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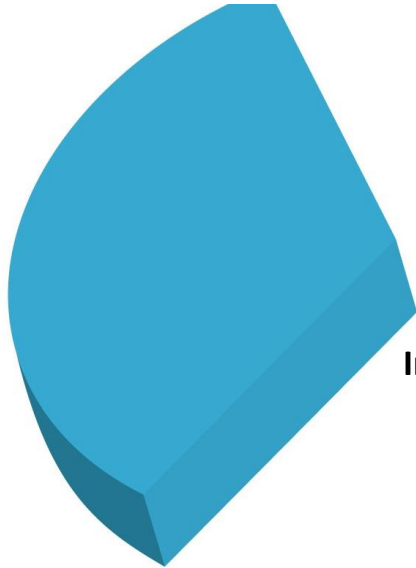
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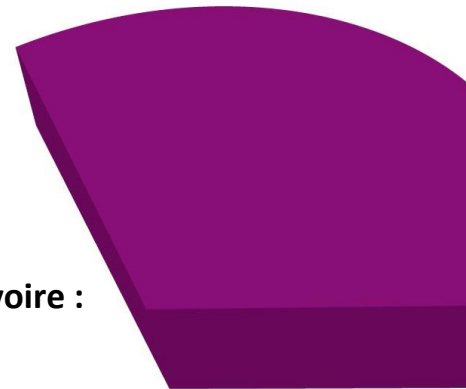
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**Indoor air pollution and health in Côte d'Ivoire :  
Does the age group matter?**



**Macoura DOUMBIA**



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# Indoor air pollution and health in Côte d'Ivoire : does the age group matter?

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## Abstract

In sub-Saharan Africa, indoor air pollution is a major public health problem. Through an original indicator of indoor air pollution constructed from household characteristics and outdoor air quality, this study evaluates the effect of indoor air quality on the health of household members in Côte d'Ivoire. After using a mixed-effect model, the results show the effect varies according to age group, and is highly significant for children under 5. Also, the impact varies according to household characteristics and the level of development of the area of residence.

**Keywords :** *indoor air pollution, environmental health, respiratory disease, Côte d'Ivoire*

**JEL classification :** I15, I18, Q53, Q56

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# 1 Introduction

Degradation of air quality is undoubtedly one of the major environmental challenges in developing countries and especially in sub-Saharan Africa. Indeed, the socio-economic development of Africa in general and the West African sub-region in particular, increases the quantities of pollutants discharged into the atmosphere (Coalition pour le Climat et l’Air pur, 2019). According to World Health Organisation (WHO thereafter), air pollution is now the greatest environmental risk to health with more than eight (8) million premature deaths in 2014 worldwide. In 2017, an estimated 670,000 premature deaths in Africa were linked to exposure to air pollution; of which about 13,000 were in Côte d’Ivoire (Coalition pour le Climat et l’Air pur, 2019). Increasing levels of urbanisation and poor urban planning in sub-Saharan Africa have contributed to rising levels of air pollution and, consequently, increased adverse health effects, including non-communicable diseases. Indoor air pollution was the largest contributor to deaths from non-communicable diseases in sub-Saharan Africa in 2016 (Milanzi et al., 2021). And this pollution associated with the use of biomass as fuel was responsible for 7 million deaths in 2016 and most of these deaths occurred in low- and middle-income countries (Kouao et al., 2019). Furthermore, according to The LANCET<sup>1</sup>, in Côte d’Ivoire, for the whole population, lower respiratory infections were responsible for 9.31% of total deaths in 2019. And, the top 3 causes of death in children under 5 years of age were neonatal disorders (35.56%), malaria (21.59%) and lower respiratory infections (13.76%) in 2019.

Côte d’Ivoire is aware of the issues related to air pollution caused by economic development and has joined several international conventions and mechanisms, including the United Nations Framework Convention on Climate Change (UNFCCC) and the Climate and Clean Air Coalition (CCAC) (Coalition pour le Climat et l’Air pur, 2019). This awareness has also manifested itself at the sub-regional level with the adoption in 2009 of the Abidjan Agreement, a regional framework agreement for the improvement of air quality in Central and West Africa Coalition pour le Climat et l’Air pur (2019). This agreement is a starting point to address the issue of air pollution in Central and West African countries. In October 2018, in the framework of the Abidjan agreement, a workshop was initiated in Abidjan with the aim of producing an evaluation report and a roadmap 2019-2023 (UNEP, 2019).

From a technical support point of view, Côte d’Ivoire benefits from a program financed by Norway and Sweden and implemented in seven cities, five of which are in Africa (Abidjan, Addis Ababa, Kigali, Nairobi and Ouagadougou) and two in Asia-Pacific (Agra and Phnom Penh) to help *better define and measure the magnitude of air pollution and its main sources, review regulatory and institutional frameworks and develop recommendations through a consultative process with key stakeholders. Program is linked to regional and sectoral activities carried out by UNEP and its partners in the areas of clean mobility, waste management and clean industries* (UNEP, 2019). The country has embarked on a process of reducing the footprint of its economic development on its natural environment through the commitment to reduce its greenhouse gas emissions by 28% by 2030 and the adoption of an Air Quality Decree to control air pollution (UNEP, 2019).

In addition, as part of the implementation of the ECOWAS Renewable Energy Policy (PERC),

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<sup>1</sup><https://www.thelancet.com/lancet/visualisations/gbd-compare>

Côte d’Ivoire put in place a National Renewable Energy Action Plan (PANER) in 2016<sup>2</sup>. The main objective of the PANER is to contribute to the achievement of the targets set by the PERC for 2030. To achieve this overall goal, Côte d’Ivoire has set itself some specific objectives. The first is to increase access to clean energy and to reduce the demand for polluting energy, more specifically to reduce the amount of wood energy used to meet household energy needs. To achieve this, awareness-raising activities on the use of improved stoves and butane gas have been undertaken (MPE, 2016). The second is the reduction of polluting emissions and the preservation of the forest cover. Indeed, in terms of cooking, biomass energy (firewood, charcoal, vegetable waste) represents a little more than 2/3 of the total final energy consumption of households (MPE, 2016). In view of the consumption of wood-energy, the vegetation cover of Côte d’Ivoire risks disappearing if nothing is done, as the Ivorian forest has gone from 9 million ha in 1965 to 2.8 million ha in 2021<sup>3</sup>. To achieve this, the PANER aims to increase the share of the population consuming modern alternative cooking fuels such as LPG to 90% by 2030 (MPE, 2016). Another important specific objective is to achieve gender equity in terms of cooking fuel use (MPE, 2016). Through PANER, Côte d’Ivoire is working to reduce the use of solid fuels (coal and biomass). This could consequently improve indoor air quality through the use of clean fuel.

Worldwide, 41% of households, or over 2.8 billion people, use solid fuels for cooking and heating (Amegah and Jaakkola, 2016). In Asia and sub-Saharan Africa where these fuels are mainly used, women, who are usually responsible for cooking, and their young children are most exposed to the resulting air pollution (Amegah and Jaakkola, 2016). Solid fuels are still widely used and intervention efforts are apparently not keeping pace with population growth in developing countries (Amegah and Jaakkola, 2016). According to data from the 2015 Household Living Standards Survey, 81.27% of households in Côte d’Ivoire use biomass (charcoal or wood) as fuel for cooking. The objective of this study is to show the causal relationship between indoor air quality and the risk of respiratory diseases in Côte d’Ivoire. To do this, I create an original indoor air pollution index to approximate level of pollution to which households were exposed in Côte d’Ivoire in 2015 when they are inside the house.

This study differs from the previous ones on several points. The first concerns the sample. Previous studies have focused on a particular area of Côte d’Ivoire, and more precisely on one municipality in the city of Abidjan (René et al., 2019; Rosine et al., 2021). While this study focuses on all the sub-prefectures of Côte d’Ivoire. The broadening of the study sample allows me to have a wider overview of the effects of indoor air pollution on household members health. The second and major contribution of the study is the creation of an original indoor air pollution index based on emission sources. This allows us to approximate indoor air quality. Another contribution is that the analysis is done by age group. This is of interest with regard to the development of appropriate public policies. A mixed-effect logistic model has been used to perform the analysis. Random effects at the household and sub-prefecture level were added to the model to take into account certain factors that may affect the health of household members. The results show that indoor air pollution increases the risk of respiratory diseases among children under five. The effects vary according to the characteristics of the households and the household’s place of residence.

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<sup>2</sup><https://www.householdenergypolicies.org/policy/173>

<sup>3</sup><https://www.timbertradeportal.com/en/republic-of-cote-divoire/176/country-context>

The rest of the study is organised as follows: the next section presents the literature review on the subject. The materials are presented in the third section. The fourth and fifth sections describes respectively the stylized facts and the econometric analysis. Then, the sixth and seventh sections are devoted respectively to the presentation of the robustness checks and the heterogeneity tests. The last section discusses the conclusion and policy implications.

## 2 Background

Larson and Rosen (2002) support the idea that there is a willingness to pay to prevent indoor air pollution in developing countries. This demand for better air quality is partly related to the health effects of pollution. In this section I will first discuss the different sources of indoor air pollution and in the second part I will talk about the health effects on household members.

### 2.1 Sources of indoor air pollution and major toxic pollutants

Agbo et al. (2021) show that vehicle traffic, industries, forest fires and biomass burning are important sources of PM, CO, NO<sub>2</sub>, SO<sub>2</sub> and VOCs in Africa. Also the Sahara desert is an important source of PM especially during the harmattan. Average indoor concentrations of PM, CO, NO<sub>2</sub> and SO<sub>2</sub> exceed WHO limit values and even more so in poorly ventilated wood-fired kitchens in rural areas. In this sense, Abdul Raheem et al. (2022) show that NO<sub>2</sub>, SO<sub>2</sub>, and CO concentrations were higher in kitchens using charcoal and firewood in Nigeria. In addition, firewood contributed significantly more than charcoal to the emission of the pollutants. This implies a potentially high exposure of women and children in Africa.

Biomass is a source of energy that has been used for many years and by about half the world's population. The majority of use is in developing countries for economic activities, basic cooking, heating and lighting (Balat and Ayar, 2005). According to Bruce et al. (2006), in rural areas of several african countries, biomass is the main fuel used by almost 100% of the population. Energy can be obtained by direct or indirect combustion. The use of this type of energy is the main source of indoor air pollution in these countries because biomass combustion generates important pollutants such as airborne particles and polycyclic organic matter, which include a number of carcinogenic substances (Ludwig et al., 2003).

Furthermore characteristics of the house are also an important source of pollution. First of all, level of ventilation is very important because it favours the evacuation of pollutants from the indoor air. The more the house is well ventilated, the better the indoor air quality (Xu et al., 2010; Apte and Salvi, 2016; Kouao et al., 2019). Kouao et al. (2019) prove this by looking at the exposure to outdoor and indoor air pollution of children under 5 years old in the municipality of Yopougon in Abidjan. The results reveal the number of windows in bedrooms and kitchens located outside are negatively related to the level of PM<sub>2.5</sub> concentration inside the house. Pollutants are also related to materials (e.g. cement), coatings, paint and furnishings. The use of certain construction materials contributes to the emission of volatile organic compounds. For example, the fact that the wall or floor or roof is made

of cement releases volatile organic compounds that affect the level of indoor air pollution (Apte and Salvi, 2016). In addition, the use of some high-tech devices increase the level of ozone in home (Apte and Salvi, 2016). Also, the use of insecticides and pesticides (e.g. mosquito repellents), deodorants, perfumes and incense release organic compounds that could be toxic (Apte and Salvi, 2016). Table 1 is a summary of the different sources of household air pollution according to Apte and Salvi (2016).

In addition to internal sources, there are also external sources that contribute to the deterioration of indoor air quality. Pollutants produced outside influence the level of indoor air pollution (Jones, 1999; Koponen et al., 2001). This is because pollutants are transported by the wind, which is considered the main carrier of concentrated pollutants in the air. These wind-borne pollutants are concentrated in houses.

Table 1: Sources of household air pollution (Apte and Salvi, 2016)

Sources of household air pollution	Examples
Cooking methods (using liquefied petroleum gas or electricity)	Stir frying, frying, roasting, grilling, baking, basting, and broiling methods which lead to an increase in particulate matter (PM2.5)
Biomass fuels	Wood, crop residue, animal dung, and charcoal
Tobacco smoke	Active smokers and second-hand and third-hand smoke
Incense sticks	Agarbatti and dhoop (incense sticks), Bakhoor, and Oudh
Mosquito repellents	Mosquito coils, flammable paper mats, and aerosols
Cleaning agents, products of personal care, air fresheners, wood varnishes, paint, and carpet solvents	Volatile organic compounds
Fire-retardant foam-containing furniture, electronic gadgets, and building material	Polybrominated diphenyl ethers
Fungi such as Aspergillus, Cladosporium, and Penicillium	Damp walls and ill-maintained air conditioning
Bacteria such as Legionella	
Domestic pets	Pet dander

Also, Table 2 from Smith et al. (2004) gives an idea about the main indoor air pollutants and their emission sources. We can see that there are several types of pollutants. Some of them come from the type of fuel used. These include fine particles, carbon monoxide, polycyclic aromatic hydrocarbons, nitrogen oxides and volatile and semi-volatile organic compounds. The use of solid or biomass fuel (wood or charcoal) for cooking, heating or lighting leads to increased concentrations of these pollutants. Other pollutants such as sulphur oxides, arsenic and fluorine are emitted through coal combustion. Building materials can cause indoor air pollution through the emission of pollutants such as aldehydes, asbestos and radon. Again in Table 2, it can be seen that most pollutants have several emission sources. In addition, it is important to note that the level of concentration of these pollutants will also depend on the level of ventilation in the house or kitchen. Indeed, when the house has a better ventilation system, this favours the dissipation of pollutants.

At the end of this section, one could conclude that the main source of indoor air pollution in sub-Saharan Africa is the use of traditional fuels. The following lines will discuss the adverse effects of these emitted pollutants on the health of household members.

Table 2: Major toxic pollutants of indoor air (Table from (Smith et al., 2004))

<i>Pollutant</i>	<i>Major indoor sources</i>
Fine particles	Fuel/tobacco combustion, cleaning, fumes from food being cooked, e.g. from cooking oil
Carbon monoxide	Fuel/tobacco combustion
Polycyclic aromatic hydrocarbons	Fuel/tobacco combustion, fumes from food being cooked, e.g. from cooking oil
Nitrogen oxides	Fuel combustion
Sulfur oxides	Coal combustion
Arsenic and fluorine	Coal combustion
Volatile and semi-volatile organic compounds	Fuel/tobacco combustion, consumer products, furnishings, construction materials, fumes from food being cooked, e.g. from cooking oil
Aldehydes	Furnishing, construction materials, cooking
Pesticides	Consumer products, dust from outside
Asbestos	Remodelling/demolition of construction materials
Lead <sup>a</sup>	Remodelling/demolition of painted surfaces
Biological pollutants	Moist areas, ventilation systems, furnishings
Free radicals and other short-lived, highly reactive compounds	Indoor chemistry
Radon	Soil under building, construction materials

<sup>a</sup> Lead-containing dust from deteriorating paint is an important indoor pollutant for occupants of many households, but the most critical exposure pathways are not usually through air. See chapter 19.

Source: Zhang and Smith (2003).

## 2.2 Indoor air pollution and health

Poor indoor air quality has adverse effects on people’s health. In this section I will first discuss the different impacts of indoor air pollution on children’s health, then on women’s health and finally on the health of the elderly.

Previous studies show that indoor air pollution affects the health of children in several ways. In this sense, Basu et al. (2020) show that indoor air pollution induced by solid fuel use increases the risk of neonatal and infant mortality by 4.9% in India. And Kinney et al. (2021) found that prenatal household air pollution exposure increased risk of pneumonia and severe pneumonia in the first year of life of children in Ghana. Air pollution also causes underweight babies (Hackley et al., 2007). Furthermore, Edwards and Langpap (2012) finds that children aged 0-5 years living in households that use more wood, and where exposure to indoor air pollution is higher because the mother cooks while caring for the children or because cooking takes place indoors, are more likely to have symptoms of respiratory infection in Guatemala. In the same vein, Padhi and Padhy (2008) show that exposure to cooking smoke from biomass combustion is significantly associated with decreased lung function and increased prevalence of asthma among children in rural India. Also, solid fuel smoke has most of the toxins found in tobacco smoke and has also been associated with various diseases, such as acute respiratory infections in children when exposed to solid fuel smoke (Pérez-Padilla et al., 2010). Ranathunga et al. (2019) assess the association between household air pollution due to solid fuel combustion and self reported childhood respiratory tract diseases among children under 5 in Sri Lanka. They find significantly higher concentrations of CO and PM2.5 in households using biomass as cooking fuel. The risk of developing asthma was 1.6 times higher in the highly exposed group compared to the less exposed children. Health effects of indoor air pollution on children under 5 years have been tested also in Côte d’Ivoire. In this sense, René et al. (2019) are interested in the relationship between indoor air



pollution from biomass burning and the prevalence of asthma in children under 5 years old in the municipality of Yopougon in Abidjan. They find a positive relationship between nocturnal dry cough and outdoor PM<sub>2.5</sub> concentration and a relationship between wheezing and indoor PM<sub>2.5</sub> concentration. Furthermore, a study by [Rosine et al. \(2021\)](#) on a sample of 200 asthma patients in the commune of Yopougon in Adidjan shows 63% of individuals in the sample combined the use of charcoal and butane gas as fuel at home. This result supports the idea that the use of biomass as fuel increases the level of indoor air pollution. In addition, [Yu \(2011\)](#) find an improvement in the respiratory health of children aged five and under in rural China through stove and behavioural interventions to reduce indoor air pollution.

Indoor air pollution also affects women's health. According to [de Koning et al. \(1985\)](#), in rural areas of developing countries, women are most exposed and so is the foetus for pregnant women and children. The effects of this pollution vary according to the weather conditions, the size and ventilation level of the house and the type of food being cooked ([de Koning et al., 1985](#)). Women are the most vulnerable to indoor air pollution and the effect on the level of morbidity is higher for women aged between 14 and 40 years ([Dutta and Banerjee, 2014](#)). In the same vein, [Oluwole et al. \(2013\)](#) show that the use of firewood for cooking is responsible for indoor air pollution in Nigeria and a deterioration in the respiratory health of women. The authors find that the use of low-emission stoves reduces the level of pollution and thus reduces the symptoms of respiratory diseases. Air pollution is also the cause of underweight births, intrauterine pregnancies, premature births and abortions ([Hackley et al., 2007](#)). Similarly, through a meta-analysis, [Gebremeskel Kanno and Hussen Kabthmyer \(2021\)](#) shows that mothers living in households that use biomass as fuel have a 74% higher risk of giving birth to a low birth weight child compared to mothers living in households without air pollution due to biomass fuel use. The study concludes that indoor air pollution from cooking fuels increases the risk of low birth weight in sub-Saharan Africa. Also, solid fuel smoke has been associated with various diseases, such as chronic obstructive pulmonary disease and lung cancer in women ([Pérez-Padilla et al., 2010](#)).

The health of the elderly is also affected by indoor air pollution. Indeed, the effects of indoor air pollution are much more severe in the elderly due to their weakened immune system and multiple health risk factors [Rani et al. \(2021\)](#). For example, [Weuve et al. \(2012\)](#) show that long-term exposure to PM<sub>10</sub> and PM<sub>2.5</sub> is associated with significant cognitive decline in elderly women in the US and also increases the risk of breast cancer. In addition, [Rani et al. \(2021\)](#) investigated the effect of indoor air pollution from fuel use on cognitive function in elderly people in India. The findings show lower cognitive function scores in elderly people living in households using solid fuels. And elderly people from low socio-economic backgrounds were more exposed to indoor air pollution than their counterparts, which indirectly increases the risk of poor cognitive function. [Qiu et al. \(2019\)](#) looking at middle-aged and elderly people in China, using the propensity score matching method, they find that indoor air pollution increases the likelihood of being diagnosed with respiratory and cardiovascular diseases including lung disease, heart disease, and hypertension, and reporting poor health status. They also find a significant adverse impact on cognitive abilities, specifically short-term memory and mathematical reasoning. In the same vein [Saenz et al. \(2018\)](#) find that indoor air pollution may be an important factor in the cognitive health of older people in Mexico.

Exposure of individuals to indoor air pollution from biomass burning is the cause of several diseases in developing countries. Indeed, exposure to emissions from these types of fuel have been found to be associated with many respiratory diseases such as acute lower respiratory tract infections, chronic obstructive pulmonary disease, lung cancer, pulmonary tuberculosis, asthma, childhood pneumonia, pneumoconiosis, bronchitis, head and neck cancers and cardiovascular diseases (Prasad et al., 2012; Balmes, 2019; Simkovich et al., 2019). This is the case of Albalak et al. (1999) who study the relationship between biomass burning and chronic bronchitis in Bolivia. They find a positive relationship between the prevalence of chronic bronchitis and cooking indoors using biomass as an energy source. This is because the pollutants emitted settle in the respiratory tract and cause illness. Also, the pollution resulting from biomass burning contains carcinogenic polycyclic aromatic hydrocarbons (PAHs) which cause blood diseases and several human morbidities in developing countries as these countries account for 99% of the world’s biomass fuel use (Kamal et al., 2015; Prasad et al., 2012). According to Balmes (2019), the mechanisms by which solid fuel smoke causes health problems in humans are quite similar to those involved in tobacco smoke. Indeed, after smoke inhalation, oxidative stress in the airways and alveoli leads to stimulation of alveolar macrophages and damage to the mucosal lining of the epithelium, which in turn attracts inflammatory cells from the circulation. This local pulmonary inflammatory reaction can spread to the systemic circulation and contribute to problems in other organs, such as the cardiovascular system, and the foetus in pregnant women. Alveolar macrophages loaded with carbon particles from smoke may contribute to an increased risk of respiratory tract infections. Furthermore, the pathways involved in lung carcinogenesis induced by solid fuel smoke are probably identical to those by which tobacco smoke induces lung cancer. Semple et al. (2014); Mocumbi et al. (2019); Pope III et al. (2009) show that indoor air pollution increases the risk of cardiovascular disease and that premature cardiovascular death and disability in sub-Saharan African countries could be prevented by addressing the use of biomass fuels by the poorest households.

### 3 Materials

The strength of this study lies in the construction of an original database that combines ambient air quality and nightlight data from satellite imagery with data from the 2015 Household Living Standards Survey in Côte d’Ivoire. Also, the hierarchical structure of this database allows contextual effects to be taken into account. Using this database, I construct an original indoor air pollution index. This section describes the data used and the data sources.

#### 3.1 Data

The unit of observation is the individual, whose main characteristics are given by the 2015 household living standards survey. Main purpose of the Côte d’Ivoire household living standards survey is to provide the information needed to improve planning and evaluation of economic and social policies in Côte d’Ivoire. The survey provides information on household composition, education, employment and health, among other things. It was conducted by the National Institute of Statistics (INS) of Côte d’Ivoire. The sampling frame used to draw the sample is the 2014 General Census of Population and Housing. The sampling is based on a two-stage draw. The first stage consists of a proportional allocation of the Enumeration Areas (EAs). The second is a systematic drawing of 12 households

per enumeration area. The total sample obtained consists of 12,900 African households residing in Côte d’Ivoire (INS, 2023). Furthermore, I do not use the DHS databases because the information on household residence is limited to the regional level only. In order to have more variability, I choose the household living standards survey data to do the analysis.

The study is based on a sample of 2060 individuals divided into four (4) age groups who had visited a health care provider in the last 4 weeks at the time of the survey in 2015. I use the dependency ratio to create age groups to see how the impact of indoor air pollution varies according to age group. Dependency ratio is calculated according to the age structure of the population. It corresponds to the ratio of the number of individuals who are supposed to be "dependent" on others for their daily life (young and old people) and the number of individuals who are able to assume this dependence of individuals able to assume this burden. Generally, the number of individuals under 15 and over 65 years of age is related to the population aged 15 to 64 years because it is assumed that individuals aged 15 to 64 years are workers and the others are dependents (Delaunay and Guengant, 2019). Based on this indicator, I obtain 4 age groups. The first group is made up of children under the age of 5. I focus on this age group because they are very vulnerable due to the immaturity of their organs. The second group is children between 5 and 14 years old. The third group includes people between 15 and 64 years old who are considered active people. And the fourth group is for people aged 65 and over.

In addition to the survey data I use the database of van Donkelaar et al. (2018) which contains annual concentrations of fine particles at ground level (PM2.5), without dust and sea salt. The data are gridded to 0.01 degrees and expressed in micrograms per cubic metre. These data give an idea of the ambient air pollution level and are also used in the construction of the indoor air pollution index. I also use night-time luminosity data which is satellite imagery data from The Earth Observations Group database. These data allow me to have information on the level of development of the sub-prefectures of Cote d’Ivoire. The concentrations of PM2.5 and luminosity data at sub-prefecture level are extracted using QGIS software.

The following lines describe the variables used in the analysis and obtained from the constructed database.

### 3.2 Outcome variable

The dependent variable informs us about the number of people who report having recently consulted a doctor because of a respiratory or cardiac disease during the last 4 weeks (question C.1.c in the survey form). The value is 1 when the individual consults for reasons related to nasal breathing (sinus), pulmonary breathing (chest, lungs), asthma, flu, sore throat or heart problems. And the variable is 0 when the individual consulted because of another health problem. In the rest of the analysis, I will refer to the risk of respiratory diseases and not to the risk of respiratory and cardiac diseases because most of the diseases mentioned above are related to the respiratory tract. In the sample, 2862 individuals consulted a doctor for various health reasons (Table A1).

### 3.3 Interest variable

#### 3.3.1 Indoor air pollution measures

Several measures are used to measure indoor air quality. Some researchers use indirect measurements and others use direct measurements. The indirect measure frequently used is the type of fuel used for cooking, heating or lighting. Indeed, inefficient combustion of solid fuels in poorly ventilated homes is a major source of exposure to indoor air pollution (Balmes, 2019). As a result, some previous studies use the type of fuel used to approximate the level of indoor air pollution and its different impacts on the health status of household members (Pérez-Padilla et al., 2010; Saenz et al., 2018; Balmes, 2019; Qiu et al., 2019).

In addition, direct measurements of indoor air pollution are used to investigate its impact on health (Ranathunga et al., 2019; Rani et al., 2021; Kinney et al., 2021). These authors use sensors (Kinney et al., 2021) which can be placed in the kitchen, living room or bedroom. The pollutants measured are usually particulate matter (PM10, PM2.5 or PM0.1), carbon monoxide, nitrogen dioxide and sulphur dioxide and are harmful to health (Chen and Zhao, 2011; Leung, 2015; Saenz et al., 2018).

These previous measures have limitations. The indirect measure is an incomplete measure because it only captures a part of the indoor pollution. Indeed, indoor air quality may depend on outdoor air quality because ambient air pollutants are transported inside houses. It is therefore very important to take into account the outdoor air quality. Furthermore, direct measurement of indoor air quality is more difficult to implement, which limits its deployment. Indeed, this kind of measurement on a national scale require a lot of financial resources. This is why it is usually done for a few households and in one or more localities. In this study I compute an original measure of indoor air pollution. To my knowledge, this study is the first to construct this type of indoor air quality index. This index has some advantages over previous measurements because it combines internal and external sources of pollution and gives an idea of the indoor air quality of households in all sub-prefectures of Côte d'Ivoire in 2015. The following section gives the details of the construction of the indoor air pollution index.

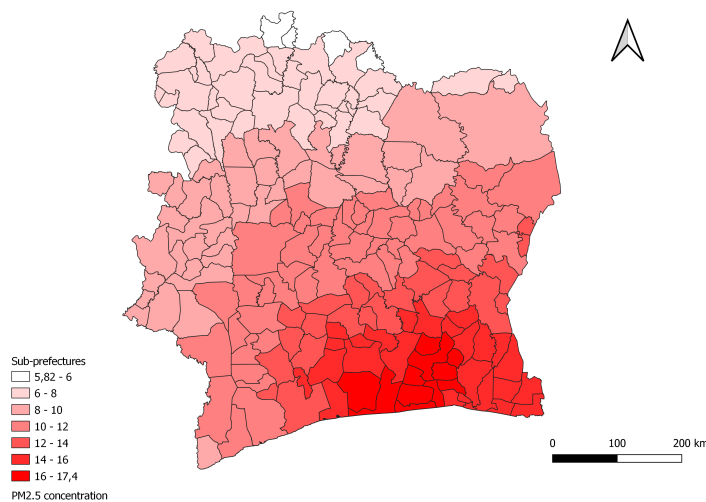
#### 3.3.2 Indoor air pollution index

Indoor air pollution results from emissions of pollutants from both external and internal sources. This section describes the construction of the index. For this purpose I combine external and internal sources of pollution. In the first part of the section I discuss external sources and the second part focuses on internal sources.

Primary source of ambient air pollution in Côte d'Ivoire is road traffic. Indeed, cars that serve as public transport and are commonly called woro-woro and gbaka are old. Despite the decree banning import of vehicles more than five years old, the fleet of vehicles remains old and polluting. The older the vehicles, the higher their particle emission rate. In addition, most of the cars used run on diesel. Another source of pollution is the burning of waste and agricultural residues in urban and rural centres (Ehsani et al., 2017). This ambient air pollution affects indoor air quality because pollutants from

outside, carried by the wind, are deposited inside houses. This is why I take into account the ambient air quality in the construction of the index. To do that, I use the annual average concentration of PM2.5 set by WHO that the country should not exceed in order to ensure that the air people breathe is safe. The new annual limit set by the WHO is  $5\mu\text{g}/\text{m}^3$ . Thus, the "outdoor pollution" indicator equals 1 when the sub-prefecture has an annual concentration of fine particles above  $6\mu\text{g}/\text{m}^3$ <sup>4</sup> and 0 otherwise. Graph 1 shows the average concentration level of fine particles. In the graph, the sub-prefectures located in the south and south-east have a very high level of PM2.5 concentration compared to the other sub-prefectures. This level of PM2.5 would be explained by the fact that the autonomous district of Abidjan is located in this area. Indeed, Abidjan has a high level of PM2.5 mainly because of the very dense road traffic. In addition, industries, domestic fires, bush fires and open dumps are also at the origin of poor ambient air quality in Cote d'Ivoire in 2015<sup>5</sup>. Thermal power plants are also a source of ambient air pollution. Indeed, in 2015, 50.6% of the electricity came from fossil fuel and 49.4% from renewable energy<sup>6</sup>. Most of these natural gas-fired power plants are located in Abidjan. They thus contribute to the deterioration of the ambient air quality of the locality.

Figure 1: PM2.5 concentration in ambient air in  $\mu\text{g}/\text{m}^3$



Source: Author's own elaboration

Furthermore, indoor air quality depends on household behaviour, especially with regard to the choice of energy for cooking and lighting. I construct a "fuel" indicator which is equal to 1 when cooking fuel is biomass and 0 if households use clean fuel like gas or electricity. The households for which I have information on the type of fuel, 81.07% use biomass as cooking fuel, mainly firewood (wood collected or purchased) and charcoal and only 18.93% use clean fuel. The second indicator "lighting mode" is 1 when it is a polluting mode and 0 if the lighting mode is electricity, solar panel or torch. Only 2.95% of the sample uses a polluting lighting mode. These include the use of lamps (paraffin, oil, gas), generators and firewood. Since the type of cooking fuel and lighting system are not the only source of indoor air pollution, I also take into account the characteristics of the house-

<sup>4</sup>I used the value of  $6\mu\text{g}/\text{m}^3$  instead of  $5\mu\text{g}/\text{m}^3$  because the annual ambient air pollution level of each sub-prefecture exceeds  $5\mu\text{g}/\text{m}^3$ . Since we want to get as close as possible to the revised value ( $5\mu\text{g}/\text{m}^3$  instead of  $10\mu\text{g}/\text{m}^3$ ) of the annual pollution level limit, we choose  $6\mu\text{g}/\text{m}^3$ .

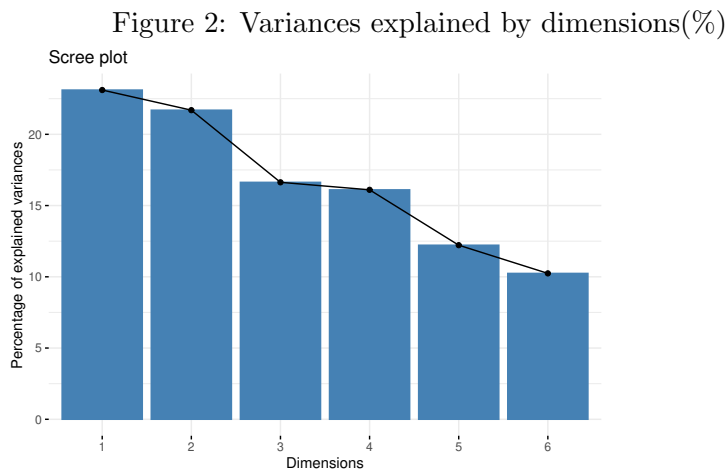
<sup>5</sup><https://wedocs.unep.org/bitstream/handle/20.500.11822/17174/CotedIvoire.pdf?sequence=1&isAllowed=y>

<sup>6</sup><https://wedocs.unep.org/bitstream/handle/20.500.11822/17174/CotedIvoire.pdf?sequence=1&isAllowed=y>

hold accommodation such as the type of housing and the type of construction material of the dwelling.

I create an indicator to categorise the type of housing. The indicator "type of dwelling" is 1 when it is a less ventilated dwelling and 0 otherwise. The data shows that 14.97% live in less ventilated houses such as traditional huts or shacks and the rest of the sample live in well-ventilated dwellings such as villas, flats or courtyard houses. The "floor material" indicator is 1 when floor of the dwelling is made of cement (68.2% of the sample) and 0 if floor is made of tile, marble, carpet, wood or soil. otherwise. "Roof material" indicator is 1 when the roof is made of concrete (2.21% of the sample) and 0 if the roof is made of plant fibre, sheet metal or tiles.

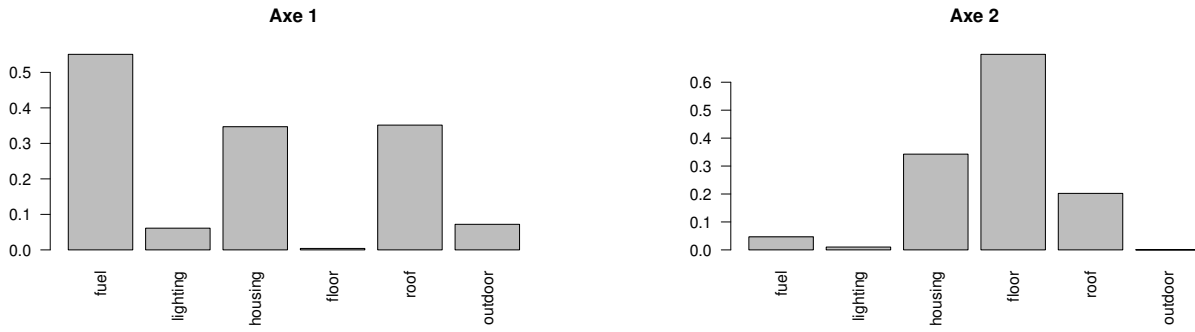
Using multiple component analysis I get an indoor air pollution index from different indicators mentioned above. I use the first dimension of the index because the objective is to have a single synthetic index. This dimension represents 23.1% of the total inertia (Figure 2). The index obtained varies between -2.82 and 4.07. The higher the index, the worse the indoor air quality. The average index for the sample is 0.21 and the standard deviation is 1.07 (Table A1).



Source: Author's own elaboration

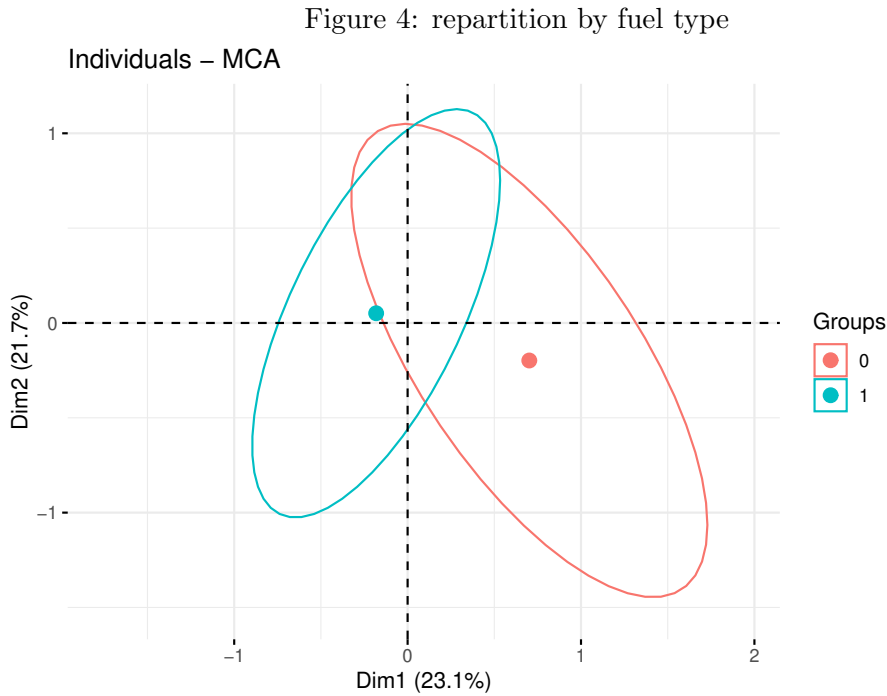
Figure 3 represents the overall contribution of each variable in the construction of the axes. The main variables that have a large contribution in the construction of the first axis are the type of fuel, the roof material, the type of dwelling and the level of pollution of the ambient air which contribute respectively to 54%, 36%, 35% to the construction of the first axis.

Figure 3: Contribution to axes construction



Source: Author's own elaboration

Since the type of fuel is the most important contributing variable in the construction of the first dimension, I make graph 4 below which shows the distribution of households along the axes according to the type of cooking fuel. Group 0 corresponds to households that use clean fuel and group 1 to households that use biomass. On the graph, we can see households in group 1 are much closer to the first axis than those in group 0.



Source: Author's own elaboration

### 3.4 Covariates

Several factors act on the health status of the members of the household. Grossman (1972) through a theoretical modelling of health demand shows that certain demographic and socio-economic characteristics affect the health status of individuals. He shows that each individual is born with a stock of health capital which depreciates with age. Age thus becomes an important determinant of health status. The age of those who consulted ranged from 0 to 99 years, with an average age of about 26 years (Table A1).

The age of the head of the household is a very important characteristic that could affect the consumption choices of household members. Through an empirical study on the determinants of the transition to cleaner cooking energy in Ghana, [Bofah et al. \(2022\)](#) find that youth-headed households have a low probability of using dirty energy compared to elderly-headed households in Ghana. The authors explain this by the decrease in income of the elderly head of household. As a result, the household chooses cheaper fuels that unfortunately pollute a lot. To add, the author's result could be explained by the fact that these elderly-headed households do not have information about the harmful effects of using dirty energy.

Gender is an important determinant of exposure to indoor air pollution. Women are not exposed in the same way as men. Indeed, in developing countries, where households generally use biomass as cooking fuel, women spend much more time in the kitchen than men because they are responsible for cooking for the household. As a result, they are more exposed to smoke ([Amegah and Jaakkola, 2016](#)).

Furthermore, [Grossman \(1972\)](#) shows that health capital can be maintained through investments in health, more precisely through health expenditure. This expenditure on health depends on the level of income of individuals. The level of income thus becomes an important determinant of health. Indeed, the higher the household income, the more it will be able to spend to preserve its health and thus increase its health capital. In the database, households are divided into five wealth groups, namely very poor, poor, medium, rich and very rich.

Still with the aim of taking into account the financial capacities of the household, I add the gender of the head of household. Indeed, households headed by women are likely to be poorer than those headed by men ([Javed and Asif, 2011](#)). This could be due to the fact that these women do not have financial support from a spouse or because they are single, divorced or widowed. In addition, the type of occupation of the head of household is taken into account in the analysis. The type of occupation of the head of household was categorised into three classes which are: agriculture, white collar, and other occupation <sup>7</sup>.

Furthermore, the level of education affects the health of individuals ([Grossman, 1972, 1976; Thomas et al., 1991; Currie and Gruber, 1996](#)). Indeed, an individual with a certain level of education will be better able to take care of his health because he/she knows what is dangerous for his health or not. These earlier studies show the importance of education. I take this into account in the analysis through the level of education of the individual. The individuals are divided into four education classes: no education, primary education, secondary education and higher education.

Also, the health of one member of the household is produced by all the other members of the household ([Jacobson, 2000](#)). Indeed, each member of the family is a producer of his or her own health and that of the others. The influence of other family members in the production of health is important. One palpable case is that of the influence of the mother's level of education on the health of the children ([Thomas et al., 1991; Currie and Gruber, 1996](#)). Another tangible example is the negative

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<sup>7</sup>This class includes, for example, non-agricultural workers, unpaid trainees, domestic staff, self-employed non-agricultural business owners, etc.



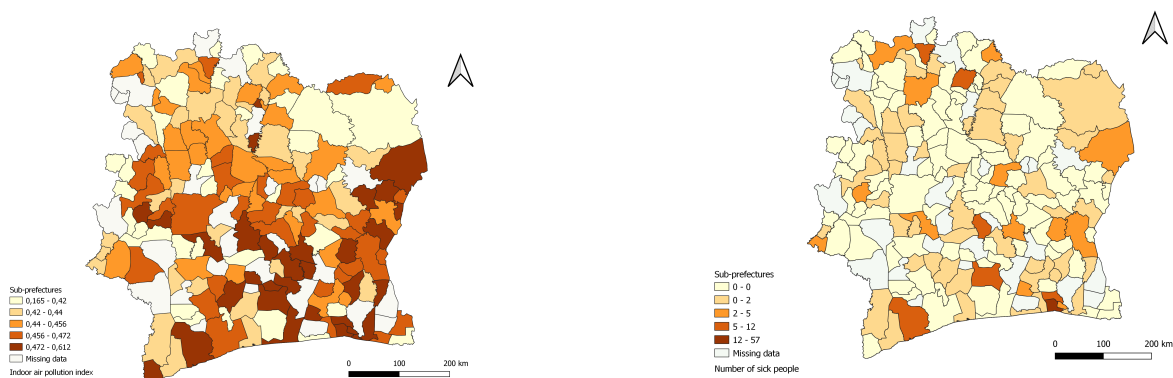
effect of parental divorce on children’s health (Delaney, 1995; Tucker et al., 1997). These studies show the importance of other household members in producing individual health. I take this into account by controlling for household size. Household size ranges from 1 to 34 individuals with an average size of 5 individuals.

## 4 Stylized facts

In this section, I investigate the existence of correlation between indoor air quality and health, and the factors that would influence health and the level of indoor air pollution in Côte d’Ivoire.

In graph 5, I am interested in the geographical distribution of the level of indoor air pollution and the total number of people who consult for respiratory diseases. A fairly high level of indoor air pollution can be observed in most of the sub-prefectures of the country. In addition, in the east, on the border with Ghana and in the centre-south, there is a concentration of sub-prefectures with a fairly high level of indoor air pollution. This would be due to the poor quality of the ambient air in these areas (Figure 1). On the other hand, the sub-prefectures located towards the north have the particularity of being less polluted due to the low level of ambient air pollution in this part of the country (Figure 1). On the figure 5 on the right, there is a distribution of the number of patients by sub-prefecture. Only seven sub-prefectures have a high number of patients. And 5 of these sub-prefectures have a fairly high level of indoor air pollution. Also, a large majority of the sub-prefectures with a high level of indoor air pollution have a very low or even zero number of patients. From graph 5, it can be seen that **there is no linear correlation between indoor air quality and the number of sick people at the sub-prefecture level. The effect of indoor air quality on health depends on certain factors related to the sub-prefecture of residence.**

Figure 5: Indoor air pollution index (left) and medical consultation (right) by sub-prefectures

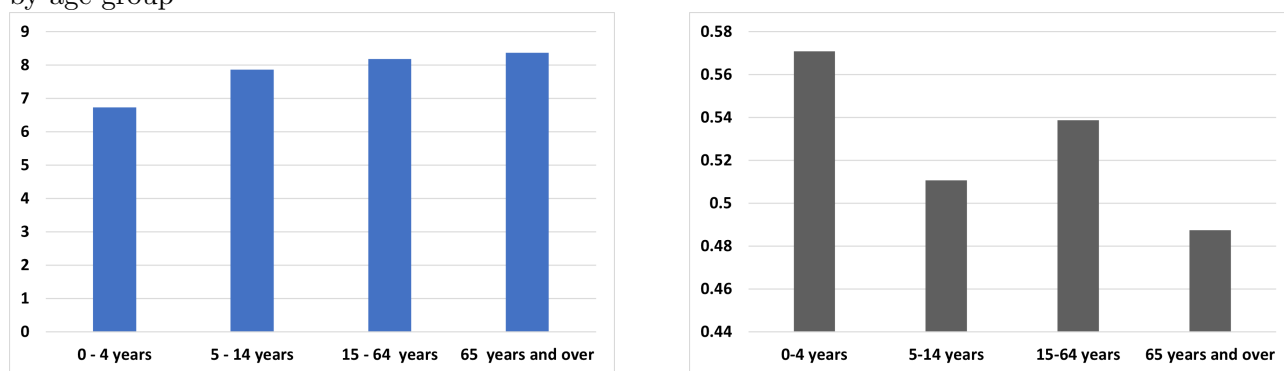


Source: Author’s own elaboration

To go further, I am interested in the relationship between indoor air quality and the consultation rate for respiratory diseases by age group (graph 6). In the left-hand graph, there is a positive correlation between the consultation rate and age. On the left graph, there is no correlation between age and the level of indoor air pollution of the ill persons. The analysis of the two graphs together shows a

high consultation rate for people aged 65 and over, although these people live in less polluted housing compared to the other age groups. Subsequently, the age groups 5-14 and 15-64 are characterised by a high consultation rate but the level of indoor air pollution does not follow the same trend in these two groups. For children under 5 years of age, a lower consultation rate can be noticed compared to the other groups, but these children live in a more polluted environment compared to patients of the other age groups. This graph shows the existence of a positive correlation between the consultation rate and the level of indoor air pollution for children under 5. For the other age groups there is no clear linear correlation between the two phenomena. In sum, it can be said that **indoor air pollution is not the only factor explaining the risk of respiratory diseases**.

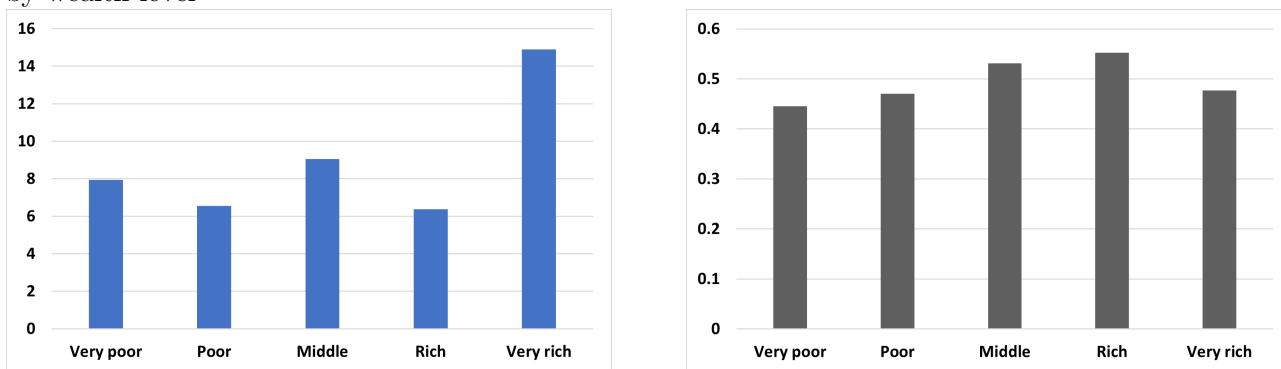
Figure 6: Respiratory disease consultation rate (left) and the average indoor air pollution index (right) by age group



Source: Author's own elaboration

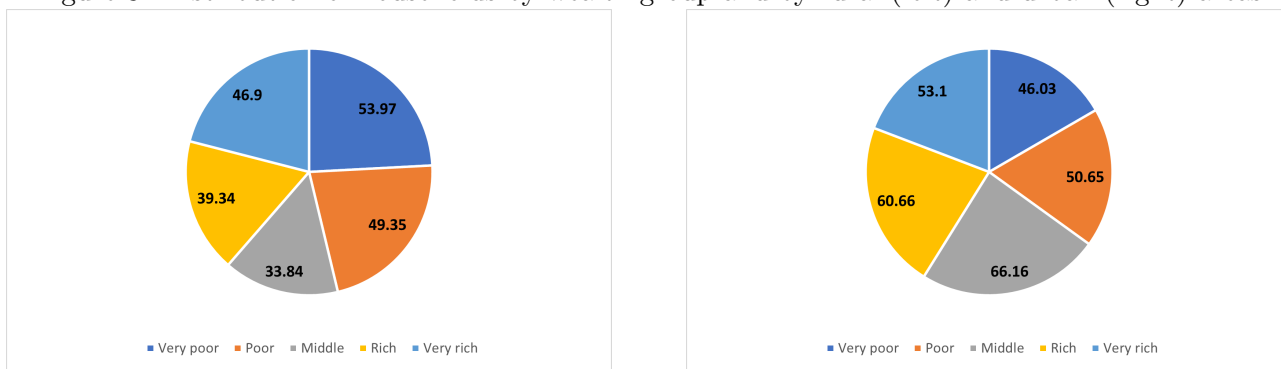
The graph 7 shows the relationship between the consultation rate, indoor air pollution and the level of wealth of households. The graph on the left shows that there is no clear correlation between the consultation rate and the level of wealth. Indeed, very poor households have a higher consultation rate than poor and rich households but their consultation rate is lower than that of middle and very rich households. On the other hand, there is a positive correlation between indoor air pollution and wealth. Indeed, in the graph on the right, we can see that the richer the household, the higher the level of pollution. This could be explained by the fact that more than half of the average, rich and very rich households live in urban areas (graph 8) where the ambient air quality is generally not good. From the graphs 7 and 8 we can say that **the level of wealth has little effect on the risk of respiratory diseases. Moreover, the level of indoor air pollution would increase with the level of wealth because of the residential choice.**

Figure 7: Respiratory disease consultation rate (left) and the average indoor air pollution index (right) by wealth level



Source: Author's own elaboration

Figure 8: Distribution of households by wealth group and by rural (left) and urban (right) areas



Source: Author's own elaboration

The health status of households could be correlated with the level of development of the locality because more development would mean more health services. To verify this, using the night light data, I make a distribution of sick people according to the level of development of the area of residence (graph 9). On the graph, we can see that there is no correlation between the level of development and the consultation rate. This could mean that **the level of development of the place of residence has no effect on the risk of respiratory diseases.**

Figure 9: Consultation rate (left) and sub-prefecture development level (right)



Source: Author's own elaboration

The remainder of the study will focus on econometric analysis to verify the stylized facts that have

just been discovered.

## 5 Econometric Analysis

This section describes the econometric modelling and the baseline results.

### 5.1 Econometric modeling

In this study I use a dichotomous model which is a model where the explained variable has two (02) modalities (0 and 1). The modality is 1 when individuals consulted a doctor because of respiratory diseases and 0 otherwise. I can choose between two types of dichotomous models: probit model and logit model. Difference between the two models lies in the mathematical law of the distribution function used. Logistic model uses the distribution function of the logistic distribution while probit model uses the distribution function of the reduced centred normal distribution. These two models provide fairly similar results because of the similarities between logistic and the reduced centred normal distribution. On the other hand, logit model has advantages in the interpretation of marginal effects. Furthermore, my data are at 3 levels: sub-prefecture, household and individual. Indeed, beyond the characteristics of each household, several households live in common sub-prefectures. It is important to take into account the "context effects" in order to estimate the impact of the variables without bias. Therefore, for the econometric analysis, I use the multilevel mixed-effects logit model because it allows us to take into account the hierarchical nature of the data. I also add random effects at the household and the sub-prefecture level because this allows to take into account the influence of certain factors at the household and sub-prefecture level that may affect the health status of individuals. These factors could be, for example, those that determine households' choice of fuel and the availability of health services at sub-prefecture level.

The likelihood-ratio test is done to evaluate the goodness of fit of the chosen model. The test is done between a model with the control variables and another model without the control variables. The P-value of the test results can be found in the results tables. Furthermore, I calculate the intra-class correlation coefficient (ICC) at the sub-prefecture level and at the household level. The ICC is used in mixed models to give a sense of how much variance is explained by a random effect. It is calculated by dividing the variance of the random effect by the total random variance, i.e. sum of all random effects and error. In the results tables, "*ICC sub-prefecture*" refers to the intra-class correlation at the sub-prefecture level. And "*ICC HH/sub-prefecture*" is the intra-class correlation at the sub-prefecture level with the household. For the case of column 1 of Table 3, the "*ICC sub-prefecture*" is 0.04. This means that the random effects of the sub-prefecture make up about 4% of the total residual variance. The "*ICC HH/sub-prefecture*" is 0.238. This means that the random effects of the sub-prefecture and the household make up about 24% of the total residual variance.

## 5.2 Baseline results

Baseline results (column 2 Table 3) show a significant effect of indoor air quality on the risk of respiratory disease in children under 5 years old. An increase in the level of indoor air pollution increases the risk of respiratory diseases by 1.64%. This result is in line with that of studies which found a negative impact of poor indoor air quality on the health status of children in Côte d'Ivoire René et al. (2019); Rosine et al. (2021). This result could be explained by the fact that children at this age spend a lot of time at home and in the company of their mothers. Households that use biomass as fuel are highly exposed to indoor air pollution. Pollutants emitted penetrate the respiratory tract and other human organs, settling in and causing respiratory, cardiovascular and blood diseases.

In the whole sample and the group of people aged between 15-64 years old, being a male significantly increases the risk of respiratory diseases compared to being female (columns 1 & 4 Table 3). This result could be explained by the consumption habits of men. Indeed, generally in Africa, men smoke the most compared to women.

Education has a positive marginal effect on the risk of lung disease for individuals aged 15-64 years (column 4 Table3). Indeed, having a higher level of education has a marginal effect of 6.5% on the risk of respiratory disease compared to an individual who has not been to school. This result could be explained by the fact that the vast majority (94.38%) of these individuals live in urban areas that are likely to have high levels of ambient air pollution.

The age of the household head also affects the health status of household members (columns 1 and 4 table3). This could mean that as heads of households age, declining incomes force them to make do with relatively cheaper energy options, most of which are unclean.

The fact that the head of the household is male affects the risk of respiratory disease for people aged 65 and over (column 5 Table3). The fact that the head of the household is male has a positive marginal effect of 9.68% on the risk of respiratory disease compared to a female head of household.

The employment status of the head of household affects the risk of lung disease for the whole sample and for the 5-14 age group (columns 1 & 3 Table3). Indeed, the fact that the head of the household is a white collar worker marginally increases the risk of lung disease by 4.3% compared to a farmer head of household (columns 1 Table3). A likely reason for this result would be that 90.11% of white collar workers reside in urban areas which generally do not have good ambient air quality. For the 5-14 year old group, by a farmer household head, the fact that the household head works in other types of employment has a marginal positive effect of 6.19% on the risk of respiratory disease (columns 3 Table3).

For the whole sample, the level of wealth positively affects the risk of respiratory disease (column 1 table 3). This result could be explained by the area of residence of rich households and the type of fuel used for cooking. Indeed, according to the data, about 30% of middle, rich and very rich households reside in large cities such as Abidjan, Yamoussokro, Korogho, Bouaké and San-Pedro. And 70% of these households reside in Abidjan. Most of these wealthy households live in areas with poor ambient air quality. In addition, I found that 69.65% of the middle-income and wealthy households use biomass

for fuel. As a result, most of these households are exposed to both ambient and indoor air pollution, which would increase the risk of respiratory disease.

The following section provides evidence on the robustness and heterogeneity of the impact of indoor air quality on respiratory disease risk.

Table 3: Baseline results

	All sample	0-4 years	5-14 years	15-64 years	65 and over
Indoor air pollution index	0.00254 (0.50)	0.0164*** (3.96)	-0.00806 (-0.35)	0.000140 (0.03)	-0.00670 (-0.39)
Individual age	0.00560 (1.18)				
Individual gender (female)	ref.		ref.	ref.	ref.
Individual gender (male)	0.0186* (1.80)		-0.0310 (-1.05)	0.0341** (2.17)	0.0209 (0.40)
No education (individual)				ref.	ref.
Primary education (individual)				-0.0113 (-0.59)	-0.0239 (-0.46)
Secondary education (individual)				0.00119 (0.08)	-0.0496 (-1.28)
Higher education (individual)				0.0650** (1.97)	0.0605 (0.65)
Head age	0.00124*** (3.88)	0.000831* (1.75)	0.000260 (0.17)	0.00194*** (3.95)	-0.00000926 (-0.01)
Head gender (female)	ref.	ref.	ref.	ref.	ref.
Head gender (male)	0.00919 (0.71)	0.0103 (0.49)	0.0440 (1.44)	-0.0110 (-0.57)	0.0968* (1.94)
Agriculture (head)	ref.	ref.	ref.	ref.	ref.
White collar (head)	0.0430** (2.43)	0.0584 (1.62)	0.0714 (1.53)	0.0350 (1.43)	0.0105 (0.14)
Other occupation (head)	0.0214 (1.48)	0.0157 (0.59)	0.0619** (2.03)	0.0173 (0.91)	0.00348 (0.08)
Wealth	0.0139* (1.73)	0.0115 (0.82)	-0.00799 (-0.33)	0.0107 (1.02)	0.0146 (0.46)
Household size	-0.00690 (-0.86)	-0.0291 (-1.26)	0.00121 (0.03)	-0.00320 (-0.32)	-0.0373 (-1.59)
Observations	2685	639	368	1634	199
Number of household	1,001	412	226	785	158
Number of sub-prefectures	170	143	99	161	80
ICC sub-prefecture	.0367908	3.50e-33	8.18e-31	1.64e-31	.0491092
ICC HH/sub-prefecture	.2290265	4.15e-33	.3880053	.1884091	.0491092
LR test P value	0.0000	0.5896	0.4443	0.0000	0.0871

*t* statistics in parentheses

\*  $p < 0.1$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

## 6 Robustness checks

The robustness of the results is tested test using a poisson modelling. The dependent variable is the number of people in the household per age group who consulted for respiratory diseases. The results

(Table B1) reveal that for children under 5, indoor air pollution positively affects the number of sick people.

In the following lines, I test the non-linearity of the impact as a function of the socio-economic characteristics of the household and of the area of residence.

## 7 Heterogeneity<sup>8</sup>

The effect could vary according to the socio-economic characteristics of households. In Table 4 I focus on children under 5 years old. In columns 1 and 2 Table 4, the idea is to see if having older siblings aged between 5 and 15 years in the household could decrease the risk of respiratory diseases by reducing the level of exposure to indoor air pollution. Indeed, older siblings are a source of support for younger siblings (Wikle et al., 2018; Eriksen and Gerstel, 2002). So I suppose a child with older siblings might spend less time with the mother in the kitchen because the older siblings would hold the child while the mother cooks. The results show an opposite effect (column 2 Table 4). Having older siblings increases the risk of respiratory diseases. There are two likely reasons for this result. The first reason would be the fuel choice of a household with several children under 15 years oage. Indeed, being a poor household, having several children who cannot yet help financially, leads the household to use a fuel that would be cheaper. Second reason, could be the fact that older siblings are present but do not hold their younger sibling when the mother is cooking because they are also busy doing something else. Furthermore, in columns 3 and 4 (Table 4), I am interested in how the impact of indoor air pollution varies with household size. I find that the marginal effect of indoor air pollution remains positive and highly significant only for households above the median size (5 members). The choice of cheaper fuel due to the size of the household added to the lack of financial means could explain this result.

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<sup>8</sup>In the results tables are only those regressions that have converged. This is why you will not see all age groups in some tables

Table 4: Heterogeneity by oldest sibling presence and household size

	Have older siblings No	Have older siblings yes	HH size <median	HH size >median
Indoor air pollution index	-0.00526 (-0.67)	0.0227*** (4.46)	-0.00277 (-0.17)	0.0230*** (3.72)
Head age	-0.000658 (-1.31)	0.00341*** (2.81)	0.000229 (0.33)	0.000930 (1.07)
Head gender (female)	ref.	ref.	ref.	ref.
Head gender (male)	-0.00657 (-0.34)	0.0108 (0.32)	0.0310 (0.74)	-0.0425 (-0.89)
Agriculture (head)	ref.	ref.	ref.	ref.
White collar (head)	-0.00231 (-0.06)	0.0703 (1.49)	0.141* (1.71)	0.0536 (1.09)
Other occupation (head)	-0.00858 (-0.30)	0.0326 (0.97)	0.0308 (0.82)	0.0138 (0.38)
Wealth	-0.00417 (-0.23)	0.0301 (1.23)	0.00995 (0.48)	0.00349 (0.13)
Household size	0.00463 (0.20)	-0.103* (-1.70)	0.0609 (0.65)	-0.0591 (-0.66)
<i>Observations</i>	309	330	278	241
Number of household	228	238	215	171
Number of sub-prefectures	111	109	102	87
ICC sub-prefecture	.5043725	3.15e-34	.1437866	7.68e-37
ICC HH/sub-prefecture	.5043725	6.51e-33	.1437866	4.95e-34
LR test P value	0.9939	0.0420	0.3654	0.8149

*t* statistics in parentheses

\*  $p < 0.1$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

Moreover, the place of residence of households modifies their living conditions. Urban areas are more developed in terms of economic activities, public services and, above all, health services are much more developed than in rural areas. Urban households would tend to have better access to health services than rural ones. In addition, the development of economic activity in urban areas could allow households to have a higher standard of living. The results of the Table 5 shows that the residence environment has an influence on the impact of indoor air pollution on the risk of respiratory diseases for the whole sample. Indeed, living in a rural area has a marginal positive effect (1.94%) on the risk of respiratory disease (column 3 Table 5). This could be explained by the high level of exposure of the rural population to indoor air pollution. In effect, according to the data, 80.59% of less ventilated dwellings are located in rural areas. While a less ventilated dwelling contains a significant amount of pollutants.



Table 5: Heterogeneity by milieu

	All sample	15-64years	All sample	15-64years
	Urban	Urban	Rural	Rural
Indoor air pollution index	-0.00110 (-0.18)	-0.00351 (-0.52)	0.0194** (2.17)	0.0274 (1.59)
Individual age	-0.00191 (-0.39)		0.0144*** (2.67)	
Individual gender (female)	ref.	ref.	ref.	ref.
Individual gender (male)	0.0178 (1.58)	0.0311 (1.57)	0.0113 (0.63)	0.0308 (1.18)
No education (individual)		ref. (.)		ref. (.)
Primary education (individual)		-0.0227 (-1.10)		0.00673 (0.21)
Secondary education (individual)		-0.00528 (-0.30)		0.0345 (0.93)
Higher education (individual)		0.0750* (1.90)		0 (.)
Head age	0.00142*** (3.76)	0.00199*** (3.37)	0.00107** (2.14)	0.00217*** (2.60)
Head gender (female)	ref.	ref.	ref.	ref.
Head gender (male)	-0.00914 (-0.43)	-0.0253 (-0.97)	0.0548*** (4.15)	0.0405 (1.55)
Agriculture (head)	ref.	ref.	ref.	ref.
White collar (head)	0.0699*** (2.99)	0.0751** (2.54)	-0.0285 (-0.99)	0 (.)
Other occupation (head)	0.0370* (1.68)	0.0428 (1.55)	0.0315 (1.57)	0.0350 (1.27)
Wealth	0.0166 (1.57)	0.00547 (0.42)	0.00863 (0.76)	0.0197 (1.16)
Household size	-0.0140 (-1.63)	-0.00734 (-0.74)	0.00190 (0.14)	0.00978 (0.47)
Observations	1672	1068	1013	541
Number of household	531	438	650	434
Number of sub-prefectures	106	102	147	137
ICC sub-prefecture	.0332444	2.54e-20	.0095087	1.81e-34
ICC HH/sub-prefecture	.2899731	.2072478	.2165138	.122438
LR test P value	0.0000	0.0000	0.0000	0.0060

*t* statistics in parentheses

\*  $p < 0.1$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

In order to better capture the level of development of the sub-prefecture, I use nightlight data. Table 6 shows that the effect of indoor air pollution remains significant only for children under 5 living in the sub-prefectures with a level of development above the median (column 2).

Table 6: Heterogeneity by nightlight

	All sample <median	0-4 years <median	15-64 years <median	All sample >median	0-4 years >median	15-64 years >median
Indoor air pollution index	0.000616 (0.07)	0.0273** (2.10)	-0.0101 (-0.74)	0.00488 (0.61)	0.00689 (1.26)	0.00695 (1.27)
Individual age	0.0192*** (3.08)			-0.00336 (-0.72)		
Individual gender (female)	ref.		ref.	ref.		ref.
Individual gender (male)	0.0247 (1.32)		0.0476** (2.12)	0.0126 (1.00)		0.0266 (1.05)
No education (individual)			ref.			ref.
Primary education (individual)			-0.00973 (-0.36)			-0.00481 (-0.19)
Secondary education (individual)			0.00978 (0.31)			0.00621 (0.38)
Higher education (individual)			0.0330 (0.47)			0.0749* (1.74)
Head age	0.00157*** (2.83)	0.00100 (1.22)	0.00240*** (2.91)	0.00108*** (3.18)	0.000804 (1.49)	0.00175*** (2.59)
Head gender (female)	ref.	ref.	ref.	ref.	ref.	ref.
Head gender (male)	-0.00612 (-0.25)	0.00118 (0.05)	-0.0467 (-1.15)	0.0117 (0.89)	0.0241 (0.79)	-0.000387 (-0.02)
Agriculture (head)	ref.	ref.	ref.	ref.	ref.	ref.
White collar (head)	0.0494 (1.64)	0.0523 (0.65)	0.0396 (0.96)	0.0427 (1.61)	0.0625 (1.59)	0.0317 (0.76)
Other occupation (head)	0.0316* (1.72)	-0.0215 (-1.14)	0.0280 (1.16)	0.0177 (0.77)	0.0421 (1.01)	0.00475 (0.13)
Wealth	0.00447 (0.37)	-0.0257* (-1.79)	0.0150 (0.93)	0.0214** (2.18)	0.0492** (2.53)	0.00757 (0.45)
Household size	0.00586 (0.40)	-0.0449 (-1.40)	-0.00216 (-0.11)	-0.0136** (-2.14)	-0.0204 (-0.57)	-0.00345 (-0.37)
Observations	1068	286	636	1617	353	998
Number of household	606	233	456	395	179	329
Number of sub-prefectures	115	93	108	55	50	53
ICC sub-prefecture	.0410572	2.91e-33	8.06e-34	.0323717	9.19e-34	9.41e-27
ICC HH/sub-prefecture	.3111397	3.05e-33	.4373947	.1455135	1.52e-32	.0745
LR test P value	0.0000	0.1867	0.0163	0.0000	.	0.0006

*t* statistics in parentheses

\*  $p < 0.1$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

## 8 Conclusion

In Côte d'Ivoire, as in most developing countries, a large majority of population is exposed to poor indoor air quality. This is mainly due to the fuel used, especially biomass fuels, which emit pollutants that are toxic to human health. In our sample 87.20% of households use biomass as fuel because it is the most affordable type of fuel.

This study looks at the effect of indoor air pollution on different age groups in Côte d'Ivoire. The results obtained are in line with the existing literature (Padhi and Padhy, 2008; Edwards and Langpap, 2012; Ranathunga et al., 2019; René et al., 2019; Basu et al., 2020; Kinney et al., 2021). Indeed, indoor air pollution increase the risk of respiratory diseases in vulnerable children under 5 years old. Moreover, the marginal effect of indoor air pollution varies according to the characteristics of the household, the area of residence and the level of development of the sub-prefecture. Furthermore,

several factors such as the gender and education level of the individual, the age and occupation of the household head, and the level of household wealth affect the respiratory health of the household members.

In order to achieve Sustainable Development Goal 7, which is to ensure access to affordable, reliable, sustainable and modern energy for all, it would be important for Côte d'Ivoire to ensure the implementation of the PANER. This could be done by raising awareness among the population about the harmful effects of indoor air pollution caused largely by the use of solid fuel, as the pollutants emitted as a result of the poor combustion of biomass are very dangerous for human health, especially that of children, women and elderly. Mothers could be made aware of the need to keep children away from cooking areas in order to protect them from the smoke emitted and also the need to air the houses very well regularly. To do this, public decision-makers must set up education and prevention programmes on the risks associated with the use of solid fuels, in schools, maternity wards, etc. In order to limit the use of biomass, another recommendation would be to subsidise the purchase of gas stoves so that they are accessible to the population, as poverty is a major determinant of the choice of cooking fuel (Ouedraogo, 2006; Bofah et al., 2022; Zhou et al., 2022). This would encourage households to use less polluting fuels such as butane gas. Furthermore, Ivorian public policymakers could provide the population with stoves that can burn all types of biomass cleanly and encourage Ivorian households to use them. These include the Ultra-Clean Biomass Cookstove, Mimi Moto forced air gasifier stove and Shengzhou Charcoal Stove<sup>9</sup>. In addition, the government should promote the introduction and use of renewable energy as a fuel by households.

Like any study, this one has limitations. The first limitation is that the PM2.5 concentration level I use to approximate ambient air quality is an annual data. It would have been interesting to have the PM2.5 level a few months or weeks before the survey. The second is that I do not have the exact geographical location of the households. This information could allow me to better quantify the PM2.5 concentration of the ambient air to which the household is exposed.

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<sup>9</sup><https://www.who.int/tools/clean-household-energy-solutions-toolkit/module-7-defining-clean>

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## A Descriptive statistics

Table A1: Descriptive statistics

Variable	Observations	Mean	Std. dev.	Min	Max
Sick people	2,862	0.0782669	0.2686381	0	1
Indoor air pollution index	2,862	0.2088955	1.065497	-2.823349	4.071756
Age	2,805	25.52086	20.80195	0	99
Gender	2,862	0.4350105	0.495845	0	1
Education level	2,401	0.4760516	0.4995302	0	1
Head age	2,861	42.96994	14.0855	16	120
Head education level	2,862	0.5527603	0.4972954	0	1
Wealth group	2,862	1.444444	0.7021878	0	4
Household size	2,862	4.992662	2.937592	1	34

## B Robustness checks

Table B1: Poisson model

	All	0-4 years	5-14 years	15-64 years	65 and over
Indoor air pollution index	0.00534 (0.54)	0.0148** (2.01)	-0.0127 (-0.56)	-0.0131 (-1.08)	-0.00709 (-0.49)
Individual age	0.00459 (0.61)				
Individual gender (female)	ref.		ref.	ref.	ref.
Individual gender (male)	0.0284 (1.25)		-0.0697** (-2.18)	0.0491* (1.92)	0.0200 (0.35)
No education (individual)				ref.	ref.
Primary education (individual)				0.0220 (0.75)	-0.0240 (-0.48)
Secondary education (individual)				0.0379 (1.33)	-0.0483 (-1.01)
Higher education (individual)				0.166** (2.31)	0.0496 (0.55)
Head age	0.00319*** (5.10)	0.00103 (1.59)	0.000936 (0.71)	0.00406*** (5.39)	-0.0000981 (-0.01)
Head gender (female)	ref.	ref.	ref.	ref.	ref.
Head gender (male)	0.0385* (1.74)	0.00365 (0.13)	0.0455 (1.34)	0.00350 (0.13)	0.0967** (2.14)
Agriculture (head)	ref.	ref.	ref.	ref.	ref.
White collar (head)	0.213*** (3.88)	0.0659 (1.43)	0.0628 (1.64)	0.165*** (2.86)	-0.000873 (-0.01)
Other occupation (head)	0.0701*** (3.70)	0.0175 (0.73)	0.108*** (3.25)	0.0406** (2.03)	0.00388 (0.08)
Wealth	0.00450 (0.29)	0.00982 (0.56)	0.00312 (0.18)	-0.0168 (-0.77)	0.0126 (0.37)
Household size	0.0721*** (4.01)	-0.0248 (-0.91)	0.0292 (0.78)	0.0553*** (2.81)	-0.0367 (-1.52)
<i>Observations</i>	2685	639	368	1634	199
LR test P value	0.0000	0.6659	0.0307	0.0000	0.0987

*t* statistics in parentheses

\*  $p < 0.1$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$