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Household and behavioral determinants of indoor $PM_{2.5}$ in a rural, solid fuel burning Native American community

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Abstract

Indoor and outdoor concentrations of $PM_{2.5}$ were measured for 24-hours during heating and non-heating seasons in a rural, solid fuel burning, Native American community. Household building characteristics were collected during the initial home sampling visit using technician walkthrough questionnaires, and behavioral factors were collected through questionnaires by interviewers. To identify seasonal behavioral factors and household characteristics associated with indoor $PM_{2.5}$, data were analyzed separately by heating and non-heating seasons using multivariable regression. Concentrations of $PM_{2.5}$ were significantly higher during the heating season (Indoor: 36.2 $\mu g/m^3$; Outdoor: 22.1 $\mu g/m^3$) compared to the non-heating season (Indoor: 14.6 $\mu g/m^3$; Outdoor: 9.3 $\mu g/m^3$). Heating season indoor $PM_{2.5}$ was strongly associated with heating fuel type, housing type, indoor pests, use of a climate control unit, number of interior doors and indoor relative humidity. During the non-heating season, different behavioral and household characteristics were associated with indoor $PM_{2.5}$ concentrations (indoor smoking and/or burning incense, opening doors and windows, area of surrounding environment, building size and height, and outdoor $PM_{2.5}$). Homes heated with coal and/or wood, or a combination of coal and/or wood with electricity and/or natural

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Author Contributions

Steven Hadeed wrote the initial draft of the manuscript with conceptual, interpretive and editorial assistance from Mary Kay O'Rourke, Robert A. Canales, Jefferey Burgess and Robin Harris. Robert A. Canales consulted on statistical approaches for data analysis, helped with interpretation and edited the statistical components of the manuscript. Lorencita Joshweseoma helped prepare the original manuscript, checked for compliance related to Hopi cultural concerns and ushered the manuscript through the Community Advisory Board and other tribal approval requirements. Gregory Sehongva contributed assessments of activity and behavioral data while Morris Paukgana contributed to the interpretation of the pollutant results. Emmanuel Gonzalez-Figueroa and Modhi Alshammari helped prepare data sets and assure data quality for all statistical analysis. All authors read and edited the final version of the manuscript.

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

gas had elevated indoor $PM_{2.5}$ concentrations that exceeded both the EPA ambient standard (35 μg/m^3) and the WHO guideline (25 μg/m^3).

Keywords

solid fuel use; household air pollution; indoor $PM_{2.5}$; household environmental risk factors; rural health

Introduction

Solid fuels (biomass, coal) are used for cooking, heating, and lighting by approximately 3 billion people globally (WHO, 2016). The reliance on these fuels results in an estimated 3.8 million premature deaths per year attributable to household air pollutants (HAPs) from combustion of these fuel sources (WHO, 2016). Fine particulate matter ($PM_{2.5}$) is a hazardous air pollutant widely associated with adverse health outcomes such as stroke, respiratory disease, asthma, lung cancer and death (Apte et al., 2015; Bruce et al., 2000). People are exposed through inhalation to $PM_{2.5}$ generated from the burning of solid fuels for heating and cooking. A large proportion of the global population relying on the use of these fuels reside in low-income communities of developing nations. Neighborhood and household level environmental monitoring is necessary to understand the health effects from $PM_{2.5}$ exposures, and to guide targeted interventions and develop appropriate public health policy.

Despite the prevalent use of solid fuels in developing nations, recent studies (Bulkow et al., 2012; Rogalsky et al., 2014; Semmens et al., 2015) suggest that low income rural populations of the United States, and other affluent countries, experience similar exposures to HAPs. Rogalsky et al., (2014) estimate that more than 2.5 million households and 6.5 million people in the United States use solid fuel as a primary heating source. Exposure to HAPs is strongly associated with poverty, lack of access to cleaner fuels, and improper stove maintenance. In northern and western regions of the United States, solid fuel use is highly prevalent in rural communities with high poverty levels. Solid fuel use and poverty rates are highest in the Southwestern United States, specifically the Four Corners region of Arizona, Utah, Colorado and New Mexico (Rogalsky et al., 2014). Native American communities are disproportionately affected by air pollution and are at greater risk for exposures and adverse health effects due to the economic disadvantages and health disparities that exist on tribal lands (U.S. EPA, 2015).

Monitoring of indoor air pollutants in tribal communities in the United States is limited. Robin et al. (1996) examined the association between indoor concentrations of PM_{10} and respiratory infection in children living in solid fuel burning homes on the Navajo Nation. In wood heated homes (n=3) that cooked with electricity or gas, median concentrations of PM_{10} were 100.9 μg/m^3 (GM=57.4), whereas homes that cooked and heated with only wood (n=4) had median indoor concentrations of 85.6 μg/m^3 (GM=62.8). Homes using electricity or gas for heating and cooking had the lowest indoor concentrations (median=22.2 μg/m^3, GM=18.8). In homes cooking with wood, acute lower respiratory infection in children was five times higher than children living in gas or electric homes. Quantifying and characterizing $PM_{2.5}$ concentration in coal burning homes on the Navajo Nation was most recently assessed in 19 homes and reported an average 24-hour $PM_{2.5}$ concentration of 37.9 μg/m^3, with mean daily concentrations as high as 109 μg/m^3, exceeding the EPA 24-hour ambient standard of 35 μg/m^3 (Bunnell et al., 2010). Although these two studies were conducted in a different tribal community, the Navajo Nation and Hopi Tribe border one another, use coal originating from the same coal mine, and experience similar socioeconomic constraints.

Relatively few studies have assessed rural, indoor air quality in the United States, where populations continue to experience greater health disparities and disease burden. The prevalent use of solid fuel in rural households highlights the need for quantifying indoor concentrations of $PM_{2.5}$ in these communities. The Hopi Tribe of rural Northern Arizona is among those affected. A large proportion of Hopi households report burning coal (37%) and wood (33%) for heating (U.S. Census Bureau, 1995). Alarmingly, roughly half of youth on Hopi lands live in poverty (U.S. Census Bureau, 2010). A 2012 health survey reported 24% of participants experience asthma attacks (Joshweseoma, 2015). No prior environmental air monitoring study has been undertaken with the Hopi Tribe. The goal of this study is to determine behavioral and household characteristics associated with indoor $PM_{2.5}$ concentrations during heating and non-heating seasons in households of a rural, solid fuel burning, Native American community.

Methods

Study Population & Setting

The Hopi are a Native American Tribe of Pueblo People in rural, Northern Arizona who live in 12 villages within the 6,557 square kilometers of Hopi land. The area contains 7,185 Hopi residing in 2,081 households with a median income of $34,016 (US) per year (U.S. Census Bureau, 2010). The Hopi Tribal lands are situated on the Colorado Plateau in northeastern Arizona with an average elevation of 7200 feet. It also experiences wide variability in temperature and precipitation with substantial variability between winter and summer wet seasons and dry intervening seasons (Crimmins et al., 2015). Until 2020, members of the Hopi Tribe were provided free coal from a large nearby mining operation, which served as a major heating source. Although coal was widely available, it was used exclusively for seasonal heating purposes, whereas electricity and liquid propane gas were used primarily for cooking.

Hopi homes were classified into three categories: Traditional, modern or modular/mobile and building materials varied among these home types. Traditional homes were frequently built of rock and plastered with mud mortar and included packed dirt floors and roofing of traditional tuuma (dirt over brush or sticks). Some of these homes were built prior to 1,100 AD based on archaeological records of the area (Carson et al., 2020, Whiteley, 1988). Most modern homes had concrete slab floors with frame or block walls and asphalt roofs. Modular/mobile homes were constructed in a factory and had air flowing under the structure, a metal exterior, coated with a sprayed insulation and finished with paneling and ceiling tile. Hopi homes could have elements of each building type and were categorized by the percent of the dominant material. Some homes lacked electricity, and running water depending on age and location. In general, heating stoves at Hopi were located in the main living area where people spend most of their waking hours.

There are no standard floor plans for Hopi homes and there are no building code requirements. People build and modify their homes as they choose. The Hopi Environmental Health Project (HEHP) is a community based participatory research (CBPR) project conducted with Hopi partners and with oversight by a Community Advisory Board (CAB). The CAB prohibited photos of homes or people to protect privacy.

Recruitment & Selection of Participants

Potential households were identified spatially using Google Earth with 222 potential housing structures randomly selected and approached for recruitment. Of the 222, 126 households were eligible and 76 households were enrolled in the study. The enrolled households were distributed across Hopi land in proportion of the population of each village relative to the tribal population. Inclusion criteria were that members of the Hopi Tribe lived in the household and someone 18 years or older (i.e., head of household) agreed to individual and household monitoring. All participants provided a signed consent form. The protocols and consenting documents were approved by the University of Arizona Institutional Review Board. In addition, the project was approved by the Hopi Tribal Council. The CAB reviewed all procedures and all local research staff were members of the Hopi Tribe and living at Hopi.

Field Work Training & Data Monitoring

The Hopi field office was located more than six hours from the university research staff. The HEHP university research faculty and staff provided required and regular training, both in-person and virtual, for all elements of the study including: use of the air quality monitors, maintenance and calibration of the monitors, recruitment and consenting of study participants, individual measurements and interviewing techniques. As required by the CAB and agreements with the Hopi Tribe, all personally identifiable information was retained at Hopi and not returned to the university research team. Only de-identified measurements were returned to the university for data entry and analysis. Data and equipment coordinators regularly checked with the field teams and visits were conducted to provide oversight and additional training.

Air Quality Monitoring

Attempts were made to sample homes twice for 24-hours, once during the heating season, and again during the non-heating season. Longer sampling times were proposed, however the CAB viewed sampling for longer periods as too intrusive. Of the 76 homes sampled, 70 were sampled during the heating season and 66 during the non-heating season; 60 households completed both winter and summer sampling.

Indoor and outdoor concentrations of $PM_{2.5}$ were collected each season using real-time area monitors (pDR-1500, ThermoFisher) set at 1-minute logging intervals for 24-hours. Samplers operated concurrently. Monitors were calibrated by field technicians prior to placement at each home and in accordance with the instruction manual. Further, all project monitoring equipment was returned for annual factory calibration. Unfortunately, the field implementation office was located 6 hours away from the laboratory and lacked the resources for gravimetric assessment of filter weights in the field. Each area monitor simultaneously measured air temperature and relative humidity. Monitors were placed approximately 1.5 meters off the ground to represent the breathing zone of inhabitants. The indoor air monitor was placed in the living room where household occupants spent most of their time and the outdoor monitor was placed near the main entrance of the household. Combustion gases (NO, NO_2, SO_2, CO) were measured using a real-time passive monitor (GrayWolf AdvancedSense Pro), co-located with the indoor $PM_{2.5}$ monitor and set at the same 1-minute logging interval. The GrayWolf sampler was returned to the manufacturer for annual factory calibration.

Home & Activity Assessments

Household building characteristics were assessed using questionnaires collected during the initial home sampling visit. Important residential characteristics including primary heating fuel type (solid fuel: coal and/or wood; EG: electric and/or gas; combination: coal and/or wood with electric and/or gas) and housing type (modern, traditional, mobile) were noted. The technician also recorded the size of the house, building and flooring material, number of rooms, number of doors and windows. Other factors reported were presence of pets inside the home, dustiness of the interior environment, condition of the roof, visible crack or gaps in the walls or ceiling, noticeable signs of mold or pests, the condition and number of household appliances, and ventilation devices (fans, air conditioning). Characteristics of the exterior home environment were collected; they included categorizing the area surrounding the home (natural, cleared, actively used for livestock/gardening), the outside parking area (paved, gravel, unpaved), and the surrounding roadways leading to the residence (paved or unpaved).

Primary respondents also were interviewed using culturally appropriate and population specific both pre and post-sampling questionnaires for each of the season visits. These questions were developed and modified under the guidance of the CAB. Questions were designed to identify specific indoor and outdoor behavioral activities practiced by household occupants that may be associated with indoor $PM_{2.5}$. Participants were asked general questions regarding cooking, cleaning, burning of incense, smoking, craft-activity (art or traditional cooking), other traditional practices, and whether solid fuel or air circulating devices were used during the sampling period. More specific activity questionnaires were determined by the CAB to be too burdensome and were not used.

Statistical Data Analysis

Mean imputation was used for homes with partial or incomplete real-time monitoring data. A detailed explanation of imputation methods in this context has been discussed in a previous paper (Hadeed, et al., 2020). Indoor $PM_{2.5}$ concentration was averaged over 24-hours and was naturally log-transformed. Variables collected from questionnaires were entered as categorical, binary, or nominal variables. Frequency tables were used to assess the distribution of responses for categorical variables, and cells with low counts were collapsed into appropriate categories. Categorical variables were analyzed with appropriate reference categories assigned.

Univariable linear regression was used to identify household and behavioral explanatory variables that were significantly associated with indoor $PM_{2.5}$ and to assess the magnitude of their association. To ensure important variables were not excluded from potential selection into multivariable regression, a relaxed significance level ($p \leq 0.20$) was used to screen candidate variables. Collinearity among explanatory variables was tested prior to development of a multivariable model. Two explanatory variables highly correlated ($r \geq 0.70$) resulted in exclusion of one of the two variables. To identify the seasonal behavioral factors and household characteristics associated with indoor concentrations of $PM_{2.5}$, separate analyses were conducted for heating and non-heating sample periods. Multivariable regression was used to determine the household and behavioral factors associated with indoor $PM_{2.5}$ concentrations for each season. Variable selection was carried out using backwards elimination with a cutoff of 10% ($p \geq 0.10$).

Results

Summary of Housing Characteristics

Household building characteristics are summarized in the supplemental material (Table S1). A large proportion of households were considered as modern construction homes (59%; n=45), followed by traditional (24%; n=18) and modular/mobile (17%; n=13) homes. Homes had an average size of 93.7 m^2 and 3–4 rooms. Three heating fuel types were common during the winter heating season, EG as fuel (28%; n=21), solid fuel of coal and/or wood (38%; n=29), and “combination” fuels of both EG and solid fuel (34%; n=26). Most homes in this rural community were surrounded by natural undisturbed vegetation (41%) or were cleared of vegetation (42%).

Reporting of the dustiness of the interior environment by the primary field technician indicated more than one-third of homes were fairly dusty (37%) and 13% were extremely dusty, with the remainder of homes being relatively dust free. This variable was dichotomized due to low cell count in extremely dusty homes. Concrete and wood were dominant flooring components in these homes, 34% and 49%, respectively; however, 12% of homes had packed earth floors. Twenty percent of homes had greater than 20% of their interior floor covered with carpeting or rugs. Additional housing characteristics are summarized in supplemental Table S1 and include the number of interior and exterior doors and windows, the height of the home, and surface of the parking area outside the home.

Household Air Quality by Season

Of the 70 homes sampled during the heating season, two homes had missing indoor air monitoring data and one household was excluded (participant limitation). During the heating season, the 24-hour indoor mean $PM_{2.5}$ concentration in these 67 homes was 36.2 $\mu g/m^3$ and the mean outdoor concentration was 22.1 $\mu g/m^3$ (Table 1). Of the 66 homes sampled in the non-heating season, 5 homes had missing indoor air monitoring data and an additional 5 homes had missing outdoor monitoring data. Indoor non-heating 24-hour mean concentration of $PM_{2.5}$ in these 61 homes was 14.6 μg/m^3 and the mean outdoor 24-hour concentration was 9.3 μg/m^3 (Table 1). Indoor concentrations of combustion gases (NO, NO_2, CO, SO_2) were measured in ppm. Most homes had concentrations below the instrument detection level. As a result, seasonally averaged values are in fractions of ppb. As expected, values are lower in the non-heating season than during the heating season (Table 1).

Indoor Activities Performed by Season

During the heating season, 25% of participants reported they engaged in craft-activities (art/cooking) during the 24-hour sampling period. Seven homes (10.4%) reported smoking or burning incense indoors, and participation in the removal of ash generated from heating devices was reported in over 50% of households. Half of participants reported cleaning their floors or having their pets indoors during a sampling period. A central or wall mounted climate control unit was used in 16% of homes, and about one-third of participants reported seeing an indoor pest within the past 24-hours (Table 2). During the non-heating sampling, over 80% of homes reported opening doors and windows for ventilation, and over 25% of participants engaged in craft-activities indoors. Smoking and burning of incense indoors was reported in 8 homes (13.1%) and more than 50% of homes reported seeing a pest indoors during the 24-hour period (Table 2).

Indoor $PM_{2.5}$ Across Household & Behavioral Factors by Season

During the heating season, the more modern style homes had lower indoor mean concentrations (27.8 μg/m^3) compared to traditional (53.2 μg/m^3) and mobile (46.1 μg/m^3) homes (Figure 1). Homes heated with solid fuel had mean indoor 24-hour concentrations of 45.2 μg/m^3, whereas combination and EG fueled homes had indoor levels of 39.2 μg/m^3 and 21.2 μg/m^3, respectively. A substantial reduction in indoor $PM_{2.5}$ was observed between heating and non-heating season by housing and heating fuel type (Figure 1).

Average indoor $PM_{2.5}$ concentrations were greater during the heating season compared with the non-heating season. Differences in household characteristics, behaviors and activities by residents (Table 2) may be related to the seasonal increases. The primary difference across seasons was the use of heating fuel type. Homes heated exclusively with coal and wood had indoor concentrations that exceeded the EPA 24-hour ambient $PM_{2.5}$ standard of 35μg/m^3 and the WHO recommendation of 25μg/m^3. Even homes that used a combination of EG and solid fuel during the heating season had indoor concentrations that exceeded both the EPA standard and WHO guideline. Interestingly, ambient $PM_{2.5}$ concentrations recorded outside of coal and wood burning homes were higher (30.0 μg/m^3) compared to EG fueled homes (9.2 μg/m^3), suggesting the potential effect household burning of these fuels can have on local ambient air quality. Activities such as indoor smoking or burning of incense also resulted in elevated indoor concentrations (64.0 μg/m^3) during the heating season, whereas homes that used climate control units (fans and thermostats) had much lower indoor concentrations (17.1 μg/m^3) than homes without climate control units (40.0 μg/m^3).

Seasonal differences in household and behavioral factors associated with indoor $PM_{2.5}$ concentrations were observed. Indoor $PM_{2.5}$ was strongly associated with housing type, heating fuel type, presence of indoor pests, use of a climate control unit, number of interior doors and indoor relative humidity during the winter heating season. Presence of a pest indoors may be an indicator of indoor cleanliness, structural integrity, and other factors associated with indoor air pollutants. Compared to modern homes, mobile homes had elevated indoor $PM_{2.5}$ concentrations, which may reflect the expansion and contraction of building material during the day when fuel use for heating is greatest. There is a positive association between indoor relative humidity and $PM_{2.5}$. Perhaps hygroscopic growth of ultrafine particles or aggregation of particles is responsible. Winkler (1988) states that particles < 0.1 µm and those above 1 µm grow hygroscopically with similar patterns. He et al. (2019) state that humidity can serve a bridge that aggregates particulate matter. Negative associations between climate control devices (fans and thermostats) could be a function of increased air circulation, exchange rate and filtration of air, whereas the number of interior doors could serve as a barrier for compartmentalizing the living room from highly polluted rooms (such as the kitchen).

During the non-heating season, indoor $PM_{2.5}$ concentrations gradually declined as the size of the home increased (Table 2). For example, homes <55.5 m^2 had concentrations of 21.6 $\mu g/m^3$ compared to homes sized 55.6 m^2 – 69.2 m^2 (17.9 $\mu g/m^3$), 69.3 m^2 – 130 m^2 (10.5 $\mu g/m^3$), and homes over 130 m^2 (7.0 $\mu g/m^3$). In homes that burned incense or had a smoker, indoor concentrations were 28.0 $\mu g/m^3$ compared to 12.5 $\mu g/m^3$ in homes without smoking or incense. Other behavioral and household characteristics were associated with indoor $PM_{2.5}$ concentrations (opening doors and windows, area of surrounding environment, and outdoor $PM_{2.5}$). Elevated indoor $PM_{2.5}$ concentrations among homes cleared of ground cover may be explained by fugitive dust being suspended during high wind events and making entry into the home. To reduce windblown dust from entering homes, villages and household owners may consider opting for natural vegetation that anchors soil or avoiding clearing vegetation around their homes. Paving roads and driveways may also assist in reducing indoor dust. Opening of doors and windows, as well as the size and height of the home, were negatively associated with indoor $PM_{2.5}$, possibly due to dilution of indoor air with outside clean air and increased volume of the home.

Univariable Analysis: Heating Season

Candidate variables for inclusion into multivariable regression were identified from univariable regression (Table 3). Many other variables, including the combustion gases of Table 1, were evaluated, and they were not significantly associated with $PM_{2.5}$, so they were not included in the modeling. Log-natural (LN) indoor $PM_{2.5}$ was significantly associated ($p<0.05$) with various behavioral and household variables during the winter heating season, that included heating fuel type, indoor smoking or burning of incense, presence of pests, housing type, parking area of the home, dustiness of interior environment indoor, use of a climate control unit, use of kitchen or bathroom ventilation, presence of carpet or rug, number of interior doors, area of home, and indoor relative humidity.

For example, compared to EG heated homes, indoor $PM_{2.5}$ concentrations were 170% higher in homes heated with solid fuels, and 125.3% higher in homes using a combination of EG and solid fuel. Additionally, use of a climate control unit was associated with a 65.8% reduction in indoor $PM_{2.5}$ compared to homes without climate control units. Dustiness of the interior environment was positively associated with indoor concentrations. Compared to non-dusty homes, indoor concentrations of $PM_{2.5}$ were 107.5% higher in dustier homes (Table 3). Compared to modern housing types, indoor concentrations were 110.7% and 39.5% higher in traditional and mobile homes, respectively.

Other household and behavioral variables moderately associated ($p \leq 0.1$) with LN-indoor $PM_{2.5}$ during the winter heating season included removal of ash, number of exterior doors, height of the home, and outdoor $PM_{2.5}$. Indoor concentrations were 56.7% higher in homes that removed ash generated from heating fuels during the 24-hour sampling period (Table 3). Additionally, for every 1-unit increase in the number of exterior doors, indoor $PM_{2.5}$ decreased by 24.2%.

Dustiness of interior environment, use of kitchen or bathroom vents, and parking area surfaces were identified as collinear with other explanatory variables and were removed from inclusion into variable selection. Dustiness correlated with climate control unit, fuel category, and ash removal. Use of kitchen or bathroom vent was correlated with housing type and use of a climate control unit, whereas parking area was correlated with housing type, climate control unit and heating fuel type.

Multivariable Analysis: Heating Season

Results of the multivariable regression modeling (R^2=0.45) included six important household and behavioral factors associated with indoor $PM_{2.5}$ concentrations during the heating season in 65 homes with complete monitoring and questionnaire data (Table 3). Housing type, heating fuel type, presence of pests, and indoor relative humidity were all positively associated with indoor concentrations, whereas use of a climate control device and number of interior doors were negatively associated with indoor levels.

After adjusting for behavioral and household characteristics, compared to homes heated with EG fuel, indoor $PM_{2.5}$ concentrations were 90.1% higher in homes burning solid fuels and 72.2% higher in homes heated with a combination of EG and solid fuel sources. Homes reporting the presence of a rodent during the 24-hour sampling period had 90.7% higher indoor concentrations compared to homes with no pests. Additionally, mobile homes had 127.4% higher indoor concentration of $PM_{2.5}$ compared to modern homes. Indoor relative humidity was significantly associated with indoor heating PM concentrations. For every 1-percent increase in indoor relative humidity, indoor $PM_{2.5}$ concentrations increased by 3.1%. Homes using a climate control device had 45.8% lower indoor concentrations compared to homes that did not use a climate control device, and concentrations decreased by 12.6% for every 1-unit increase in the number of interior doors.

Univariable Analysis: Non-Heating Season

Univariable regression identified 7 household and behavioral factors that were significantly associated with indoor $PM_{2.5}$ concentrations in the non-heating season and were candidates for inclusion into multivariable regression (Table 4). Opening of doors and windows, the number of exterior windows, and the area and height of the home were negatively associated with indoor $PM_{2.5}$ concentrations. For example, opening of doors and windows for ventilation was associated with a 61.2% decrease in indoor concentrations. Similarly, indoor $PM_{2.5}$ decreased by 4.2% for every 1 foot (0.3048 m) increase in the height of the house.

Outdoor $PM_{2.5}$ was positively associated with indoor concentrations. For every 1 μg/m^3 increase in outdoor $PM_{2.5}$, indoor $PM_{2.5}$ increased by 3.5%. Indoor concentrations were 136.7% higher in homes that reported indoor smoking or burning of incense. The surrounding environment in which homes were located was also associated with indoor $PM_{2.5}$. Compared to homes surrounded by natural vegetation, homes cleared of natural vegetation had 63.7% higher indoor concentrations (Table 4).

Multivariable Analysis: Non-Heating Season

Six of the seven candidate variables were selected into multivariable regression yielding a model with significant performance (R^2=0.60). After adjusting for behavioral and household factors, there is an apparent increase in indoor $PM_{2.5}$ as outdoor concentrations increase (Table 4). Indoor smoking and burning of incense remained the greatest contributor to indoor concentrations (118.8%). Compared to homes surrounded by natural vegetation, indoor $PM_{2.5}$ concentrations were 43.5% higher in homes cleared of natural vegetation, despite a modest reduction in significance (p=0.059). Similar to univariable analysis, the area and height of homes were both negatively associated with indoor concentrations. Significant reduction of indoor $PM_{2.5}$ was observed in homes opening doors and windows for ventilation (61.2%), compared to homes that kept doors and windows closed.

Discussion

Air pollution remains a significant public health hazard, especially indoor air pollutants from the burning of solid fuels. Relatively few studies assess rural ambient and indoor air quality in the United States, where populations continue to experience greater health disparities and disease burden (Rogalsky et al., 2014; Semmens et al., 2015). Our study explored this gap by quantifying household indoor concentrations of $PM_{2.5}$ in a rural, solid fuel burning, Native American community in the United States, and examined household and behavioral factors associated with indoor concentrations during heating and non-heating seasons using each home as its own control.

We found elevated indoor $PM_{2.5}$ in communities burning solid fuel for heating. Similar studies addressing use of solid fuel for both heating and cooking have reported greater concentrations. High indoor concentrations of $PM_{2.5}$ were observed in 53 open fire wood burning homes in an indigenous rural Mexican community (Zuk et al., 2007). Pre-intervention 48-hour $PM_{2.5}$ concentrations were measured 1 m from a woodstove (693 μg/m^3), in kitchens 1.5 m from the woodstove (658 μg/m^3), and outside the homes (94 μg/m^3). Our study sampled homes with closed stoves, while the study by Zuk et al., (2007) evaluated homes using open fires which contributed to significantly higher indoor concentrations.

In rural China, Hu et al., (2014) measured 24-hour indoor $PM_{2.5}$ in homes burning "smoky" bituminous coal (185μg/m^3), "smokeless" anthracite coal (104 μg/m^3), mixed coal (164 μg/m^3), wood (393 μg/m^3), plant material (417 μg/m^3), and mixed fuel (210 μg/m^3). Regardless of stove ventilation type, indoor $PM_{2.5}$ concentrations were well in excess of the WHO indoor guideline and EPA ambient standards. These concentrations far exceeded indoor levels observed in our study, and may be due to differences in stove design, inadequate venting, coal type, and burning duration by participants. Regardless, solid fuel clearly contributed to increased concentrations of $PM_{2.5}$ indoors.

Seasonal and household characteristics associated with indoor $PM_{2.5}$ concentrations were examined in 2258 households in a low income urban community in Dhaka, Bangladesh (Gurley et al., 2013). Average 24-hour indoor $PM_{2.5}$ concentration inside homes fueled only with biomass had the highest indoor concentrations (308 μg/m^3). A reduction in 24-hour average concentration was observed among homes burning a combination of EG and biomass fuel (193 μg/m^3) and homes cooking with only EG fuel (165 μg/m^3). These values were much greater than those we found on Hopi land. Indoor concentrations were found to be greater during the winter season (225 μg/m^3 increase) in households with 1 or fewer external windows or doors. This finding was similar to ours. Gurley et al. (2013) found that reduced ventilation results in higher winter concentrations. Air infiltration resulted in a 22 μg/m^3 reduction in $PM_{2.5}$ for every 1 unit increase in the number of external windows or doors. Homes in our study may be "tighter", resulting in an increase of indoor $PM_{2.5}$ among homes burning coal and wood.

Pokhrel et al., (2015) identified similar effects of biomass and solid fuel use on indoor $PM_{2.5}$ concentration in Nepal. Twenty-four hour concentrations of $PM_{2.5}$ were measured in kitchens of 824 homes of four primary cooking fuel types. Average concentrations of $PM_{2.5}$ were 656 μg/m^3 in biomass households (n=218), 169 μg/m^3 in kerosene burning homes (n=187), 101 μg/m^3 in propane gas burning homes (n=238), and 80 μg/m^3 in electric powered homes (n=181). Indoor $PM_{2.5}$ concentrations exhibited strong seasonal affects, with higher concentrations observed during winter months in biomass burning homes. Similar to the Hopi community, biomass may be burned more frequently in the winter, and windows and doors kept shut. However, the authors also suggested higher winter indoor concentrations may occur when brick kilns are in high operation (Pokhrel et al., 2015). Although the location of monitoring and fuel source differed from our study, similar increases in $PM_{2.5}$ were observed inside and outside of coal and wood heated homes, demonstrating the adverse effects of these fuels on local ambient and indoor air quality.

Differences in the magnitude of indoor concentration between our study and other studies conducted outside the United States are due to differences in housing characteristics (including ventilation), ambient/local conditions, stove design, and most importantly fuel types (Naeher et al., 2007; Semmens et al., 2015; Hu et al., 2014). Prevalent use of low temperature combustion of biomass is one reason for significantly greater concentrations of indoor air pollutants observed in these studies. Furthermore, solid fuel was used only for seasonal heating in our study, as opposed to daily use for both heating and cooking among other international studies.

Many household studies conducted in the United States rely on self-reported use of wood stoves and other solid fuels (Morris et al., 1990; Browning et al., 1990; Honicky et al., 1991; Noonan & Ward, 2007; Noonan et al., 2012; Ware et al., 2014), and report inconsistent associations between woodstove use and respiratory health outcomes. Our study used trained Hopi Tribal technicians to collect all information and examine woodstoves. Few studies (Sexton et al., 1984; Leaderer et al., 1994; Ward et al., 2008; Ward et al., 2011; Ward et al., 2017; Semmens et al., 2015; Noonan et al., 2012; Robin et al., 1996; Bunnell et al., 2010; Weichenthal et al., 2013) in the United States have quantified indoor concentrations and exposures to $PM_{2.5}$ in solid fuel heated homes, and the potential health effects of these exposures remains largely unknown among populations at the greatest risk. Sexton et al. (1984) quantified indoor concentrations of PM_{10} in rural Vermont (n=163) homes and reported 24-hour average concentrations of 24 μg/m^3 in wood burning homes (n=116) compared to 18 μg/m^3 in non-wood burning homes (n=28). We collected $PM_{2.5}$ and report higher particulate concentrations.

Leaderer et al., (1994) measured weekly outdoor and indoor $PM_{2.5}$ concentrations in wood-gas burning and non-wood burning suburban communities in Suffolk and Onondaga County, New York. In Suffolk County, weekly geometric mean outdoor concentration (n=19) of $PM_{2.5}$ was 16.9 μg/m^3, and indoor concentration in wood-gas burning homes (n=15) was 18.1 μg/m^3 and 17.3 μg/m^3 in non-burning homes (n=30). In Onondaga County, weekly geometric mean outdoor $PM_{2.5}$ concentration (n=36) was 15.8 μg/m^3, and indoor concentration in wood-gas burning (n=16) was 19.1 μg/m^3 and 14.1 μg/m^3 in non-burning (n=45) homes (Leaderer et al., 1994). Indoor concentrations in these studies were much lower compared to our study, and may be due to differences in household construction and environments (suburban vs rural), sampling duration and methodology, supplementing wood heating with gas heating, or possibly due to differences in demographic and socioeconomic factors in these communities. The authors note that the elemental composition of indoor $PM_{2.5}$ in homes burning wood-gas was similar to profiles in non-burning homes, suggesting appliances in these homes were well maintained and did not leak $PM_{2.5}$ into the indoor environment, which may be a function of household income.

More recently, indoor concentrations of $PM_{2.5}$ were measured in a composite study of 96 rural wood heated homes in the Northwestern United States (Montana, Idaho, Alaska) as part of a larger randomized trial. During two winter pre-intervention sampling periods, concentration of $PM_{2.5}$ inside wood heated homes was 28.8 μg/m^3 and 29.1 μg/m^3 during the first and second winter sampling periods, respectively (Semmens et al., 2015). Thirty percent of homes had concentrations of $PM_{2.5}$ that exceeded the EPA standard and WHO guideline. Similar to our study, indoor relative humidity and housing type were associated with increased indoor $PM_{2.5}$ concentrations. Semmens et al., (2015) found that every 1% increase in indoor relative humidity was associated with a 2% increase in indoor $PM_{2.5}$, and compared to mobile homes and apartments, modern homes had 36% lower indoor $PM_{2.5}$ concentrations. An important finding was the inverse relationship between household income and indoor $PM_{2.5}$ concentrations, which may be attributed to properly installed and maintained stoves in higher income households. A similar relationship may exist in our findings, as low income households are unable to afford modern, well maintained, stoves when heating with solid fuels.

Heating stove changeout may be a viable approach for mitigating indoor air pollution inside solid fuel heated homes in rural and tribal communities. Sixteen wood burning homes in Libby, Montana had pre-intervention 24-hour average indoor $PM_{2.5}$ concentrations of 51.2 μg/m^3 and post-intervention concentrations of 15.0 μg/m^3 (Ward et al., 2008). The efficacy of woodstove changeout interventions was further demonstrated in the rural Nez Perce tribal community in Idaho. Pre-stove intervention median 24-hour indoor concentrations of $PM_{2.5}$ was 39.2 μg/m^3 in 16 wood heated households. Post-intervention, indoor concentrations dropped to 19.0 μg/m^3, suggesting the potential benefits of woodstove changeout interventions on reducing indoor air pollutants (Ward et al., 2011).

Exposure to HAPs is strongly linked with poverty (Rogalsky et al., 2014). Few studies have been completed in rural low-income solid fuel burning communities of the United States (Robin et al., 1996; Bunnell et al., 2010; Ward et al., 2011). Each of these studies conducted in tribal communities report similar results showing increased concentrations in solid fuel heated households. The Hopi Tribe, much like other rural solid fuel burning communities in the United States, has a high rate of poverty. Over one quarter (28%) of households make less than $20,000 per year (U.S. Census Bureau, 2010). Poverty rate on the Hopi Lands (35%) is more than double the poverty rate in the state of Arizona (15%) (U.S. Census Bureau, 2010). Similar to findings from Semmens et al., (2015), indoor concentrations of air pollutants may be inversely associated with household income. Household concentrations of $PM_{2.5}$ reported in this study may be similar across other low-income solid fuel burning communities in the United States.

There are several limitations to our study. First, predictor variables and activities performed during the sampling period were self-reported to interviewers by participants and are prone to potential recall bias and thus misclassification error. Second, fuel heating type is unlikely to be the only contributing source of indoor $PM_{2.5}$, and other behavioral sources (home furniture, frequency and duration of cooking/cleaning, social gathering, and traditional practices) may not have been accounted for in our analysis as the home was measured only one time per season. Additionally, the amount of fuel used during the sampling period and the number of times participants stoked and fed the fire was not measured. Such activities may have contributed to elevated indoor $PM_{2.5}$. Further, the pDR-1500 monitors were not calibrated with gravimetric measurements in the Hopi homes. Instead, they were calibrated by the manufacturer using test dust that might differ from local, house dust.

Despite these limitations, this study makes strides in quantifying indoor concentrations of air pollutants in a rural, Native American tribal community where heating with solid fuels is widely practiced. Fuel use and behavioral factors were examined in relationship to indoor concentrations of $PM_{2.5}$. After adjusting for these factors, we were able to quantify the magnitude of their association with $PM_{2.5}$. These variables enabled us to gauge the representativeness of households in our study across Hopi Lands and communities that share similar behavioral and housing characteristics. We were able to demonstrate a clear seasonal difference in factors associated with indoor $PM_{2.5}$. Information gathered from this study can inform the Tribe about household environmental hazards present within their community and help guide policy development and targeted interventions for reducing exposures to environmental contaminants.

Conclusion

Millions of households in the United States relying on solid fuels for heating, yet research on respiratory health effects from HAPs in low income rural communities continues to remain largely ignored. Native Americans experience greater respiratory morbidity; exposure to indoor air pollutants may be a contributing factor. We observed a seasonal difference in behavioral and household characteristics associated with indoor $PM_{2.5}$ in Hopi households. Homes heated with solid fuels, or a combination of solid and cleaner burning fuels, had indoor $PM_{2.5}$ concentrations that exceeded the EPA 24-hour ambient standard and the WHO guideline during the winter heating season. These results are similar to other studies across the globe that show indoor use of solid fuels without adequate ventilation is significantly associated with indoor air pollution. Occupants residing in these households may be exposed to hazardous levels of indoor air pollutants and subject to acute and chronic adverse health effects. Results from this study will help to address the current gap in the literature by highlighting the environmental hazards associated with solid fuel use in rural, low-income communities within the United States. Further effort is needed to quantify environmental concentrations of air pollutants and respiratory health outcomes in underserved rural and tribal communities throughout the United States.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Practical Implications

Indoor air pollution associated with solid fuels has been researched extensively in developing nations, yet it has been largely ignored in low-income, rural, solid fuel burning communities in the United States and other developed countries.

As found in other studies across the globe, homes heated with solid fuels had significantly elevated indoor concentrations of $PM_{2.5}$.

Knowledge of housing characteristics associated with exposures can inform residents and housing authorities of important factors that contribute to indoor air pollution, and help guide policy development and targeted interventions, thereby reducing exposures to environmental contaminants.

Behavioral factors that contributed to elevated indoor $PM_{2.5}$, may be modified to reduce household occupants' exposures to hazardous pollutants.

These findings call attention to the potential hazards facing many low-income, rural households in the United States that rely on solid fuels for heating.

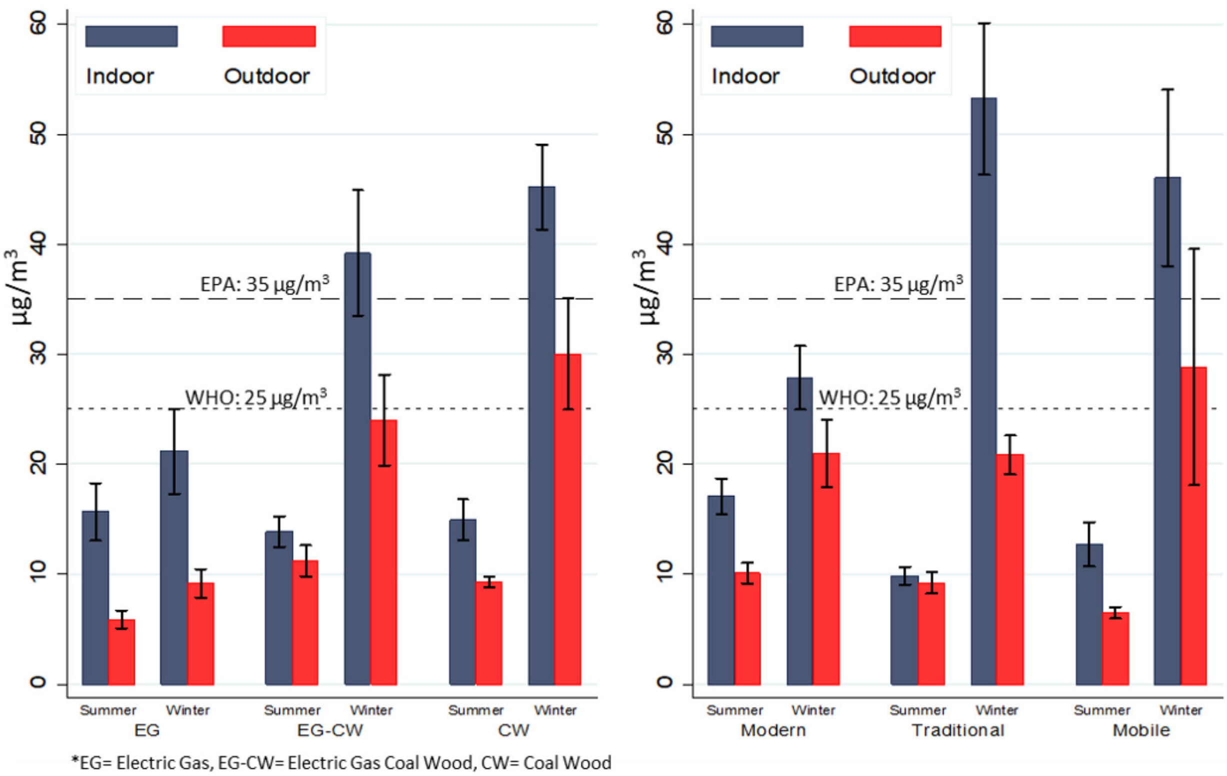

Figure 1:
Mean Concentrations of $PM_{2.5}$ across Fuel & Housing Type by Season

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Table 1:

Concentrations of Air Pollutants by Sampling Season

	Heating		Non-Heating	
Variable	**Mean**	**SD**	**Mean**	**SD**
Indoor $PM_{2.5}$ (μg/m^3)	36.2	45.0	14.6	17.0
Outdoor $PM_{2.5}$ (μg/m^3)	22.1	40.2	9.3	9.8
Indoor NO (ppb)	0.089	0.140	0.0056	0.023
Indoor NO_2 (ppb)	0.089	0.099	0.0860	0.067
Indoor CO (ppb)	3.100	5.900	0.5900	0.890
Indoor SO_2 (ppb)	0.030	0.086	0.0160	0.035

Table 2:

Mean (24-hour) Indoor $PM_{2.5}$ Concentrations (μg/m^3) by Household Characteristics and Behavioral Factors for Each Sampling Season.

	Heating			Non-Heating		
Variable	**Mean**	**SD**	**Freq (%)**	**Mean**	**SD**	**Freq (%)**
Area of Home (m^2)						
< 55.5	31.4	37.1	15 (22.4)	21.6	24.4	16 (26.2)
55.5 – 69.2	51.1	55.2	17 (25.4)	17.9	17.7	16 (26.2)
69.3 – 130.0	32.3	49.3	19 (28.4)	10.5	10.5	15 (24.6)
130.1 – 504.0	29.7	33.2	16 (23.9)	7.0	3.9	14 (23.0)
Indoor Smoking or Incense						
No	33.0	43.6	60 (89.6)	12.5	15.3	53 (86.9)
Yes	64.0	50.2	7 (10.4)	28.0	22.6	8 (13.1)
Parking Area						
Paved-Gravel	27.8	47.3	22 (32.8)	12.6	9.9	16 (26.2)
Unpaved	40.4	43.7	45 (67.2)	15.2	19.0	45 (73.8)
Surrounding Area of Home						
Natural Undisturbed	24.7	27.5	25 (37.3)	11.3	11.7	26 (42.6)
Cleared	40.1	46.8	29 (43.3)	20.4	22.4	25 (41.0)
Actively Used	51.2	65.8	12 (17.9)	9.0	7.1	9 (14.8)
Missing	32.4	0.0	1 (1.5)	3.0	0.0	1 (1.6)
Pests Found in House						
No Pest	31.6	40.5	46 (68.7)	12.7	15.2	27 (44.3)
Tick-Roach-Insect	32.4	60.1	11 (16.4)	17.8	20.1	27 (44.3)
Rodent	61.6	42.1	10 (14.9)	9.0	7.4	7 (11.5)
Dustiness of Interior Observed by Technician						
Not Dusty	25.6	31.4	35 (52.2)	12.8	17.5	30 (49.2)
Dusty	47.8	54.4	32 (47.8)	16.6	16.8	30 (49.2)
Missing				3.6	0.0	1 (1.6)
Open Doors/Windows						
No	32.0	43.1	35 (52.2)	31.6	28.4	10 (16.4)
Yes	40.9	47.2	32 (47.8)	11.2	11.6	51 (83.6)
Floor Cleaning During Sampling						
No	43.3	54.6	34 (50.7)	13.9	16.6	27 (44.3)
Yes	28.9	31.4	33 (49.3)	15.1	17.6	34 (55.7)
Any Craft Activities During Sampling						
No	38.6	49.6	50 (74.6)	13.5	16.6	44 (72.1)
Yes	29.4	27.5	17 (25.4)	17.4	18.2	17 (27.9)
Climate Control Device						

	Heating			Non-Heating		
Variable	**Mean**	**SD**	**Freq (%)**	**Mean**	**SD**	**Freq (%)**
No	40.0	46.9	56 (83.6)	15.0	16.8	44 (72.1)
Yes	17.1	28.1	11 (16.4)	13.3	18.1	17 (27.9)
Ash Removal During Sampling						
No	31.8	44.8	30 (44.8)	14.2	17.2	59 (96.7)
Yes	39.8	45.4	37 (55.2)	23.6	11.5	2 (3.3)
Pets Indoors During Sampling						
No	37.7	48.1	29 (43.3)	14.7	18.3	27 (44.3)
Yes	35.1	43.1	38 (56.7)	14.4	16.2	34 (55.7)

Table 3:

Factors Associated with $PM_{2.5}$ Concentrations Measured in Heating Season - Univariable and Multivariable Regression Models

	Univariable Regression			Multivariable Regression		
LN-$PM_{2.5}$	**Coef.**	**Percent Change**	**p-value**	**Coef.**	**Percent Change**	**p-value**
Household Characteristics						
Area of Home	−0.0003	−0.03	0.06		*NS*	
Number of Interior Doors	−0.16	−15.0	0.01	−0.135	−12.6	0.014
Number of Exterior Doors	−0.28	−24.2	0.10		*NS*	
>20% Carpet/Rugs (Yes vs No)	−0.66	−48.1	0.05		*NS*	
Height of Home	−0.05	−5.3	0.12		*NS*	
Home (Traditional vs Modern)	0.75	110.7	0.03	0.219	24.5	0.464
Home (Mobile vs Modern)	0.33	39.5	0.39	0.822	127.4	0.02
Pest (Insect vs no pest)	−0.50	−39.1	0.17	−0.136	−12.8	0.644
Pest Rodent vs no pest)	0.86	137.2	0.02	0.646	90.7	0.05
Dusty (Yes vs No) *	0.73	107.5	0.01		*NS*	
Behavioral						
Any Kitchen or Bathroom Vent Use (Yes vs No) *	−0.96	−61.7	0.00		*NS*	
Climate Control Device (Yes vs No)	−1.07	−65.8	0.00	−0.612	−45.8	0.06
Fuel Category (Combination EG-CW vs EG)	0.81	125.3	0.01	0.543	72.2	0.073
Fuel Category (Solid fuel CW vs EG)	0.99	170.0	0.00	0.642	90.1	0.033
Smoke or Incense (Yes vs No)	0.94	156.9	0.02		*NS*	
Ash Removed (Yes vs No)	0.45	56.7	0.08		*NS*	
Environmental						
Indoor Relative Humidity	0.04	3.7	0.03	0.031	3.1	0.029
Outdoor $PM_{2.5}$	0.006	0.6	0.11		*NS*	
Parking Area (Unpaved vs Paved-Gravel) *	0.74	109.0	0.01		*NS*	

* Excluded from multivariable regression due to collinearity (Dusty correlated with Climate Control Device, Fuel Category, and Ash Removed; Any Kitchen or Bathroom Vent Use correlated with Housing Type and Climate Control Device; Parking Area correlated with Housing Type, Climate Control Device and Fuel Category)

NS= Not Selected

Table 4:

Factors Associated with $PM_{2.5}$ Concentrations Measured for Non-Heating Season - Univariable and Multivariable Regression Models

	Univariable Regression			Multivariable Regression		
LN-$PM_{2.5}$	**Coef.**	**Percent Change**	**p-value**	**Coef.**	**Percent Change**	**p-value**
Household Characteristics						
Area of Home	−0.0004	−0.04	0.004	−0.00023	−0.02	0.042
Number of Exterior Windows	−0.054	−5.3	0.079		*NS*	
Height of Home	−0.043	−4.2	0.140	−0.048	−4.7	0.038
Behavioral						
Open Doors (Yes vs No)	−0.946	−61.2	0.001	−0.947	−61.2	0.001
Smoke or Incense (Yes vs No)	0.862	136.7	0.009	0.783	118.8	0.004
Environmental						
Outdoor $PM_{2.5}$	0.035	3.5	0.003	0.026	2.6	0.005
Area of Home (Cleared-Scraped vs Natural Undisturbed)	0.493	63.7	0.045	0.361	43.5	0.059
Area of Home (Actively Used vs Natural Undisturbed)	−0.092	−8.8	0.782	−0.121	−11.4	0.661

NS= Not Selected