Residential Wood Burning and Pulmonary Function in the Agricultural Lung Health Study

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BACKGROUND: In low- and middle-income countries, burning biomass indoors for cooking or heating has been associated with poorer lung function. In high-income countries, wood, a form of biomass, is commonly used for heating in rural areas with increasing prevalence. However, in these settings the potential impact of chronic indoor woodsmoke exposure on pulmonary function is little studied.

OBJECTIVE: We evaluated the association of residential wood burning with pulmonary function in case–control study of asthma nested within a U.S. rural cohort.

METHODS: Using sample weighted multivariable linear regression, we estimated associations between some and frequent wood burning, both relative to no exposure, in relation to forced expiratory volume in 1 s (FEV1), forced vital capacity (FVC), their ratio (FEV1/FVC), and fractional exhaled nitric oxide (FeNO). We examined effect modification by smoking or asthma status.

RESULTS: Among all participants and within smoking groups, wood burning was not appreciably related to pulmonary function. However, in individuals with asthma (n = 1,083), frequent wood burning was significantly associated with lower FEV1 (β: −164 mL; 95% confidence interval (CI): −261, −66 mL), FVC (β: −125 mL; 95% CI: −230, −20 mL), and FEV1/FVC (β: −2%; 95% CI: −4, −0.4%), whereas no appreciable association was seen in individuals without asthma (n = 1,732). These differences in association by asthma were statistically significant for FEV1 (pinteraction = 0.0044) and FEV1/FVC (pinteraction = 0.049). Frequent wood burning was also associated with higher FeNO levels in all individuals (n = 2,598; β: 0.1 ln(ppb); 95% CI: 0.02, 0.2), but associations did not differ by asthma or smoking status.

DISCUSSION: Frequent exposure to residential wood burning was associated with a measure of airway inflammation (FeNO) among all individuals and with lower pulmonary function among individuals with asthma. This group may wish to reduce wood burning or consider using air filtration devices.

https://doi.org/10.1289/EHP10734

Introduction

For low- and middle-income countries, burning biomass in the home is well understood to pollutle household air, increase airway-related disease, and negatively impact lung function.1–3 Exposure to household air pollution from solid cooking fuels, including biomass, was estimated as one of the major global risk factors negatively impacting health.4 In high-income countries, wood, a type of biomass, is commonly used as a primary or supplemental heating fuel, especially in places that are rural, cold, and have abundant forage.5 Exposure to wood burning in the home has also increased in the United States. In 2009, approximately 2.8 million U.S. households used wood as their primary fuel, and 8.8 million more used wood as a supplemental fuel.6 In 2015, these numbers increased to 3.5 million households using wood as their main heating fuel and an additional 9.2 million households using wood as a supplemental heating fuel7; others have estimated that up to 30 million Americans may live in a home where wood is used for heating.8 Despite this prevalence, relatively few studies have evaluated the impact of exposure to combustion by-products from indoor wood burning on adults in high-income countries.9–13

Pulmonary function metrics, including forced expiratory volume in 1 s (FEV1), forced vital capacity (FVC), and their ratio (FEV1/FVC), are objective quantitative measures of the physiological state of the lungs. These measurements assist in diagnosing airway disease and help monitor the severity of respiratory illnesses. Further, pulmonary function measures are independent predictors of morbidity and mortality in the general population, even when within the normal range.14

Wood-burning stoves, fireplaces, and furnaces emit respirable particulate matter (PM) with diameters ≤10 μm (PM10) and diameters ≤2.5 μm (PM2.5), as well as carbon monoxide, nitrogen and sulfur dioxides, polycyclic aromatic hydrocarbons, and volatile organic compounds.15 In Sweden, the median concentration of the carcinogenic combustion product benzo(a)pyrene was four times higher in wood-burning than in nonburning homes.16 Concentrations of PM2.5 were significantly higher in Norwegian homes with an indoor wood-burning device in comparison with homes without,17 consistent with studies from the United States and Ireland and Scotland.18,19 Most recently, wood-burning homes in northern New England were shown to have 61.5% [95%
Confidence interval (CI): 11.6%, 133.6%] higher levels of black carbon, a component of PM2.5, than nonwood-burning homes. Long-term measurements comparing PM2.5 levels in homes with and without wood burning are not available, but 48-h winter measurements before and 1 y after an air filter intervention showed a 69% (95% CI: 59, 76%) reduction in median PM2.5 levels and minimal change in the nonintervention group. Thus, even in high-income countries, wood-burning devices are significant contributors to household air pollution and remain an important environmental risk factor for human lung health.

In comparison with the extensive literature on the contribution of household biomass burning to adverse health outcomes in adults from low- and middle-income countries, associations between household wood burning exposure and illness in adults from high-income countries has received less attention. In short-term controlled human exposure studies with realistic residential concentrations of woodsmoke and sample sizes of 10 to 48 persons, accumulating evidence suggests that acute exposure leads to increased markers of inflammation, but little evidence points to acute changes in pulmonary function. In epidemiological studies (reviewed by Naehr et al. and Sigsgaard et al.), nonsmoking individuals who reported habitual use of a wood-burning device were more likely to report symptoms of cough and sore throat, shortness of breath, and more severe asthma symptoms. To our knowledge, only one prior study has specifically assessed the impact of residential wood burning exposure on pulmonary function in adults from a high-income country. Among 1,827 individuals from the Lovelace Smokers Cohort, Sood et al. identified self-reported woodsmoke exposure (yes, no) as a significant contributor to lower percent predicted FEV1 and airflow obstruction.

Given the paucity of published data, the goal of this study was to assess whether residential exposure to wood burning from home heating practices was associated with several measures of pulmonary function. This case-control study of current asthma in adults, nested within a U.S. rural agricultural cohort, provided the ability to examine potential differences in the associations between exposure to residential wood burning and lung function in individuals with and without asthma.

Materials and Methods

Study Population

The Agricultural Lung Health Study (ALHS) is a case-control study of adults with current asthma nested within the Agricultural Health Study (AHS), a prospective study of farmers and their spouses from Iowa and North Carolina (ALHS data release P3REL201209.00). The ALHS enrolled 3,301 participants from 2009 to 2013. This study was approved by the institutional review board at the National Institute of Environmental Health Sciences (NIEHS) and all participants provided written informed consent.

Pulmonary Function Measurement

During a home visit, trained staff measured pulmonary function using an EasyOne Spirometer (NDD Medical Technologies) based on American Thoracic Society guidelines. FEV1 and FVC were obtained from the spirometer, and FEV1/FVC was calculated as a proportion. All spirometry tests were reviewed by one author (J.L.H.), who graded each test for quality on a five-point scale. Valid spirometry was defined by at least two acceptable curves with both FEV1 and FVC values repeatable within 200 mL. Fractional exhaled nitric oxide (FeNO) was measured using the Niox Mino portable electrochemical device (Aerocrine AB), following manufacturer guidelines and published procedures for FeNO measurements. Participants were instructed to inhale through the scrubbing filter and exhale into the Niox Mino device for 10 s at a standard exhalation rate (50 mL/s), guided by the device screen. The procedure was performed twice, and the mean of the two measurements was used for this analysis. Individuals with FeNO values below the limit of detection (LOD: <5 ppb; 6.4%) were assigned to LOD/√2 = 3.5 ppb.

Asthma and Atopy Classification

As described previously, asthma cases in the ALHS were defined at enrollment by a) self-reported current diagnosed asthma, without any self-reported diagnosis of chronic obstructive pulmonary disease (COPD) or emphysema (n = 876); b) current asthma symptoms or use of asthma medication without reported diagnosis of COPD or emphysema among never smokers or former light smokers (≤10 pack-years; n = 309); or c) current diagnosed asthma with COPD or emphysema diagnosis among never smokers or former light smokers (≤10 pack-years; n = 38). Noncases (n = 2,078) were enrolled into the ALHS by random selection from the AHS participants who did not meet the above criteria. Atopy was classified as a positive blood IgE test (IgE ≥ 0.70 IU/mL) to at least one of 10 common antigens: Bermuda grass, ragweed, Timothy grass, mountain cedar, Alternaria, dust mite, cat dander, milk, egg, and wheat, as previously described.

Classification of Exposure to Residential Wood Burning

During a computer-assisted telephone interview conducted shortly after the home visit [median 9 d; interquartile range (IQR) 7–16 d], ALHS participants answered questions regarding their primary and secondary (if used) home heating sources during the previous 12 months. Participants who reported wood as a primary or secondary heating source were additionally asked whether they burned wood in a woodstove, and if so, the frequency of burning. All participants, regardless of reported heating sources, were asked if they burned wood in a fireplace, and if so, the frequency of burning (Table S1). We classified unexposed individuals as those who did not report using wood as either their primary or secondary home heating source and did not report burning wood in a fireplace. Individuals with some exposure were a) those who reported burning wood in a woodstove or fireplace “rarely” or “occasionally” or b) those who reported having wood as their primary or secondary heating fuel but also reported minimal or no burning in a wood stove or fireplace. Individuals were classified as having frequent exposure if they reported using a wood stove or fireplace during the cold season “frequently” or “most days/night in winter,” regardless of their primary or secondary heating source. Participants with responses insufficient to classify exposure were not analyzed.

Statistical Analyses

Among the 3,301 total participants enrolled in the ALHS, 3,123 had valid and complete spirometry measurements. In 490 instances where both the farmer and their spouse received a home visit at the same address (always on different occasions), only one member from each pair was included to avoid data correlated at the household level, leaving 2,878 individuals. After removing 54 individuals with missing covariate information and 9 individuals who were members of the control sample in comparison with the...
Table 1. Characteristics stratified by exposure to residential wood burning among \( n = 2,815 \) participants from the Agricultural Lung Health Study (2009–2013).

| Characteristic                          | Total \( n = 2,815 \) | Unexposed \( n = 2,217 \) | Some exposure \( n = 250 \) | Frequent exposure \( n = 348 \) |
|----------------------------------------|------------------------|---------------------------|-----------------------------|-------------------------------|
| Gender                                 |                        |                           |                             |                               |
| Female                                 | 1,372 (49%)            | 1,098 (80%)               | 123 (9.0%)                  | 151 (11%)                     |
| Male                                   | 1,443 (51%)            | 1,119 (78%)               | 127 (8.8%)                  | 197 (14%)                     |
| Age                                    | 63 ± 11                | 63 ± 11                   | 63 ± 10                     | 62 ± 11                       |
| Height (cm)                            | 169 ± 10               | 169 ± 10                  | 169 ± 9                     | 169 ± 10                      |
| Weight (kg)                            | 87 ± 20                | 87 ± 20                   | 88 ± 20                     | 86 ± 20                       |
| Race/ethnicity                         |                        |                           |                             |                               |
| White                                  | 2,770 (98%)            | 2,187 (79%)               | 249 (9.0%)                  | 334 (12%)                     |
| Non-White                              | 45 (1.6%)              | 30 (67%)                  | 1 (2.2%)                    | 14 (31%)                      |
| Education                              |                        |                           |                             |                               |
| Up to high school graduate             | 1,278 (45%)            | 1,010 (79%)               | 100 (7.8%)                  | 168 (13%)                     |
| More than high school                  | 761 (27%)              | 608 (80%)                 | 62 (8.1%)                   | 91 (12%)                      |
| College graduate and above             | 701 (25%)              | 549 (78%)                 | 77 (11%)                    | 75 (11%)                      |
| Missing                                | 75 (2.7%)              | 50 (69%)                  | 11 (41%)                    | 14 (31%)                      |
| Smoking status                         |                        |                           |                             |                               |
| Never                                  | 1,860 (66%)            | 1,490 (80%)               | 168 (9.0%)                  | 202 (11%)                     |
| Former                                 | 832 (30%)              | 639 (77%)                 | 74 (8.9%)                   | 119 (14%)                     |
| Current                                | 123 (4.4%)             | 88 (72%)                  | 8 (6.3%)                    | 27 (22%)                      |
| Pack-years among ever smokers          | 18 ± 21                | 18 ± 21                   | 15 ± 18                     | 18 ± 21                       |
| Asthma status                          |                        |                           |                             |                               |
| Noncase                                | 1,732 (62%)            | 1,378 (80%)               | 145 (8.4%)                  | 209 (12%)                     |
| Case                                   | 1,083 (38%)            | 839 (77%)                 | 105 (9.7%)                  | 139 (13%)                     |
| Atopy status                           |                        |                           |                             |                               |
| Noncase                                | 2,206 (78%)            | 1,749 (79%)               | 196 (8.9%)                  | 261 (12%)                     |
| Case                                   | 527 (19%)              | 398 (76%)                 | 49 (9.3%)                   | 80 (15%)                      |
| Missing                                | 82 (2.9%)              | 70 (69%)                  | 5 (31%)                     | 7 (31%)                       |
| Diagnosis of COPD and/or emphysema     |                        |                           |                             |                               |
| Noncase                                | 2,753 (98%)            | 2,169 (79%)               | 246 (8.9%)                  | 338 (12%)                     |
| Case                                   | 59 (2.1%)              | 46 (78%)                  | 4 (6.8%)                    | 9 (15%)                       |
| Missing                                | 3 (0.1%)               | 2 (31%)                   | 0 (31%)                     | 1 (31%)                       |
| Season                                 |                        |                           |                             |                               |
| Spring (21 March–20 June)              | 727 (26%)              | 573 (79%)                 | 71 (9.8%)                   | 83 (11%)                      |
| Summer (21 June–20 September)          | 824 (29%)              | 648 (79%)                 | 69 (8.4%)                   | 107 (13%)                     |
| Fall (21 September–21 December)        | 637 (23%)              | 514 (81%)                 | 47 (7.4%)                   | 76 (12%)                      |
| Winter (22 December–20 March)          | 627 (22%)              | 482 (77%)                 | 63 (10%)                    | 82 (13%)                      |

Note: Statistics presented: \( \% \) for categorical variables; unweighted mean ± (standard deviation) for continuous variables. Chi-square test of independence for categorical variables and Kruskal-Wallis test for continuous variables were performed to compare values across wood burning categories. \( p \)-Values were <0.05 for differences in exposure prevalence by race/ethnicity, smoking status, and state.

We estimated the probability of inclusion of asthma cases and noncases in the nested case–control study sample relative to the overall proportions of asthma cases and noncases in the parent AHS and used the inverse of these probabilities as sample weights in all analyses (\( w_{\text{case}} = 1.51; w_{\text{non-case}} = 0.18 \)). Using sample weighted multivariable linear regression, we estimated betas and 95% CIs for associations between wood burning exposure categories and FEV\(_1\) (in milliliters), FVC (in milliliters), and FEV\(_1\)/FVC (as a percentage). Covariates were those normally included in pulmonary function prediction equations (gender, age, age\(^2\), height, height\(^2\)), with body weight added for FVC. Additional covariates [race/ethnicity, cigarette smoking (current or former, both relative to never smoking), pack-years of cigarette smoking, and state of residence (Iowa, North Carolina)] were included to control for confounding by these variables. Race was defined by participant answers to the question “Which of the following groups best describes your race?” with possible answers being “White,” “Black,” “American Indian or Alaskan Native,” “Asian or Pacific Islander,” and “Other (Please describe below [in open-text box]).” For \( n = 30 \) people, missing self-identified race information was filled in with the category input into the EasyOne Spirometer (possible values: “Caucasian,” “African-American,” “Hispanic,” “Asian,” or “Other”). Because nearly all participants reported race/ethnicity as “White,” this variable was dichotomized for analysis into “White” or “non-White” and was included as a covariate because of associations to both exposure and response variables. Sensitivity analyses were additionally performed, restricting to individuals self-identifying as “White” and with spirometry measures performed during the cold season (November–April). FeNO models were adjusted for age, height, weight, gender, race/ethnicity, state, smoking status, pack-years, and, because of the well-known influence of atopy on FeNO, atopy status (atopic, nonatopic). FeNO measurements, in parts per billion (ppb), displayed a positive skew, so \( \ln(\text{FeNO}) \) values were used, as in previous studies. All analyses were performed using individuals without any missing information. We examined interaction product terms to assess statistical significance of differences in the association between wood burning exposure and pulmonary function metrics by smoking or by asthma status, considered separately. Statistical significance was assessed at \( p \leq 0.05 \). All analyses were performed using R (version 4.0.2; R Development Core Team), with weighted linear regression performed using the survey package (version 4.1-1).

Results

Study Population Characteristics

In the 2,815 ALHS participants analyzed, slightly more than half were male, and the mean age was 63 y (Table 1). Exposure to residential wood burning differed by race/ethnicity, state, and...
smoking status. The small proportion of individuals self-reporting as something other than “White” were more likely to be in the frequent wood burning category than individuals self-reporting as “White.” A higher proportion of North Carolinians than Iowans were exposed to residential wood burning. The small proportion of current smokers were more likely to be in the frequently exposed category than never or former smokers. Gender, age, height, weight, education, pack-years, asthma status, atopy status, COPD and/or emphysema diagnosis, and season in which the home visit occurred were unrelated to residential wood burning exposure classification.

**Multivariable Associations between Exposure to Residential Wood Burning and Pulmonary Function**

In sample weighted multivariable linear regression for the overall sample, beta estimates for the effect of frequent wood burning on lung function were negative for all pulmonary function measures, though 95% CIs included the null value (Table 2). Results of unweighted analyses are presented in Table S2. Results were similar when restricted to individuals visited in the cold season (November–April; Table S3) and when restricted to individuals self-identifying as “White” (Table S4). We found no appreciable interaction between wood burning category and smoking status (Figure S2; Table S5; unweighted associations in Table S6).

The association between frequent exposure to residential wood burning and pulmonary function appeared to differ by asthma status. The intermediate exposure category of “some” wood burning was not appreciably associated with any of the pulmonary function metrics among all individuals (Table 2), although all coefficients were negative among individuals with asthma (Table 3; unweighted associations in Table S7). Frequent wood burning exposure was not related to any of the pulmonary function metrics in individuals without asthma (n = 1,732; Table 3). However, among individuals with asthma (n = 1,083), we found reductions in all pulmonary function measures for individuals with frequent exposure to residential wood burning in comparison with those unexposed (Table 3; Figure 1; Table S8). Among individuals with asthma, frequent wood burning, relative to no exposure, was associated with 164 mL lower FEV1 (95% CI: −261, −66 mL; \( p_{\text{interaction}} = 0.0044 \)), 125 mL lower FVC (95% CI: −230, −20 mL; \( p_{\text{interaction}} = 0.068 \)), and 2 percentage points lower FEV1/FVC (95% CI: −4, −0.4%); \( p_{\text{interaction}} = 0.049 \).

**Multivariable Associations between Exposure to Residential Wood Burning and Exhaled Nitric Oxide**

Frequent residential wood burning was related to higher values of ln(FeNO) values in all individuals \( [n=2,598]; \beta = 0.1 \text{(ppb)}; 95\% \text{CI:} 0.02, 0.2; \text{Table 4} \). Frequent wood burning was also related to higher ln(FeNO) values in never and current smokers, but not former smokers. Last, when examining differences in associations by asthma status, frequent wood burning was related to higher ln(FeNO) values in noncases \( [n=1,594]; \beta = 0.1 \text{ln(ppb)}; 95\% \text{CI:} 0.02, 0.2] \) but not individuals with asthma \( [n=1,004]; \beta = 0.01 \text{ln(ppb)}; 95\% \text{CI:} −0.1, 0.1] \), but this difference by asthma status was not statistically significant \( p_{\text{interaction}} = 0.24 \). Unweighted associations between wood burning and fractional exhaled nitric oxide are presented in Table S9.

**Discussion**

In this United States farming population comprising older individuals from Iowa and North Carolina, frequent burning of wood in the home was associated with lower lung function for individuals with asthma. Wood burning was relatively common in this rural population, with 12% having frequent exposure and an additional 9% having at least some exposure. By comparison, the 2009 U.S. Residential Energy Consumption Survey estimated that 2.5% of U.S. households (2.8 million of 113.6 million housing units surveyed) used wood as a primary heating source and 7.7% (8.8 million

| Table 2. Association between exposure to residential wood burning and pulmonary function among \( n=2,815 \) participants in the Agricultural Lung Health Study (2009–2013). |
|---|---|---|---|---|---|---|---|
| Residential wood burning exposure | \( FEV_1 \text{ (mL)} \) | \( FEV_1 \text{ (mL)} \) | \( FVC \text{ (mL)} \) | \( FVC \text{ (mL)} \) | \( FEV_1/FVC \text{ (%)} \) | \( FEV_1/FVC \text{ (%)} \) |
| Unexposed | \( n \) | Mean \( \pm \) SD | Beta \( \beta \) (95% CI) | Mean \( \pm \) SD | Beta \( \beta \) (95% CI) | Mean \( \pm \) SD | Beta \( \beta \) (95% CI) |
| Unexposed | 2,217 | 2,666 \( \pm \) 813 | Ref | 3,584 \( \pm \) 1,007 | Ref | 74 \( \pm \) 8 | Ref |
| Some | 250 | 2,660 \( \pm \) 783 | −3 (−78, 72) | 3,595 \( \pm \) 1,019 | 30 (−61, 122) | 74 \( \pm \) 8 | −0.2 (−1, 0.9) |
| Frequent | 348 | 2,661 \( \pm \) 813 | −5 (−73, 63) | 3,605 \( \pm \) 1,013 | −12 (−92, 68) | 74 \( \pm \) 9 | −0.4 (−1, 0.6) |

Note: CI, confidence interval; FEV1, forced expiratory volume in 1 s; FVC, forced vital capacity; Ref, reference. SD, standard deviation.

*Mean \( \pm \) SD columns are sample weighted averages that account for the oversampling of individuals with asthma from the parent cohort. These are based on crude values not adjusted for age, gender, height, or any other covariates.

**Table 3. Association between exposure to residential wood burning and pulmonary function measure by asthma status among \( n=2,815 \) participants in the Agricultural Lung Health Study (2009–2013).**

| Asthma status | Residential wood burning exposure | \( n \) | \( FEV_1 \text{ (mL)} \) | \( FVC \text{ (mL)} \) | \( FEV_1/FVC \text{ (%)} \) |
|---|---|---|---|---|---|
| Noncase | Unexposed | 1,378 | Ref | Ref | Ref |
| Noncase | Some | 145 | 1 (−80, 82) | 37 (−62, 135) | −0.2 (−1, 1) |
| Noncase | Frequent | 209 | 10 (−62, 82) | −1 (−87, 84) | −0.2 (−1, 0.8) |
| Case | Unexposed | 839 | Ref | Ref | Ref |
| Case | Some | 105 | −14 (−122, 95) | −31 (−153, 91) | −0.3 (−2, 2) |
| Case | Frequent | 139 | −164 (−261, −66) | −125 (−230, −20) | −2 (−4, −0.4) |

\( p_{\text{interaction}} = 0.0044 \), 0.068, 0.049

Note: CI, confidence interval; FEV1, forced expiratory volume in 1 s; FVC, forced vital capacity; Ref, reference.

*Regression coefficients (beta estimate and 95% confidence interval) representing the difference in mean response between participants exposed to wood burning vs. unexposed individuals, holding all covariates constant. Analyses conducted using sample weighted linear regression with wood burning \( x \) asthma interaction term. Models adjusted for age, gender, height, height\(^2\), weight (for FVC only), race/ethnicity, smoking status, and pack-years. In parentheses, lower and upper bounds for 95% confidence intervals.

\( ^\text{a} \)p-Value for difference in the effect of frequent wood burning exposure by asthma status, from frequent wood burning \( x \) asthma case interaction product term, after accounting for main effects of wood burning exposure and asthma status.
of 113.6 million housing units) used wood as a secondary heating source. Among all participants and within smoking categories, residential wood burning was not appreciably related to three pulmonary function measures. However, associations between frequent residential wood burning and lung function differed by asthma status. Frequent wood burning was not appreciably associated with any pulmonary function metric among individuals without asthma, whereas it was related to lower pulmonary function among individuals with asthma. These reductions in pulmonary function were not trivial; the 164 mL lower FEV₁ among individuals with asthma and frequent exposure to household wood burning is equivalent to more than 5 y of age-related decline in this parameter in general population studies.37

Synthesis of results from short-term controlled woodsmoke exposure studies have identified increases in markers of inflammation after exposure, including FeNO.22–27 In our study examining habitual wood burning exposure, we found that self-report of frequent wood burning in the home was associated with slight increases in FeNO, an association that held after removing former smokers and our relatively low number of current smokers, who have depressed FeNO values.38 FeNO correlates with eosinophilic inflammation39,40 and appears to reflect the dynamic connections between allergen response and evolving eosinophilic airway inflammation.41,42

We note that short-term controlled exposure studies have not identified acute decreases in pulmonary function.25–27 The lack of lung function detriment in controlled woodsmoke exposure studies is likely due to the short exposures, the generally healthy, young populations used for these studies, and the much smaller sample sizes that are practical in such studies (range of 10–48 persons).

Our findings of associations between frequent residential wood burning and reduced pulmonary function in adults with asthma mirror those identified in U.S. children5 and the literature.

Figure 1. Associations between exposure to residential wood burning and pulmonary function by asthma status among n = 2,815 participants from the Agricultural Lung Health Study (2009–2013). Each pulmonary function measure was regressed on wood burning exposure, asthma status, and their interaction, adjusting for age, age², gender, height, height², weight (for FVC only), race/ethnicity, state, smoking status, and pack-years using sample weighted linear regression. Shown are the estimated pulmonary function measures from the model for each combination of wood burning category and asthma status, calculated at the mean values of age (63.30 y), height (169.80 cm), weight (85.97 kg), and pack-years (6.96 pack-years) and at the reference category for gender (female), race/ethnicity ("White"), state (Iowa), and smoking status (never smoker). Age² and height² were calculated by squaring the mean age and height, respectively. Vertical bars denote 95% confidence interval around the estimated value (Table S8).
Table 4. Association between exposure to residential wood burning and the natural log of fractional exhaled nitric oxide, for all individuals, and by smoking and asthma status, respectively, among \( n = 2,598 \) participants from the Agricultural Lung Health Study (2009–2013).

| Group               | Mean ± SD\(^a\) | Model estimates\(^b\) | Unexposed Some | Frequent |
|---------------------|------------------|------------------------|----------------|---------|
| All                 | 2.7 ± 0.63       | Beta (95% CI) Ref       | 2.040          | 235     |
|                    |                  |                        |                | 323     |
| Never smokers       | 2.70 ± 0.62      | Beta (95% CI) Ref       | 1.373          | 159     |
|                    |                  |                        |                | 189     |
| Former smokers      | 2.76 ± 0.61      | Beta (95% CI) Ref       | 0.583          | 68      |
|                    |                  |                        |                | 110     |
| Current smokers     | 2.19 ± 0.63      | Beta (95% CI) Ref       | 0.84           | 8       |
|                    |                  |                        |                | 24      |
| Noncase             | 2.68 ± 0.62      | Beta (95% CI) Ref       | 1.265          | 136     |
|                    |                  |                        |                | 193     |
| Asthma case         | 2.87 ± 0.73      | Beta (95% CI) Ref       | 0.775          | 99      |
|                    |                  |                        |                | 130     |

Note: —, not applicable; CI, confidence interval, Ref, reference; SD, standard deviation.

\(^a\)Mean ± SD columns are sample weighted and calculated in units of ln(ppb). These are based on crude values not adjusted for age, gender, height, or any other covariates.

\(^b\)Regression coefficients representing the difference in mean response between participants exposed to wood burning vs. unexposed individuals, holding all covariates constant. Analyses conducted using sample weighted linear regression. Models adjusted for age, gender, height, weight, race/ethnicity, state, smoking status, pack-years, and atopy status.

\(^c\)Beta (95% CI) Ref

| Interaction          | 0.03 (−0.06, 0.1) |
|----------------------|-------------------|
|                      | 0.05 (−0.2, 0.1)  |
|                      | 0.097             |

**Showing a negative relationship between biomass fuel burning and lung function in low- and middle-income countries.**

Our results also complement epidemiological studies of U.S. adults, which showed that wood burning in the home was associated with increased cough and sore throat, shortness of breath, and asthma severity and confirm results from Sood et al., who reported reduced percent predicted FEV\(_1\) associated with self-reported woodsmoke exposure in a smoking population. With this study, we extended previous knowledge on the impacts of wood burning exposure to include a large number of adults with asthma. To our knowledge, no other study has assessed the relationship between wood burning practices for residential home heating and fractional exhaled nitric oxide in adults residing in the United States or other high-income countries.

Limitations of our study include the use of an exposure measure constructed from self-reported information. Further, we asked questions about habitual home heating practices only at one point in time, potentially several weeks or months after the cold season, depending on when the participant was interviewed, and did not ask the participants about the length of wood stove use. Reassuringly, however, we found no relationship between season of interview (spring, summer, fall, winter) and reported wood burning practices. These data are cross-sectional and limited to farmers and their spouses, which limits the ability to make causal inference and reduces our generalizability to nonfarmering populations. Individuals with asthma who noticed impaired breathing after periods of wood burning may have reduced their frequency of wood burning. This avoidance behavior would attenuate the association between wood burning and reduced lung function in individuals with asthma. Given the cross-sectional nature of this study, we cannot conclusively quantify whether such avoidance occurred in the ALHS. However, the proportion of individuals who burned wood frequently did not differ by asthma status in this study, indicating low likelihood of wood burning–related behavior modification. We did not make measurements of combustion products to verify the exposure categories. Additionally, we did not adjust for outdoor levels of air pollution to control for possible exposure from wood burning by neighbors. However, this farming population tends to live much farther from neighbors than suburban or urban dwellers. Further, we previously found in a study in Oslo, Norway, that self-reported use of wood stoves correlated with higher levels of PM\(_{2.5}\) in the home and similar correlations have been found in other places. In addition, the fact that associations were predominantly seen for our higher exposure category, frequent as opposed to just some exposure, lends credibility to our findings.

By oversampling individuals with asthma, we had adequate power to identify associations independently in this important group, because asthma impacts over 300 million people worldwide. To account for the oversampling, we performed linear regression weighted by the selection probability of inclusion into the study based on asthma status. This approach allows for inference back to the entire parent cohort, the AHS, where the proportion of individuals with asthma is low. An unweighted analysis makes inference back to the studied population where we intentionally oversampled on asthma. Consequently, overall estimates from the weighted and unweighted analyses are expected to differ. Specifically, in unweighted analyses, frequent wood burning was overall inversely related to FEV\(_1\) (65 mL decrease, 95% CI: −124, −6; Table S2), an association driven by the high number of individuals with asthma in the sample. In weighted analyses the contribution of individuals with asthma was down-weighted, and thus no association was observed overall (Table 2). On the other hand, in interaction analyses where separate associations for those with and without asthma were compared, evidence for interaction was seen in both weighted and unweighted analyses (Table 3, Table S7). Moreover, the association with frequent wood burning was seen only among individuals with asthma in both analyses (Table 3, Table S7).

Additional strengths of the study include a large sample size. Although overlap or mistaken diagnosis between asthma and COPD is a concern in adults, we asked participants about diagnoses of COPD and emphysema and enrolled primarily persons with asthma who had no previous diagnosis of these conditions. The low prevalence of current smokers was also a strength of our study and makes overlap between asthma and COPD less problematic than in most studies of adults. Last, because this study population was largely rural, the prevalence of wood burning was higher than in general population studies, thus increasing power to identify associations.

Our study in a U.S. population provided evidence that habitual burning of wood in the home is associated with harmful reductions in lung function, especially for individuals with asthma. We also found evidence in the overall population that frequent exposure to residential wood burning may increase airway inflammation, as evidenced by slight increases in fractional exhaled nitric oxide. These results extend evidence for associations between adverse...
respiratory outcomes and burning wood and other types of biomass in low- and middle-income countries to a high-income country and to adults with asthma. Thus, these results have relevance to lifestyle recommendations for individuals with asthma regarding the choice to burn fuel for recreational purposes or to rely on wood burning as a primary or secondary form of home heating. Air filtration devices, which have been shown to reduce household air pollution from wood-burning devices, could be an alternative resource for individuals who continue to rely on wood burning. Reduction of household exposure to wood combustion by-products, especially as smoke exposure from wildfires increases, may be an important approach for combating respiratory illness.

Acknowledgments

The authors are grateful to the participants and study team members involved in the AHS and ALHS. The authors thank the numerous study staff at Social & Scientific Systems, Inc., who played a role in the data collection. The authors thank J. Hoppin, ScD, of North Carolina State University for her earlier contributions to the ALHS. This work was supported by the Intramural Research Program of the National Institutes of Health, NIHES (Z01-ES04930, Z01-ES102385, and for ABW contract no. HHSN273201600003I) and National Cancer Institute (Z01-CP010119), and in part by American Recovery and Reinvestment Act (ARRA) funds through NIHES contract no. N01-ES5554.

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