCormic *et al.*, 2010), lupus (Hogan *et al.*, 2001; Parks *et al.*, 2002) and antineutrophil cytoplasmic autoantibody positive vasculitis (Parks *et al.*, 1999; Brener *et al.*, 2001; Steenland *et al.*, 2001). Extrapulmonary deposits of silica have also been reported (Slavin *et al.*, 1985; Osorio *et al.*, 1987). Silica particles may be transported from the lungs and tracheobronchial lymph nodes to the spleen, liver, kidneys, bone marrow and extrathoracic lymph nodes.

The carcinogenicity of quartz in humans has been strongly debated in the scientific community and not universally accepted (Hessel *et al.*, 2000; Soutar *et al.*, 2000), but the

International Agency for Research on Cancer (IARC) reviewed the published experimental and epidemiologic studies of cancer in animals and workers exposed to silica and concluded that there was "sufficient evidence in humans for the carcinogenicity of inhaled crystalline silica in the form of quartz or cristobalite from occupational sources" (IARC, 1997).

Two issues of concern when interpreting studies of quartz and lung cancer are whether there has been adequate adjustment for smoking and whether sufficient account has been taken of potential concomitant exposures e.g. asbestos, coal dust, radon, ionising radiation *etc.*

Silicosis is the only silica – associated disease specific to the mineral, and silica – associated TB is of particular concern in regions with high background HIV and TB rates. These two conditions are described below.

Silicosis, a fibrotic nodular disease of the lung parenchyma, is caused by the inhalation and deposition of respirable crystalline silica particles (i.e., particles with an aerodynamic diameter <7 μm) (Ziskind *et al.*, 1976; IARC, 1987). Importantly, the "dose" of respirable silica containing dust in the workplace setting is important in the development of silicosis (IARC, 1997). Once deposited in the lungs, however, silica remains biologically active and hazardous for a long period, so the length of residence is an additional factor.

Table 4. Diseases associated with respirable crystalline silica

Disease	
Pneumoconiosis	Chronic silicosis Accelerated silicosis Alveolar lipoproteinosis Progressive massive fibrosis (PMF)
Chronic bronchitis Chronic obstructive bronchitis Emphysema Mineral dust airways disease (MDAD)	
Mycobacterial disease	Pulmonary and extra-pulmonary tuberculosis Non-tuberculous mycobacterial (NTM) disease
Lung cancer	
Autoimmune diseases	Scleroderma Systemic lupus erythromatosis Rheumatoid arthritis
Renal disease	

Adapted from Rees and Murray, 2007

Three types of silicosis may occur, depending on the airborne concentration of respirable crystalline silica. Chronic (nodular) silicosis, the most common form of the disease, occurs after 10 – 20 years of exposure to silica dust. The development of silicotic nodules in the lung tissue (Figures 2 a and b) is the distinguishing feature (Murray *et al.*, 1991).

a) b)

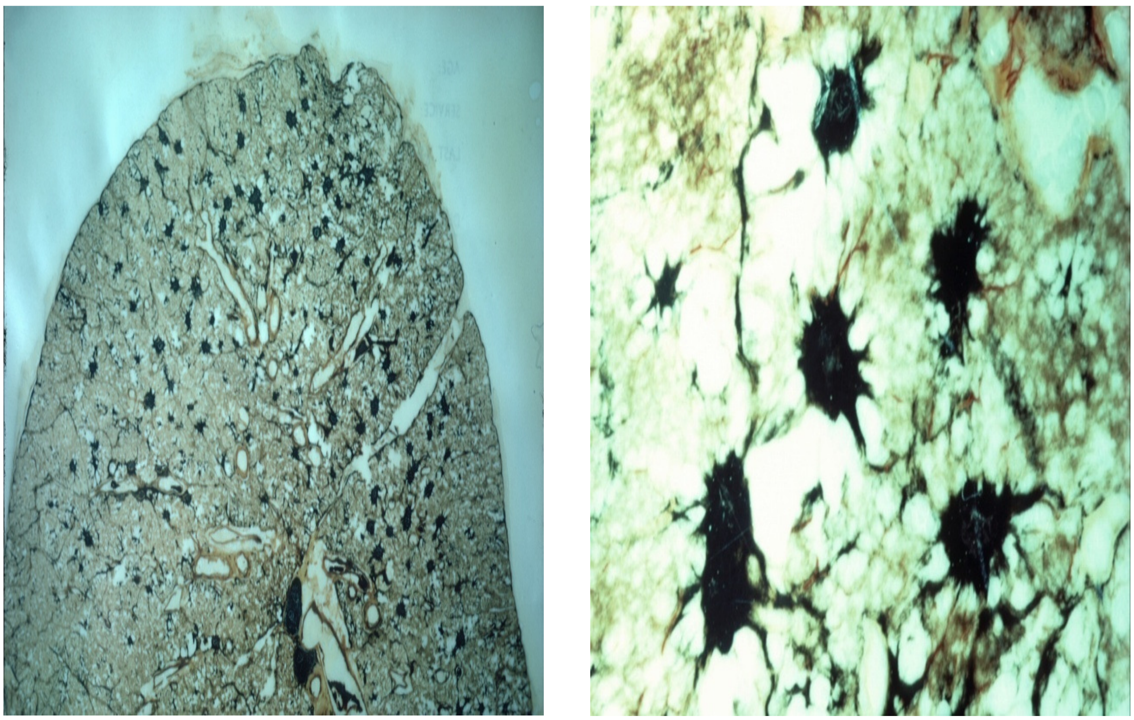

Figure 2. Whole lung section with chronic silicosis. Small circumscribed nodules are seen in the upper zone (a) and are magnified in (b) (pictures obtained from Professor Jill Murray, NIOH, NHLS)

The nodules initially involve both upper lobes of the lungs (Figure 2) and measure around 3 mm in diameter. The nodules may become confluent, destroying normal intervening lung parenchyma resulting in progressive massive fibrosis (PMF) (Parkes, 1994).

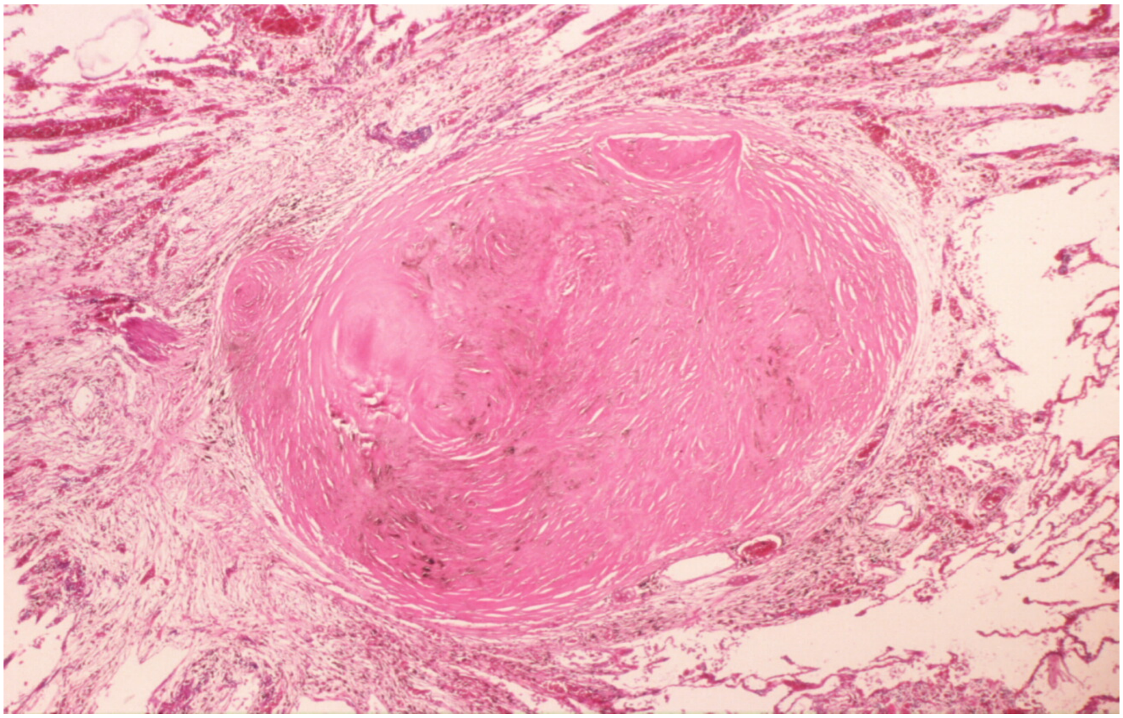

Figure 3. Silicotic nodule characterised by a central zone of hyalinised collagen. (picture obtained from Professor Jill Murray, NIOH, NHLS)

Accelerated silicosis occurs after 3 – 10 years of exposure. The changes are similar to those seen in chronic silicosis, however the nodules develop sooner and are more cellular than fibrotic in nature. Acute silicosis develops after exposure to very high concentrations of respirable crystalline silica and results in symptoms within a period ranging from a few weeks to 5 years after the initial exposure.

Chronic silicosis is often a radiological diagnosis and is characterised by symmetrically distributed, small (usually 1–3 mm) rounded opacities, initially in the upper zones of the chest radiograph (Figure 4). Silicosis itself often does not produce symptoms.

A productive cough may be present and is usually due to chronic bronchitis; it may, however, be due to lung cancer or TB. Clubbing or systemic symptoms, such as fever and weight loss, should be attributed to lung cancer or TB until proven otherwise. The clinical features of accelerated silicosis are similar to those of chronic silicosis, but develop sooner. Patients with acute silicosis may become disabled within months of exposure, with clinical features similar to alveolar proteinosis of other aetiologies (Rees and Murray, 2007).

Figure 4. Chest X – Ray of patient with advanced silicosis (picture obtained from Professor David Rees, NIOH, NHLS)

In South Africa, silicosis is very common in gold miners: the prevalence of silicosis in a cross -sectional study of 520 gold miners (with mean length of service of 21.8 years) was found to be 18.3–19.9% (Churchyard *et al.*, 2004). Similar findings was recently reported with a prevalence of silicosis of 24.6% in 624 gold miners examined 18 months after cessation of employment with mean length of service of 25.6 years (Girdler-Brown *et al.*, 2008). Possible explanations for the high levels of silicosis in gold miners include that the quartz is freshly fractured by drilling, blasting, and moving rock, and that the particles are probably very small (Phillips, 2007).

Epidemiologic studies of South African gold miners have shown that chronic silicosis may develop or progress even after occupational exposure to silica has been discontinued (Hessel *et al.*, 1986; Ng *et al.*, 1987; Hnizdo *et al.*, 1997; Hnizdo and Murray, 1998). As a result, removing a worker from exposure after diagnosis does not guarantee that silicosis or silica-related disease will stop progressing or that an impaired worker's condition will stabilize (Weber and Banks, 1994; Wagner, 1995; Parker and Wagner, 1998). This means that, silicosis can develop or progress well after exposure to silica has ended. In addition, there is good evidence that the risks of silicosis do not increase uniformly with increases in airborne concentrations, but increase disproportionately at higher concentrations (ILO, 2001).

The association between silicosis and TB is well known (Sander, 1946; Balogh *et al.*, 1972; Snider, 1978; Morgan, 1979; Snider, 1979), but more recent findings show that exposure to silica, without silicosis, may also predispose individuals to TB (Hnizdo and Murray, 1998; teWaternaude *et al.*, 2006).

The increased risk of both pulmonary and extra - pulmonary TB is lifelong even if exposure ceases (Hnizdo *et al.*, 1997). TB rates in subjects with advanced silicosis in high background TB settings can be very high, up to three - fold higher than those in the same workforce without silicosis (Cowie, 1994), and the risk increases with severity of silicosis. The risk is considerably higher in patients with acute and accelerated silicosis (ATS, 1997). The prevalence of silica - related TB is exacerbated by the HIV, epidemic in some low - income countries (Churchyard and Corbett, 2001), with the result that TB remains as much a silica-related occupational disease in non - HIV - infected as in infected miners (Corbett *et al.*, 2000).

Pulmonary TB rates can be extremely high in silica-exposed groups with high background population TB and HIV rates, as is the case in South African farm workers. Limited data are available on TB and HIV rates specifically amongst farm workers in South Africa, but the FAO reported that AIDS has killed around 7 million agricultural workers since 1985 in the 25 hardest - hit countries in Africa and that the disease could kill 16 million more before 2020 (FAO, 2000). Thus, without appropriate interventions, up to 25 % of the agricultural labour force could be lost in countries of sub-Saharan Africa by 2020.

Importantly, in some high - income countries such as the USA the prevalence of silicosis has been decreasing (Bang *et al.*, 2008) and Sweden have shown that silica – associated disease can be prevented (Gerhardsson, 2002). But in low and middle income countries "even with a focus on primary prevention, silica-associated diseases with long latency will occur well into the future due to contemporary exposure" (Rees and Murray, 2007). New cases of silicosis and associated lung cancer, TB and COPD are likely to occur for decades in low - income countries, because reduction to very low concentrations of silica will take time to achieve. In addition, occupational exposure limits (OELs) in some low – income countries are high and protective standards have not even been established for some silica - associated diseases such as TB.

2.6 Farming as a global industry

Agriculture, a very old industry, developed at least 10 000 years ago and has undergone significant developments since the time of earliest cultivation (WHO, 1962). It continues to be an important occupation as the world's population may increase from approximately six billion to nine billion by 2050 - all to be fed, clothed and even fueled by agricultural products (Godfray *et al.*, 2010).

Globally, agriculture is the overwhelmingly dominant occupation, bigger than mining, manufacturing, and service industries (ATS, 1998) and employs an estimated 1.3 billion people worldwide (FAO, 2000; ILO, 2005). Additionally, the relative size of the agricultural workforce is substantially greater in developing countries than in industrialized nations (Sekimpi, 1992). In developed countries such as the United States and Japan, less than 9% of the economically active population is involved in agriculture. However, it rises to 50 - 70% for many Asian countries (including India) and even 70 - 90% for many countries in Africa (ILO, 2000).

During the past four decades however, the number of farms and farm workers globally has declined and coincided with the introduction of more intensive and productive agricultural methods. Consequently, the average farmer's productivity has increased six – fold and has also been associated with the use of agrochemicals, fertilizers, increased mechanization, more intensive animal husbandry, and other far - reaching changes (May, 1995). Additionally, the number of migrant and seasonal farm workers has increased and regions with labour -

intensive agriculture have a dominance of migrant and seasonal farm workers. This in itself makes it difficult to perform epidemiologic investigations in agriculture (Schenker, 1995).

Changes in agricultural methods have introduced new risks of potential exposures to high concentrations of respiratory toxins. Unlike most occupational settings, the farm is frequently a place where workers work and stay. Consequently, family members not directly engaged in the farm work may be exposed to respiratory hazards. Thus farming may result in extensive exposure risk to workers' family members, increasing the population at risk by several - fold. Moreover, family members may include susceptible groups such as children, the elderly, and individuals with chronic respiratory and other diseases. Residents living near farming operations may also be at significant risk from exposure to dusts carried by aerial drift. An extended population, by no means restricted to farm operators and workers themselves, may thus be at risk.

Figure 5. Farming activities may involve family members resident on the farm

The nature of agricultural practice also varies with climate, geography and other determinants of the commodities grown, and with the degree of industrialization of the country or region (ATS, 1998). Consequently farming involves a range of activities in diverse geographic and climatic settings, combinations of potential exposures of respiratory toxins may therefore be vast. In small, often family based farms, there may be little task separation, resulting in a wide range of potential occupational exposures for all involved. Additionally, exposure patterns may be cyclic, related to growth cycles of animals and crops or to seasonal variations. The exposure of farm workers involved in the same or similar activities may also differ between countries, due to differences in climate as well as regional agricultural practices.

Unfortunately, agriculture globally has generally been a low priority for the regulatory and enforcement activities of statutory agencies such as the Occupational Safety and Health Administration (OSHA) in the US and the DoL in South Africa. Nevertheless, there are several reasons why it is important to address issues in agricultural respiratory disease (ATS, 1998). First, in many developing countries, more than 80% of the economically active population may be involved in agricultural production (doPico, 1990; Bank, 1992; Sekimpi, 1992; FAO, 2010). Second, more than 70% of the world's population lives in developing countries and these countries are undergoing rapid population growth. Third, the principles of control approaches will be similar around the world, although the actual measures implemented will be modified by geographical circumstances and resources. More specifically, South Africa is a developing country and agriculture plays a major role in the country's economy.

2.7 Farming in South Africa

South Africa occupies the southern tip of Africa and is a medium-sized country, with a population of around 50 million people. Although the country is classified as semi-arid, it has considerable variation in climate as well as topography. The seasons are typical for the southern hemisphere, with the coldest days in July – August, and precipitation is expected mainly in the summer months (October – March), with the exception of the Western Cape, which is a winter - rainfall area.

South Africa has an agricultural population of 4.9 million people (including forestry and fisheries) and contributes around 11% of formal employment. This is relatively low compared to other parts of Africa but provides work for casual labourers and contributes around 2.6 % of GDP for the nation. Cereals and grains are South Africa's most important crops, occupying more than 60 % of hectarage under cultivation (FAO, 2011).

Maize, South Africa's most important crop, is a dietary staple, a source of livestock feed, and an export crop. Additionally, maize is grown commercially on large farms, and on more than 12 000 small farms, primarily in the North-West, Mpumalanga, Free State and KwaZulu - Natal provinces. Maize production generates at least 150 000 activities in years with good rainfall and uses almost one - half of the inputs of the modern agricultural sector (Statistics-South-Africa, 2002). Maize planting (and sunflower planting) normally occurs over a period of six weeks (middle October – middle November) and is harvested over a longer period, typically from middle May to the end of July.

Wheat production, which is concentrated in large, highly mechanised farms, has increased over the years. Wheat planting occurs during the winter months (middle May – end of July) and is usually harvested in the summer (early December – middle January). Both wheat and maize planting operations are associated with soil preparation activities where pesticides or mechanical techniques are used to eradicate weeds that may negatively affect the growth of the commodity.

Because of the vast climate disparity in South Africa, some farmers may only farm with live stock or only with cereal grains, or both. For example, in the very dry areas of South Africa (Northern Cape and southern Free State) farmers will only farm with sheep and cattle whereas in rainfall rich areas (North - West and Gauteng provinces) farmers will be involved in cereal grain farming.

Figure 6. Some agricultural activities can be dusty during maize planting operations

2.8 Quartz exposure in farming

There is a very small body of literature on inorganic agriculture dust exposure (Nieuwenhuijsen *et al.*, 1998; Nieuwenhuijsen and Schenker, 1998; Nieuwenhuijsen *et al.*, 1999), but some studies have reported on quartz levels in agriculture (Gustafsson *et al.*, 1978; Dynnik *et al.*, 1981; Popendorf *et al.*, 1982; Green *et al.*, 1990; Lawson *et al.*, 1995; Stopford and Stopford, 1995a; Stopford and Stopford, 1995b; Nieuwenhuijsen and Schenker, 1998; Nieuwenhuijsen *et al.*, 1999; Archer *et al.*, 2002; Molocznik, 2002; Wu *et al.*, 2003; Lee *et al.*, 2004).

Of the quartz studies, two studies measured area respirable quartz (Gustafsson *et al.*, 1978; Lawson *et al.*, 1995), three personal respirable quartz in the breathing zone of workers (Popendorf *et al.*, 1982; Archer *et al.*, 2002; Lee *et al.*, 2004), and seven quartz percentages in the respirable fraction of the dust (Popendorf *et al.*, 1982; Green *et al.*, 1990; Stopford and Stopford, 1995a; Stopford and Stopford, 1995b; Nieuwenhuijsen *et al.*, 1999; Archer *et al.*, 2002; Molocznik, 2002).

Area respirable quartz

A study of exposure in tractor cabs found average area respirable quartz concentrations of 2000 $\mu g.m^{-3}$and 50 $\mu g.m^{-3}$ in open - cab and closed tractor cabs respectively (Gustafsson *et al.*, 1978). During rice farming operations in California (Sacramento Valley) area respirable quartz exposures ranged from 20 to 90 $\mu g.m^{-3}$ with the highest respirable quartz levels being detected during field preparation (Lawson *et al.*, 1995). In both these studies the presence of an enclosed cabin was associated with reduced levels of respirable dust and respirable quartz levels. Although no personal measurements were done in these two studies, high levels of respirable quartz during farming activities were demonstrated.

Personal respirable quartz

Personal respirable quartz concentrations exceeding generally accepted OELs have been reported (Popendorf *et al.*, 1982; Archer *et al.*, 2002; Lee *et al.*, 2004). A study on personal respirable quartz exposures of citrus, peach, and grape crops harvesters found that 50% of the measurements among grape harvesters exceeded 25 µg.m^{-3} (range 7 - 105 µg.m^{-3}) (Popendorf *et al.*, 1982). Respirable quartz levels were measured on seven different farms in three eastern North Carolina counties: Pitt, Lenoir and Wayne (Archer *et al.*, 2002). Relatively low personal respirable dust concentrations (overall mean of 1.3 ± 2.9 mg.m^{-3}) were measured amongst the 27 farm workers on the majority of the farms. Nevertheless, surprisingly high personal respirable quartz concentrations were measured during sweet potato transplanting (maximum of 3 910 µg.m^{-3} and overall mean concentration of 700 ± 1600 µg.m^{-3}). In another study the characteristics of personal exposure to inorganic and organic dust during manual harvest of California citrus and table grapes were investigated (Lee *et al.*, 2004). Similarly, relatively low geometric means of respirable dust exposures were reported (1.14 mg/m^{3} for citrus harvest and 0.23 mg.m^{-3} for table grape operations, respectively). Yet, geometric means of respirable quartz exposures during citrus harvest and table grape operations measured 80 µg.m^{-3} and and 20 µg.m^{-3} respectively. As expected, the proportion of respirable quartz to respirable dust was similar in both crops: averaging 7% for citrus harvest samples and 9% for table grape operation samples. Importantly, these studies showed that respirable dust does not act as a good surrogate for respirable quartz exposure and illustrated that personal over - exposure to respirable quartz may occur.

Quartz percentages

The studies on quartz percentages in the respirable fraction of dust are summarized below. Respirable quartz content of respirable dust collected from citrus, peach, and grape crops' harvesting machine filters ranged from 1 - 12% (Popendorf *et al.*, 1982) and in a study on 12 farms in Alberta, Canada quartz content measured on tractor cab filters ranged from 0.85 to 17%. Additionally 50 to 97% of the dust had aerodynamic diameters less than 5 µm (Green *et al.*, 1990). Higher levels of quartz in the respirable fraction of sandy soils than in clay soils have been reported (10.5 to 44.5%, mean 29.0% and 1.32 to 3.42%, mean 2.17% respectively) (Stopford and Stopford, 1995a; Stopford and Stopford, 1995b). Hence, exposure to quartz from sandy and sandy loam soils may be greater than from clay soils. High average percentage quartz in the respirable fraction of dust samples was reported during hand and machine harvesting of field crops (21–23%), and ground preparation operations (20.5%) in California (Nieuwenhuijsen *et al.*, 1999). Mean percentage silica levels of 34.7% (highest of 54.3% during sweet potato planting) were reported in 34 respirable dust measurements (Archer *et al.*, 2002) and were almost twice as high as percentage silica levels reported in studies of California agriculture (Nieuwenhuijsen *et al.*, 1999). The respirable fraction of dust in the respiratory zone of workers during an annual work cycle together with the free silica content in airborne and settled dust have been investigated (Molocznik, 2002). The study was done on five farms with farmers performing 40 main identifiably distinct work activities which contributed to the annual work cycle. Respirable fractions in airborne dust of up to 25% and higher levels of respirable quartz in settled dust samples collected from the farmers workplace were reported (64.6% in dust settled on a tractor and beets combine harvester during harvesting of beetroots). These studies have shown that quartz made up a substantial fraction of the respirable dust and that sandy and sandy loam soils may produce higher quartz concentrations (Dynnik *et al.*, 1981; Stopford and Stopford, 1995a; Stopford and Stopford, 1995b; Archer *et al.*, 2002).

Some deduction can be made from the above studies: the literature on personal occupational respirable quartz exposure in agriculture is limited and the few studies reporting on personal quartz exposure had very few measurements. Additionally, most studies were on non - randomly selected populations and thus a population – based picture of quartz exposure in farming is lacking. Available data on quartz exposure in farming reflect exposure for only a small range of activities and the data come exclusively from North America and northern Europe. Nevertheless, the results reported are convincing of a risk of over exposure to quartz in a variety of farm settings and that high levels of respirable dust and personal respirable quartz can be generated during farming activities.

It should be born in mind, though, that exposure assessments during farming are difficult because of the variability and cyclical nature of the farmers' work and the many potential exposure determinants (Preller *et al.*, 1995; de Cock *et al.*, 1998). In extreme circumstances, 8 - hour shift exposures can vary between 3 - 4000 fold (Kromhout and Vermeulen, 2001). The variability in farming may be at the extreme end because workers perform many activities, often while moving from field to field with potentially different soil types and, of course, much of the work is outdoors resulting in even more variability due to changing meteorological conditions (Preller *et al.*, 1995; de Cock *et al.*, 1998).

2.9 Determinants of quartz exposure in farming

Farm size, quantity and variety of commodities, farming practices, soil types and climate are extremely diverse and substantially different in parts of the world. Additionally, farm workers conduct many activities throughout the year suggesting that several potential determinants (factors that are associated with some of the variation in quartz exposure levels) of exposure may exist.

The literature on determinants is scant, but in summary, three studies described determinants of exposure to respirable dust (Nieuwenhuijsen *et al.*, 1998; Nieuwenhuijsen and Schenker, 1998; Wu *et al.*, 2003) and only one study described the determinants of quartz exposure during farming activities (Archer *et al.*, 2002). Plowing wet soil produces less dust than plowing dry soil and the presence of an enclosed cab substantially reduces particle exposure (Nieuwenhuijsen *et al.*, 1996). Many other factors also determine exposure, ranging from the tractor's size and speed to implement size, type, and adjustment to soil type and wind speed. Effective cab enclosure is the most significant determinant (Gustafsson *et al.*, 1978; Atiemo *et al.*, 1980; Nieuwenhuijsen and Schenker, 1998). The presence of an enclosed cabin on the tractor reduced respirable dust exposures (geometric mean (GM) = 1.6 $mg.m^{-3}$) during discing operations as opposed to no cabin present (GM = 81.9 $mg.m^{-3}$). Additionally, decreased respirable dust exposures were associated with higher relative humidity (R^2 = 0.24; p = 0.0015) and lower tractor speed (R^2 = 0.14; p = 0.02) as opposed to field crop operations, in particular tractor driving, where higher dust exposures occurred (Nieuwenhuijsen and Schenker, 1998).

In a subsequent study, a 60 – fold and 4 - fold reduction of larger dust particles (50% cut - off < 9.8 µm) and smaller dust particles (50% cut - off < 3.5 - 4 µm) respectively amongst tractor operators operating cabbed tractors were reported (Nieuwenhuijsen *et al.*, 1998). Furthermore task duration, specific activities and task frequency were all reported to be important determinants of respirable dust exposure (Wu *et al.*, 2003). Even though results were based on limited field measurements and more on qualitative dust exposure ratings e.g questionnaire for exposure duration, the study suggested that exposure duration of activities may contribute more to respirable dust exposure than the exposure intensity of a task (some activities generate a lot of dust but are done quickly).

Task and soil conditions may be important determinants of quartz exposures (Archer *et al.*, 2002). In Eastern North Carolina quartz exposures in farm workers were observed to be associated with agriculture activity (F-value = 26.25; p = 0.0001), percent soil moisture (F-value = 13.6; p = 0.0009), relative humidity (F-value = 25.71; p = 0.0001) and average wind speed (F-value = 7.83; p = 0.0089). Seventy nine percent of the variation in exposure was explained by farming activity and soil moisture.

Another important determinant suggested when quartz exposures are assessed is soil type (Stopford and Stopford, 1995a; Stopford and Stopford, 1995b; Archer *et al.*, 2002). Indeed, sandy and sandy loam soils have been found to contain higher levels of quartz in the respirable fraction than clay soils. Mean quartz percentages in the respirable fraction of sandy soils (29.0 ± 11.1%) in North - Carolina were consistently higher than in clay soils (2.17 ± 0.85%). In addition, 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%) (Stopford and Stopford, 1995a).

A subsequent larger study reported that the average respirable fraction of sandy soils was 29.0 % [standard deviation (SD) 11.1] versus 15.2 % (SD 4.1) in sandy loam soils and 2.2 % (SD 0.8) in clay soils. Interestingly, quartz percentages 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 (Stopford and Stopford, 1995b). In summary, these studies suggest that, during farm activities, there is potential for greater quartz exposures on sandy or sandy loam soils than clay soils.

The only study on the association between personal TWA quartz exposures and soil type showed high personal TWA quartz concentrations amongst farm workers on a sandy soil farm (Archer *et al.*, 2002). Surprisingly, in a group of 27 workers, the highest personal quartz concentration measured was 3,910 $\mu g.m^{-3}$ during sweet potato transplanting with an overall mean concentration of 700 ± 1,600 $\mu g.m^{-3}$ (Archer *et al.*, 2002). Importantly, soil type is a continuum and can range from very sandy to mostly clay. No studies have investigated at which point of a soil spectrum personal exposures to quartz may be dangerous.

In addition to determinants that may influence personal exposure to quartz in farming, modifiers of quartz potency as described earlier should also be considered.

2.10 Quartz related diseases reported in agriculture

The literature on silica - associated disease in agriculture is scant (Sherwin *et al.*, 1979; Fennerty *et al.*, 1983; Gylseth *et al.*, 1984; Dubovsky, 1999; ILO, 2002; Rottoli *et al.*, 2003;

Schenker *et al.*, 2009) and there is unconvincing evidence of a significant burden of pneumoconiosis in farming. Although very rarely, silicosis has been diagnosed in agricultural workers (Fennerty *et al.*, 1983; Rottoli *et al.*, 2003). Many of the silica - associated diseases have not been reported on, for example silica associated TB and lung cancer. Generally poorer access to health services by farm workers may explain some under ascertainment of cases. Nevertheless, cases of pneumoconiosis in farm workers have been reported, but very rarely and in the main with clinical features not typical of silicosis. However, the substantial burden of disease seems unlikely.

2.11 Non occupational and environmental exposure to quartz

In the main, farmers and farm workers work and live on the land and are thus exposed to both occupational and environmental dusts. The published literature on environmental quartz exposure and associated diseases is small, but of interest in considering the quartz burden faced by farmers as if substantial environmental exposure can occur it would add to the risk of farmers at least in selected settings.

Lung deposition of siliceous dust and pneumoconiosis, some with radiological features of silicosis, have been reported from desert regions of the world; particularly, in areas of severe sand storms (Policard and Collet, 1952; Bar-Ziv and Goldberg, 1974; Norboo *et al.*, 1991; Saiyed *et al.*, 1991; Franco and Massola, 1992). These studies indicate that environmental (non-occupational) exposure to dust may be substantial and result in pneumoconiosis, and that dust generated from the land may contribute to the silica burden of farmers; especially, those living in these and similar regions of the world (Norboo *et al.*, 1991).

Some studies also reported non-industrial deposition of siliceous dust in lungs without typical silicosis (Policard and Collet, 1952; Bar-Ziv and Goldberg, 1974). In the former, the lungs of three inhabitants of the Sahara desert contained dust but no fibrosis, but in the latter there were dust nodules and collagen fibres in an irregular distribution in autopsy lung specimens of 54 Bedouins for whom the Negev formed a permanent habitat. In addition, bifirengent silica dust particles were noted in 46 of the 54 patients' lungs. The relatively benign lung response, termed simple pneumoconiosis, was attributed to the "old dust" associated with desert sand, the fractured surfaces having undergone transformation and weathering thus making them less "noxious".

Findings more persuasive of silicosis have been found in the Himalayan villages of Chuchot Shamma and Stok (Norboo *et al.*, 1991) and Saboo, Shey and Chushot – all in central Ladakh (Saiyed *et al.*, 1991). Chuchot Shamma was exposed to frequent dust storms but Stok less so. Five of seven men and all of the nine women examined from Chuchot Shamma showed varying grades of radiological silicosis, compared with three of the 13 men and seven of 11 women from Stok. On X-ray diffraction, 21 % of the inorganic dust extracted from the lungs of a deceased resident of a neighbouring village was found to be quartz. The authors concluded that silicosis is common among the older inhabitants of these Himalayan villages and that the dust exposure was environmental and not industrial.

The central Ladakh villages had no mines or industries but investigations of 449 randomly selected subjects from the three villages found radiological pneumoconiosis in 101 (22.5 %) with ten (9.9 %) having progressive massive fibrosis and 12 (2.7 %) egg shell calcification of hilar glands. Chushot had the most severe dust storms and the highest prevalence of pneumoconiosis (45.3 %). Notably, the free silica content of the unspecified dust generated by storms was between 60 and 70 % (Franco and Massola, 1992).

In conclusion, quartz is a well recognised health hazard in other industries, but exposure data on quartz levels and the possible determinants thereof in agriculture, internationally and in South Africa, are scarce. Since a large workforce may be exposed, it is important that quartz levels are quantified, particularly during dusty activities.

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CHAPTER 3

Methodology

Chapters 6 - 9 comprehensively cover the methodology used in this study. In this Chapter, the farms where the exposure assessments were done are described and the methods of measuring respirable dust and silica are briefly explained, particularly those for respirable quartz. The section concludes by briefly summarizing the quality assurance and ethical procedures followed during the study.

3.1 Selection of study worksites

In consultation with a pedolodist, geological maps were used to identify sandy, sandy loam and clay soil regions in South Africa. The study was done on three medium scale farms, one located in each of these regions (Figure 7) and they were representative of the regions in terms of size, farming methods, farming activities and the livestock and crops produced on the farms, which typically included cattle and sheep, maize, wheat, sunflower, water melon, pumpkin and potatoes. The owners of the farms on which the quartz exposure assessments were done were known to the investigator, and the workplaces selected in this study were therefore by means of convenience sampling.

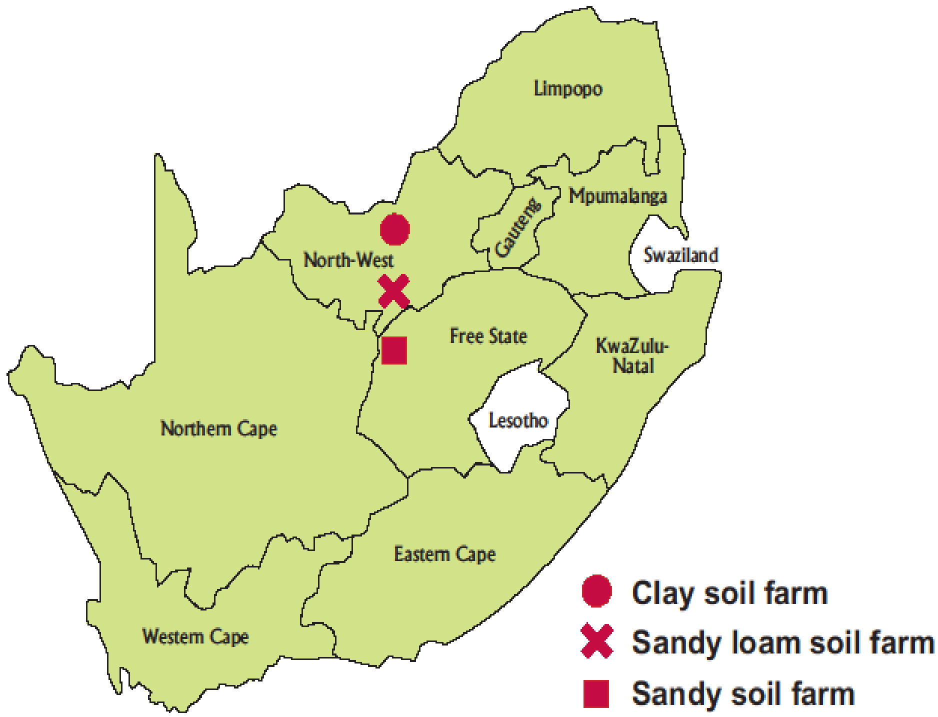

Figure 7. Locations of the three farms in the Free State and North - West provinces of South Africa (drawn by Roy Hollowday, Graphics unit, University of the Witwatersrand)

The sandy farm was located in the eastern Free State province of South Africa and was approximately 850 hectares in size. Farming on this farm was predominantly grain and livestock with a median rainfall of 450 - 500 mm/annum (Statistics South Africa, 2002). The sandy loam and clay soil farms were situated in the southern and eastern part of the North West province of South Africa and were approximately 2000 and 800 hectares in size, respectively. Farming on sandy loam and clay soil farms was predominantly grains with a median rainfall of 300 - 700 mm. All workers on the three farms agreed to participate voluntarily in the study, were resident on the farms and did not specialise in one specific task.

Maize and sunflower planting typically occur during summer (wet season) over a six week period (middle October – middle November) and crops are harvested during winter (dry season) over a longer period, typically 8 – 10 weeks from middle May to the end of July. Conversely, wheat planting occurs during winter over 8 – 10 weeks (middle May – end of July) and are normally harvested in summer (begin December – middle January). Additionally, both wheat and maize planting operations were associated with soil preparation activities during which pesticides or mechanical techniques were used to eradicate weeds. Farming with livestock typically involved herding the cattle and sheep into pens to count and medicate them on a daily basis.

As expected, numerous maintenance activities were observed on the farms throughout a farming year. Farming often relies on highly mechanized processes to produce cereal grains, as a result implements used during production need to be maintained. Similarly, cattle and sheep management requires maintenance, e.g. broken fences on the farms need to be fixed and feeding and water sites often require attention.

Throughout the study, no respiratory protective equipment (RPE) was observed to be used by any of the farm workers. They occasionally used some type of personal protection (e.g., a bandana or scarf covering the nose and mouth) during very dusty activities. All tractor drivers measured during the study used “open-cabbed” tractors as medium and small scale farmers usually cannot afford modern tractors fitted with enclosed cabins.

The major activities undertaken on the three farms over the annual farming cycle were identified in conjunction with the farmer and those representative of potentially dusty activities were selected for the study. All activities investigated during the study are summarized in Table 2 of **Chapter 6**.

3.2 Study population

All workers employed on the three farms participated in this study (none of the workers on the farms were excluded). Resident family members of the farm workers did not form part of this study and all study participants were male and older than eighteen. Job histories of the participants were not collected but generally in this industry farm workers and their families reside on the farm over much of their life time.

3.3 Sampling strategy

The farms were visited nine times over a 36 months period which summated to 27 days of sampling in total. The farmers informed the study investigators when selected activities were anticipated to be done and respirable dust and quartz measurements were subsequently planned accordingly.

The sandy and sandy loam soil farms produced cereal grains and livestock whereas the clay soil farm only produced cereal grains. The predominant cereal grains produced on the sandy and sandy loam soil farms were maize, wheat and sunflower and the livestock produced were cattle and sheep. Dust and quartz measurement on these two farms were representative of activities associated with cereal and livestock production. Maize was the only product farmed on the clay soil farm. Respirable dust and quartz exposures were only measured during maize planting and maize harvesting activities.

When the farms were visited, all workers on the particular farm were measured, regardless of the task being performed. Throughout the study, activities were selected to be representative of potentially dusty activities for all the three farms. As far as could be ascertained, the activities were done in the usual way during measurement days. Measurements were done during the summer (wet season) and winter (dry season) months. During summer sampling, no unusual meteorological conditions were experienced and during winter sampling there was no rain which is usual to the region.

3.4 Measurement methodology

This study involved several measurement and analytical methodologies which are summarized in the following section.

3.4.1 Respirable dust and quartz measurement

Two hundred and ninety eight (298) personal breathing zone (PBZ) respirable dust measurements were taken by means of calibrated Gillian battery - operated air - sampling pumps set at a flow rate of 2.2 $\ell.min^{-1}$ and a Higgins - Dewell cyclone using pre - weighed 25 mm PVC filters. PBZ measurements were collected over a period of approximately 8 hours (mean = 460 minutes, range = 360-520 minutes).

The widely used Health and Safety Executive (HSE) Methods for the Determination of Hazardous Substances (MDHS) 14/3 methodology was followed to collect the 298 PBZ respirable dust measurements (HSE, 2000) and quartz analyses were done by South Africa's National Institute for Occupational Health (NIOH) using X - ray diffraction (XRD) as specified in the HSE MDHS 101 method (HSE, 2005). The analytical limit of detection (LOD) reported by the NIOH was 22 µg. Three blank filters were kept and treated in the same manner as the filters used during actual sampling for each day of measurement and analysis of all blank filters showed concentrations below the limit of detection.

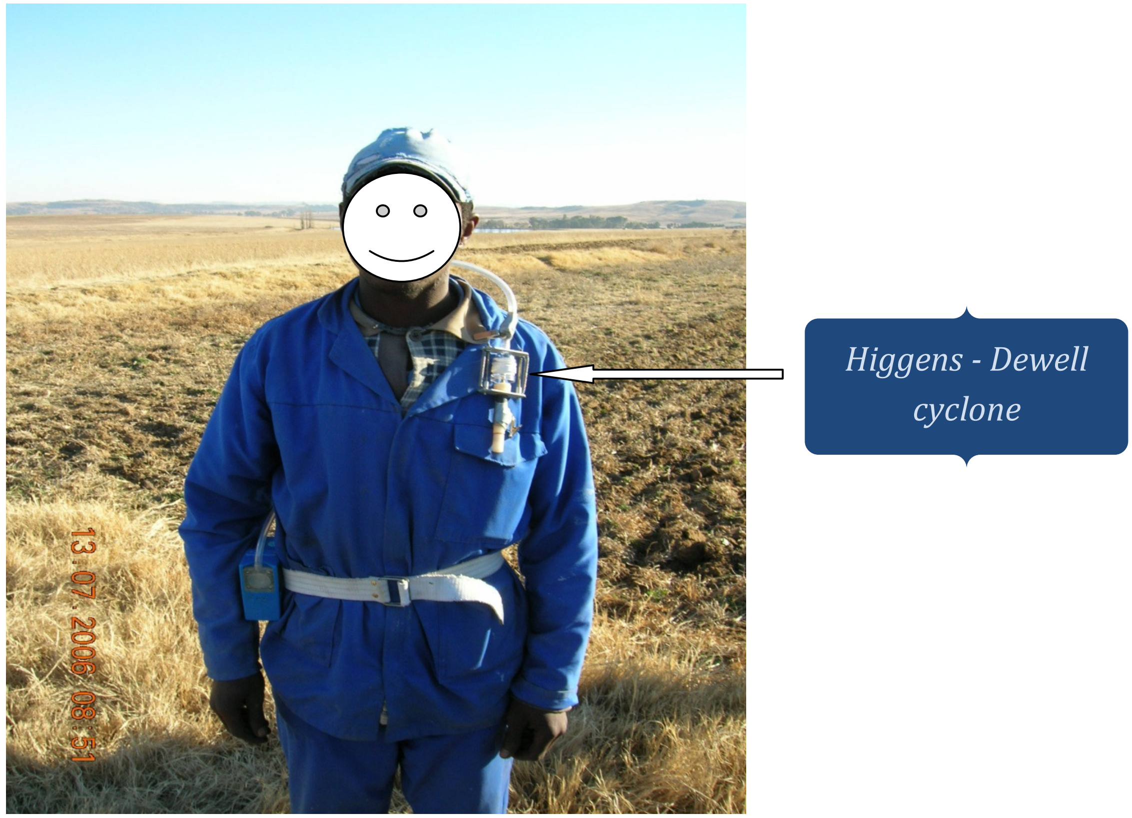

Figure 8. A personal sampling train used to draw a measured volume of air through a collection substrate

3.4.2 Soil grain size analysis

Grain size analysis, a common technique for classifying sediments and soils (Lewis and McConchie, 1994), was used to classify farm soils by sand and clay content; details of the method and the results are presented in Chapter 7 (Swanepoel *et al.*, 2011). In summary, two surface soil samples were collected from different actively farmed locations on each of the three farms and transported for analysis. Soil grain size analysis was done by an experienced laboratory in the School of Geosciences of the University of the Witwatersrand (Johannesburg).

3.4.3 Meteorological measurement

Five weather variables were obtained during this study: humidity, air pressure, wind force, temperature and rainfall. Weather data were obtained from eight days before up to the day of quartz measurement. These meteorological conditions were measured using calibrated instruments as prescribed by the South African National Standards (SANS) organization and results were compiled by a qualified climatologist working for the South African Weather Service. All weather stations were situated within three kilometers of the farms under study.

3.4.4 Particle size and mineralogy analysis

A random sample of respirable quartz filters (n = 31) were collected on the sandy and sandy loam soil farm and were analysed to determine the particle sizes of the dust. Results were expressed in terms of the D50 value which is the median value of the particle size distribution on the filter. The dust concentration of only one sample was reported to be too low to determine a reliable particle size distribution. Particle size analysis (PSA) was done by the Council for Scientific and Industrial Research (CSIR) using a standard laser light scattering method (ASTM, 2007).

Bulk surface soil samples were collected from different actively farmed locations on the sandy and sandy loam soil farms and these were analyzed by the School of Geosciences of the University of the Witwatersrand (Johannesburg) to determine the mineralogy of the soils using a standard X – Ray diffraction method (Soukup *et al.*, 2008).

3.5 Data analysis

Summary statistics and hypothesis testing for all respirable dust and quartz measurements were done using the S - PLUS (version 8.1) and SAS System Software packages (version 9.1). Respirable dust and quartz measurements were best described as log - normally distributed. Consequently, geometric means (GMs) and geometric standard deviations (GSDs) were used to describe measures of central tendency and distribution of the concentrations. A hundred and twenty three of the 298 measurements were reported to be below the analytical Limit of Detection (LOD). Consequently, the method of multiple imputation as described by Lubin and co - workers (Lubin *et al.*, 2004) was used to estimate values below the LOD. Additionally, these imputed values were used to calculate GMs and GSDs, and in the hypothesis testing procedures applied to compare respirable quartz measurements among the three types of soil.

Three respirable quartz reference values (one national and two international standards) were used to evaluate measured respirable quartz concentrations: 100 $\mu g.m^{-3}$ (South African OEL); 50 $\mu g.m^{-3}$ (NIOSH REL) and 25 $\mu g.m^{-3}$ (ACGIH TLV). Quartz percentages in the respirable fraction of the dust were calculated by dividing the respirable quartz concentration by the respirable dust concentration.

Classic hypothesis testing methods was applied to determine whether there were statistically significant differences in quartz exposures between the sandy, sandy loam and clay soil farms. Non – parametric tests i.e., *Kruskal.test, Wilcoxon.test, and prop.test* were used to calculate the p - values during hypothesis testing to determine if there were statistically significant differences in quartz exposures among the three farms. The rank - based non - parametric tests were used because the data were somewhat skewed even after log transformation.

Potential determinants of exposure

Possible determinants of respirable quartz exposure investigated were continuous variables including respirable dust and weather data (i.e., humidity, air pressure, temperature, wind strength and rain fall) and categorical variables i.e., soil type (sandy soil, sandy loam soil and clay soil), season (summer and wet), commodity (cereal grains, ground crops and live stock), activity (cereal grain planter operator, cereal grain tractor operator, cereal grain soil preparation and other) and process (manual and mechanical).

For each day of measurement (n = 27), the mean quartz concentration was correlated against the mean of the weather determinant measured. This was done during three time windows: the average of eight days preceding quartz measurement, the average of the day before quartz measurement and on the day of quartz measurement. Each of the three time windows were measured in the morning (00:00:00 - 05:59:59), afternoon (06:00:00 - 15:59:59) and evening (16:00:00 - 23:59:59). Pearson's correlation coefficient was used to determine if respirable quartz exposure was correlated with any of the continuous variables measured during the three time windows. Kruskal - Wallis tests were done to determine significant differences in quartz exposures between various categories of categorical variables. Where differences exist, subsequent Wilcoxon - tests were done to determine the relations between the subgroups of the categorical variables.

Multiple linear regression was used to identify possible independent determinants of respirable quartz concentrations and to explain the variation in these concentrations. Both continuous and categorical variables were evaluated for possible inclusion in the model prior to multiple linear regression using analysis of variance (ANOVA) and graphical methods. For example, to acquire insight into possible relation structures in the data set, the covariance matrix and pair wise scatter plots of all the variables of interest were used. Multi - collinearity was avoided by choosing dummy variables and by omitting correlated weather variables, while minimizing loss regarding fitting criteria. Inclusion criteria to the model involved the following three steps: (i) one - by - one stepwise sequential addition of continuous variables to the model using sum of square patterns, Cp - values, R^2 and adjusted R^2 values to identify variables for inclusion; (ii) sequential addition of dummy variables representing the categorical variables (allocated to prevent multi - collinearity) using the same processes and criteria explained above; and (iii) interaction terms were identified via stepwise procedures and included in hierarchical models as above. The resulting regression model was tested for violation of the model assumptions.

Additional analysis, aiming to identify determinants of respirable quartz > 50 $\mu g.m^{-3}$ and to deal with data points below the detection limit without including multiple imputation methods was done using logistic regression. This analysis was applied to the original multivariate data set, where the response variable was defined as respirable quartz values greater than 50 $\mu g.m^{-3}$. Potential determinants were carefully chosen to prevent multi -

collinearity, and were formally identified as possible determinants of quartz exposure. Humidity on the day of measurement was the only weather variable that satisfied the inclusion criteria. The categorical regressor variables soil type (sandy, sandy loam and clay soil), season (winter, summer), commodity (cereal, ground crops, live stock), activity (cereal planter operator, cereal tractor driver, cereal soil operators and others), process (manual or mechanical) were used for univariate and multivariate logistic modeling. Continuous determinants (quartz %, humidity on the day of measurement, and respirable dust exposure) were each divided into three approximately equal size subgroups: quartz % = 0 – 10 %, > 10 – 20 % and > 20 %; humidity on the day of measurement = $\leq$ 25 $g.m^{-3}$, > 25 - $\leq$ 45 $g.m^{-3}$ and > 45 $g.m^{-3}$, and respirable dust exposure = $\leq$ 0.2 $mg.m^{-3}$, > 0.2 - $\leq$ 0.5 $mg.m^{-3}$ and > 0.5 $mg.m^{-3}$. Odds ratios (ORs) and 95% Confidence intervals (CIs) were calculated to compare the association between group differences in quartz exposures while adjusting for the above mentioned variables. Conditioning for all categorical and continuous variables was done on the lowest level of the determinants except for respirable dust concentrations.

All data and regression analysis were done using the TIBCO Spotfire S - plus (version 8.1) software package.

Cumulative quartz exposure estimated over a farming year for the sandy soil farm were evaluated against yearly cumulative exposures that would occur at three general OELs i.e., the South African OEL, the NIOSH PEL and the ACGIH TLV. Summary statistics were done on the particle sizes of the dust, and the mineralogy of the soils are presented.

3.6 Quality assurance

A quality control system was in place for both the gravimetric and XRD analytical procedures. All aspects of sample collection and gravimetric analysis from filter preparation, calibration of the pumps, filter weighing, respirable dust measurements to gravimetrical procedures were monitored by a South African Institute for Occupational Hygiene (SAIOH) registered occupational hygienist. All measurement equipment was explained to farm workers and they reported any malfunctioning units to the occupational hygienist and were then subsequently issued with a new unit.

Both the gravimetric and analytic laboratories were experienced and South African National Accreditation System (SANAS) accredited. In addition, a number of samples (n = 31) was randomly selected and sent to the UK's Health and Safety Laboratory (HSL) to be re - analysed and the quartz levels reported by both laboratories were not significantly different (results are presented in Chapter 7).

3.7 Ethics

Informed consent was obtained from all study participants and confidentiality was respected regarding farms, farmers and farm workers. All results of the exposure assessment were communicated to farmers and farm workers. Ethics clearance (please see Appendix I) was obtained from the Human Research Ethics Committee (medical) of the University of the Witwatersrand (Wits) and the study has been approved (clearance number M070252).

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CHAPTER 4

Results

The results obtained during this study are reported in detail in **Chapters 6 – 8**. The following Chapter (4) will briefly summarize the main findings of the study.

As described in **Chapter 6**, very few studies could be found on quartz exposure and quartz associated disease in agriculture. As a result of the less than comprehensive literature, only 17 original articles were found in a PubMed search: eleven respirable quartz studies; and six studies on quartz associated disease in agriculture were identified. A summary of these studies [i.e. place (author, date), soil type and population, exposure assessment method and main findings] are displayed in Table 1 of **Chapter 6.** Typical farming activities from a single farm recognized to have sandy soils were identified in conjunction with the farm owner, and 138 personal respirable dust and quartz samples were collected. The respirable dust and quartz concentrations by agriculture activity are summarized in Tables 3 and 4 of **Chapter 6**. The overall geometric mean TWA respirable dust and quartz concentrations were 0.32 $mg.m^{-3}$ and 35.35 $\mu g.m^{-3}$, respectively; with the GSDs being 3.24 $mg.m^{-3}$ and 2.28 $\mu g.m^{-3}$, respectively. Although respirable dust concentrations were relatively low (the highest concentration measured during wheat planting operations was 6.49 $mg.m^{-3}$), over - exposure to respirable quartz in all farming activities occurred. Thirteen % of the measurements exceeded the South African Department of Labour (DoL) OEL of 100 $\mu g.m^{-3}$, however, 31 % and 57 % of measurements exceeded the National Institute for Occupational Safety and Health (NIOSH) recommended exposure limit (REL) of 50 $\mu g.m^{-3}$ and the widely used reference value of the American Conference of Governmental Industrial Hygienists (ACGIH) TLV - TWA of 25 $\mu g.m^{-3}$, respectively, with a maximum of 626 $\mu g.m^{-3}$ measured during wheat planting operations. Quartz percentages of the respirable dust ranged from 0.3 - 94.4% with a median of 13.4% (Table 5, **Chapter 6**).

Chapter 7 reported on respirable dust and quartz concentrations measured on three farms in South Africa with the aim to ascertain whether soil type is a determinant of exposure to respirable quartz. Soil grain size analysis was done on each of the farms and results showed that the three farms could be classified as sandy, sandy loam and clay soil farms (Table 1, **Chapter 7**). Two hundred and ninety eight respirable dust concentrations for the three farms were measured and are summarized in Tables 2 of **Chapter 7**. As expected, the respirable dust concentrations differed across the three farms (Kruskal - Wallis test; $p = 0.0006$). However, the median respirable dust concentrations of the sandy soil and sandy loam soil farms did not differ significantly (Wilcoxon test; $p = 0.2$). Surprisingly, 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 was measured on the sandy soil farm, during wheat planting operations (6.49 $mg.m^{-3}$).

TWA respirable quartz concentrations for all three farms are shown in Tables 3 of **Chapter 7**. The clay soil farm had a greater proportion of quartz measurements below the analytical limit of detection (64%) and no value exceeded 100 $\mu g.m^{-3}$. As with the respirable dust concentrations, the sandy and sandy loam soil farms showed very similar respirable quartz results with respect to the distribution of the concentrations; although the sandy soil farm had the highest concentration measured (626 $\mu g.m^{-3}$). 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 $\mu g.m^{-3}$, and large proportions of the measurements exceeded the more stringent standards of the National Institute for Occupational Safety and Health (NIOSH) and the American Conference of Governmental Industrial Hygienists (ACGIH) TLW-TWA.

Comparisons between the average respirable quartz concentrations on the clay soil farm and the other two farms showed no statistically significant difference (Kruskal-Wallis test; $p = 0.17$). However, the percentage of measurements exceeding the exposure limits of 100, 50 and 25 µg.m^{-3} differed statistically significantly among the three farms (*prop.test*; all p values < 0.0002). Although the proportions of measurements above the 100 µg.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). The clay soil farm had a larger proportion of measurements above the 25 µg.m^{-3} level than the other two farms, but the sandy soil farm had the largest proportion of measurements above the 50 µg.m^{-3} level (*prop.test*; all p values <0.003). Not shown in the table is that for measurements over the 100 µg.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 µg.m^{-3}; Wilcoxon test; $p = 0.0001$).

Quartz percentages of the respirable dust were determined for all three farms on measurements > the LOD and are summarised in Table 4 of **Chapter 7**. On all three farms the percentage respirable quartz in the respirable dust fraction varied greatly; 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; $p = 0.91$).

Additionally, respirable quartz exposures were measured for two similar occupations on the sandy, sandy loam and clay soil farms, namely maize planter operators and maize planter tractor operators. Lower respirable quartz exposures on the clay soil farm than on sandy soil and sandy loam soil farms for maize planter operators were measured, 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.

In **Chapter 8,** determinants of respirable quartz exposure and annual cumulative exposures are estimated. Mean quartz exposures on the sandy, sandy loam and clay soil farm was similar (Kruskal - Wallis test; $p = 0.17$) (Table 2, **Chapter 8**). Commodities showed different mean quartz concentrations (Kruskal - Wallis test; $p = 0.001$). Exposure during live stock farming was significantly greater than during both ground crops and cereal grains farming (Wilcoxon tests $p = 0.001$ and 0.014 respectively), but cereal grain farming exposure exceeded that of ground crops (Wilcoxon tests; $p = 0.007$). Quartz exposure varied by activity (Kruskal - Wallis test; $p = 0.001$) with cereal planter operators' exposures exceeding those of cereal tractor operators, cereal soil operators and Other activity (Wilcoxon tests; $p = 0.001$, 0.004 and 0.002 respectively). As expected, respirable quartz concentrations were significantly higher during mechanical than manual processes (Wilcoxon test; $p = 0.003$), but, surprisingly, quartz levels were significantly higher during summer (rainy season) than winter (Wilcoxon test; $p = 0.003$).

Multiple linear regression model results (Table 4, **Chapter 8**) showed that the three soil types (i.e., sandy, sandy loam and clay) had similar effects on the log - transformed quartz exposure data and can be regarded as having no significant overall effect in the model ($p = 0.55$ and 0.52). At least two of the levels of the determinants "commodity" were statistically significant to the model ($p = 0.001$ and $p = 0.002$, respectively), as were at least two of the levels of the determinants "activity" ($p = 0.001$ and $p = 0.002$, respectively). The categorical variables "season" and "process" were both contributory (both p values < 0.001). Regarding continuous potential determinants, quartz percentage, respirable dust and humidity on the morning of measurement were found to be significant determinants of quartz exposure (all p - values were < 0.01). In summary, the most significant independent determinants of exposure were season, commodity, activity, process, quartz percentage and humidity on the morning of measurement. However, by including interactions terms between activity, dust exposure and quartz percentage, the final regression model explained close to 85% of the variability in quartz exposure (multiple R - squared value = 0.8516; adjusted R - squared value = 0.8431). Assumptions of normality of residuals, homogeneity of variance and linearity were satisfied by the regression model.

Logistic regression results (Table 5, **Chapter 8**) showed that, in univariate analyses, soil type, season, commodity and process were not significant determinants of respirable quartz exposure > 50 $\mu g.m^{-3}$; but cereal planter operator, increased quartz % in respirable dust, decreased humidity on the day of measurement and increased respirable dust concentration were all significantly associated with quartz exposure > 50 $\mu g.m^{-3}$. ORs in the multivariate analysis are adjusted for these latter four variables. Soil type was unimportant in determining whether exposure exceeded 50 $\mu g.m^{-3}$ as was the case for commodity and process. Despite being the dry season, winter was protective of higher exposure (OR = 0.53 95% CI 0.28 - 1.01). Cereal planter operator remained a strong determinant of higher level of exposure relative to other activity (OR 3.76 95% CI 1.64 - 8.63). Increased levels of quartz % in respirable dust increased the ORs for exposure > 50 $\mu g.m^{-3}$, but there was not a trend in increasing ORs with increasing levels of quartz % (OR 5.16 vs 2.03 for the second and third level of quartz % respectively). Surprisingly, ORs for decreasing humidity on the day of measurement, when adjusted for the other variables, were well below one (and 95% CIs spanned 1 widely) suggesting that the difference between the results for the univariate and multivariate analysis is due to confounding in the multivariate case. Lastly, lower levels of respirable dust exposure were very strongly protective of higher respirable quartz exposure (ORs close to zero).

The median D50 particle size of the 31 respirable dust measurements was 5.53 µm with the smallest five D50 values reported by the laboratory of 3.39, 4.01, 4.25, 4.58 and 4.72 µm, respectively during maize and wheat planting activities.

Estimated annual cumulative exposure (Table 6 and 7, **Chapter 8**) for a typical farm worker on the sandy soil farm showed that at median quartz exposures the chances of exceeding cumulative exposure if exposed at the South African OEL are small (0.29). However, estimated cumulative exposure is likely to exceed annual cumulative exposure if exposed at the ACGIH TLV of $25\mu g.m^{-3}$. In contrast, if a worker were exposed to maximum respirable quartz levels for each task measured in the study then annual cumulative exposure would substantially exceed cumulative exposures if exposed at the SA OEL and ACGIH TLV (1.46 and 5.84, respectively).

Soil mineralogy results of the sandy and sandy loam soil farms confirmed that quartz was the predominant mineral present in the bulk soil samples (average 91 % and 95 % respectively) and that other minerals present were K - feldspar, plagioclase, mica, kaolinite and Illite, which are typical minerals found in sandy and sandy loam soils.

In **Chapter 9**, results of the respirable quartz exposure assessment on three South African farms are summarized showing that there is a potential for over - exposure to silica in South African farming. Some occupational health implications for occupational health professionals are discussed and the need for future research is identified. In summary, primary prevention of silica - associated diseases, i.e. the control of dust to concentrations at which disease will not occur, is the optimum form of prevention and should be the overriding goal of national and workplace occupational health programmes. The provision and use of PPE should be considered by farmers particularly for farm workers involved in dusty activities. Even with the limited exposure data available it seems reasonable to recommend case - finding for silicosis and tuberculosis in long service farm workers (possibly those employed for 20 years or longer). Besides the health reasons, this would be an important step to determine the burden of disease in farming. Initially surveillance could be limited to large well - resourced farms targeting long service workers, particularly those involved in the most dusty activities for substantial times during their yearly routine. General practitioners practising in farming areas need to be aware of the potential for silica - associated disease and submit claims under the Compensation for Occupational Injuries and Diseases Act (COID Act) if disease is identified.

Future studies investigating exposure assessments in farming, should examine the role of potential determinants of silica exposure [e.g. soil types, commodities, activities, processes (mechanical vs manual) and weather]. Additionally, activities that may enhance potency, for example those that produce small dry particles of freshly fractured quartz during farming, need to be identified. Moreover, radiological surveys on long service farm workers (possibly more than 20 years service and performing dusty activities) on sandy soil farms need to be conducted. This will give some indication if silicosis occurs in farm workers during worst case exposure scenarios. The duration and intensity of silica exposure in farming over the annual cycle should also be investigated. Processes and activities that produce high levels of silica in the breathing zone of a worker, particularly those done for a large number of days in a farming year, need to be identified. Cumulative exposure relative to activities that are known to cause silica - associated diseases are essential to better understand the risk of these diseases in farming. Cost - effective methods to reduce respirable dust and quartz exposure in farming should be explored. South Africa and other resource poor countries have large small to medium scale farming sectors employing a considerable number of people. The majority of these farmers do not have the money to introduce costly control solutions such as closed - cabbed tractors. But, policies need to be considered that will make closed cabs affordable in these settings e.g. subsidised shared usage. There is a need to identify cost-effective dust control methods appropriate for settings in resource poor countries.

CHAPTER 5

Discussion and Conclusion

5.1 Discussion

Silica exposure and silica - associated disease have been investigated extensively in industries previously known as the 'dusty trades", however very little is known to what extent silica exposure is a risk in farming. This exposure could be an important public health concern as the work force that may be affected is large and, especially in resource poor countries, there may be high TB and HIV rates. Therefore the aim of this study was to quantify personal respirable dust and quartz concentrations across three South African farms. Secondary objectives were to identify possible determinants of quartz exposure during farming activities, and to describe some modifiers of quartz exposure.

This study is the biggest of its kind in that it is the first to measure a large number (298) of personal respirable quartz concentrations across various tasks on three farms known to have different soil types. It is also the first study in farming attempting to relate personal respirable quartz exposures to possible determinants, and to consider potential modifiers of quartz exposure. The study considerably adds to the evidence that over - exposure to quartz maybe a hazard to health in farming and has identified the need for practical interventions and research gaps. In addition, this study makes it possible to use the detailed analyses of silica exposure determinants in farming in other settings with similar conditions.

Some methodological issues have emerged through this research process and they are described in the section below. **Chapters 6, 7, 8 and 9** cover study limitations and these are not repeated in this Discussion.

Several methodological issues regarding the sampling strategy and data analysis occurred during this study. Three of these are discussed, namely exposure assessment strategies, values below the limit of detection, and measuring quartz in respirable dust on farms.

Exposure assessment

From an occupational hygiene perspective, designing an effective exposure assessment strategy to reliably quantify personal quartz exposures during farming may be challenging because of the nature of agriculture. Exposure assessment in agriculture is complicated by a number of factors (Archer *et al.*, 2002). Several activities are done on farms for short periods in a year using a selection of farming implements; but other activities are performed for many hours during a day. Shift durations varied substantially during the study depending on activity and often exceeded 12 hours. Occupational exposure limits (OELs) are based on an eight - hour workday, and the effect of respirable quartz exposures for farm workers working 10 – 12 hours may be important because extended work shifts not only increase exposure time, but reduce the recovery period between exposures. Additionally, farm workers do multiple activities over the working year. Therefore designing an effective and comprehensive exposure assessment strategy is particularly problematic in farming and should take account of extended exposures for a spectrum of activities.

Numerous activities performed on a farm contribute to the cumulative dust and quartz exposure over a calendar year (Wu *et al.*, 2003). Some activities are clearly dusty and would be obvious candidates for inclusion in a sample strategy, but others may be excluded because they appear not to be dusty; fixing fences or servicing farm implements are examples. For at least three reasons these activities should be evaluated, particularly in epidemiologic studies of exposure risk. First, fugitive exposure from more dusty nearby operations may be important, especially since fine respirable dust is likely to travel across the farm and be less visible; second, these activities may be done for prolonged periods and may thus make up a substantial number of the work - days in a year; and third, very little is known about exposures during these activities. A related matter is non - occupational exposure. If farm workers live on the farm, environmental exposure during off - work periods could add to the cumulative exposure. Future studies may need to consider this exposure in designing sampling strategies. In contrast, quartz exposures might not at the face of it appear to be important when activities are assessed individually. Quartz exposures may appear to be low during less dusty activities i.e. maintenance work (fixing fences or servicing farm implements), however these activities need to be part of the sampling strategy because it is unknown what the exposures are.

Additionally, soil types are a continuum from very sandy to mostly clay (Archer *et al.*, 2002). The farms studied were probably not optimally distributed along the soil spectrum with the sandy loam soil farm likely towards the sandy end of the spectrum. Similarly, the clay soil farm selected in this study may not have been at the extreme for clay soils, therefore lower quartz exposures may be found in further studies. Careful characterisation of soil type to locate the farm soil on this continuum is necessary to refine the quartz risk by soil type. In addition, soil type may vary on an individual farm so, for example, in classifying a farm as clay soil it is probably necessary to sample from potentially sandy locations (if actively farmed)

Similarly, many determinants and potency modifiers of quartz exposure in farming exist which may influence personal exposure of farm workers. Farming is usually an outdoor activity and quartz exposures may be affected greatly by weather conditions (e.g., rainfall, humidity, wind speed, wind direction and pressure) (Preller *et al.*, 1995; de Cock *et al.*, 1998) which may play an important role in exposure variability. Additionally, tractor characteristics (cabbed vs open - cabbed) may also influence personal quartz exposure in farming. In this study, personal quartz measurements were done on open - cabbed tractors only, therefore respirable quartz concentrations are not generalizable to farming activities using cabbed tractors.

Additional exposure assessments should further examine the role potential determinants of silica exposure (e.g., soil types, commodities, activities, processes (mechanical vs manual) and weather) may have on silica exposures in farming so that the occupational health professional can be on the alert for farming activities producing very fine, freshly fractured, dry particles.

Modifiers affecting the potency of quartz in farming are not generally considered. There is good evidence that freshly fractured quartz is biologically more reactive and produces enhanced lung injury and disease (Vallyathan *et al.*, 1991; Vallyathan *et al.*, 1992; Shi *et al.*, 1994; Shi *et al.*, 1995; Shoemaker *et al.*, 1995; Fenoglio *et al.*, 2003; Gwinn *et al.*, 2009). In addition, animal studies have shown that smaller particle silica dust is more potent in mice (Hetland *et al.*, 2001; Lu *et al.*, 2011; Wittmaack, 2011) and hence particle size may be an important quartz potency modifier during farming. No studies have investigated whether respirable quartz is freshly fractured during farming and no real attempt has been made to characterise quartz particle sizes across agricultural activities.

Values below the limit of detection

Dealing with quartz values below the analytical limit of detection (LOD) was of concern in this study: the LOD is defined as the level at which a measurement has a 95% probability of being different than zero (Taylor, 1987) and corresponds to the mean blank response (that is, the mean response produced by blank samples) plus three standard deviations of the blank response. A common problem faced by researchers analyzing data in occupational health settings is how to appropriately handle measurements reported to have non - detectable levels of a contaminant.

Although statistically different from zero, values near the LOD are generally less accurate and precise (that is, less reliable) than values that are much larger than the LOD (though many researchers might prefer highly unreliable over nothing). Thus, a researcher faced with data containing non - detects must decide how to appropriately use them in statistical analyses. One might reason that since the actual values of these observations are extraordinarily small, they are unimportant. However, these observations can still have a large effect on the parameters of the distribution of the entire set of observations. Treating them incorrectly may introduce bias when estimating the mean and variance of the distribution (Lyles *et al.*, 2001), which may consequently distort regression coefficients and their standard errors and reduce power in hypothesis test.

The problem of estimating the parameters of distributions with non - detects (also known as left censored data) in occupational health settings has been extensively studied (Cohen, 1959; Gleit, 1985; Helsel and Gilliom, 1986; Helsel, 1990; Lambert *et al.*, 1991; Özkaynak *et al.*, 1991; Finkelstein and Verma, 2001; Succop *et al.*, 2004; Hewett and Ganser, 2007; Finkelstein, 2008; Krishnamoorthy *et al.*, 2009; Flynn, 2010) and recently reviewed (Helsel, 2010). The main approaches to handling non - detects are: 1) simple replacement (substitution), 2) extrapolation, and 3) maximum likelihood estimation (MLE). The most common, and easiest, strategy is simple replacement. This substitution method involves replacing every result below the level of detection with an estimate, or rather a guess, for what it might be. At least four systems have been used. However, all may produce bias and imprecision in calculated parameters of the results distribution (Helsel, 2010). Often zero or the LOD itself has been substituted for each missing value but this leads to 'particularly erroneous results, and it is hard to see that these approaches can be defended' (Ogden, 2010). Non – detects can also be replaced by some fraction of the LOD, usually either LOD/2 or LOD/√2 (Helsel, 1990; Hornung and Reed, 1990; Helsel, 2010; Ogden, 2010). However, substitution of non – detects has been considered not to be ideal (Helsel, 1990). In fact, in a recent review the substitution method was described as so flawed compared to other methods that journals should 'reject papers that use it' (Helsel, 2010).

If a large proportion of measurements are below the LOD, the method of multiple imputation has been suggested to be the best approach to ensure unbiased estimates of effects and nominal confidence intervals (Lubin *et al.*, 2004). However, to optimize the multiple imputation method if a high proportion of values in a dataset are below the LOD, a large number of measurements are needed.

Based on the above, the method of multiple imputations was used in this PhD study (Lubin *et al.*, 2004). In summary, based on the structure of the available data greater than the detection limit, this method estimates quartz levels for values below the LOD by imputing new data repeatedly. The method of imputation is more suitable for general datasets that have somewhat symmetric distributions. Since a large proportion of the quartz levels on the farms was below the LOD and the available data above the LOD contained large outliers this may have resulted in imputing relatively large estimated respirable quartz levels. This may explain why inferences for clay soils were on the high side. It should be noted, though, that imputed values estimated above the LOD (for values ostensibly below the LOD) are not necessarily incorrect. Since measurement error is likely to produce values both above and below the LOD some measurements labeled < LOD would have actually been larger than this value. Additionally, the LOD for quartz of the XRD laboratory used for this PhD was 22 µg. This value is very close to the TWA TLV of 25 $\mu g.m^{-3}$ at a sampling pump flow rate of 2.2 $\ell.min^{-1}$ over an eight hour shift (2.2 $\ell.min^{-1}$ = 1056 ℓ, i.e., close to a 1000 ℓ or a m^3 of air). Measuring for less than eight hours could result in less than 22 µg of quartz on the filter i.e., below the LOD. But, a full eight hour measurement might well have resulted in quartz reaching levels greater than 22 µg. Given the very small quantities of quartz being measured, at least some values below the LOD would plausibly be above the TLV of 25 $\mu g.m^{-3}$ had a full eight hour shift been measured.

In essence, then deriving some imputed estimates above the LOD is not of concern in general. But deriving a higher proportion is less satisfactory, as was the case in this PhD, probably as a consequence of the nature of the dataset.

As mentioned, quartz levels measured on the three farms were found to be heavily skewed to the right, and if this is typical for farming more specialized methods need to be developed and future studies need to take this into account when analyzing quartz exposure data during farming.

Measuring quartz in respirable dust from farms

A further issue is the reliability of methods to measure quartz at low levels particularly in samples with other minerals. In general, one of three analytical techniques is used for the determination of quartz: X - ray diffraction (XRD) spectrometry, infrared absorption (IR) spectrometry, or colorimetric spectrophotometry (NIOSH, 2002). The choice of analytical technique depends largely on other materials present on the filter which may interfere with the analysis. XRD allows differentiation of the three most widely encountered forms of crystalline silica (quartz, cristobalite and tridymite) (Kauffer *et al.*, 2005), but may be more costly. IR is generally recognized as being one of the least costly but also the least specific technique, however, these methods are periodically reviewed in the literature (Miles, 1999). In South Africa, XRD and IR are the common techniques used to quantify quartz and the mining industry especially quantifies quartz exposures by means of IR. The question may arise, which of the two common techniques is the most accurate and reliable in the farming setting? With respect to the quantitative analysis of quartz, direct analytical methods (i.e., XRD and IR) keep sample handling operations to a minimum as opposed to indirect analytical methods (i.e., colorimetric spectrophotometry), but the deposit of dust on the sampling filter is not uniform which may influence the analytical conditions. In particular, the standards used to produce the calibration curves must be obtained under the same conditions as the filters undergoing analysis, therefore the sampling operations and the analyses need to be conducted by the same laboratory to ensure the coherence of practices.

Some studies comparing the techniques for airborne crystalline silica analysis have been published (SRI, 1983; Pickard *et al.*, 1985; Lorberau *et al.*, 1990; Addison, 1991; Stacey *et al.*, 2003) and agreement between the two techniques was in general close, but considerable differences can exist for certain filters. Typical collection media (filters) include glass fibre, cellulose nitrate, polyvinyl chloride (PVC) and mixed esters of cellulose (MEC) filters. Some filters may have shortcomings (HSE, 2000), for example (i) fibre loss from glass fibre filters may occur during handling and can be significant if less than 1 milligram (mg) of dust is collected; (ii) cellulose nitrate can show excessive weight changes due to moisture absorption; and (iii) PVC filters can show excessive static build - up. In this PhD, PVC filters were used for silica measurement as the analytical laboratory conducting the XRD diffraction recommended PVC filters based on previous testing of their method.

Nevertheless, although some studies concluded that both methods can be used, XRD is probably less sensitive to potential interference and to particle size (Addison, 1991). Laboratories analysing α - quartz as part of a Workplace Analysis Scheme for Proficiency (WASP) also reported results comparing XRD methods with IR methods (Stacey *et al.*, 2003). No significant difference were found between the average results of the laboratories using direct on - filter IR when compared to the average result of the laboratories using direct on - filter XRD analysis.

Additionally, studies have reported on quartz determination in the presence of clays and other minerals. The absorption peak interference was identified to be a disadvantage during IR quartz determination. Therefore, the presence of clay or other minerals that have an absorption peak corresponding to the analytical peak for silica may increase the apparent silica concentration, resulting in excessive regulation of the administrative control level for the OEL (Ojima, 2003). To a lesser extent, XRD analysis based on peak intensity or areas under the peaks might strongly cause an overestimation or underestimation of the quantity of clay minerals (Ouhadia and Yongb, 2003). Clays and minerals (e.g., kaolinite and Illite) are common in soil types and may influence quartz levels when using IR and XRD methods.

Although more costly, XRD methods are described to be more reliable and may be the preferred method of determining quartz exposure. In summary, the agreement between the two direct methods is on average close but results obtained with the indirect method (i.e., colorimetric spectrophotometry) were on average lower by 13% when compared to the two direct methods (Kauffer *et al.*, 2005).

Silica - associated disease risk

Although quartz exposure above generally used OELs were measured on all three farms and in many activities, some caution is needed before concluding that these findings are a clear indication that silica - associated diseases will occur in farm workers. No quantitative exposure studies have been done to determine the effect of duration and intensity of silica exposure in farming over the annual cycle. Some dusty processes like ploughing and discing may produce high levels of silica in the PBZ of a farm worker (Nieuwenhuijsen and Schenker, 1998) and workers may be involved in these processes for a large number of days in a farming year, but this is largely unknown. To better understand the risk of silica –

associated diseases in farming, cumulative exposures in farming need to be better defined and related to cumulative exposures in activities known to cause these diseases.

Globally, no study has been done to define the burden of silica – associated diseases in farming and a lack of attention and research into the agriculture area may be a possible reason why quartz related diseases are rarely mentioned. Although not part of this PhD, radiological surveys on long service farm workers (possibly more than 20 years service and performing dusty activities) on a sandy soil farm, as sandy soils are likely to produce the highest silica levels, (Archer *et al.*, 2002) should be considered. This would be the first step to determine if silicosis can occur in farm workers during worst case exposure scenarios. Surveillance of long service farm workers for silicosis and tuberculosis should also be considered. This would be an important step to determine the burden of disease in farming globally. Initially surveillance could be limited to large well – resourced farms targeting long service workers, particularly those involved in the most dusty activities for substantial times during their yearly routine. Moreover, general practitioners practising in farming areas need to be aware of the potential for silica – associated disease.

Lastly, although only introduced once health risk is established, cost – effective methods to reduce respirable dust and silica exposure in farming in resource poor countries should be identified. The effects of quartz dust in this section population may be amplified by simultaneous TB and HIV infections which could be expected to inflate the prevalence of respiratory disease. Developing countries such as Asia, India and Southern Africa have a large small - to - medium - scale farming sector that employ a considerable number of people. Financial constraints restrict affordability of state - of - the - art dust control solutions in these settings often used by those farmers in developed countries such as the US and Europe. Therefore, it is imperative to identify cost - effective dust control methods appropriate for settings in developing countries.

5.2 Conclusion

Although little is known about respirable quartz exposure in farming, this thesis demonstrates that there may be significant potential for over - exposure to respirable quartz in farming, globally. Even clay soil farming may pose a risk in some agricultural settings. Given the large numbers of farm workers possibly exposed to silica and the seriousness of silica - associated diseases, especially in countries with high background levels of TB and HIV, personal respirable quartz concentrations need to be quantified systematically. Soil type may influence respirable quartz exposures in farming, but future exposure assessments in agricultural settings should explicitly address the job type, commodity farmed, weather conditions and the manner in which the task is performed (e.g. mechanical or manual) as they may be important determinants of respirable quartz exposure. Identifying possible modifiers of respirable quartz will be of particular importance in developing countries to focus on implementation of controls. Further research is warranted to quantify quartz exposure and to identify settings and activities that may place farmers and farm workers at risk of silica - associated diseases so that controls can be implemented. Importantly, practitioners working in farming areas should be aware that silica - associated diseases may occur in farm workers.

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CHAPTER 6

Quartz exposure in agriculture: literature review and South African survey

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Quartz Exposure in Agriculture: Literature Review and South African Survey

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Objectives: To review the published literature on respirable quartz exposure and associated disease in agricultural related settings systematically and to describe personal respirable dust and quartz measurements collected on a sandy soil farm in the Free State province of South Africa.

Methods: The published studies on exposure to respirable silica and quartz in agriculture and related settings (to June 2009) were searched systematically through 'PubMed' and critiqued. A farm in the sandy soil region of the Free State province of South Africa producing typical crops for the region was identified and 138 respirable dust and respirable quartz measurements were collected from July 2006–August 2008 during major farming operations.

Results: In total, 17 studies were identified: 11 investigated respirable quartz exposure on farms and 6 quartz-related diseases in agricultural settings. They provided convincing evidence of a respirable quartz risk on sandy soil farms but scant evidence of associated disease. Respirable quartz measurements from the South African farm ranged from not detectable to 626 μg m^{-3} and confirmed the 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 a commonly used occupational exposure limit of 2 mg m^{-3}. Twelve of 138 respirable dust measurements (9%) and 18 of 138 respirable quartz measurements (13%) exceeded commonly used occupational exposure limits of 2 mg m^{-3} and 100 μg m^{-3}, respectively. The highest time weighted average respirable quartz concentration of 626 μg m^{-3} was during wheat planting activities. Fifty-seven percent of the respirable quartz measurements exceeded the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value (TLV) of 25 μg m^{-3}. Quartz percentages of the respirable dust ranged from 0.3 to 94.4% with an overall median of 13.4%.

Conclusion: Despite its ubiquity, little is known about quartz exposure in the agricultural industry; but this study demonstrates significant potential for overexposure in some settings. Further research is required to quantify quartz exposure and identify settings and tasks that place farmers and farmworkers at risk of quartz-associated diseases so that controls can be implemented.

Keywords: agriculture; quartz; silica; silicosis

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INTRODUCTION

Agriculture has the largest labor force globally, estimated at 1.1 billion people as reported by the International Labor Organization (ILO, 2005). It is not known to what extent quartz (the common polymorph of respirable crystalline silica) exposure poses a risk in this industry. It could be an important public health issue not only because quartz exposure is associated with serious illnesses, including silicosis and lung cancer (IARC, 1997) and increased mortality (Steenland, 2005), but also, because in geographies where there is concomitant TB, it increases the risk of pulmonary tuberculosis (Hnizdo and Murray, 1998). This is compounded further in poor and middle-income countries (which have >80% of the world's population and where agriculture is often the main sector of employment) where there are high HIV infection rates because silicosis in HIV-positive individuals increases the risk of contracting tuberculosis substantially (Corbett *et al.*, 2000).

As expected, organic dusts are a well-recognized hazard in agriculture, but there is much less certainty on inorganic dust exposure (Schenker, 2000). Some authoritative publications list agriculture as a source of quartz exposure (NIOSH, 2002) but many standard reference works do not (Parkes, 1994; Stellman, 1998; Hendrick *et al.*, 2002). As a result of the less than comprehensive literature, only 17 original articles were found in a PubMed search: 11 respirable quartz studies and 6 studies on quartz-associated diseases in agriculture were identified. Despite significant effort, only the abstract was obtained for three (Gustafsson *et al.*, 1978; Dynnik *et al.*, 1981; Popendorf *et al.*, 1982), so details of study populations and measurement methodology are incomplete for these.

Respirable quartz exposure in agriculture

Eleven studies reported quartz exposures in agricultural settings. Table 1 summarizes important aspects of these studies. Of these, two measured area respirable quartz, three personal respirable quartz in the breathing zone of workers, and seven quartz percentages in the respirable fraction of the dust. No studies were found which reported an absence of respirable quartz in agriculture dust.

Two studies reported on area respirable quartz concentrations, one in tractor cabs (Gustafsson *et al.*, 1978) and one during rice farming operations (Lawson *et al.*, 1995). Gustafson and coworkers found average area respirable quartz concentrations of 2000 $\mu g\ m^{-3}$ and 50 $\mu g\ m^{-3}$ in open-cab and closed tractor cabs, respectively. Lawson and coworkers investigated rice farming in California (Sacramento Valley). Respirable dust concentrations ranged from 0.52 to 2.16 $mg\ m^{-3}$ outside the harvester vehicle and from 1.77 to 5.24 $mg\ m^{-3}$ outside the tractor during field preparation. Area respirable quartz exposures ranged from 20 to 90 $\mu g\ m^{-3}$ with the highest respirable quartz levels being detected during field preparation. The presence of an enclosed cabin was associated with reduced levels of respirable dust and respirable quartz in both these studies. These two studies demonstrate that farming activities can generate high levels of respirable quartz.

Only three studies investigated personal respirable quartz exposures in agriculture. Generally accepted occupational exposure limits (OELs) were exceeded in all of them (Popendorf *et al.*, 1982; Archer *et al.*, 2002; Lee *et al.*, 2004). Popendorf and coworkers investigated personal respirable quartz exposures of citrus, peach, and grape crops harvesters and reported that 50% of the samples among grape harvesters exceeded 25 $\mu g\ m^{-3}$ (range 7–105 $\mu g\ m^{-3}$) (Popendorf *et al.*, 1982). Remarkably high respirable quartz levels were measured by Archer and coworkers on seven different farms in three eastern North Carolina counties (Pitt, Lenoir, and Wayne) (Archer *et al.*, 2002). A total of 37 respirable dust personal breathing zone (PBZ) samples from 27 farmworkers was collected and exposures were relatively low on the majority of the farms (overall mean of 1.3 ± 2.9 $mg\ m^{-3}$). However, the highest respirable quartz concentration measured in the breathing zone of a worker was 3910 $\mu g\ m^{-3}$ during sweet potato transplanting with an overall mean concentration of 700 ± 1600 $\mu g\ m^{-3}$ in the group of 27 workers. Lee and coworkers investigated the characteristics of personal exposure to inorganic and organic dust during manual harvest of California citrus and table grapes. The geometric means of respirable dust exposures were 1.14 $mg\ m^{-3}$ for citrus harvest and 0.23 $mg\ m^{-3}$ for table grape operations. The geometric means of respirable quartz exposures were 80 $\mu g\ m^{-3}$ for citrus harvest and 20 $\mu g\ m^{-3}$ for table grape operations. The proportion of respirable quartz to respirable dust was similar in both crops: averaging 7% for citrus harvest samples and 9% for table grape operation samples (Lee *et al.*, 2004). Overexposure in PBZ samples were found in all three studies and these studies indicated that respirable dust does not act as a good surrogate for respirable quartz exposure.

Seven studies measured quartz percentages in the respirable fraction of dust (Popendorf *et al.*, 1982; Green *et al.*, 1990; Stopford and Stopford, 1995a; Stopford and Stopford, 1995b; Nieuwenhuijsen *et al.*, 1999; Archer *et al.*, 2002; Molocznik, 2002).

Table 1. Summary of publications reporting respirable quartz exposure in agricultural settings

Place (Authors/Year)	Soil type and population	Exposure assessment method	Main findings
Upsala, Sweden (Gustafsson *et al.*, 1978).	Soil type not specified Study population not known	Area measurements	Open-cab exposure to respirable quartz averaged 2000 μg m^{-3}. Closed tractor cab respirable quartz exposure averaged 50 μg m^{-3}
Russia (Dynnik *et al.*, 1981)	Sandy soils Forestry workers	Area measurements	High concentrations of respirable quartz found in the atmosphere of tractor cabs. No personal exposures were measured
USA (Popendorf *et al.*, 1982)	Soil type not specified Citrus, peach, and grape crops' harvesters	Respirable quartz measurements	Quartz content of respirable dust ranged from 1 to 12%, >50% of samples among grape harvesters exceeded 25 μg m^{-3} (range 7–105 μg m^{-3})
Alberta, Canada (Green *et al.*, 1990)	Soil type not specified Dust samples obtained from tractor cab filters of grain growing district, forage, and irrigated crop production	Bulk dust samples Quartz was determined by infrared absorption spectro-photometry after ashing in a RF plasma furnace	Free silica (quartz) content was very variable and ranged from 1 to 17 % by mass
Sacramento Valley, USA (Lawson *et al.*, 1995)	Soil type not specified Quartz content of dust generated during rice farming operations	PBZ measurements Samples were analyzed using X-ray fluorescence to identify composition and electron diffraction to determine the crystalline state of fibers	Respirable quartz concentrations ranged from 20 to 90 μg m^{-3}, with the highest levels during field preparation
North Carolina, USA (Stopford and Stopford, 1995a)	Sandy and clay soils Soils from 14 active farms in the Piedmont and coastal regions of North Carolina	Bulk dust samples Quartz was analyzed using the carbonate fusion method of Dobreva (as modified by Stopford)	Quartz levels in the respirable fraction of sandy soils (29.0 ± 11.1%) were consistently higher than in clay soils (2.17 ± 0.85%)
North Carolina, USA (Stopford and Stopford, 1995b)	Sandy loam, sandy, and clay soils Sandy loam soils from six active farms in the coastal plains of North Carolina (USA) compared with clay soils of the Piedmont and sandy soils from the sand hills of North Carolina	Bulk dust samples Quartz was analyzed using the carbonate fusion method of Dobreva as modified by Stopford	Quartz content in the respirable fraction of sandy loam soils averaged 15.2 (SD = 4.1) % versus 2.2 (SD = 0.8) % in clay soils and 29.0 (SD = 11.1) % in sandy soils. These results suggest that, during dusty farm activities, there is a potential for greater respirable quartz exposures associated with work with sandy or sandy loam soils than from work with clay soils

Table 1. *Continued*

Place (Authors/Year)	Soil type and population	Exposure assessment method	Main findings
Carolina, USA (Nieuwenhuijsen *et al.*, 1999)	Soil type not specified Measured personal exposure to dust, endotoxin and crystalline silica during various agricultural operations in California over a period of one year. 144 respirable samples were collected	PBZ measurements Silica content analyzed using X-ray diffraction	Respirable dust levels were generally low, except for machine harvesting of tree crops (GM = 2.8 mg m^{-3}) and vegetables (GM = 0.9 mg m^{-3}). The percentage of crystalline silica was overall higher in the respirable dust samples than the inhalable dust samples. Twenty-three percentage silica in the respirable dust samples during machine harvesting was reported
North Carolina, USA (Archer *et al.*, 2002)	Sandy soils Assessed respirable silica exposure of farmworkers in eastern North Carolina. PBZ samples (n = 37) were collected from 27 workers at seven farms during various agricultural activities	PBZ measurements Samples were collected using pre-weighed 37-mm polyvinyl chloride filters (5.0 um). Aluminum cyclones were used. Respirable silica analysis by X-ray powder diffraction	Highest respirable silica concentrations were measured during sweet potato transplanting (3910 ± 2.07 µg m^{-3})
Lublin, Poland (Molocznik, 2002)	Soil type not specified Five farms specializing in cultivation of cereals, root plants, vegetables, dairy cattle and swine breeding, and mixed production. Airborne dust exposure of farmers measured while performing 40 main work activities which contributed to the annual work cycle	PBZ and area measurements Inhalable and respirable dust levels were determined by a weighing method (PN-91/Z-03040/05 and PN-91/Z 0403/06) Free silica was determined by a colorimetric method (PN-91/ Z-04018/04)	Reported respirable fraction in airborne dust up to 25%. Higher level of pathogenic-free silica in settled dust samples in the working environment of a farmer, compared with dust in respiratory zone. A comparable level of free silica in total and respirable airborne dust
California, USA (Lee *et al.*, 2004)	Soil type not specified Two groups of agricultural fieldworkers in the San Joaquin Valley of California. Airborne dust exposures were measured for a total of five working days for each crop over the peak labor months of June through September 1992	PBZ measurements For respirable dust and respirable quartz samples, a 10-mm nylon cyclone was used with a 5-µm pore size PVC filter, and a pump flow rate of 1.7 l min^{-1}. Samples were collected for 6–8 h. Quartz analysis by X-ray diffraction	Geometric means of respirable dust concentrations were 1.14 mg m^{-3} for citrus harvest and 0.23 mg m^{-3} for table grape operations. Geometric means of respirable quartz exposures were 80 µg m^{-3} for citrus harvest and 20 µg m^{-3} for table grape operations

Popendorf and coworkers found respirable quartz content of respirable dust collected from citrus, peach, and grape crops' harvesting machine filters to range from 1 to 12% (Popendorf *et al.*, 1982). Green and coworkers, in a study on 12 farms in Alberta, Canada, found that quartz content measured on tractor cab filters ranged from 0.85 to 17% and 50–97% of the dust had aerodynamic diameters <5 µm (Green *et al.*, 1990).

Stopford and coworkers found higher levels of quartz in the respirable fraction of sandy soils (10.5–44.5%, mean 29.0%) than in clay soils (1.32–3.42%, mean 2.17%) suggesting that exposure to quartz from sandy and sandy loam soils may be greater than clay soils (Stopford and Stopford, 1995a; Stopford and Stopford, 1995b). A study of Californian farmworkers reported high average percentage quartz in the respirable fraction of dust samples during hand and machine harvesting of field crops (21–23%) and ground preparation operations (20.5%) (Nieuwenhuijsen *et al.*, 1999). Archer and coworkers reported that mean percentage silica levels in 34 respirable dust measurements was 34.7%; almost twice as high as that reported in studies of California agriculture (Nieuwenhuijsen *et al.*, 1999) with the highest fraction of 54.3% reported during sweet potato planting (Archer *et al.*, 2002). Molocznik *et al.* investigated the respirable fraction of dust in the respiratory zone of workers during an annual work cycle and the free silica in airborne and settled dust (Molocznik, 2002). The study was undertaken on five farms with farmers performing 40 main identifiably distinct work activities that contributed to the annual work cycle. The authors reported a respirable fraction in airborne dust of up to 25% and a higher level of respirable quartz in settled dust samples collected from the farmers' workplace (64.6% in dust settled on a tractor and beets combine harvester during harvesting of beetroots). These seven studies indicate that quartz made-up more than a substantial fraction of the respirable dust. The highest quartz concentration was found in sandy and sandy loam soils (Dynnik *et al.*, 1981; Stopford and Stopford, 1995a; Stopford and Stopford, 1995b; Archer *et al.*, 2002).

In summary, as is evident from the foregoing, the literature on respirable quartz exposure in agriculture is scant. The few studies reporting on personal quartz exposure had relatively few measurements, but the results are persuasive of a risk of over exposure to quartz in a large variety of farm settings and that high levels of respirable dust and personal respirable quartz can be generated during agricultural activities.

Quartz-related diseases reported in agriculture

The literature on silica-associated diseases in agriculture is scant (Sherwin *et al.*, 1979; Fennerty *et al.*, 1983; Gylseth *et al.*, 1984; Dubovsky, 1999; Rottoli *et al.*, 2003; Schenker *et al.*, 2009) and unconvincing of a significant burden of pneumoconiosis in farming but, although very rarely, silicosis has been diagnosed in agricultural workers (Fennerty *et al.*, 1983; Rottoli *et al.*, 2003).

Lung fibrosis or pneumoconiosis not typical of silicosis, in association with mineral particles, has been described in three reports (Sherwin *et al.*, 1979; Gylseth *et al.*, 1984; Schenker *et al.*, 2009). In the first, interstitial but no nodular fibrosis was found in seven patients, five of whom worked in vineyards, one as a produce farmer and one rural resident. Particles were examined in the lungs of four of the patients and they were mostly silicates with 5–10% silicon dioxide. The patients had inflammation and fibrosis in association with large amounts of these silicates, supporting a causal relation and a diagnosis of silicate pneumoconiosis. Alternatively, the silicates may have been merely a marker reflecting a mixture of toxic soil additives or pesticides introduced into the lungs along with the silicates. Gylseth and coworkers analyzed mineral particles in lung tissue from a farmer who underwent lobectomy due to a lung tumor (Gylseth *et al.*, 1984). Despite no clear evidence of previous non-farming occupational dust exposure, heavy deposits of birefringent particles and slight pulmonary fibrosis were found during histopathological examination. Electron microscopy and X-ray microanalysis of the mineral particles from the lung identified mica, talc, and silica as the major components of dust. Amphibole asbestos and rutile fibers were minor components. Mica, quartz, feldspars (plagioclase), and rutile fibers were also found in the soil from the farmer's potato storehouse. The authors concluded that, based on these findings, the slight pulmonary fibrosis was mixed dust pneumoconiosis, probably caused by the mineral particles. It is notable that the estimated concentration of asbestos fibers was 2.7×10^6 per gram of dried lung, a not inconsiderable burden.

Schenker and others (Schenker *et al.*, 2009) examined lung autopsy specimens from 112 consecutive coroner's cases of Hispanic males in Fresno County, California. Farmworkers made-up 51.5% of the subjects and nonfarmworkers 48.5%. Pneumoconiosis (defined as macules—collections of dust-laden macrophages without significant fibrosis—or nodules—fibrotic lesions up to 1 cm in size with round, irregular, or serpiginous borders) was found in

32.1% of the farmworkers compared with 8.3% of nonfarmworkers (chi-square 8.33, $P = 0.0033$). The prevalence of pneumoconiosis increased to 41.5% and 18.6% in agricultural and nonagricultural workers, respectively, when interstitial fibrosis was included as a feature of pneumoconiosis. In multivariate analysis controlling for age and cigarette smoking, agricultural work was a significant independent predictor of pneumoconiosis (OR = 5.36; 95% CI: 1.55–18.58). Lung dust burden was measured in the lungs of 37 subjects; mineral dust deposition was significantly associated with pneumoconiosis (OR = 166.8; 95% CI: 17.56 to >999), a relation that persisted after adjusting for age and smoking: OR = 453, 95% CI: 25 to >999. The authors concluded that agriculture dust is associated with pneumoconiosis, independent of age and cigarette smoking.

A case series without histological findings was reported by Dubovsky who reviewed 17 patients admitted over many years to two Free State, South Africa, hospitals with radiological findings of either 'diffuse discrete nodularity as seen in silicosis' or the honey combing of diffuse interstitial lung fibrosis which he attributed to dust exposure in the course of tractor plowing on maize farms or, in one case, 'diesel fumes' (Dubovsky, 1999). Analysis of soil samples collected on the farms showed that the highest content was silica; the actual concentration was not reported. Dubovsky speculated that hypersensitivity pneumonitis may be an explanation in some cases, and histology was not reported for any. The diagnosis of pneumoconiosis in these cases is thus uncertain.

Two case reports are convincing of silicosis in farmers. Fennerty and coworkers reported a case of silicosis in a 77-year-old Pakistani farmer who had worked in fields from early childhood and had spent most of his time in cultivation, although he had reared cattle as well (Fennerty *et al.*, 1983). At histology, large numbers of needle shaped dust particles were found that consisted of muscovite, quartz, kaolin, and rutile with small quantities of feldspar and actinolite. On bulk chemical analysis, silica made-up 58.4% of the dust deposits from the lung. The finding of nodular pulmonary fibrosis in association with mineral crystals, 58% of which were silica, supported the diagnosis of silicosis and the authors concluded that the farmer developed pneumoconiosis through exposure to dust during a lifetime of farming. More recently (2003), a man who worked in floriculture in northern Tuscany, predominantly in greenhouses, presented with diffuse bilateral rounded opacities on the chest radiograph (Rottoli *et al.*, 2003) read as 1/1 q/r in the International Labor Office (ILO) Classification of the Radiographs of the Pneumoconioses (ILO, 2002). Birefringent silica particles, observed by polarized light microscopy, and nodules of fibrotic tissue in a whorled pattern were found in the lung. The substrata from the patient's workplace had a silica concentration of 31%. The authors concluded that this case indicates that the inhalation of siliceous particles in a closed environment such as a greenhouse is a risk for silicosis.

In summary, cases of pneumoconiosis in farmworkers have been reported, but very rarely and in the main with clinical features not typical of silicosis, except for two single-case reports.

As a result of the inconclusive literature presented herein, the authors decided to embark upon a robust occupational hygiene survey on a sandy South African farm in order to provide a referent point and to utilize the data in the design of a much more comprehensive pan-farm type study.

METHODS

Study population and design: South African farm

Personal respirable dust and quartz measurements were collected over 17 days between July 2006 and August 2008 during major farming operations on a sandy soil farm in the eastern Free State province of South Africa. The sandy soil region was identified by a pedologist using geological maps and the actual farm was selected by virtue of 'convenience sampling' i.e. access to the farm was granted. This region is ~2 million hectares in size and the farm selected was situated centrally in the sandy soil area. Agriculture in this region is dominated by grain and livestock with a median rainfall of 450–500 mm per annum (Statistics-South-Africa, 2002). The farm under study is representative of this region in terms of farming activities and commodities and was ~850 hectares in size. Crops and livestock produced on the farm included maize, wheat, sunflower, water melon, pumpkin, potatoes, and cattle. Major tasks undertaken on the farm are shown in Table 2. Mechanical harvesting of crops was done in modern closed-cabbed harvesters and preliminary measurements in the harvesters indicated quartz exposures below the limit of detection (LOD). Therefore, for the purpose of this study, farmworkers operating cabbed harvesters were not included. However, personal occupational exposures in these harvesters will be addressed in a subsequent study. Twenty people worked on the farm during the time of the study, and major tasks undertaken over the annual farming cycle were identified by the farmer. All workers

Table 2. Tasks on a sandy soil South African farm from July 2006 to August 2008 for which respirable dust and quartz measurements were taken

Task	Task description
Wheat planter tractor drivers	Wheat planting occurred during June and July (non-rainy season). A tractor-drawn machine (planter) driven by a tractor driver was used to plant wheat seeds in the soil
Wheat planter operators	A worker sat on the back of the planter observing and managing the planting procedure
Fertilizer tractor drivers	Fields prepared in November before the planting season by plowing fertilizer into the soil. A worker drove a tractor which dragged an implement through the soil
Maize planter and tractor drivers	Maize planting occurred during November and December (rainy season). A tractor-drawn machine (planter) was used to plant maize seeds in the soil. A worker drove a tractor and another worker sat on the back of the planter observing and managing the planting procedure
Cattle management	Cattle were herded into pens to count and medicate
Maize and sunflower planter and tractor drivers	Maize and sunflower planting occurred during November and December (rainy season). A tractor-drawn machine (planter) was used to plant seeds in the soil. A worker drove a tractor and another worker sat on the back of the planter observing and managing the planting procedure
Soil preparation	Fields prepared by plowing to break up the surface and bury weeds. A worker drove a tractor which dragged an implement through the soil (ripping and disking) creating large dust clouds
Manual pumpkin harvesting	Pumpkin harvesting in March during which workers manually picked up pumpkins from the fields and loaded them into containers
Manual water melon harvesting	Water melon harvesting in March during which workers manually picked up water melons from the fields and loaded them into containers
Potato harvesting	One worker lifted potatoes to the surface with a small engine driven machine and other workers placed in the field picked up the potatoes
Sheep dosing	Sheep were herded into pens to count and medicate them

completing the tasks on the sampling days agreed to participate. Tasks were selected to be representative of those performed by farmworkers throughout the study period. No respiratory protective equipment was used by the farmworkers. Furthermore, all tractor drivers measured during the study used open-cabbed tractors to perform the tasks on the farm. No screening for the presence of respiratory disease in the worker population studied was done.

Soil grain size analysis

A soil sample was collected on the farm under study and analyzed at the School of Geosciences of the University of the Witwatersrand for grain size analysis. A sample of 150 g was soaked overnight in water with <1 g of sodium hexametaphosphate added to aid clay deflocculation. Samples were wet sieved through a 63-µ sieve in order to separate sand from silt and clay. The clay–silt suspension was poured into a cylindrical flask filled with water. After ~54 min, 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 analysis showed that the soil was 86% sand, 10.7% silt, and 3.6% clay.

Dust sampling

The farm was visited six times (which summated to 17 days in total) and during the time of the exposure assessment, 138 PBZ measurements were collected for the purposes of evaluating respirable dust and quartz exposure of the farmworkers. Respirable dust was collected using the HSE MDHS 14/3 method (HSE, 2000); wherein, PBZ samples were collected by means of a Higgins-Dewell cyclone on pre-weighed 25-mm polyvinyl chloride filters using personal sampling pumps (Gillian® Gil Air) connected to sampling trains calibrated on-site to a flow rate of 2.2 l min^{-1} in order to determine the respirable fraction. Farmwork seldom involves 8-h shifts, but management at the farm agreed to allow sampling for 8 h a day only and therefore, the duration of the PBZ measurements was ~8 h in length (mean 495 min). Calibration was verified after each measurement. After sampling, cyclones were removed and filter cassettes were closed and capped for transport. The filters were equilibrated in an environmentally controlled weighing area for at least 2 h and weighed before and after sampling on a 5-decimal (g) microbalance. A respirable dust concentration using the difference in filter weight, after adjustment for blanks, and sampling volume was calculated for each sample.

Quartz anaylsis

After post-weighing, filters were sealed in petri slides and transported to the National Institute for Occupational Health (NIOH) in South Africa for quartz analysis using X-ray diffraction (XRD) as specified in the HSE MDHS 101 method (HSE, 2005). The results were expressed in microgram per cubic meter and the LOD reported by the NIOH was 22 µg.

Data analysis

Respirable dust and quartz concentrations were evaluated against reference values of 2 mg m^{-3} for respirable dust and 100 µg m^{-3} (South African Occupational Exposure Limit), 50 µg m^{-3} [National Institute for Occupational Safety and Health Recommended Exposure Limit (REL)], and 25 µg m^{-3} (American Conference of Governmental Industrial Hygienists Threshold Limit Value) for respirable quartz. Forty-nine of 138 measurements of respirable quartz were found to be below the analytical LOD of 22-µg quartz; these were assigned a value of $LOD/\sqrt{2}$ for calculation of average exposure (Nieuwenhuijsen, 1997). Both the respirable dust and respirable quartz measurements could be best described with a lognormal distribution. Geometric means and geometric standard deviations were used to present the average and distribution of concentrations. The measurements are presented by date of visit and major tasks undertaken on the farm (Tables 3 and 4). Quartz percentages in the respirable fraction of the dust were calculated by dividing the respirable quartz concentration by the respirable dust concentration.

Ethics

Written informed consent was obtained from all participants in the study that was approved by the University of the Witwatersrand Human Research Ethics Committee (clearance number M070252).

Quality assurance

A quality control system was in place for both the gravimetric and XRD analytical analyses. For the gravimetric analysis, an approved inspection authority registered with the South African Department of Labour and a qualified occupational hygienist registered with the Southern African Institute for Occupational Hygiene monitored all aspects of the procedure from filter preparation, calibration of the pumps to filter weighing. Three blank filters were kept and treated in the same manner as the filters used during actual sampling for each day of measurement and analysis for all blank filters showed concentrations below the limit of detection. Quartz was measured in an experienced laboratory; where, both the gravimetric and analytical laboratories were accredited by the South African National Accreditation System.

RESULTS

One hundred and thirty-eight personal respirable dust and quartz samples were collected from July 2006–August 2008 during typical farming activities from a single farm identified to have sandy soils. Measured respirable dust and quartz concentrations by agriculture activity are presented in Tables 3

Table 3. Eight-hour TWA-respirable dust concentrations (milligram per cubic meter) on a central South African farm during July 2006–August 2008

Date	Task	*n*	AM	GM	GSD	Range	%≥2[a]
11–12 July 2006	Wheat planter tractor drivers	6	2.86	2.50	1.67	1.09–6.02	67
25–27 July 2007	Wheat planter operators	9	2.02	0.49	7.03	0.02–6.49	33
26–29 November 2007	Fertilizer tractor drivers	5	0.45	0.14	3.96	0.04–1.92	0
	Maize planter and tractor drivers	19	0.93	0.58	2.76	0.08–4.48	11
27 December 2007	Cattle management	4	0.20	0.15	1.99	0.09–0.48	0
	Maize and sunflower planter and tractor drivers	3	0.52	0.43	1.96	0.17–0.79	0
3–6 March 2008	Soil preparation	5	0.61	0.28	3.21	0.09–2.23	20
	Manuel pumpkin harvesting	11	0.32	0.29	1.62	0.11–0.60	0
	Manual water melon harvesting	28	0.21	0.17	1.90	0.04–0.52	0
11–13 August 2008	Potato harvesting	42	0.44	0.26	2.76	0.02–2.98	5
	Sheep dosing	6	0.81	0.69	1.86	0.27–1.13	0
Total		138	0.68	0.32	3.24	0.02–6.49	9

AM, arithmetic mean; GM, geometric mean; GSD, geometric standard deviation.
[a]Two milligram per cubic meter is a common occupational exposure limit for respirable dust.

Table 4. Eight-hour TWA-respirable quartz concentrations (microgram per cubic meter) on a central South African farm during July 2006–August 2008

Date	Task	*n*	*n* < LOD	AM	GM	GSD	Range	Percentage quartz median	Percentage $\geq 100^a$	Percentage $\geq 50^b$	Percentage $\geq 25^c$
11–12 July 2006	Wheat planter tractor drivers	6	5	119.5	32.7	3.8	15–626	0.8	17	17	17
25–27 July 2007	Wheat planter operators	9	2	53.2	36.1	2.3	12–196	19.2	11	33	56
26–29 November 2007	Fertilizer tractor drivers	5	2	61.5	34.9	2.5	16–215	30.	20	20	40
	Maize planter and tractor drivers	19	3	104.4	71.1	2.6	14–308	16.	42	58	79
27 December 2007	Cattle management	4	2	54.3	32.4	2.5	17–159	22.8	25	25	25
	Maize and sunflower planter and tractor drivers	3	0	92.3	63.7	2.7	16–160	20.6	67	67	67
3–6 March 2008	Soil preparation	5	3	79.6	31.4	3.4	13–319	11.2	20	20	40
	Manuel pumpkin harvesting	11	3	36.5	29.6	1.9	13–101	11.4	9	18	55
	Manual water melon harvesting	28	14	25.3	22.3	1.6	12–75	11.9	0	4	39
11–13 August 2008	Potato harvesting	42	15	41.2	35.3	1.7	17–135	14.6	2	38	64
	Sheep dosing	6	0	44.8	43.1	1.3	29–58	5.5	0	50	100
Total		138	49	54.2	35.4	2.3	12–626	13.4	13	31	57

n <LOD, Number of measurements under the analytical LOD; AM, arithmetic mean; GM, geometric mean; GSD, geometric standard deviation.

[a]Percentage measurements greater or equal to the South African Occupational Exposure Limit (OEL) of 100 μg m^{-3} for respirable quartz.

[b]Percentage measurements greater or equal to the NIOSH Recommended Exposure Limit (REL) of 50 μg m^{-3} for respirable quartz.

[c]Percentage measurements greater or equal to the ACGIH Threshold Limit Value (TLV) of 25 μg m^{-3} for respirable quartz.

and 4. The overall geometric mean time weighted average (TWA)-respirable dust and quartz concentrations were 0.32 mg m^{-3} and 35.35 μg m^{-3}, respectively, with the GSDs being 3.24 and 2.28, respectively. Respirable dust concentrations were relatively low: only 9% of the samples exceeded 2 mg m^{-3} with the highest concentration measured during wheat-planting operations (6.49 mg m^{-3}). Nevertheless, Table 4 shows overexposure to respirable quartz in all farming tasks evaluated. Thirteen percent of the measurements exceeded the South African Department of Labor (DoL) OEL of 100 μg m^{-3}, 31% exceeded the National Institute for Occupational Safety and Health REL of 50 μg m^{-3} and 57% of the measurements exceeded the widely used reference value of the American Conference of Governmental Industrial Hygienists (ACGIH) TLV–TWA of 25 μg m^{-3}, with a maximum of 626 μg m^{-3} measured during wheat-planting operations. Quartz percentages of the respirable dust ranged from 0.3 to 94.4% with a median of 13.4% (Table 5).

DISCUSSION

This paper has reviewed the published literature on quartz exposure and disease in agriculture, which motivated, informed, and assisted in the design of a comprehensive exposure assessment of respirable dust and quartz during farming on a central South African farm with the results presented herein.

The literature is scant but provides more than suggestive evidence that there is a respirable quartz risk in farming, in particular, that certain soils have respirable quartz percentages which can generate personal respirable quartz concentrations above generally used reference standards (Popendorf *et al.*, 1982; Green *et al.*, 1990; Stopford and Stopford, 1995a; Stopford and Stopford, 1995b; Nieuwenhuijsen *et al.*, 1999; Archer *et al.*, 2002; Molocznik, 2002). The study of quartz exposure on a South African farm adds to the small body of literature showing the presence of respirable silica in the breathing zone of farmworkers (Gustafsson *et al.*, 1978; Popendorf

Table 5. Quartz percentages of the respirable dust (%) on a central South African farm during July 2006–August 2008

Date	Task	*n*	Range	Percentage quartz median
11–12 July 2006	Wheat planter tractor drivers	6	0.7–10.4	0.8
25–27 July 2007	Wheat planter operators	9	0.3–75.0	19.2
26–29 November 2007	Fertilizer tractor drivers	5	11.2–40	30
	Maize planter and tractor drivers	19	0.6–45.6	16.0
27 December 2007	Cattle management	4	13.1–33.1	22.8
	Maize and sunflower planter and tractor drivers	3	2.6–59.4	20.3
3–6 March 2008	Soil preparation	5	8.7–14.4	11.2
	Manuel pumpkin harvesting	11	4.3–17.3	11.4
	Manual water melon harvesting	28	3.9–51.4	11.9
11–13 August 2008	Potato harvesting	42	1.4–94.4	14.6
	Sheep dosing	6	4.2–11.3	5.5
Total		138	0.3–94.4	13.4

et al., 1982; Lawson *et al.*, 1995; Archer *et al.*, 2002; Lee *et al.*, 2004). Respirable quartz measurements from the South African farm ranged from 12 to 626 μg m^{-3} and confirmed the 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 a commonly used occupational exposure limit of 2 mg m^{-3}. The overall arithmetic mean (AM)-respirable dust concentration of 0.68 mg m^{-3} was lower than overall mean respirable dust concentrations of 1.3 ± 2.9 mg m^{-3} and 1.14 mg m^{-3} reported by Archer and coworkers and Lee and coworkers, respectively (Archer *et al.*, 2002; Lee *et al.*, 2004). The overall AM personal respirable quartz concentration of 54.2 μg m^{-3} reported in this study was also lower than the overall mean of 700 ± 1600 μg m^{-3} reported during North California agriculture (Archer *et al.*, 2002) and 80 μg m^{-3} and 20 μg m^{-3} reported in citrus and table grapes manual harvesting operations (Lee *et al.*, 2004).

Although the highest percentage silica content in the respirable fraction of the breathing zone samples was 94.4%, the overall median percentage silica levels in the respirable fraction of the dust (13.4%) were similar to that reported in previous studies (Dynnik *et al.*, 1981; Popendorf *et al.*, 1982; Green *et al.*, 1990; Stopford and Stopford, 1995a; Stopford and Stopford, 1995b; Nieuwenhuijsen *et al.*, 1999). These similarities in findings may be due partly to the sandy soil type settings in some of these studies (Dynnik *et al.*, 1981; Stopford and Stopford, 1995a; Stopford and Stopford, 1995b; Archer *et al.*, 2002). The overall median percentage silica content was 13.4% as compared with 29% observed in North California agriculture (range 10.5–44.5%) (Stopford and Stopford, 1995a; Stopford and Stopford, 1995b), 21–23% and 20.5% reported during machine harvesting and ground preparation operations (Nieuwenhuijsen *et al.*, 1999), 34.7% (maximum of 54.3%) in eastern North Carolina farmworkers, and 25% reported by Molocznic in farmers (Molocznik, 2002).

Despite the potential exposure, quartz-associated disease in farmworkers has been reported very rarely. A healthy worker effect has been suggested as one explanation by Schenker (Schenker *et al.*, 2005), but there are a number of other potential explanations:

1. It may be that excessive quartz exposure occurs but in isolated and unusual settings. This seems unlikely given that published studies from a number of countries farming a variety of products have found either high percentages of quartz in the respirable fraction of the dust (Dynnik *et al.*, 1981; Popendorf *et al.*, 1982; Green *et al.*, 1990; Stopford and Stopford, 1995a; Stopford and Stopford, 1995b; Nieuwenhuijsen *et al.*, 1999) or high respirable quartz concentrations (Gustafsson *et al.*, 1978; Popendorf *et al.*, 1982; Lawson *et al.*, 1995; Archer *et al.*, 2002; Lee *et al.*, 2004) or both. Sandy soils are common in many countries, and the few studies on sandy soils or sandy loam soil farms found relatively high percentages of quartz in respirable dust (Stopford and Stopford, 1995a; Stopford and Stopford, 1995b). Nevertheless, the literature is sparse and may not be representative of most farming settings, particularly, since reliable exposure assessments are difficult because of the variability and cyclic nature of farmers' work

and the many potential exposure modifiers (de Cock *et al.*, 1998; Preller *et al.*, 1995). In extreme circumstances, 8-h shift concentrations have been estimated to vary between 3- to 4000-fold (Kromhout *et al.*, 1993); and the variability in farming may be at the extreme end because workers perform many tasks, often while moving from field to field with potentially different soil types; and, of course, much of the work is outdoors resulting in even more variability due to changing meteorological conditions (de Cock *et al.*, 1998; Preller *et al.*, 1995). The studies may be unrepresentative also as possibly the published studies are more likely to be those reporting high rather than low quartz concentrations, thus creating a perception of an exposure hazard in this industry.

2. A partial explanation for the scarcity of cases may be under-diagnosis and under-reporting of silica-associated diseases in agricultural workers (Rees and Murray, 2007). Access by farmworkers to health services is relatively poor in many countries and silica-associated diseases may not be linked to farming exposure, particularly, common diseases not unique to silica such as tuberculosis and lung cancer.
3. The potency of quartz in farm dust may be low. The United Kingdom's Health and Safety Executive (HSE) reviewed potency factors with regard to their ability to cause silicosis and summarized their conclusions in a respirable crystalline silica potency matrix (HSE, 2002). The HSE concluded that the following factors influence the potency of quartz:
   - Particle size—extremely small particle size enhances quartz potency and particle size may be relatively large in farm soils, although, this has not been characterized to any degree.
   - Age of fractured surfaces of quartz—freshly fractured silica dust is more pathogenic than 'aged' dust (Vallyathan *et al.*, 1995). Silica in soils is likely to be aged, with most farming activities producing little freshly fractured material; although, it might be caused by contact with metal during activities such as plowing and discing.
   - Clay—aluminium-containing clay coatings reduce potency and clay is a common constituent of farm soils.
4. Cumulative exposure over a year and a working lifetime in farming may be less than in traditional silica industries. Agricultural work is often seasonal and exposure to dust may be for a relatively small number of working days in a year. Nevertheless, exposure can extend throughout the growing season and, in addition, with very long working days.

The exposure assessment on the South African farm was conducted over 17 days and a fairly large number of measurements were collected (138) for close to 8 h (mean 495 min) for a wide range of farming activities. Respirable quartz exposure above generally accepted 8-h standards were convincingly demonstrated; although, in almost all of the jobs assessed, the minimum value was well below even the most stringent standard (Table 4). Exposure variability is to be expected as concentrations will vary with local farming practices, commodities grown or raised, geography, climate, and other factors such as soil temperature and tractor characteristics (tractor speed and enclosed cabins) (Nieuwenhuijsen and Schenker, 1998). In particular, meteorological conditions would be very important in determining the dustiness of agriculture tasks but is not addressed in this paper. Consequently, the quartz exposure found on this farm may not be representative of the industry and the risk faced by farmworkers. Additionally, exposure was not determined for individual workers over a farming year, and thus, cumulative exposure of these farmworkers is still unknown.

CONCLUSION

In conclusion, the published literature is inadequate to define the quartz risk in agriculture reliably and to identify jobs and activities that may lead to quartz-associated disease, but the potential for overexposure is convincing. The exposure assessment on a South African sandy soil farm supports other studies in which the potential for overexposure to respirable quartz exposure has been shown. It is important to quantify the quartz risk in this industry systematically. If quartz is a risk in the farming industry, it is a serious public health concern particularly in poor and middle-income countries given that these countries may have high background tuberculosis and HIV rates and very large numbers of people active in agriculture.

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CHAPTER 7

Respirable dust and quartz exposure from three South African farms with sandy, sandy loam and clay soils

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

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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 $\mu g \cdot m^{-3}$) 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 $\mu g \cdot m^{-3}$). 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 $\mu g \cdot m^{-3}$. Twelve and 13% of respirable quartz concentrations exceeded 100 $\mu g \cdot m^{-3}$ 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 $\mu g \cdot m^{-3}$ 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 $\mu g \cdot m^3$, 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

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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; Nieuwenhuijsen *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 % [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 $\mu g \cdot m^{-3}$ (during sweet potato transplanting) with an overall mean concentration of 700 ± 1600 $\mu g \cdot m^{-3}$ 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 $\mu g \cdot m^{-3}$ (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

Table 1. Classification of soil type on three central South African farms

Farming region	Soil start weight (g)	Sand weight (g)	Silt weight (g)	Clay weight (g)	Soil final weight (g)	Loss (g)	Loss (%)	Sand (%)	Silt (%)	Clay (%)
Sandy	150	128	16	5	149	1	0.7	86.0	10.7	3.6
Sandy loam	150	95	20	33	148	2	1.3	64.1	13.5	22.3
Clay	150	39	42	67	148	2	1.3	26.4	28.4	45.3

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 ~3 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-weighed 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 ~8 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 µg. 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 µg 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-µm 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 ~54 min, 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 used. Respirable quartz concentrations were evaluated against three reference values: 100 $\mu g \cdot m^{-3}$ (South African OEL); 50 $\mu g \cdot m^{-3}$ (NIOSH REL) and 25 $\mu g \cdot m^{-3}$ (ACGIH TLV) for respirable quartz. Quartz percentages in the respirable fraction of the dust were calculated by dividing the respirable quartz concentration by the respirable dust concentration.

Classic hypothesis testing was applied to determine whether there are statistically significant differences in quartz exposures between the sandy, sandy loam, and clay soil farms with regard to (i) overall measures of location such as means and medians; (ii) similar tasks measured on all three farms (i.e. maize planter operator and maize planter tractor drivers); (iii) similar tasks measured on the sandy soil and clay soil farm (i.e. soil preparation); and (iv) proportions of quartz measurements exceeding reference values of 100, 50 and 25 $\mu g \cdot m^{-3}$ (referred to above). The S-PLUS (version 8.1) functions, 'Kruskal.test', 'Wilcoxon.test', and 'prop.test' were used to calculate the P-values during hypothesis testing to determine if there are statistically significant differences in quartz exposures among the three farms. The rank-based nonparametric tests were used because the data were skewed even after log transformation. The prop.test was used to determine if various proportions differed statistically across the three soil types.

Ethics

This study was approved by the University of the Witwatersrand Human Research Ethics Committee (clearance number M070252) and written informed consent was obtained from all participants in the study.

Quality assurance

An approved inspection authority (AIA) registered with the South African Department of Labour (DoL) and a qualified occupational hygienist registered with SAIOH monitored all aspects of sample collection and gravimetric analysis procedure from filter preparation, calibration of the pumps to filter weighing. For each day of measurement, two blank filters were kept and treated in the same manner as the filters used during actual sampling and results showed concentrations below the LOD. Both the gravimetric and analytical laboratories were South African National Accreditation System (SANAS) accredited laboratories. Twenty of the respirable quartz samples were selected randomly and sent to the UK's Health and Safety Laboratory (HSL) to be re-analysed. The median difference between the NIOH and HSL measurements was 6 μg, which was found to be not significantly different: normal approximation to the Mann–Whitney test and a bootstrap-based t-test showed P-values of 0.3436 and 0.5638, respectively. 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 sets of observations 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

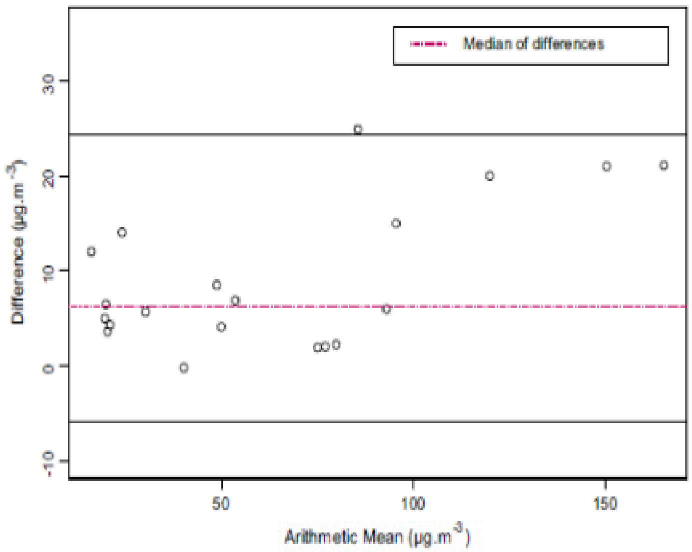

Fig. 1. Bland–Altman comparison between the NIOH and HSL of 20 respirable quartz measurements.

Table 2. Eight-hour TWA respirable dust concentrations (milligrams per cubic metre) on a sandy, a sandy loam, and a clay soil South African farm

Farm	*n*	AM	GM	GSD	Range	
Sandy soil farm	138	0.68	0.3	3.2	0.02	6.49
Sandy loam soil farm	77	0.46	0.2	2.9	0.03	3.39
Clay soil farm	83	0.73	0.5	2.5	0.06	3.97
Total	298	0.64	0.3	3.0	0.02	6.49

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 a 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% quartiles 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 μg · 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 μg · 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 μg · 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 μg · 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 μg · 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 μg · m^{-3} level than the other two farms, but the sandy soil farm had the largest proportion of measurements above the 50 μg · m^{-3} level (prop.test; all P-values <0.003). Not shown in the table is that for measurements over the 100 μg · m^{-3} level, the median quartz

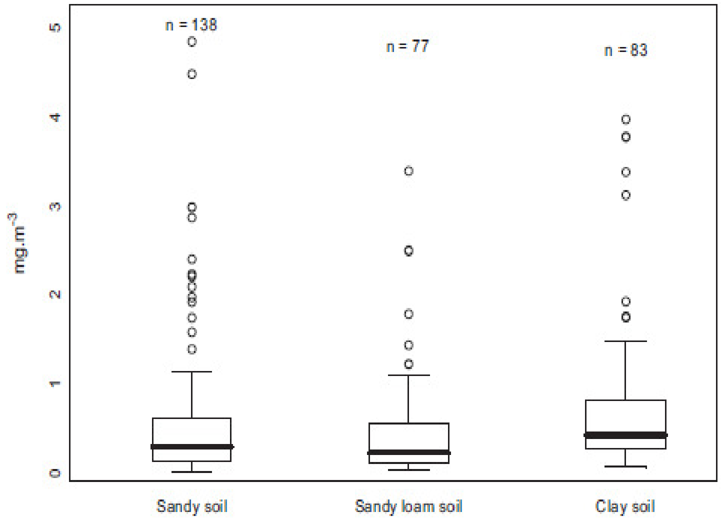

Fig. 2. Box and whisker plot comparing TWA respirable dust exposures from a sandy, a sandy loam, and a clay soil South African farm.

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

Farm	*n*	%<LOD	AM	GM	GSD	Range	%≥100[a]	%≥50[c]	%≥25[b]	%Quartz median
Sandy soil farm	138	35	53.2	31.7	2.7	<LOD – 626	12	30	57	14.3
Sandy loam soil farm	77	27	46.85	31.6	2.3	<LOD – 413	13	22	59	14.0
Clay soil farm	83	64	33.8	31.1	1.4	<LOD – 98	0	9	81	13.7
Total	298	41	46.0	31.5	2.3	<LOD – 626	9	22	64	14.0

% <LOD, % of measurements under the analytical limit of detection.

[a]% Measurements greater or equal to the South African OEL of 100 µg · m^{-3} for respirable quartz.

[b]Measurements greater or equal to the NIOSH Recommended Exposure Limit of 50 µg · m^{-3} for respirable quartz.

[c]% Measurements greater or equal to the ACGIH TLV of 25 µg · m^{-3} for intratracheal respirable 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 µg · m^{-3} from the sandy soil farm and 413 µg · 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).

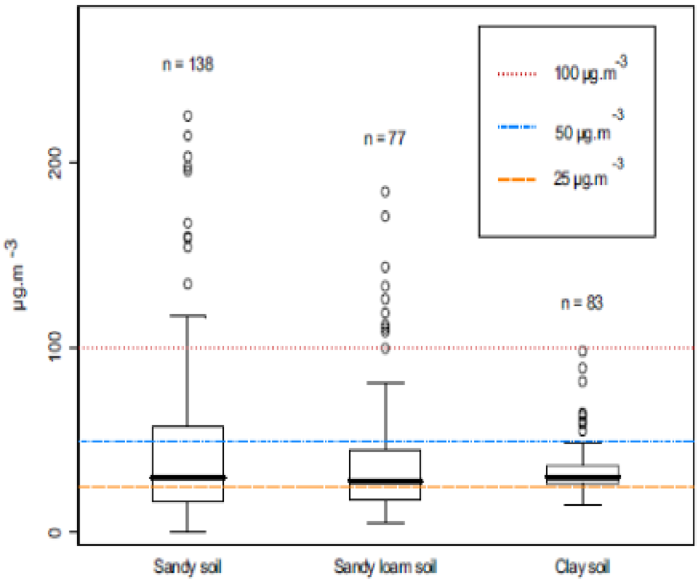

Fig. 3. Box and whisker plot comparing TWA respirable quartz exposures from a sandy, a sandy loam, and a clay soil South African farm.

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

Farm	*n*	AM	GM	GSD	Range	%Quartz median
Sandy soil farm	89	20.0	14.2	2.5	0.5–94.4	14.3
Sandy loam soil farm	55	20.4	14.4	2.4	1.5–76.0	14.0
Clay soil farm	30	20.3	13.9	2.5	1.5–72.3	13.7
Total	174	20.2	14.2	2.5	0.5–94.4	14.0

DISCUSSION

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 >50 $\mu g \cdot m^{-3}$ and none >100 $\mu g \cdot m^{-3}$. However, these differences were not as great as expected. Of particular interest is that no measurements exceeded the South African OEL of 100 $\mu g \cdot m^{-3}$ on the clay soil farm; but 9% of them were between 50 and 100 $\mu g \cdot m^{-3}$. Additionally, on each of the three farms, the median quartz exposures were all above the ACGIH TLV of 25 $\mu g \cdot m^{-3}$ (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

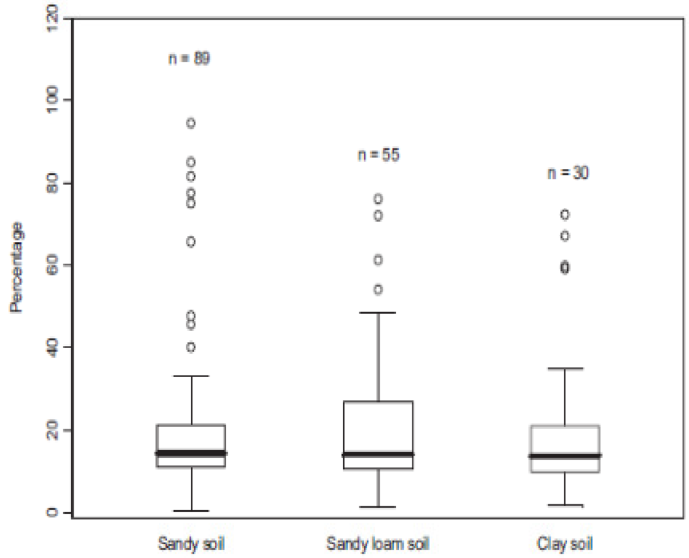

Fig. 4. Box and whisker plot comparing respirable quartz percentages of the respirable dust for measurements above the LOD from a sandy, a sandy loam and a clay soil South African farm.

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 water melon harvesting, which

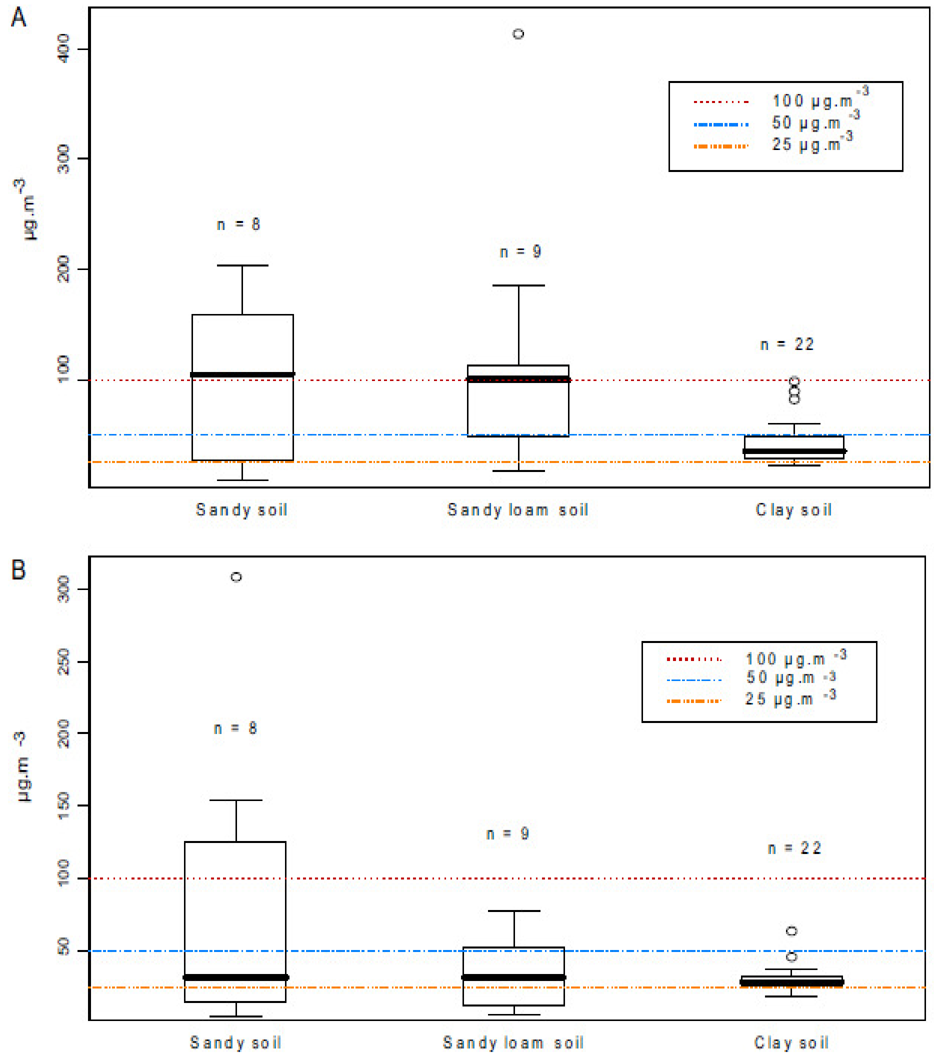

Fig. 5. (a) Box and whisker plot comparing TWA respirable quartz exposures of maize planter operators from a sandy, a sandy loam, and a clay soil farm in South Africa. (b) Box and whisker plot comparing TWA respirable quartz exposures of maize planter tractor operators from a sandy, a sandy loam and a clay soil farm in South Africa.

contributed ~50% of the measurements taken on the farm. Quartz exposures during pumpkin and water melon 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 per cent of the quartz measurements exceeded the ACGIH 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. water melon harvesting) (Swanepoel *et al.*, 2010). Nevertheless, the published literature on personal airborne exposure to quartz and the relation to soil type is 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 $\mu g \cdot m^{-3}$; 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.

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CHAPTER 8

Determinants of respirable quartz exposure and estimated annual cumulative exposure in farming

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DETERMINANTS OF RESPIRABLE QUARTZ EXPOSURE AND ESTIMATED ANNUAL CUMULATIVE EXPOSURE IN FARMING

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Abstract

Objectives: To quantify personal respirable quartz exposure on sandy, sandy loam and clay soil farms, to identify exposure determinants and to estimate annual cumulative exposure.

Methods: Soil type, commodity farmed, activity, process, quartz% and weather variables were examined. Multiple linear regression and logistic regression were used to identify determinants of respirable quartz > 50 $\mu g.m^{-3}$. The estimated annual cumulative exposure was estimated on the sandy soil farm using activity - specific measurements.

Results: The highest concentration was 626 $\mu g.m^{-3}$ and 30%, 22% and 9% of measurements were > 50 $\mu g.m^{-3}$ for sandy, sandy loam and clay soil farms respectively. Live stock farming (p = 0.001), cereal planter operator (p = 0.001), mechanical processes (p = 0.003); and summer season (p = 0.003) were associated with higher respirable quartz concentrations. Decreased humidity on day of measurement was correlated with higher exposure (r = - 0.11; p = 0.05). Variables associated with quartz levels above 50 $\mu g.m^{-3}$ were cereal planter operator, increased quartz % in respirable dust, decreased humidity on day of measurement and increased respirable dust concentration. Cereal planter operator (OR 3.76 95% CI 1.64 - 8.63) and quartz % (OR 5.16 95% CI 2.32 - 11.44) were strong determinants of quartz exposure. The estimated annual cumulative exposure of a worker exposed at highest concentrations measured for each task exceeded the estimated annual cumulative exposure if exposed at 100 $\mu g.m^{-3}$ by 1.46 times.

Conclusion: Overexposure to quartz in farming is possible. The nature of farming and weather variables should be included with soil type in future farming exposure assessments.

Introduction

Respirable crystalline silica (usually in the form of quartz) causes multiple serious diseases including silicosis, silica-associated tuberculosis (TB),[1 2] COPD[3] and lung cancer,[4] and increased mortality.[5] Consequently, quartz exposure is an important public health issue particularly in settings of high TB and HIV rates since it is well known that HIV infection increases the incidence of TB[6] and the risk of TB in individuals with both HIV infection and silicosis is larger than the sum of risks conferred by each factor.[7]

Quartz exposure is well documented in many traditional dusty industries such as mines, quarries, foundries, construction and ceramics,[8] but much less is known about exposure in farming, globally a very large employer.[9]

Quartz exposures above generally used occupational exposure limits (OELs) have been reported in farming,[10-16] but the literature on quartz exposure in farming is scant. Additionally, very little is known about the determinants of quartz exposure in this industry, the annual cumulative exposure over a farming cycle and the potency modifiers potentially associated with quartz in farm soils.

A few studies have examined determinants of respirable dust and quartz during farming activities.[17-20]

The presence of an enclosed cabin on a tractor during discing operations was associated with lower respirable dust levels (no cabin: geometric mean (GM) = 81.9 $mg.m^{-3}$; with cabin: GM = 1.6 $mg.m^{-3}$). Likewise, higher relative humidity ($R^2 = 0.24$; p = 0.0015) and lower tractor speed ($R^2 = 0.14$; p = 0.02) were both associated with a decrease in dust concentrations.[18] A subsequent study showed that an enclosed tractor cab reduced exposure of the tractor operator to larger (50% cut-off < 9.8 µm) and smaller (50% cut-off < 3.5-4 µm) dust particles by 60 and 4 – fold, respectively.[17] Additionally, task exposure duration and frequency of task have been found to be as important as exposure intensity in quantifying dust exposure assessments for farming work,[20] based largely on subjective dust exposure ratings and on limited measurements. Personal respirable quartz concentrations of Eastern North Carolina farm workers were increased by agriculture activity i.e., sweet potato planting (F - value = 26.25; p = 0.0001); low soil moisture (F - value = 13.6; p = 0.0009); low relative humidity (F-value = 25.71; p = 0.0001); and average wind speed (F-value = 7.83; p = 0.0089),[19] A large proportion of the variation in quartz exposure was explained by agricultural activity and soil moisture.

Although not conclusively demonstrated, sandy and sandy loam soils have been shown to contain higher proportions of respirable quartz in farm dust and to produce higher levels of personal respirable quartz than clay soils.[15 16 19 21 22]

Modifiers potentially affecting the silicosis-causing potency of quartz have been identified.[23] Importantly, extremely small particle size enhances the potency, while wetting, ageing and aluminum containing clay coatings were reported to reduce potency. All of these factors may be pertinent to farm settings but have not been investigated to any extent.

The limited information on determinants of quartz exposure, on modifiers of quartz potency and on the estimated annual cumulative exposure during farming motivated this study on a sandy, a sandy loam and a clay soil farm in South Africa with the objectives to identify determinants, if any, of personal exposure to respirable quartz during farming, to describe the median particle sizes in respirable dust samples and to estimate annual cumulative respirable quartz exposure.

Methods

Sampling strategy

As reported elsewhere,[16] 298 personal respirable dust and quartz measurements were collected on a sandy, a sandy loam and a clay soil farm located in the Free State and North - West provinces of South Africa. Access to the farms was granted as the researcher knew the farmers. All farm workers present on the days of measurement agreed to participate. Farming methods and products farmed on the three farms were typical of the regions in which the farms were located. The major activities undertaken on the three farms over the annual farming cycle were identified in conjunction with the farmer (Table 1). Crops and livestock produced on the sandy and sandy loam farms included maize, wheat, sunflower, water melon, pumpkin, potatoes and cattle and sheep. The only product farmed on the clay soil farm was maize; therefore, on this farm respirable dust and quartz exposure were only measured during maize planting and maize harvesting operations. Even though farm activities can produce large dust clouds, no respiratory protective equipment (RPE) was observed to be used. The farms under study were small to medium sized farms and all tractor drivers measured during the study used "open-cabbed" tractors. As expected during farming, shift durations varied substantially depending on activity and often exceeded 12 hours (up to 18 hours during planting and harvesting activities), but personal breathing zone measurements were collected over a period of approximately 8 hours (mean = 460 minutes, range = 360 - 520 minutes).

Walkthrough inspection

A Southern African Institute of Occupational Hygiene (SAIOH) registered occupational hygienist recorded detailed information on activities performed, duration of activities, commodities grown and the process i.e. manual versus mechanical.

Respirable dust and quartz measurement

The respirable dust and quartz measurement methodology has been reported in detail previously,[16] but briefly, the standard Health and Safety Executive (HSE) Methods for the Determination of Hazardous Substances (MDHS) 14/3 method[24] and HSE MDHS 101 method[25] were used to determine respirable dust and quartz, respectively. The limit of detection for quartz reported by the analytical laboratory was 22 µg. Respirable quartz concentrations are expressed as an eight - hour time weighted average (TWA) in micrograms per cubic metre ($\mu g.m^{-3}$).

Determinants of exposure

Possible determinants of interest were soil type, season, commodity, activity, farming process, quartz percentage in the respirable dust, respirable dust concentrations and five measures of weather conditions (Tables 2 - 3). Soil grain size analysis showed that three soil types were correctly classified as sandy, sandy loam and clay.[16] Only two seasons were involved, namely winter (dry) and summer (rainy). The six farming commodities were pooled as follows for the purpose of data analysis: cereal grains (maize, wheat, sunflower), ground crops (watermelon, pumpkin and potato) and animal life stock (cattle and sheep).

Fourteen farming activities were measured and pooled as follows: cereal planter operators (maize and wheat planter operators) cereal tractor drivers (maize and wheat tractor drivers, maize harvester operators and maize harvesting transport tractor operators), cereal ground preparation (maize and sunflower planting soil preparation, and maize harvesting soil preparation) and other (water melon and pumpkin harvesting and picking, maize silo workers and maize sorting and packaging, and livestock handling). Two farming processes were identified i.e., manual and mechanical. Five weather variables were obtained from the South African Weather Services. Instruments were situated within three kilometers of the farms under study and weather variables included humidity, air pressure, wind force, temperature and rainfall. Weather data were obtained for eight consecutive days prior to quartz measurements as well as on the day of airborne quartz measurement.

Particle size analysis

Dust particle size analysis (PSA) was done by South Africa's Council for Scientific and Industrial Research (CSIR) using a standard laser light scattering method.[26] Thirty of the respirable dust samples collected on the sandy and sandy loam soil farm was randomly selected for PSA analysis and results were expressed in terms of the D50 value (the median value of the particle size distribution). The dust concentration of one sample was reported to be too low to determine a reliable particle size distribution.

Estimated annual cumulative exposure

Respirable quartz cumulative exposure indices over a farming cycle year were estimated for a typical sandy soil farm worker at average respirable quartz concentrations for each task done over the year, and for a farm worker exposed at the highest concentration measured for each task. Information on major activities done by a farm worker during the year and the duration (days) of each task were obtained from the farmer, and median respirable quartz measurements for each task were used to estimate the average annual estimated annual cumulative exposure as follows: [(task 1 median exposure x days) + (task 2 median exposure x days) …+ (task n median exposure x days)] = average annual cumulative exposure index - estimated annual cumulative exposure - in $\mu g.m^{-3}$-days). The same calculation was used to estimate the highest annual cumulative exposure by replacing the median concentration with the highest for the task. These average and highest estimated annual cumulative exposures were evaluated against annual cumulative exposures at the South African OEL of 100 $\mu g.m^{-3}$, the National Institute for Occupational Safety and Health (NIOSH) Recommended Exposure Limit (REL) of 50 $\mu g.m^{-3}$ and the American Conference for Governmental Industrial Hygienist Time Threshold Value (TLV) of 25 $\mu g.m^{-3}$. The annual cumulative exposure at each OEL was derived by calculating the product of the OEL $\mu .m^{-3}$ and the annual days worked. A typical farm worker on the sandy farm worked about 253 days in a year assuming 5.5 days worked/week minus annual leave and public holidays. Annual respirable quartz exposures at the SA OEL, NIOSH REL and ACGIH TLV are 25 300 $\mu g.m^{-3}$ - days (100 $\mu g.m^{-3}$ x 253 working days), 12 650 $\mu g.m^{-3}$ - days (50 $\mu g.m^{-3}$ x 253 working days) and 6 325 $\mu g.m^{-3}$ - days (25 $\mu g.m^{-3}$ x 253 working days), respectively. The estimated annual cumulative exposure may be an underestimation of annual cumulative exposures as no adjustment was made for long working days.

Quality assurance

As described elsewhere,[16] a quality assurance plan was in place A qualified occupational hygienist registered with the Southern African Institute for Occupational Hygiene (SAIOH) monitored all aspects of data collection, from possible determinant identification through to all gravimetric and analytical analysis procedures. All of the gravimetric, analytical and PSA laboratories were experienced South African National Accreditation System (SANAS) accredited laboratories. Weather data were collected with calibrated instruments as prescribed by the South African National Standards (SANS) organization and results were compiled by a qualified climatologist working for the South African Weather Service. Soil mineralogy was done by an experienced technician in the School of Geochemistry, University of the Witwatersrand.

Data analyses

Determinants of exposure

Quartz concentrations below the limit of detection (LOD) were estimated using a multiple imputation method.[16 27] All data and regression analyses were done using the TIBCO Spotfire S-plus (version 8.1) software package.

Determinants of exposure included both categorical and continuous variables. Categorical variables were soil type (sandy soil, sandy loam soil and clay soil), season (summer and winter), commodity (cereal grains, ground crops and live stock), activity (cereal grain planter operator, cereal grain tractor operator, cereal grain soil preparation and other) and process (manual and mechanical). Continuous variables included personal respirable dust exposure, percentage quartz in respirable dust and weather data (humidity, air pressure, temperature, wind strength, rain fall).

Kruskal - Wallis tests were done to determine significant differences in quartz exposures between various categories of categorical variables. Where differences were found, subsequent Wilcoxon - tests were done to determine the relations between the subgroups of the categorical variables. The mean value for each weather variable was determined for three time windows: the average over eight days before measurement, the day before measurement and on the day of measurement, and these were evaluated against respirable quartz concentrations. Pearson's correlation coefficient was used to determine if respirable quartz exposure was correlated with any of the continuous variables.

Multiple linear regression was used to identify possible independent determinants of respirable quartz concentrations and to explain the variation in these concentrations. Respirable quartz exposure data were best described by a log normal distribution and all potential determinants were tested against the logarithm of the quartz exposures. To acquire insight into possible relation structures in the data set, the covariance matrix and pair wise scatter plots of all the variables of interest were used. Multi - collinearity was avoided by choosing dummy variables and by omitting correlated weather variables, while minimizing loss regarding fitting criteria. Inclusion criteria for the model involved three steps: (i) one - by - one stepwise sequential addition of continuous variables to the model using sum of square patterns, Cp - values, R^2 and adjusted R^2 values to identify variables for inclusion; (ii) sequential addition of dummy variables representing the categorical variables (allocated to prevent multi-collinearity) using the same processes and criteria explained above; and (iii) interaction terms were identified via stepwise procedures and included in hierarchical models as above. The resulting regression model was tested for violation of the model assumptions.

Additional analysis, aiming to identify determinants of respirable quartz > 50 $\mu g.m^{-3}$ and to deal with data points below the detection limit without including multiple imputation methods was done using logistic regression. This analysis was applied to the original multivariate data set, where the response variable was defined as respirable quartz values greater than 50 $\mu g.m^{-3}$. Potential determinants were carefully chosen to prevent multi-collinearity, and were formally identified as possible determinants of quartz exposure. Humidity on the day of measurement was the only weather variable that satisfied the inclusion criteria. The categorical regressor variables soil type (sandy, sandy loam and clay soil), season (winter, summer), commodity (cereal, ground crops, live stock), activity (cereal planter operator, cereal tractor driver, cereal soil operators and Others), process (manual or mechanical) were used for univariate and multivariate logistic modeling. Continuous determinants (quartz %, humidity on the day of measurement, and respirable dust exposure) were each divided into three approximately equal size subgroups: quartz % = 0 – 10 %, > 10 – 20 % and > 20 %; humidity on the day of measurement = $\leq$ 25 $g.m^{-3}$, > 25 - $\leq$ 45 $g.m^{-3}$ and > 45 $g.m^{-3}$, and respirable dust exposure = $\leq$ 0.2 $mg.m^{-3}$, > 0.2 - $\leq$ 0.5 $mg.m^{-3}$ and > 0.5 $mg.m^{-3}$. Odds ratios (ORs) and 95% Confidence intervals (CIs) were calculated to compare the association between group differences in quartz exposures while adjusting for the above mentioned variables. Conditioning for all categorical and continuous variables was done on the lowest level of the determinants except for respirable dust concentrations.

Ethics

Confidentiality regarding farms, farm owners and farm workers was maintained throughout the study and written informed consent was obtained from all study participants. This study was approved by the University of the Witwatersrand Human Research Ethics Committee (clearance number M070252).

Results

Over - exposure to quartz was found on all three farms and for most activities. The highest concentration was 626 $\mu g.m^{-3}$ and 12%, 13% and 0% of measurements were > 100 $\mu g.m^{-3}$ (a common OEL) for the sandy, sandy loam and clay soil farms respectively. Nine percent were > 50 $\mu g.m^{-3}$ on the clay farm.

Determinants of quartz exposure on three South African farms

Associations between categorical variables and respirable quartz are shown in Table 2. Respirable quartz exposures on the sandy, sandy loam and clay soil farm were similar (Kruskal - Wallis test; $p = 0.17$), but commodities differed by respirable quartz concentrations (Kruskal - Wallis test; $p = 0.001$), with livestock producing the highest exposure. Exposure during live stock farming was significantly greater than during both ground crops and cereal grains farming (Wilcoxon tests $p = 0.001$ and 0.014 respectively), but cereal grain farming exposure exceeded that of ground crops (Wilcoxon tests; $p = 0.007$). Quartz exposure varied by activity (Kruskal - Wallis test; $p = 0.001$) with cereal planter operators' exposures exceeding those of cereal tractor operators, cereal soil operators and Other activity (Wilcoxon tests; $p = 0.001$, 0.004 and 0.002 respectively). No significant differences were found between cereal tractor operators, and cereal soil operators (Wilcoxon tests; $p = 0.16$) nor between cereal tractor operators and cereal soil operators and Other activity (Wilcoxon tests; $p = 0.75$ and 0.10, respectively). As expected, respirable quartz concentrations were significantly higher during mechanical than manual processes (Wilcoxon test; $p = 0.003$), but, surprisingly, quartz levels were significantly higher during summer (rainy season) than winter (Wilcoxon test; $p = 0.003$).

Table 4 shows the multiple linear regression model results. Regression coefficients are for the logarithm of respirable quartz, and for the categorical variables are in terms of estimated conditional differences of effects of the sub-categories of each variable. Interpretation is thus complex. Nevertheless, with conditioning done on the clay soil farm, the three soil types (i.e., sandy, sandy loam and clay) had similar effects on the log - transformed quartz exposure data and can be regarded as having no significant overall effect in the model (p = 0.55 and 0.52). At least two of the levels of the determinants "commodity" were statistically significant to the model (p = 0.001 and p = 0.002, respectively), as were at least two of the levels of the determinants "activity" (p = 0.001 and p = 0.002, respectively). The categorical variables "season" and "process" were both contributory (both p values < 0.001). Regarding continuous potential determinants, quartz percentage, respirable dust and humidity on the morning of measurement were found to be significant determinants of quartz exposure (all p - values were < 0.01). In summary, the most significant independent determinants of exposure were season, commodity, activity, process, quartz percentage and humidity on the morning of measurement. However, by including interactions terms between activity, dust exposure and quartz percentage, the final regression model explained close to 85% of the variability in quartz exposure (multiple R - squared value = 0.8516; adjusted R - squared value = 0.8431). Assumptions of normality of residuals, homogeneity of variance and linearity were satisfied by the regression model.

Logistic regression results are shown in Table 5. In univariate analyses, soil type, season, commodity and process were not significant determinants of respirable quartz exposure > 50 $\mu g.m^{-3}$; but cereal planter operator, increased quartz % in respirable dust, decreased humidity on the day of measurement and increased respirable dust concentration were all significantly associated with quartz exposure > 50 µg.m^{-3}. ORs in the multivariate analysis are adjusted for these latter four variables. Soil type was unimportant in determining whether exposure exceeded 50 µg.m^{-3} as was the case for commodity and process (95% CI both spanned 1 widely). Despite being the dry season, winter was protective of higher exposure (OR = 0.53 95% CI 0.28 - 1.01). Cereal planter operator remained a strong determinant of higher level of exposure relative to other activity (OR 3.76 95% CI 1.64 - 8.63). Increased levels of quartz % in respirable dust increased the ORs for exposure > 50 µg.m^{-3}, but there was not a trend in increasing ORs with increasing levels of quartz % (OR 5.16 vs 2.03 for the second and third level of quartz % respectively). Surprisingly, ORs for decreasing humidity on the day of measurement, when adjusted for the other variables, were well below one (95% CI both spanned 1 widely) suggesting that the apparent effect in univariate analysis was due to confounding. Lastly, lower levels of respirable dust exposure were very strongly protective of higher respirable quartz exposure (ORs close to zero).

Particle size

The median D50 particle size of the 30 respirable dust measurements was 5.53 µm with the smallest five D50 values reported by the laboratory of 3.39, 4.01, 4.25, 4.58 and 4.72 µm, respectively during maize and wheat planting activities.

Cumulative exposures

Tables 6 and 7 show estimated annual cumulative exposures for a farm worker over a typical farming year on the sandy soil farm. The estimated annual cumulative exposures are compared to the annual cumulative exposure (CE) that would occur at three OELs. As can be seen, at median quartz exposures measured for each of the activities done during the year, the chances of exceeding the cumulative exposure if exposed at the South African OEL are small: the ratio of estimated annual cumulative exposures to OEL CE = 0.29. However, estimated annual cumulative exposures may exceed the ACGIH TLV CE, the lowest OEL: ratio = 1.17. Although an unlikely scenario, if a worker were exposed to the maximum respirable quartz concentration for all activities over a year, the chances of exceeding the SA OEL CE and ACGIH TLV CE increases substantially (estimated annual cumulative exposure /CE ratios = 1.46 and 5.84, respectively).

Discussion

This is the only study of its kind reporting on possible determinants of respirable quartz exposure during farming activities. Some important variables that need to be further explored in determining risk of quartz exposure in agriculture have been identified.

Some limitations should be borne in mind. Soil types are a continuum and the sandy loam soil farm selected in this study was probably towards the sandy end of the soil spectrum with the clay soil probably not at the extreme for clay soils. The results are, therefore, probably not generalisable across the continuum of soil types. Similarly, weather conditions will vary greatly by geographic locality and may have a more prominent effect in more extreme climates. In particular neither humidity nor rainfall was high during this study. Personal quartz measurements were done on open - cabbed tractors only, therefore respirable quartz concentrations are not generalizable to farming activities using cabbed tractors. Additionally, there was an imbalance of measurements across activity and commodities resulting in uneven contributions in the modeling process. For example, the majority of measurements was done during maize production seasons; a more comprehensive exposure assessment of all commodities and activities during farming would not only have resulted in better comparisons and more refined modeling results, but the roles of seasons and meteorological conditions may also have been better understood. Furthermore, the method of multiple imputation used to estimate quartz concentrations below the LOD might have produced slightly higher imputed concentrations on the clay soil farm than those for the sandy and sandy loam soil farms. A large proportion (41 % in total) of the quartz levels on the sandy, sandy loam and clay soil farms were below the LOD (35 %, 27 % and 64 %, respectively). In addition, the available data above the LOD contained some relatively high values. Therefore, relatively large estimated quartz levels may have been imputed, particularly on the clay soil farm. Quartz levels measured on the three farms were heavily skewed to the right, and, if this is typical for farming, imputation methods need to take this into account when analyzing quartz exposure data during farming. The imputation method did not, however, have an effect on the logistic regression results since no imputed values exceeded 50 $\mu g.m^{-3}$.

Farming activities and process (i.e., mechanical or manual) were important determinants of respirable quartz exposure in this study, although process did not explain exposure above 50 $\mu g.m^{-3}$: cereal planter operators were exposed to higher respirable quartz concentrations than cereal tractor operators, cereal soil operators and other activity. Quartz levels were significantly higher during mechanical than manual processes (Wilcoxon test; $p = 0.003$) and process contributed to the linear regression model. These findings are similar to those reported in Eastern North Carolina farm workers where respirable quartz levels varied by farming activity. In addition, low humidity on the day of measurement was associated with a decrease in respirable quartz concentrations (Pearson's Correlation Coefficient; $p = 0.05$) (Table 3) and is similar to findings reported in a previous study,[18] albeit for respirable dust not quartz. It is notable, though, that low humidity was not associated with higher exposure in multivariate logistic regression analysis, possibly due to the generally low humidity in these farming areas.

Surprisingly, the dry season (winter) was not associated with respirable quartz exposures above a widely used OEL of 50 $\mu g.m^{-3}$. It was anticipated that during the rainy season (summer), lower respirable quartz levels would have been measured compared to the dry winter season, but the opposite occurred. A possible explanation is that little rain occurred during the summer season (there was no rainfall during measurement days) and the high temperature in the absence of rain could have dried out the soil, resulting in the lack of the expected seasonal effect. Live stock handling was associated with quartz levels above 50 $\mu g.m^{-3}$ when compared to cereal and ground crop commodities. During live stock handling, large dust clouds are typical which could explain the strong relationship. However, due to the large differences in the number of measurements among the commodities the results should be interpreted cautiously. It was expected that mechanical processes would be associated with respirable quartz levels above 50 $\mu g.m^{-3}$, but this was not the case. A number of the mechanical processes involved activities that generated a lot of dust, but most of it probably organic (e.g. harvestor operator and transport tractor driver). Also, the manual task of livestock handling was very dusty. Possibly these factors explain the finding.

Modifiers affecting the potency of quartz in farming are not generally considered but are likely to be important: freshly fractured quartz is biologically more reactive and produces enhanced lung injury and disease.[28-34] Additionally, animal studies have shown that smaller particle silica dust is more potent in mice[35-37] and hence particle size may be an important quartz potency modifier during farming. No studies have investigated whether respirable quartz is freshly fractured during farming and no real attempt has been made to characterise quartz particle sizes across agricultural activities. The median D50 particle size of the 30 respirable dust samples measured in this study was 5.53 µm with the smallest D50 values reported by the laboratory of 3.39 µm. These data are presented to begin to characterise the size of respirable particles in farming but add little to understanding disease risk; much more detailed data are required, along with information on other potential potency modifiers as described by the UK's Health and Safety Executive.[23]

Generally, in farming, a fairly large number of distinct activities are done for variable periods over the farming year by the same worker. Cumulative respirable quartz exposure, presumably a major determinant of chronic disease risk, is likely to vary considerably according to the nature and duration of the activities done. Nevertheless, in this study the estimated annual cumulative exposure of a typical farm worker on a sandy soil farm at median exposure concentrations was well below the CE at 100 $ug.m^{-3}$. But if exposed at the highest concentrations measured for each task, the CE at 100 $ug.m^{-3}$ would be exceeded, suggesting that substantial risk of silica - associated disease is present in extreme farming settings. To better understand the risk of silica - associated diseases in farming, cumulative exposures in the industry need to be better defined and related to cumulative exposures in activities known to cause these diseases. Additionally, there is a potential for peak exposures in agriculture (the highest respirable quartz concentration in this study was 626 $ug.m^{-3}$). These peak exposures may be important in disease generation, as short term exposures to high silica concentrations might account for occurrence of silicosis at low cumulative or average exposure levels.[38] Farming activities producing short - term peak exposures need to be identified for targeted dust control.

Conclusion

Farming consists of a wide range of activities during many different conditions. The current study showed that soil type was not a determinant of quartz exposure as opposed to the commodity farmed, activity performed and process used on the farms. Additionally, cumulative exposures and peak exposures in the industry need to be better defined so that the risk of silica - associated disease can be clarified in a variety of farming settings. Future exposure assessments should include a more balanced number of samples across activities and commodities to further examine the role potential determinants of silica exposure (e.g. soil types, commodities, activities, processes (mechanical vs manual) and weather) and potency modifiers (e.g., particle size) may have on silica exposures in farming. Finally, a greater effort should be made to determine the burden of silica - associated diseases in farming.

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Table 1. Description of activities on South African farms during which respirable dust and quartz was measured

Activity	**Task**	**Process**	**Task description**
Wheat planting	Planter operator	Mechanical	A tractor - drawn machine (planter) driven by a tractor driver was used to plant wheat seeds in the soil.
Maize planting	Tractor operator	Mechanical	A worker sat on the back of the planter observing and managing the planting procedure
	Planter operator	Mechanical	A tractor-drawn machine (planter) driven by a tractor driver was used to plant maize seeds in the soil.
	Soil preparation	Mechanical	Fields prepared by plowing to break up the surface, bury weeds and ploughing fertilizer into the soil. A worker drove a tractor which dragged an implement through the soil (ripping and discing) creating large dust clouds.
Maize harvesting	Soil preparation	Mechanical	Fields prepared by ploughing to break up the surface and bury weeds before maize harvesting.
	Harvester operator	Mechanical	A harvester machine (combine) was used to harvest the grown maize crop.

	Transport tractor driver	Mechanical	The harvested maize crop was transferred to a wagon driven by a tractor driver to be transported to the silos for storage.
	Silo work	Manual	Workers in the silos (normally an enclosed environment) observed and managed the storing procedure.
Cattle and sheep	Handling	Manual	Cattle and sheep were herded into pens to count and them.
Watermelon harvesting	Picking	Manual	Water melon harvesting during which workers manually picked up water melons from the fields and loaded them into containers.
Pumpkin harvesting	Picking	Manual	Pumpkin harvesting during which workers manually picked up pumpkins from the fields and loaded them into containers.
Potato harvesting	Sorting and packing	Manual	One worker lifted potatoes to the surface with a small engine driven machine and other workers placed in the field picked up the potatoes.
General farm work	Maintenance	Manual	When all activities described above were done farm workers spent time doing maintenance work e.g. fixing fences and implement repair.

Table 2. Respirable quartz exposures on three South African farms by soil type, commodity, activity, process and season

Categorical variable		**N**	**IQR**	**AM**	**Median**	**GM**	**GSD**	**P - value**
Soil type	Sandy	138	40.7	53.2	30.2	31.7	2.7	
	Sandy Loam	77	26.2	46.9	28.3	31.6	2.3	p = 0.17*
	Clay soil	83	8.45	33.4	29.5	31.1	1.4	
Commodity	Cereal	214	21.4	50.2	29.3	33.0	2.3	
	Ground Crops	77	31.5	34.8	29.0	26.9	2.16	p = 0.001*
	Live Stock	7	27.6	42.9	42.2	41.2	1.33	
Activity	Cereal Planter Operator	46	71.3	83.4	39.3	50.5	2.7	
	Cereal Tractor Operator	73	16.5	37.1	27.4	28.6	1.94	p = 0.001*
	Cereal Soil Operator	82	16.9	46.2	29.0	31.3	2.25	
	Other	97	24.4	36.2	28.7	27.8	2.06	
Process	Mechanical	198	23.00	51.7	29.5	34.1	2.28	p = 0.003**
	Manual	100	30.33	34.8	29.1	26.9	2.13	
Season	Summer (rainy)	176	30.0	47.9	29.5	32.8	2.45	p = 0.003**
	Winter (dry)	122	23.2	43.4	29.1	29.6	2.24	

N, number of samples; IQR, inter quartile range; AM, arithmetic mean; GM, geometric mean; GSD, geometric standard deviation.

* Kruskal – Wallace test.

** Wilcoxon test.

Table 3. Correlation between respirable quartz exposures and weather data during three time windows, respirable dust and quartz %

Determinant	**Mean of the determinant averaged over 8 days prior to measurement**		**Mean of the determinant 1 day before measurement**		**Mean of the determinant on the day of measurement**	
	Pearson's correlation coefficient	**P - value**	**Pearson's correlation coefficient**	**P - value**	**Pearson's correlation coefficient**	**P - value**
Humidity (g.m^{-3})	- 0.03	0.63	-0.07	0.26	-0.11	0.05
Air Pressure (Pa)	0.01	0.87	-0.02	0.78	-0.02	0.71
Temperature (˚C)	0.06	0.29	0.05	0.35	0.06	0.30
Wind Strength (m/s)	0.11	0.08	0.06	0.29	0.06	0.28
Rain fall (mm)	-0.02	0.73	0.02	0.71	Rainfall equal to 0 throughout	
Respirable dust (mg.m^{-3})	0.36	0.0001				
Quartz %	0.11	0.04				

Table 4. Multiple regression modeling to identify determinants of respirable quartz exposure on three South African farms

Determinant	**Coefficient (β)**	**Standard Error (β)**	**P - value**
Soil Type: Sandy soil	-0.03	0.42	0.55
Soil Type: Sandy loam soil	0.27	0.01	0.52
Season	-0.21	0.00	0.00
Commodity: cereal grains	-0.22	0.00	0.001
Commodity: live stock	0.21	0.006	0.002
Activity: cereal grain planter operator	0.49	0.0.00	0.001
Activity: cereal grain soil preparation	-0.08	0.08	0.002
Activity: other	-0.009	0.69	0.68
Process	-0.12	0.008	0.00
Quartz %	-0.0001	0.94	0.00
Respirable dust exposure	-0.012	0.14	0.00
Humidity: morning of measurement	-0.02	0.00	0.00
Interaction: cereal grain planter operator and quartz %	0.004	0.12	0.00
Interaction: cereal grain planter operator and respirable dust exposure	-0.117	0.09	0.37
Interaction: quartz % and respirable dust exposure	0.14	0.008	0.00
Interaction: cereal grain planter operator, quartz % and respirable dust exposure	-0.06	0.006	0.00

Table 5. Logistic regression modeling to identify possible determinants of quartz exposure > 50 ug.m^{-3} on three South African farms

Variables		Crude analyses	Adjusted model
		Univariate OR (95% CI)	**Multivariate OR* (95% CI)**
Soil type	Sandy	0.93 (0.51-1.67)	1.01 (0.51-1.98)
	Sandy Loam	0.62 (0.31-1.26)	1.17 (0.48-2.85)
	Clay	1	1
Season	Winter/Summer	0.74 (0.44-1.24)	0.53 (0.28-1.01)
Commodity	Cereal	0.56 (0.12-2.56)	0.41 (0.08-1.99)
	Ground Crop	0.41 (0.08-2.04)	0.40 (0.08-2.00)
	Live Stock	1	1
Activity	Cereal Planter Operator	4.43 (2.09-9.41)	3.76 (1.64-8.63)
	Cereal Tractor Operator	0.67 (0.31-1.46)	0.55 (0.22-1.37)
	Cereal Soil Operator	1.41 (0.72-2.76)	1.64 (0.77-3.52)
	Other	1	1
Process	Manual/Mechanical	0.67 (0.39-1.17)	0.95 (0.48-1.87)

Quartz %	≤10	1	1
	>10 but ≤20	5.52 (2.72-11.2)	5.16 (2.32-11.44)
	>20	4.61 (2.24-9.50)	2.03 (0.63-6.56)
Humidity on the day of measurement	≤25	4.60 (1.90-11.30)	0.28 (0.03-2.56)
	>25 but ≤45	3.22 (1.36-7.60)	0.61 (0.15-2.55)
	>45	1	1
Respirable dust exposure	≤0.20	0.17 (0.08- 0.35)	0.00 (0.00-0.0004)
	>0.20 but ≤0.50	0.48 (0.27-0.87)	0.09 (0.004-0.24)
	>0.50	1	1

95% CI = 95% confidence interval; OR = odds ratio.

* Multivariate ORs are adjusted for cereal planter operator, quartz %, humidity on the day of measurement and respirable dust.

Table 6. Respirable quartz estimated annual cumulative exposure at median concentrations for each activity measured on a predominantly cereal sandy South African soil farm over a working year

Activity	**Task**	**Median quartz concentration (ug.m^{-3})**	**Estimated number of days per task in a year**	****Exposure index per task (ug.m^{-3} - days)**	**Exposure index (at the SA-OEL 100 ug.m^{-3})**	**Exposure index (at the NIOSH-REL 50 ug.m^{-3})**	**Exposure index (at the ACGIH-TLV 25 ug.m^{-3})**
Wheat planting	Planter operator	21.7	12	260.4	0.01	0.02	0.04
	Tractor operator	24.8	13	322.4	0.01	0.03	0.05
*Wheat harvesting	Soil preparation	32.2	10	322	0.01	0.03	0.05
	Harvester operator	26.8	11	294.8	0.01	0.02	0.05
	Silo worker	19.7	10	197	0.01	0.02	0.03

	Transport tractor driver	26.9	11	295.9	0.01	0.02	0.05
Maize planting	Planter operator	72.8	12	873.6	0.03	0.07	0.14
	Tractor operator	29.6	13	384.8	0.02	0.03	0.06
	Soil preparation	29.5	10	295	0.01	0.02	0.05
Maize harvesting	Soil preparation	32.2	10	322	0.01	0.03	0.05
	Harvester operator	26.8	11	294.8	0.01	0.02	0.05
	Silo worker	19.7	10	197	0.01	0.02	0.03
	Transport tractor driver	26.9	11	295.9	0.01	0.02	0.05

Cattle and sheep	Handling	42.2	20	844	0.03	0.07	0.13
Watermelon harvesting	Picking	22.5	10	225	0.01	0.02	0.04
Pumpkin harvesting	Picking	29	10	290	0.01	0.02	0.05
Potato harvesting	Sorting and packing	34	20	680	0.03	0.05	0.11
General farm work	Maintenance	20.8	49	1019.2	0.04	0.08	0.16
Total estimated annual cumulative exposure / CE ratio		**29.9**	**253**	**7 413.8**	**0.29**	**0.59**	**1.17**

* Actual wheat harvesting concentrations were not measured but are based on maize harvesting operations as it is the same operation on the same farm.

** Exposure index = the product of the number of days worked and the median quartz concentration of the OEL.

Table 7. Maximum respirable quartz cumulative exposure indices at median concentrations for each task measured on a predominantly cereal sandy South African soil farm over a working year

Activity	**Task**	**Maximum quartz concentration (ug.m^{-3})**	**Estimated number of days per task in a year**	****Exposure index per task (ug.m^{-3} - days)**	**Exposure index (at the SA-OEL 100 ug.m^{-3})**	**Exposure index (at the NIOSH-REL 50 ug.m^{-3})**	**Exposure index (at the ACGIH-TLV 25 ug.m^{-3})**
Wheat planting	Planter operator	626.1	12	7513.2	0.30	0.59	1.19
	Tractor operator	58.7	13	763.1	0.03	0.06	0.12
*Wheat harvesting	Soil preparation	171.1	10	1711	0.07	0.14	0.27
	Harvester operator	72.2	11	794.2	0.03	0.06	0.13
	Silo worker	52.4	10	524	0.02	0.04	0.08
	Transport tractor driver	110.6	11	1216.6	0.05	0.10	0.19

Maize planting	Planter operator	413	12	4956	0.20	0.39	0.78
	Tractor operator	308.4	13	4009.2	0.16	0.32	0.63
	Soil preparation	318.8	10	3188	0.13	0.25	0.50
Maize harvesting	Soil preparation	171.1	10	1711	0.07	0.14	0.27
	Harvester operator	72.2	11	794.2	0.03	0.06	0.13
	Silo worker	52.4	10	524	0.02	0.04	0.08
	Transport tractor driver	110.6	11	1216.6	0.05	0.10	0.19
Cattle and sheep	Handling	57.9	20	1158	0.05	0.09	0.18
Watermelon	Picking	75	10	750	0.03	0.06	0.12

harvesting							
Pumpkin harvesting	Picking	100.8	10	1008	0.04	0.08	0.16
Potato harvesting	Sorting and packing	134.5	20	2690	0.11	0.21	0.43
General farm work	Maintenance	48.6	49	2381.4	0.09	0.19	0.38
Total estimated annual cumulative exposure / CE ratio		**164.1**	**253**	**36 908.5**	**1.46**	**2.92**	**5.84**

* Actual wheat harvesting concentrations were not measured but are based on maize harvesting operations as it is the same operation on the same farm.

** Exposure index = the product of the number of days worked and the maximum quartz concentration of the OEL.

CHAPTER 9

Silica exposure in South African farming

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Personal over exposure to respirable silica may occur in South African farming and may have significant consequences for the occupational health professional

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ABSTRACT

Objectives: Little information exists on exposure to respirable silica in the agricultural industry. This paper summarises recent data from a comprehensive exposure assessment on three South African farms showing that there is a potential for over-exposure to silica in South African farming and discusses some occupational health implications and research needs.

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 using standard international measurement and analytical methods.

Results: Silica exposure above generally used OELs occurred on all three farms with the highest individual concentration measured on the sandy soil farm (626 $\mu g.m^{-3}$). Fifty seven percent, 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 $\mu g.m^{-3}$. Twelve percent and 13% of respirable quartz concentrations exceeded 100 $\mu g.m^{-3}$ on the sandy soil and sandy loam soil farms respectively, but none exceeded this level on the clay soil farm.

Conclusion: There may be significant potential for over-exposure to respirable quartz in farming and even clay soil farming may pose a risk. Given the large numbers of farm workers possibly exposed to silica and the seriousness of silica - associated diseases, some dust - related occupational health interventions should be considered in South African farming, particularly because during the course of the studies none of the South African farms had medical surveillance programmes in place and few if any dust control measures were observed.

INTRODUCTION

Diseases associated with silica exposure include silicosis, a fibrotic nodular disease of the lung parenchyma, pulmonary tuberculosis (PTB), lung cancer, chronic obstructive pulmonary disease (COPD) and autoimmune and renal diseases.[1] Silica exposure is an important public health issue particularly in settings of high TB and HIV rates. The mineral has contributed to serious epidemics of TB in southern Africa[2] and other low and middle-income regions of the world because of the increased risk of PTB in silica-exposed workers.[3] It is well known that HIV infection increases the incidence of TB and the risk of tuberculosis in individuals with both HIV and silicosis is larger than the sum of each factor.[4]

Most studies of silica exposure and silica-associated disease have focused on the historically known “dusty trades”, such as mining and quarrying, construction and sandblasting, foundries, ceramics and other industries where silica is used as a raw material or abrasive.[5] Although farming is mentioned as an industry associated with silica exposure,[1], it is still not known to what extent silica exposure is a risk in this industry. Farming may be of particular concern because of the large numbers employed, the possible high background TB and HIV rates and the generally poorer access to health services than urban residents. In many African countries, farming provides a livelihood for more than 70% of the population. South Africa also has a large agricultural labour force and is a significant employer relative to other industries. During 2004-2009 agriculture employment in South Africa ranged from 679 000-859 000 with an average of 765 833[6]. Migrant labour and poor socio-economic circumstances are common in farming, consequently there may be high HIV infection and TB rates amongst farm workers.[7] Limited data on TB and HIV rates specifically amongst farm workers in

South Africa are available, but the Food and Agriculture Organization reported that AIDS has killed around 7 million agricultural workers since 1985 in the 25 hardest-hit countries in Africa and could kill 16 million more before 2020.[8] Thus, up to 25% of the agricultural labour force could be lost in countries of sub-Saharan Africa by 2020 unless effective interventions are implemented.

SILICA EXPOSURE AND SILICOSIS IN FARMING

Studies on occupational exposure to silica in farming are limited, but have recently been reviewed.[9] Despite the paucity of data, respirable silica concentrations exceeding generally accepted OELs have been demonstrated in farming internationally.[11-13]

In grape crop harvesters, 50% of the personal exposure to silica measurements exceeded the ACGIH TLV of 25 µg/m^3 (range 7-105 µg/m^3).[11] Some remarkably high silica levels were measured on seven different farms in three eastern North Carolina counties (Pitt, Lenoir and Wayne).[12] Although the exposures determined from 37 personal respirable dust breathing-zone samples from 27 farm workers were relatively low on the majority of the farms (overall mean of 1300 ± 2900 µg/m^3), somewhat surprisingly, the highest level of time weighted average (TWA) respirable silica measured was 3 910 µg/m^3 during sweet potato transplanting (overall mean concentration of 700 ± 1600 µg/m^3). Personal exposure to inorganic and organic dusts during manual harvesting of California citrus and table grapes showed geometric means (GMs) of respirable dust exposures of 1.14 mg/m^3 for citrus harvest and 0.23 mg/m^3 for table grape operations.[13] However, the GMs of respirable silica exposures were 80 µg/m^3 for citrus harvest and 20 µg/m^3 for table grape operations.

Some determinants of silica exposure in farming have been identified and exposure may vary substantially as farming most commonly occurs outdoors. An important determinant may be the soil type as sandy and sandy loam soils (i.e. soil of clay and sand with admixture of decayed vegetable matter) have been reported to contain higher levels of silica in the respirable fraction in parts of eastern North Carolina compared with other North Carolina regions.[12,14,15]

The body of literature on silica-associated diseases in farming is small [16-21] and has been reviewed recently.[9] Silicosis has been convincingly diagnosed in agricultural workers,[17,20] but very rarely and in the main there is little evidence that pneumoconiosis occurs to any extent in the industry. Studies of other silica-associated diseases have not been published. The small number of studies and generally poor access to health services that would link diseases to workplace exposures may partly explain the paucity of reports of silica-associated diseases in farm workers.

Although the literature on occupational exposure to silica in farming is scant, some studies convincingly demonstrated that over-exposure to silica can occur in farming and that respirable dust does not necessarily act as a good surrogate for silica exposure. In view of the relatively high silica concentrations reported in the few studies conducted internationally, the lack of South African studies, the large number of people possibly exposed, and the expected high HIV and TB rates which make silica exposure a potentially serious concern, we conducted a comprehensive exposure assessment of respirable dust and silica on three South African farms. This paper briefly reviews silica exposure in farming, presents recent data showing that there is a potential for over-exposure to silica in South African farming and discusses some occupational health implications for South Africa. The South African exposure data are drawn from two articles [9,10] and from unpublished analyses to estimate annual cumulative silica exposure; the occupational health implications have not been published previously.

SILICA EXPOSURE ON THREE SOUTH AFRICAN FARMS

METHODS

Personal respirable dust and silica measurements were done on three South African farms known to have sandy, sandy loam and clay soils[10] using the Health and Safety Executive (HSE) Methods for the Determination of Hazardous Substances (MDHS) 14/3 method and MDHS 101. The farms were visited nine times over 36 months, amounting to a total of 27 days of sampling and 298 measurements. The major activities undertaken on the three farms over the annual farming cycle were identified in conjunction with the farmers. They have been listed in a previous publication[9] and were selected to be representative of potentially dusty activities performed on the sandy, sandy loam and clay soil farms. Respirable dust and silica measurements were done during the summer and winter seasons and were collected over a period of approximately 8 hours (mean = 460 minutes, range = 360-520 minutes). Throughout the study, no engineering dust controls were observed on any of the implements and no formal respiratory protective equipment (RPE) was used by the farm workers, although they may occasionally use some type of personal protection (e.g. a bandana or scarf covering the nose and mouth) during very dusty activities. All the tractor drivers measured during the study used "open-cabbed" tractors.

Ethics

Informed consent was obtained from all study participants and confidentiality was respected regarding farms, farmers and farm workers. All results of the exposure assessment were communicated to farmers and farm workers. Ethics approval was obtained from the Human Research Ethics Committee (Medical) of the University of the Witwatersrand (clearance number M070252).

RESULTS

Table 1 shows eight-hour TWA respirable dust exposures for the three farms. The highest individual respirable dust concentration (6.49 $mg.m^{-3}$) was measured on the sandy soil farm, during wheat planting operations. As expected, respirable dust concentrations differed across the three farms (Kruskal-Wallis test; $p = 0.0006$). 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 respirable dust on 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).

Eight-hour TWA respirable silica concentrations for the farms are shown in Table 2. Large proportions (41%) of the silica measurements were below the Limit of Detection (LOD) of 22 µg reported by the analytical laboratory with the clay soil farm being the main contributor (64%). Consequently, values below the LOD were estimated using multiple imputation[22] and these are presented in Table 2 for proportions above occupational exposure limits. 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 $\mu g.m^{-3}$). Respirable silica concentrations exceeded all three occupational exposure reference limits: 100 $\mu g.m^{-3}$ (South African Occupational Exposure Limit [OEL]); 50 $\mu g.m^{-3}$ (National Institute for Occupational Safety and Health [NIOSH] Recommended Exposure Limit [REL]) and 25 $\mu g.m^{-3}$ (American Conference of Governmental Industrial Hygienists [ACGIH] Threshold Limit Value [TLV]) for silica. For the sandy, sandy loam and clay soil farm, 12%, 13% and 0% of the silica measurements respectively exceeded the South African OEL of 100 $\mu g.m^{-3}$, and substantial proportions of the measurements exceeded the lower standards of the NIOSH-REL and the ACGIH TLV-TWA.

Although the proportions of measurements above the 100 $\mu g.m^{-3}$ 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 $\mu g.m^{-3}$ level than the other two farms, but the sandy soil farm had the largest proportion of measurements above the 50 $\mu g.m^{-3}$ level (*prop.test*; all p values <0.003).

Typically, the annual cycle of farming activities for each farm worker is varied with episodic dusty seasonal activities (e.g. soil preparation) interspersed with periods of relatively low dust exposure (e.g. mending fences and equipment maintenance). Annual cumulative silica exposure may therefore be poorly described by respirable silica levels found during particular dusty activities, which may be of short duration. An index of the annual cumulative respirable silica exposure can be estimated for a typical farm worker by summing the exposure for all activities done by duration in days of the task (i.e. [task 1 average exposure x days] + [task 2 average exposure x days] …+ [task *n* average exposure x *n* days] = estimated annual cumulative exposure in $mg.m^{-3}$ - days). The estimated annual cumulative exposure was estimated for a typical farm worker on the sandy soil farm using the median exposure for each task and days of exposure provided by the farmer, and it was 7.41 $\mu g.m^{-3}$ - days. This is 0.29 relative to the annual cumulative exposure of a worker exposed at 100 $\mu g.m^{-3}$ (the South African OEL) and 0.59 relative to the annual cumulative exposure of a worker exposed at 50 $\mu g.m^{-3}$ (the NIOSH REL). If the highest exposure measured for each task, rather than the median, is used to derive the estimated annual cumulative exposure i.e. a worst case exposure scenario, then the cumulative exposure would be substantially larger than 7.41 $\mu g.m^{-3}$ - days.

DISCUSSION

The study considerably adds to the evidence that over - exposure to quartz may be a risk in farming in some settings and has identified the need for practical interventions and research gaps. It is also the biggest study of its kind in that it is the first to measure a large number of personal respirable quartz concentrations (298) across various activities on three farms known to have different soil types.

We have shown that silica exposure above two generally used OELs was 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 above 50 and none above 100 $\mu g.m^{-3}$. Of particular interest is that no measurements exceeded the South African OEL of 100 $ug.m^{-3}$ on the clay soil farm; but 9% of them were between 50 - 100 $\mu g.m^{-3}$. Additionally, on each of the three farms the median silica exposures were all above the ACGIH TLV of 25 $\mu g.m^{-3}$ suggesting a possible risk of over-exposure to silica even on the clay soil farm. The annual cumulative exposure to silica of the most heavily exposed farm worker on a sandy soil farm may exceed the annual cumulative exposure if exposed at the NIOSH REL of 50 $\mu g.m^{-3}$.

Two important considerations should be borne in mind when considering these results: the findings may not be generalisable to farming in South Africa; and the potency of silica may be reduced on farms. Farming covers a large variety of commodities and activities of differing sophistication from simple manual handling to the use of large combine harvesters. Additionally, weather and soil type may affect respirable dust and respirable silica generation. Consequently, findings on three farms are unlikely to reliably describe exposure on the many thousands of South African farms. A number of factors affect the potency of respirable silica, most of them pertinent to farming. The United Kingdom's Health and Safety Executive (HSE) reviewed potency factors with regard to their ability to cause silicosis and summarised their conclusions in a respirable crystalline silica potency matrix.[23] The HSE concluded that the particle size, age of fractured silica, clays and wetting of freshly cut surfaces influence the potency of silica. Extremely small particle size enhances silica potency and particle size may be relatively large in farm soils; although, this has not been characterised to any degree. Freshly-fractured silica dust is known to be more pathogenic than silica aged by contact with air (e.g. most silica in soil).[24-25] Silica in soils is likely to be aged, with most farming activities producing little freshly fractured material; although, it might be caused by contact with metal during activities such as ploughing and discing. Only a small portion of the soil is in contact with machinery, while the majority of dust is from the disturbed soil. Thus, it seems likely that freshly fractured dust would not comprise more than a small fraction of respirable soil dust.

Aluminium-containing clay coatings on silica particles reduce potency and clay is a common constituent of farm soils. Wetting of surfaces reduces silica potency compared to dry freshly cut surfaces, but wetting to reduce dust is infrequently practised in farming as big tractors and implements may get stuck in wet soils.

Despite the probable presence of silica potency reducing factors in farming, given the large numbers of farm workers possibly exposed to silica and the seriousness of silica-associated diseases, a number of dust-related occupational health interventions should be considered in South Africa, particularly because during the course of the studies on these South African farms few if any dust control measures were observed and none of the farms had medical surveillance programmes.

POTENTIAL DUST-RELATED OCCUPATIONAL HEALTH INTERVENTIONS

Primary prevention of silica-associated diseases, i.e. the control of dust to concentrations at which disease will not occur, is the optimum form of prevention and should be the overriding goal of national and workplace occupational health programmes. Methods to improve dust control in farming are challenging but are important to protect the health of farm workers particularly those involved in the most dusty activities. The most common approach followed by occupational hygiene professionals is the "hierarchy of controls", which suggests that the hazard be removed or controlled at source followed by engineering and administrative controls ultimately ending with the use of PPE. Since silica cannot be removed from farm soils, other methods are necessary to control exposure. Limited studies describe dust control in farming (none in South Africa), but some evidence exists that differences in equipment and the manner in which a task is done may affect exposures.[26]

The presence of an enclosed cabin on the tractor has been associated with a decrease in personal dust levels[27,28] and so has lower tractor speed.[27] However, the effect of machinery on exposure potential should be carefully considered, since mechanisation may either increase or decrease potential for dust exposure.[29] The proper use of a closed cab may reduce dust exposure of a tractor driver but excessive silica exposure has been reported even for drivers of cabbed tractors in North Carolina.[12] Although an enclosed tractor cab has been suggested to be the single most effective intervention to reduce inorganic dust exposure,[30] it is very costly and dust filters need proper maintenance. Modern tractors fitted with enclosed cabins typically cost around R 2,000,000.00, probably unaffordable for the majority of small scale farmers. Theoretically, wetting, either with water or water with wetting agents, could be used to reduce dust (as is done in quarries, for example) but given the large areas to be covered on farms, the cost, the potential damage to seeds and crops and that wet soils may hinder movement of heavy machinery, wetting is a problematic solution.

Although engineering methods can be used to control dust in farming, the likelihood of their use depends upon the attitudes of farmers and farm workers toward dust exposure and legislation among other things. Two thirds of Californian farm workers perceived farming to be less hazardous than other occupations, and respiratory problems ranked after injuries and exposure to pesticides.[27]

The provision and use of PPE should be considered by farmers particularly for farm workers involved in dusty activities. The use of PPE amongst farm workers may however pose a challenge. One study showed that PPE use increased with an increase in exposure to noise and pesticides but not with an increase in dust exposure.[31] Perceptions of workers about dust and silica dust in farming may be a barrier to the implementation of exposure reduction measures, consequently raising awareness of the health effects of dust exposure is needed to promote their use.

Even with the limited exposure data available it seems reasonable to recommend surveillance of long-service farm workers (possibly those employed for 20 years or longer) for silicosis and tuberculosis. Besides the health reasons, this would be an important step to determine the burden of disease in farming. Initially surveillance could be limited to large well-resourced farms targeting long service workers, particularly those involved in the most dusty activities for substantial times during their yearly routine.

General practitioners practicing in farming areas need to be aware of the potential for silica-associated disease and submit claims under the Compensation for Occupational Injuries and Diseases Act. Silicosis cases should be eligible if they have clinical features consistent with the disease and no other occupations to account for it, but other silica-associated diseases are less clear. The Circular Instruction Regarding Compensation for Pulmonary Tuberculosis Associated with Silica Dust Exposure[32] stipulates that PTB is an occupational disease if the claimant has silicosis and PTB or if there is no radiological evidence of silicosis but the employee has been exposed to silica for two years and silica dust exposure is inherent to his/her work process or occupation. Too little is known about exposures in farming to conclude that silica dust exposure is inherent to many farming activities. COPD and lung cancer present the same difficulties. A possible approach is to submit long-service heavily dust-exposed workers with these diseases; even if rejected the claims would constitute a rudimentary register of cases.

RESEARCH NEEDS

Despite evidence that silica exposure in farming can exceed generally accepted standards[9-10,12,30] the role of determinants of silica exposure in farming has not been explicitly addressed. Exposure assessment in agriculture is difficult and complicated by a number of factors.[12] For example, workers often perform many activities, making it difficult to characterise exposure over time. It is not unusual for workers to walk from field to field with potentially different soil types, thereby introducing further variability in personal exposure to silica. This is compounded by the fact that farming is usually conducted outdoors; weather conditions (e.g. rainfall, humidity, wind speed, wind direction and pressure) are likely to play an important role in exposure variability. Additional exposure assessments should further examine the role these potential determinants of silica exposure (i.e. soil types, commodities, activities, processes [mechanical versus manual] and weather) may have on silica exposures in farming.

Potency modifiers of silica exposure also need to be better defined. The HSE describes possible silica potency modifiers [23] but very little research exists on the impact of these factors in farming. The role of particle sizes and dry, freshly fractured silica during farming activities need to be explicitly addressed so that occupational health professionals can be alert to farming activities producing very fine, freshly fractured, dry particles.

In South Africa, no study has been done to define the burden of silica-associated diseases in farming. A starting point may be to perform radiological surveys on long service farm workers (possibly more than 20 years service and performing dusty activities) on a sandy soil farm, as sandy soils are likely to produce the highest silica levels.[12] This will give some indication if silicosis occurs in farm workers during worst case exposure scenarios.

An effort should also be made to define the duration and intensity of silica exposure in farming over the annual cycle. Some processes and activities may produce high levels of silica in the breathing zone of a worker (for example during ploughing and discing) [27] and workers may do these activities for a large number of days in a farming year, but this is largely unknown. Better definition of cumulative exposure relative to activities that are known to cause silica-associated diseases are required to better understand the risk of these diseases in farming.

Lastly, cost-effective methods to reduce respirable dust and silica exposure in farming in South Africa should be identified. South Africa has a large small to medium scale farming sector employing a considerable number of people. These farmers do not have the money to introduce costly control solutions such as closed-cabbed tractors. There is a need to identify cost-effective dust control methods appropriate for settings in South Africa.

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University of the Witwatersrand Individual Faculty Research Grant and National Institute for Occupational Health, National Health Laboratory Service Research Grant (001-254-8511101-5121105-4526).

LESSONS LEARNED

1. Over-exposure to respirable quartz may occur in farming in South Africa;
2. Over-exposure is probably not only limited to sandy soil farms;
3. Practitioners working in farming areas should be aware that silica associated diseases may occur in farm workers;
4. Despite limited evidence for silica associated disease, occupational health interventions appear justified; and
5. Further research is required to identify possible determinants and exposure modifiers of respirable quartz during farming and to determine if silicosis occur in farm workers.

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Table 1 Eight-hour TWA respirable dust concentrations ($mg.m^{-3}$) on a sandy, a sandy loam and a clay soil South African farm

Farm	**n**	**AM**	**GM**	**GSD**	**Range**	
Sandy soil farm	138	0.68	0.3	3.2	0.02	6.49
Sandy loam soil farm	77	0.46	0.2	2.9	0.03	3.39
Clay soil farm	83	0.73	0.5	2.5	0.06	3.97
Total	**298**	**0.64**	**0.3**	**3.0**	**0.02**	**6.49**

GM - geometric mean; GSD - geometric standard deviation; AM - arithmetic mean; TWA - time weighted average.

Adapted from Swanepoel et al., 2011 with kind permission from RightsLink[10]

Table 2 Eight-hour TWA respirable quartz concentrations ($\mu g.m^{-3}$) on a sandy, sandy loam and clay soil South African farm

Farm	**n**	**%<LOD**	**AM**	**GM**	**GSD**	**Range**	**%≥100***	**%≥50†**	**%≥25‡**	**%quartz Median**
Sandy soil farm	138	35	53.2	31.7	2.7	<LOD - 626	12	30	57	14.3
Sandy loam soil farm	77	27	46.85	31.6	2.3	<LOD - 413	13	22	59	14.0
Clay soil farm	83	64	33.8	31.1	1.4	<LOD - 98	0	9	81	13.7
Total	**298**	**41**	**46.0**	**31.5**	**2.3**	**<LOD - 626**	**9**	**22**	**64**	**14.0**

%<LOD, % of measurements under the analytical limit of detection; AM - arithmetic mean; GM - geometric mean; GSD - geometric standard deviation; TWA - time weighted average.

*% Measurements greater or equal to the South African Occupational Exposure Limit of 100 $\mu g.m^{-3}$ for respirable quartz.

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

‡% Measurements greater or equal to the ACGIH Threshold Limit Value of 25 $\mu g.m^{-3}$ for respirable quartz.

Adapted from Swanepoel et al., 2011 with kind permission from RightsLink[10]

APPENDIX

Appendix I Ethics Clearance Certificate

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

Division of the Deputy Registrar (Research)

HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)
R14/49 Swanepoel

CLEARANCE CERTIFICATE	**PROTOCOL NUMBER M070252**
PROJECT	Exposure to Respirable Crystalline Silica in Central South African Farm Workers
INVESTIGATORS	Mr AJ Swanepoel
DEPARTMENT	School of Public Health
DATE CONSIDERED	07.03.02
DECISION OF THE COMMITTEE*	Approved unconditionally

Unless otherwise specified this ethical clearance is valid for 5 years and may be renewed upon application.

DATE 07.03.05 **CHAIRPERSON** ....
(Professors PE Cleaton-Jones, A Dhai, M Vorster, C Feldman, A Woodiwiss)

*Guidelines for written 'informed consent' attached where applicable

cc: Supervisor : Prof D Rees

DECLARATION OF INVESTIGATOR(S)

To be completed in duplicate and **ONE COPY** returned to the Secretary at Room 10005, 10th Floor, Senate House, University.
I/We fully understand the conditions under which I am/we are authorized to carry out the abovementioned research and I/we guarantee to ensure compliance with these conditions. Should any departure to be contemplated from the research procedure as approved I/we undertake to resubmit the protocol to the Committee. **I agree to a completion of a yearly progress report.**

PLEASE QUOTE THE PROTOCOL NUMBER IN ALL ENQUIRIES