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Magnetic Susceptibility of Tree Leaves as a Simple, Cost-Effective Means of Monitoring Air Quality

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Abstract

The high cost of air quality monitoring stations ($10K - $70K, not including maintenance and operation) makes it difficult for citizens or local governments to monitor air quality in their own neighborhoods, especially in low-income communities. The air-quality stations monitor levels of CO, NO_2, O_3, PM-2.5 (concentration of particulate matter smaller than 2.5 microns), and PM-10. The objective of this study was to find a cheaper method of measuring long-term air quality with a wider distribution. The objective was initially addressed by measuring the magnetic susceptibilities of forty leaf samples of 12 species of trees, and then later additional samples were taken. All of the samples were collected within a two-mile radius of each of the four air-quality monitoring stations in Utah County and Salt Lake County. After air-drying and crushing the samples, both low-frequency (0.46 kHz) and high-frequency (4.6 kHz) magnetic susceptibilities were measured with the Bartington MS3 Magnetic Susceptibility Meter. The best correlations between tree leaf magnetic susceptibilities and air-quality parameters were between the three-year average of PM-2.5 and the high-frequency magnetic susceptibility of leaves of pine (*Pinus aristata*) (R^2 = 0.87, P = 0.005). The correlation was used with measured high-frequency magnetic susceptibilities of pine to estimate PM-2.5 in two unmonitored locations heavily impacted by highway traffic (corner of 800 N and I-15 and corner of University Parkway and I-15, both in Orem, Utah) on one day in August 2013. It was found that estimated levels of PM-2.5 were 9.5 $\mu g/cm^3$ and 8.9 $\mu g/cm^3$, respectively, which were below the EPA PM-2.5 annual standard of 12 $\mu g/cm^3$ for Utah.[1] Further results included samples tested in Salt Lake County, additional samples in Utah County, as well as in Kentucky while at NCUR in 2014. All of the results obtained from this study suggest that there is a strong correlation between magnetic susceptibility and air concentrations of PM-2.5.

Keywords: Leaf, Magnetic Susceptibility, PM-2.5

1. Introduction

The high cost of air quality monitoring stations ($10K - $70K, not including maintenance and operation) makes it difficult for citizens or local governments to monitor air quality in their own neighborhoods, especially in low-income communities. For example, Utah County, Utah, with an area of 2141 mi^2, and a population of approximately 540,000, has only four air quality monitoring stations (see Table 2 & Fig. 1). The air quality stations monitor levels of CO, NO_2, O_3, PM-2.5 (concentration of particulate matter smaller than 2.5 microns), and PM-10 (concentration of particulate matter smaller than 10 microns). However, with such a low density of air quality monitoring stations, the data representing Utah County's air quality are not sufficient to give an accurate representation of the county as a whole. The monitoring stations are not adequately distributed across Utah County, which prevents proper air monitoring in the county. In 2010, cities such as Orem had a population density of 4828.5 persons per square mile[2], and the city of Highland had a population density of 1821.5 persons per square mile.[3] Due to Orem's higher population density, higher traffic is expected and thus results in worse air quality; yet Orem has no monitoring station. Moreover, in 2012, "Highland's air monitoring station was disabled due to trees growing in the way of the air monitoring station", according to personal communication with the Utah DAQ.[4]

The objective of this study was to determine whether magnetic susceptibility of leaves could be used as a method of estimating air quality. The idea is that leaves and needles may adsorb the contaminants onto the surface as well as absorb them over time. The parameter PM-2.5 was chosen as the focus of this study due to the danger it presents to society and the lack of correlation with the other monitored particles of CO, NO_2, O_3, and PM-10; also because not all of the monitoring stations monitor the same particles. Particles smaller than 2.5 microns are able to enter the respiratory system and become trapped in the lungs, causing medical problems including decreased lung function, irregular heartbeats, and heart attacks.[5] These particles arise from a number of sources, primarily from pollutants from motorized vehicles, construction, industrial pollution from oil refining, smelting and powder coating plants, agricultural burning, and wood burning stoves.[6] Weather and atmospheric conditions have a large impact on the PM2.5 concentration levels. The objective was addressed by testing whether the magnetic susceptibilities of various tree leaves could be correlated with PM 2.5 concentrations as measured at the four Utah County air quality monitoring stations and the three Salt Lake County monitoring stations. A prior study[7], which used a different method of particulate matter collection involving wiping stop signs with paper towels, was unable to show any correlation between magnetic susceptibility and air pollution. The study concluded that the paper towel diluted the magnetic susceptibility measurements. Initially, ten samples were collected within a two-mile radius of the four monitoring stations in Utah County, from 12 different tree species (below table 1 lists the tree species). For this project a total of 64 leaf samples were taken and analyzed. The two-mile radius was chosen so that the leaves could be considered to be in similar environmental conditions as the air quality monitoring stations.

Table 1. Types of tree which were sampled for analysis.

Common Name	**Genus species**	**Family**	**Order**
Pine	*Pinus aristata*	Pinaceae	Pinales
Flowering Pear	*Pyrus calleryana*	Rosaceae	Rosales
Spruce	*Picea engelmannii*	Pinaceae	Pinales
Red Maple	*Acer rubrum*	Aceraceae	Sapindales
Norway Maple	*Acer platanoides*	Sapindaceae	Sapindales
Russian Olive	*Elaeagnus angustifolia*	Elaeagnaceae	Rosales
Green Ash	*Fraxinus pennsylvanica*	Oleaceae	Lamiales
Elm	*Ulmus americana*	Ulmaceae	Rosales
Cypress	*Actinostrobus acuminatus*	Cupressaceae	Pinales
Crab Apple	*Malus fusca*	Rosaceae	Rosales
Honey Locust	*Gleditsia triacanthos*	Fabaceae	Fabales
Linden	*Tilia americana*	Malvaceae	Malvales

If a correlation could be determined, then our method of finding an alternative and far cheaper approach to air quality monitoring would be possible. The approach used here costs roughly $4000 in equipment in addition to the time and travel expenses for collecting and measuring the collected samples. Also since the equipment is small and portable, one magnetic susceptibility meter could be used in multiple locations. Compared to the cost of currently used laboratory, staffing, and equipment, there is significant cost savings.

Table 2. Utah County and Salt Lake County air quality monitoring locations

County	Location	Address
Utah	Highland	10865 North 6000 West, Highland
	Lindon	50 North Main Street, Lindon
	Provo	1355 North 200 West, Provo
	Spanish Fork	2050 N 300 W, Spanish Fork
Salt Lake	Hawthorne	1675 S 600 E, Salt Lake City
	Rose Park	1400 Goodwin Ave, Salt Lake City
	University of Utah	201 Presidents Circle, Salt Lake City

Legend	
1	Hawthorne
2	University of Utah
3	Rose Park
4	Highland
5	Lindon
6	Provo
7	Spanish Fork

Figure 1: Maps of Salt Lake County (top) and Utah County (bottom), the red X's indicate the locations of the monitoring stations; the numbers show name/location for each monitoring station.

2. Methodology

Samples collected near stations in Provo and Lindon were collected on the same day (7-17-13), whereas samples collected near stations in Highland (7-26-13) and Spanish Fork (7-25-13) were collected on different days (see tables 3-5). The sampled leaves were still attached to the tree they were chosen from and were removed by hand. All leaf samples were placed in individual zip-lock bags. Each leaf sample was air-dried for seven days to ensure uniform water content.

Table 3. Samples Collected 7-17-2013, between 7:30am - 9:30am MST; Samples Analyzed 7-23-2013

Tree Species	Location	Air Quality Station	Mass (g)	χ_{LF} [1] (SI units x 10^{-6})	χ_{HF} [2] (SI units x 10^{-6})
Pine	Lindon Elementary	Lindon	1.75	-3.95	-3.98
Flowering Pear	Lindon Elementary	Lindon	1.69	-2.01	-10.6
Spruce	Lindon Elementary	Lindon	1.95	1.94	-5.28
Red Maple	State Street, Lindon Nursery	Lindon	0.80	25.1	-13.9
Norway Maple	State Street, Lindon Homes	Lindon	0.71	4.59	-14.6
Norway Maple	State Street, Lindon Homes	Lindon	0.54	-0.678	4.68
Russian Olive	Galvanizing Plant, Geneva Rd.	Lindon	1.13	0.678	-17.8
Pine	Steel Plant, Lindon	Lindon	2.61	11.9	23.2
Flowering Pear	Steel Plant, Lindon	Lindon	1.33	-3.31	33.7
Green Ash	Mt. States Steel Plant, Lindon	Lindon	0.61	6.63	15.8
Norway Maple	Provo Air Monitoring Station	Provo	0.98	-2.64	-9.26
Norway Maple	Provo High School	Provo	0.86	-3.93	-15.9
Elm	BYU MRI Research Center	Provo	1.73	-5.28	-13.3
Colorado Spruce	BYU Science Building	Provo	1.92	-0.664	8.60
Pine	BYU Science Building	Provo	1.48	-0.00590	7.97
Cypress	Provo Power Plant	Provo	2.37	-60.8	7.92
Crab Apple	Provo Power Plant	Provo	1.34	-19.8	5.96
Honey Locust	UV Regional Medical Center	Provo	1.43	-5.26	-3560
Pine	UV Regional Medical Center	Provo	1.36	3.34	-4.61
Linden	UV Regional Medical Center	Provo	1.72	3.95	-3.98

[1] χ_{LF} = low frequency magnetic susceptibility [2] χ_{HF} = high frequency magnetic susceptibility

Table 4. Samples Collected 7-25-13, between 8:00am-10:00am MST; Samples Analyzed 7-30-13

Tree Species	Location	Air Quality Station	Mass (g)	χ_{LF} [1] (SI units x 10^{-6})	χ_{HF} [2] (SI units x 10^{-6})
Crab Apple	Spanish Fork Airport	Spanish Fork	1.51	-2.59	-17.8
Maple	Spanish Fork Airport	Spanish Fork	1.82	-3.29	-26.4
Honey Locust	Spanish Fork Airport	Spanish Fork	1.41	-4.65	-6.58
Pine	Spanish Fork Airport	Spanish Fork	1.78	1.32	-4.65
Crab Apple	Spanish Fork Airport	Spanish Fork	1.17	-13.2	0.652
Crab Apple	Spanish Fork Airport	Spanish Fork	0.93	-9.26	-2.67
Elm	Spanish Fork Airport	Spanish Fork	1.1	-1.32	-5.26
Linden	Spanish Fork Airport	Spanish Fork	2.13	1.99	-7.30
Maple	Spanish Fork Airport	Spanish Fork	0.96	-9.94	-13.2
Pine	Spanish Fork Airport	Spanish Fork	1.54	1.33	-7.27

[1] χ_{LF} = low frequency magnetic susceptibility [2] χ_{HF} = high frequency magnetic susceptibility

Table 5. Samples collected 7-26-13, between 4:30pm-5:00pm MST; samples analyzed 7-30-13

Tree Species	**Location**	**Air Quality Station**	**Mass (g)**	**χ_{LF}[1] (SI units x 10^{-6})**	**χ_{HF}[2] (SI units x 10^{-6})**
Flowering Pear	5720 W 10776 N, Highland	Highland	1.55	-7.26	-4.02
Pine	6000 W 11000 N, Highland	Highland	1.57	-0.690	-0.696
Spruce	1048 N 5000 E, Highland	Highland	2.56	-6.62	-13.8
Crab Apple	5400 N 10770 W, Highland	Highland	1.74	1.32	-5.29
Red Maple	6000 W 11000 N, Highland	Highland	1.76	-6.58	-6.61
Flowering Pear	16000 W 10550 N, Highland	Highland	0.53	-6.02	-2.00
Norway Maple	6000 W 10550 N, Highland	Highland	1.48	13.8	-4.65
Colorado Spruce	Air Quality Monitoring, Highland	Highland	3.03	-8.60	-5.96
Russian Olive	10930 N 55600 W, Highland	Highland	2.38	-5.95	-31.7
Norway Maple	10777 N 5770 W, Highland	Highland	0.88	-2.68	-4.61

[1] χ_{LF} = low frequency magnetic susceptibility [2] χ_{HF} = high frequency magnetic susceptibility

All the samples from Utah were taken to Linden Nursery to identify the tree species. The magnetic susceptibility system used was a Bartington MS3 Magnetic Susceptibility Meter with the MS2B Dual Frequency Sensor. The MS2B sensor accepts plastic paleomagnetic sample containers with cubic dimensions of 25.4 mm. For ease of loading the sample boxes, the leaves were chopped into small pieces using a Black and Decker mini-food processor and scissors. Each sample was then tightly packed into its respective paleomagnetic box. Additionally, the weight of each sample was obtained using a Mettler AE 200 Scale. To further check whether magnetic susceptibility and PM 2.5 concentration can be correlated, samples from Salt Lake County, Utah, were collected in the spring and analyzed in the same manner as Utah County samples.

Each sample's magnetic susceptibility was determined on both the low (0.46 KHz) and high (4.6 KHz) frequency settings. It was ensured that the magnetic susceptibility meter was zeroed prior to each reading. The collection time for each sample was taken for a period of ten seconds, which also was the time taken to zero the meter. Data taken from each of the seven stations were found using the Utah Department of Environmental Quality website.[8] The above procedure was repeated again less than one year later (summer 2013 - spring 2014; see tables 6-7).

Table 6. Samples collected 3-6-14, between 9:30am-11:30am MST; samples analyzed 3-13-14

Tree Species	**Location**	**Air Quality Station**	**χ_{LF}[1] (SI units x 10^{-6})**	**χ_{HF}[2] (SI units x 10^{-6})**
Pine	Air Monitoring Station, Lindon	Lindon	-1.34	-3.33
Pine	Park Color slide 200N, Lindon	Lindon	-1.32	-4.59
Pine	200S 800W, Lindon	Lindon	21.9	17.9
Pine	Nature's Sunshine Loading Dock, Spanish Fork	Spanish Fork	-1.31	-1.35
Pine	200E Ind. Prk Dr., Spanish Fork	Spanish Fork	-2.65	-6.62
Pine	Kapstone, Spanish Fork	Spanish Fork	-5.29	-5.95
Pine	Pioneer Park, Provo	Provo	-4.62	-7.31
Pine	Utah Valley Regional Hospital, Provo	Provo	8.58	-2.59
Pine	Sonic Car Wash, Provo	Provo	-3.98	-5.99

[1] χ_{LF} = low frequency magnetic susceptibility [2] χ_{HF} = high frequency magnetic susceptibility

Table 7. Samples collected 3-6-14, between 1:00pm-3:00pm MST; samples analyzed 3-13-14

Tree Species	**Location**	**Air Quality Station**	**χ_{LF}[1] (SI units x 10^{-6})**	**χ_{HF}[2] (SI units x 10^{-6})**
Pine	400 E 1770 S, Salt Lake City	Hawthorn	1.34	-5.29
Pine	559 E 1770 S, Salt Lake City	Hawthorn	-1.97	-6.61
Pine	718 E 1490 S, Salt Lake City	Hawthorn	2.67	-3.93
Pine	700 E 1955 S, Salt Lake City	Hawthorn	2.01	-2.04
Pine	University of Utah, Salt Lake City	U of U	8.58	-3.29
Pine	University of Utah, Salt Lake City	U of U	-6.35	3.9
Pine	University of Utah, Salt Lake City	U of U	2.63	-2.61
Pine	University of Utah, Salt Lake City	U of U	1.62	-0.667
Pine	960 W 11000 N, Salt Lake City	Rose Park	5.26	-1.33
Pine	900 W 640 N, Salt Lake City	Rose Park	1.29	-4.01
Pine	1660 W 1000 N, Salt Lake City	Rose Park	2.65	-4.65
Pine	1320W 1200N, Salt Lake City	Rose Park	1.98	-3.33

[1]χ_{LF} = low frequency magnetic susceptibility [2]χ_{HF} = high frequency magnetic susceptibility

While on the University of Kentucky campus for NCUR, three white pine (*Pinus strobus*) samples were selected and collected for analysis prior to presenting this research at the 2014 National Conference on Undergraduate Research (NCUR). The three pine needles were chosen in three differing air quality conditions based on their proximity to possible PM 2.5 pollution. Based upon the tree locations, it was hypothesized that the Journalism Building sample would have the lowest PM 2.5 pollutants and thus the lowest magnetic susceptibility reading of the three samples. The Journalism Building sample was between two buildings with just foot traffic below and no busy streets nearby. Next, the Student Center sample was positioned approximately 200 feet off of a semi-busy road called the Avenue of Champions and near the University of Kentucky's Student Center. Based upon the Student Center's location, it should have more exposure to PM 2.5 pollutants than the Journalism Building sample due to higher traffic, since car pollution is a contributing source of PM 2.5 pollution.[6] Lastly, the Front Entrance sample was located near the front entrance of the University of Kentucky, where a higher volume of traffic was apparent than on the Avenue of Champions. Additionally the Front Entrance sample was also near a nearly completed construction site and heavier traffic. Therefore the Front Entrance was exposed to more PM 2.5 pollution than either the Journalism Building sample or the Student Center Sample.

3. Data

Each of the seven listed air quality monitoring stations takes hourly measurements of PM 2.5 and other particulates[8] such as: NO_2, CO_2, SO_2, Ozone, and PM 10; however there is no state air monitoring station near the University of Kentucky. The PM 2.5 data are posted two months after measuring and the yearly report for 2013 has now been finalized. The PM 2.5 data for each of the seven monitored stations are available online in differing length periods including: daily, one-year, and three-year averages for the past ten years (see Table 8), and older data can be obtained by request to the DAQ. Based upon the discrepancy in magnetic susceptibility measurements between low and high frequency values (see Figure 2), it was determined to focus solely on one of the coniferous species, pine. Pine was chosen because its magnetic susceptibility readings were most consistent between high and low frequencies. Also pine is one of the most common species found in Utah and Salt Lake Counties.

Table 8. Three-year average (2010-2012) for PM 2.5 concentration at each station[9]

County	Air Monitoring Site	PM 2.5 ($\mu g/m^3$) (2010-2012)	PM 2.5 ($\mu g/m^3$) (2011-2013)
Utah County	Lindon	8.41	9.59
	Provo	8.14	9.09
	Spanish Fork Airport	7.86	8.56
	Highland	8.22	NA
Salt Lake County	Hawthorne	8.94	9.57
	Rose Park	9.21	9.99

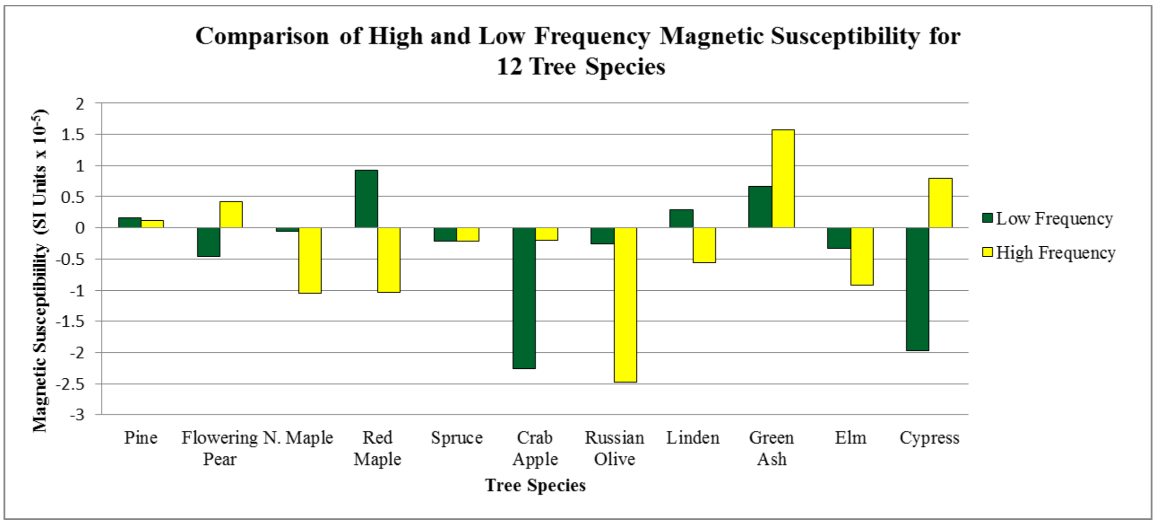

Figure 2. Out of 12 tree species, pine and spruce showed the least variation between low and high frequency magnetic susceptibility measurements. Pine is commonly found in Utah and Salt Lake Counties, therefore in it was chosen as the focus for this study.

It was found that magnetic susceptibility measurements obtained varied greatly with the use of either high or low frequency settings of the Bartington Magnetic Susceptibility meter (see Figure 2). For instance the low frequency magnetic susceptibility measurement for red maple was 9.28×10^{-6} SI units, whereas the high frequency magnetic susceptibly measurement of the same sample yielded a value of -10.3×10^{-6} SI units.

Figures 3a shows the relation between PM 2.5 and magnetic susceptibility (measured on high frequency); the excellent R^2 value, 0.87, shows that the data correlate very well and indicate that PM 2.5 concentration is linearly proportional to magnetic susceptibility. However, a weaker relation is observed (Figure 3b), when magnetic susceptibility is measured on low frequency, an R^2 value of 0.17.

Using equation (1) with measured high-frequency magnetic susceptibilities of two pine samples the PM 2.5 concentration was estimated. Where y = PM 2.5 ($\mu g/m^3$), and x = magnetic susceptibility (SI units). Both samples were located in unmonitored air quality locations in Orem. It was found that estimated levels of PM-2.5 were 9.5 $\mu g/cm^3$ and 8.9 $\mu g/cm^3$, respectively, which were below the EPA PM-2.5 annual standard for Utah which is 12 $\mu g/cm^3$.[1]

$$y = 32849x + 8.1196 \qquad (1)$$

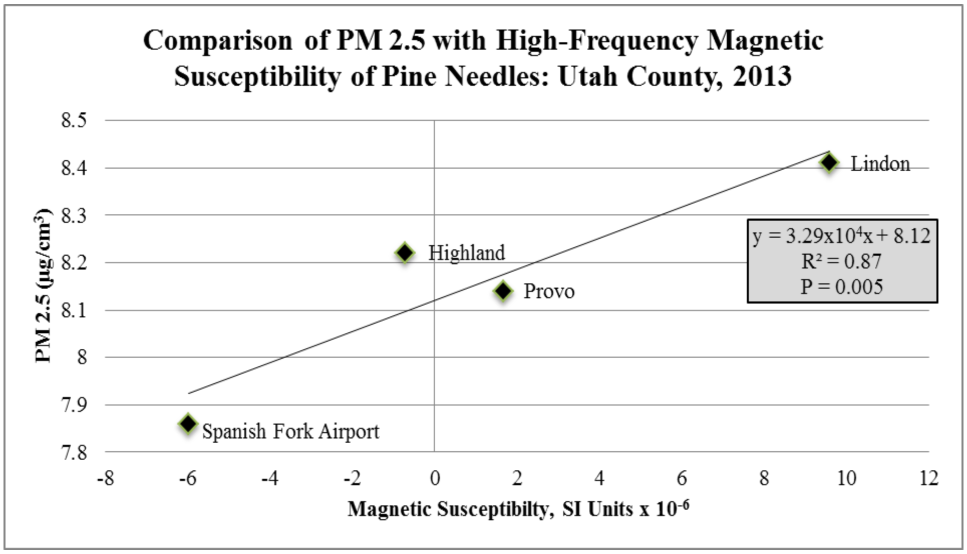

Figure 3a. There was an excellent (R^2 = 0.87) linear correlation between PM-2.5 and the high-frequency magnetic susceptibility of pine needles. The correlation was statistically significant at the 99% confidence level (P = 0.005).

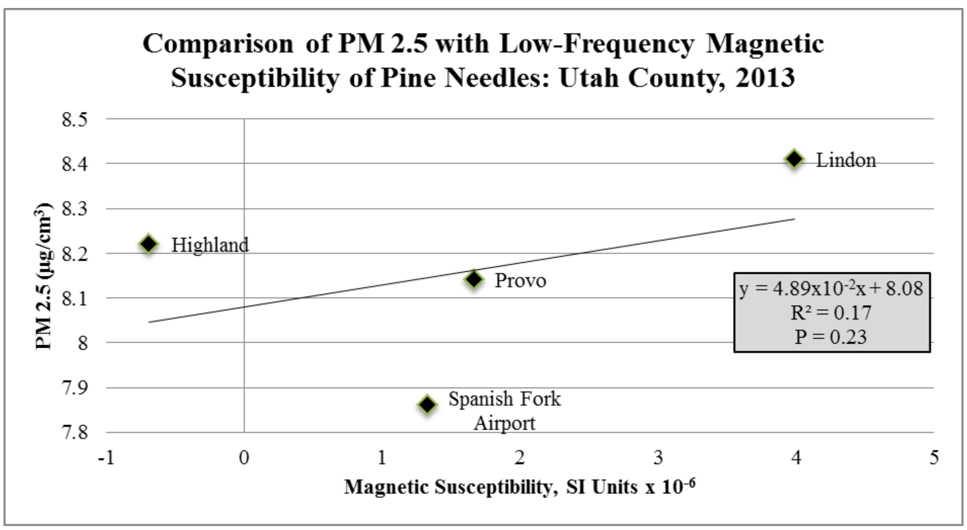

Figure 3b. There was a poor (R^2 = 0.17) linear correlation between PM-2.5 and the low-frequency magnetic susceptibility of pine needles. The correlation was not statistically significant.

The above Figures 3a-b represent the pine samples collected in Summer 2013, whereas Figure 4 represents pine samples collected in Spring 2014. The 2014 also differ from the 2013 samples in that the magnetic susceptibility readings are graphed against a one year PM 2.5 average whereas the 2013 samples were graphed against three year PM 2.5 average. However due to trees growing in the way of the Highland air quality monitoring station, the station was disabled and therefore had no PM 2.5 data.

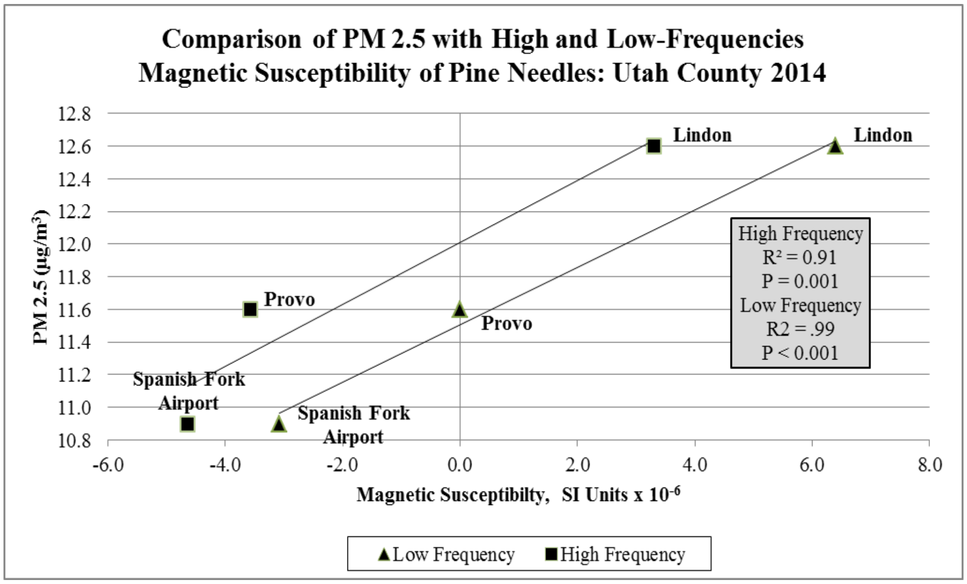

Figure 4. Spring 2014 pine needle samples showed excellent correlations between PM 2.5 and magnetic susceptibility of pine needles for both high (R^2 = 0.91, P = 0.001) and low frequencies (R^2 = 0.99 , P < 0.001).

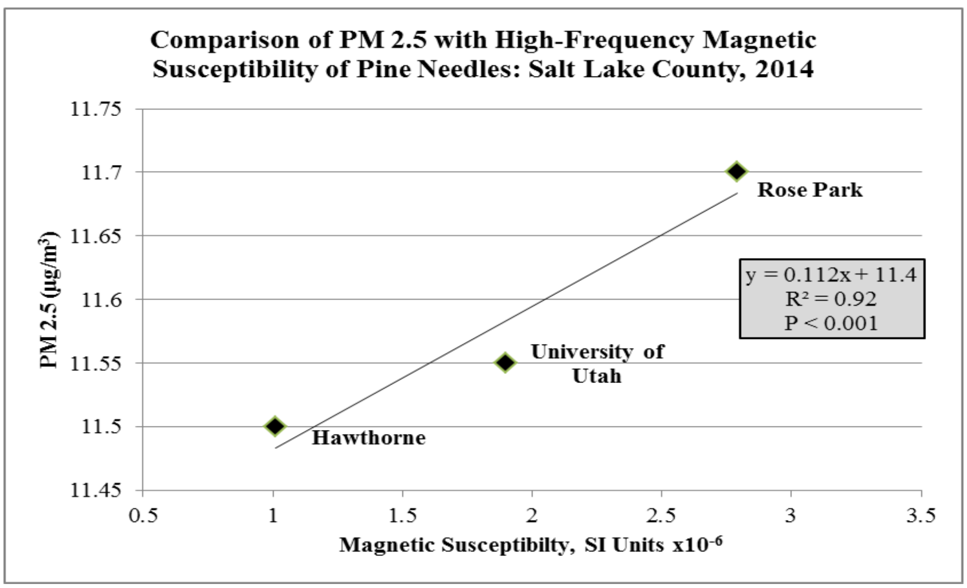

Figure 5a. The Salt Lake County samples yielded an excellent (R^2 = 0.92) linear correlation between PM 2.5 and the low frequency magnetic susceptibility of pine needles collected in the summer of 2013. The correlation was statistically significant at the 99% confidence level (P < 0.001).

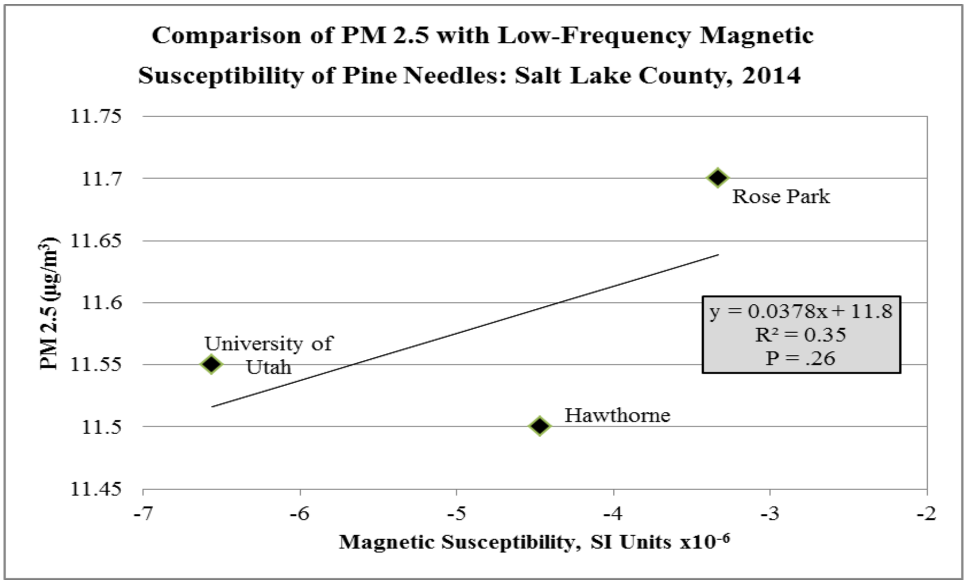

Figure 5b. There was a poor (R^2 = 0.35) linear correlation between PM 2.5 and the high-frequency magnetic susceptibility of pine needles collected in 2013. The correlation was not statistically significant.

The results from the samples taken in Kentucky at the 2014 NCUR Conference shows that PM 2.5 and magnetic susceptibility are correlated. Graphical representation of measured magnetic susceptibilities of white pine needles sampled at NCUR 2014 on the University of Kentucky Campus can be seen in Figure 6. It was further determined that magnetic susceptibility and PM 2.5 concentration do correlate; the graphical results were similar to those found in Utah.

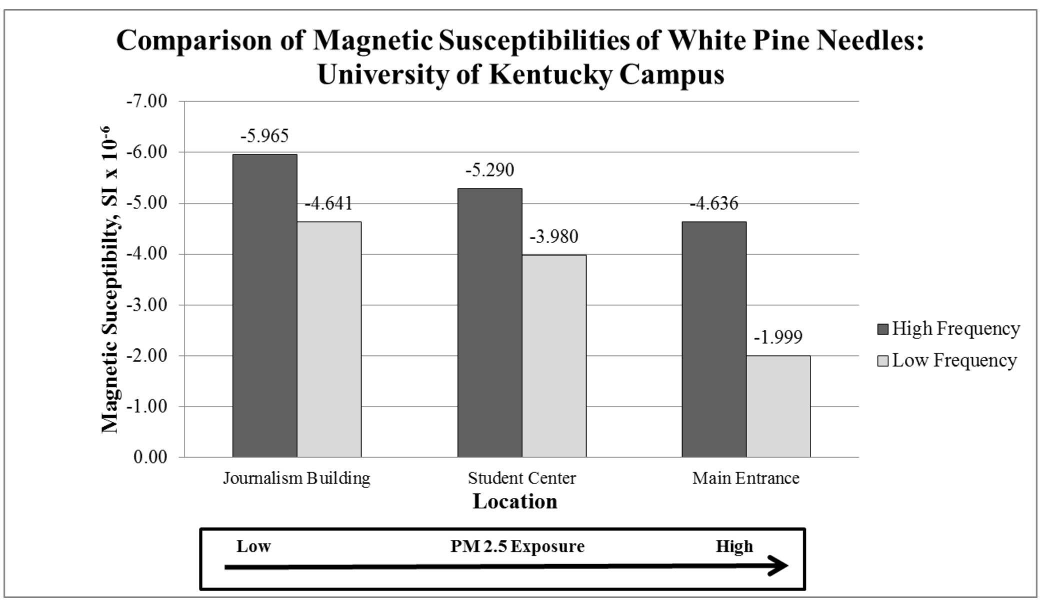

Figure 6. As hypothesized, the sampled pine needles with the greatest PM 2.5 exposure recorded the highest magnetic susceptibility value~~,~~ thus indicating that magnetic susceptibility and PM 2.5 concentration are proportional.

4. Conclusion

In finding that PM 2.5 is proportional to magnetic susceptibility of pine needles; other avenues may open for further research in air quality studies.

Our methodology could be improved in a number of ways. The first would be to ensure that samples are obtained from the same tree species from each of the sampling locations. Also taking careful note of the samples' proximity to a potential PM 2.5 sources such as automobile, power plants, residential wood burning, and agricultural burning[8,10] would be beneficial when attempting to correlate the magnetic susceptibilities and air quality monitoring data.[4]

There was a great amount of variance between magnetic susceptibility measurements (see Figure 2) when switching between high and low frequencies, both among and between species. Complexity arises when various tree species are used for comparison. The surface structure and composition of tree leaves differs from one tree type to another. Therefore further examination into the actual surface structure and composition of the sampled tree leaves could help explain the leaf's ability to trap PM 2.5. Also it must be noted that coniferous trees (pine and spruce) maintain their leaves for approximately 3-5 years, whereas deciduous trees (maple, ash, olive, linden, etc.) maintain their leaves for 6-8 months, resulting in differing accumulation times for PM 2.5 to settle on a given leaf.

5. Acknowledgements

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