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The impact of fossil fuel combustion on children's health and the associated losses of human capital

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A B S T R A C T

To more fully assess the far-reaching effects of fossil fuel combustion on humanity, it is necessary to gain an in-depth understanding of the full impact of fossil fuels on human health and lifetime potential. However, current knowledge of the long-term consequences of fossil fuel use on health damage in early life, such as human capital impacts in adulthood, is still insufficient. This paper aims to summarize the current evidence on the health effects of fossil fuel-driven air pollution and climate change on children and the consequent effect on human capital stemming from these early health damages. Evidence indicates that climate change and air pollution not only deteriorate children's health but also affect the entire human capital in their adulthood and can be deeply affected through damaged early-life health. Fossil fuel combustion can significantly impact the lifelong health and human capital for generations. We call for a more holistic assessment of the full range of impacts borne by children, including direct damages to children's health, losses of human capital, and associated economic costs. Cross-disciplinary collaboration is vital to facilitate research on such assessments, thereby enriching our understanding of the multifaceted impact of fossil fuel combustion on the early life and its long-term implications on human capital and economic potential.

1. Introduction

Fossil fuel-driven climate change and air pollution is already significantly threatening human health and well-being [1]. More than a century of fossil fuel emissions has mainly led to the Earth's average surface temperature increasing by approximately 1.1 °C since pre-industrial times [2]. The Intergovernmental Panel on Climate Change (IPCC) has concluded that urgent action is needed to limit global warming to 1.5 °C above pre-industrial levels, which can significantly reduce climate-related losses and damage to human health and ecosystems [2]. Meanwhile, fossil fuel combustion has caused an air pollution crisis, which releases plenty of inhalable fine particles and gaseous pollutants, directly affecting human health. The World Health Organization (WHO) estimates that air pollution leads to approximately 4.2 million premature deaths each year, and climate change will cause an additional 250,000 deaths every year from 2030 to 2050 [3]. Although exploiting fossil fuels have brought undeniable benefits for modern living, this development pattern is unsustainable as irreversible deterioration of the Earth's environment can lead to shortages of necessary ecological

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resources and services which human beings depend for survival. Hence, promoting clean energy and a low-carbon economy is imperative, and it will be the main challenge and the significant opportunity in the 21st century.

Due to substantial economic benefits observed or predicted, various policies to reduce fossil fuel combustion emissions have been implemented worldwide to reduce air pollution and mitigate climate change [4]. Previous studies have documented substantial evidence on the pathophysiological consequences of air pollution and climate change. Significant health outcomes, including morbidity and mortality for cardiovascular or respiratory cases, are commonly used to estimate the impacts of environmental pollution or potential benefits of climate mitigation policies [5–7]. However, these routine health endpoints are more likely to occur in adults than children. Therefore, using adult health outcomes as the primary measure to evaluate the benefits of such policies is more common, and only a few adverse consequences for children have been considered [4,8]. Additionally, though research of climate change and air pollution in children's health has increased in recent years, effort in multi-stage effects on child health, especially the life course perspectives, is lacking. Evaluating the health and profound effects of fossil fuel combustion on children still need to be improved in current assessments, which leads to a severe underestimate of the health benefits of this highly vulnerable groups. A more holistic assessment of the impacts of fossil fuel burning on current and future human health and potential is essential for incentivizing policies to facilitate this transition.

Fetuses, infants, and children are uniquely vulnerable to air pollution and climate change [9]. Children's health is profoundly affected over a long period from fetuses to adolescence due to their immature physiology, metabolism, and unique behaviors and exposures. Such effects are mediated by chronic inflammation, oxidative stress, endocrine disruption, and even genetic mechanisms across the life span. According to the “fetal origins hypothesis”, health damages in fetuses and early childhood can further impede the lifetime development of human capital [10,11], which is vital to the fate of individuals and nations. Hence, today's children encounter significant intergenerational inequalities associated with fossil fuel combustion in terms of health and even the whole human capital. Globally, young people have been at the forefront of climate change activism partly because they appreciate intergenerational inequalities [12,13], and these health or potential impacts on children have been largely excluded from research for fossil fuel combustion. The incomplete evaluations of the impacts on children can severely underestimate the potential benefits of relevant policies and actions and undermine the determination of clean energy transition.

The implications of climate change and air pollution have gone beyond the health aspect, as the labor capacity of adults is indirectly influenced by their daily health insults, and even their human capital is impeded by environmental exposures and health damages in early life [14]. Without fully understanding the multi-stage effects of fossil fuel combustion on child health and the multidimensional impacts on children's future potential, policymakers will likely to underestimate the significant harm to human society from burning oil. Therefore, this review summarizes the effects of air pollution and climate change on developmental children's health from fetuses to adolescence and the ensuing multidimensional impacts on later-life human capital development from such health impacts. We further conclude with recommendations for future research directions to conduct a more holistic assessment of child impacts from environmental risks to provide a fuller picture of the profound effects of fossil fuel combustion.

2. Multi-stage effects on child health

Fossil fuels, the primary source of air pollution and climate change, represent approximately eighty percent of the total primary energy supply [15]. Fossil fuel combustion causes significant health damage to the child born today through air pollution and climate change. Here, we summarize the scientific evidence of the major health effects on developing fetuses and children to reflect the impacts of fossil fuel combustion (Fig. 1). This review discusses the current understanding of children's health impacts from a life-course perspective in terms of how air pollution and climate change may affect the development of children. These include adverse birth outcomes that reflect damages to the fetuses, effects on the neural system whose development is dominant in the first year of life, malnutrition and infectious disease which occur primarily in infancy, respiratory effects commonly seen in young children, and physical trauma and mental illness that adolescents are more likely to be affected.

2.1. Adverse birth outcomes

Adverse birth outcomes, including birth defects, preterm birth (PTB), low birth weight (LBW), small for gestational age (SGA), and intrauterine growth restriction (IUGR), are known risk factors for premature death and neurodevelopmental disorders in children [16–18]. Due to the increase in metabolism, oxygen demand, and consumption during pregnancy, maternal environmental exposure is one of the crucial causes of adverse birth outcomes. Maternal exposure to multiple air pollutants, particularly particulate matter (PM), ozone (O_3), and nitrogen dioxide (NO_2), has been significantly associated with adverse birth outcomes, particularly PTB, LBW, and small for gestational age (SGA) [4,19]. These air pollutants can lead to various biochemical or physiological changes during the gestation period, including oxidative stress, inflammation, and hemodynamic changes in pregnant mothers, and placental impacts such as inflammation, reduced size, and placental abruption [20], triggering the incidence of multiple adverse birth outcomes. Some researchers have found that the middle and late pregnancy may be the most sensitive windows for gestational exposure to numerous environmental pollutants and PTB [21]. Recent evidence confirmed that cord plasma insulin levels significantly increased by 15.8% for each SD increment in $PM_{2.5}$ levels during the entire pregnancy and was most pronounced in the 2nd trimester [22]. Particulate air pollution induced changes in cord plasma insulin levels during early life and might be a risk factor in developing metabolic disease, such as glucose intolerance or type 2 diabetes, later in life.

Extreme climatic events are also essential triggers of PTB, and LBW. A recent systematic review of high temperatures and adverse birth outcomes revealed that the relative risks due to high-temperature exposures ranged from 1.05 to 1.16-fold [23]. In addition, prenatal exposure to extremely intense rainfall has a significant associated with PTB, restricted intra-uterine growth and lower mean birth weight [24]. Biological mechanisms indicated that the fetus/child is still immature for detoxifying chemicals, repairing DNA damage, and providing immune protection. Therefore, the adaptive responses of fetuses/children to adverse early-life environmental exposures may lead to epigenetic changes and contribute to later disease predisposition [25]. Climate change can also elevate the concentrations of several of the most common air pollutants emitted through increased heatwaves, wildfires, and

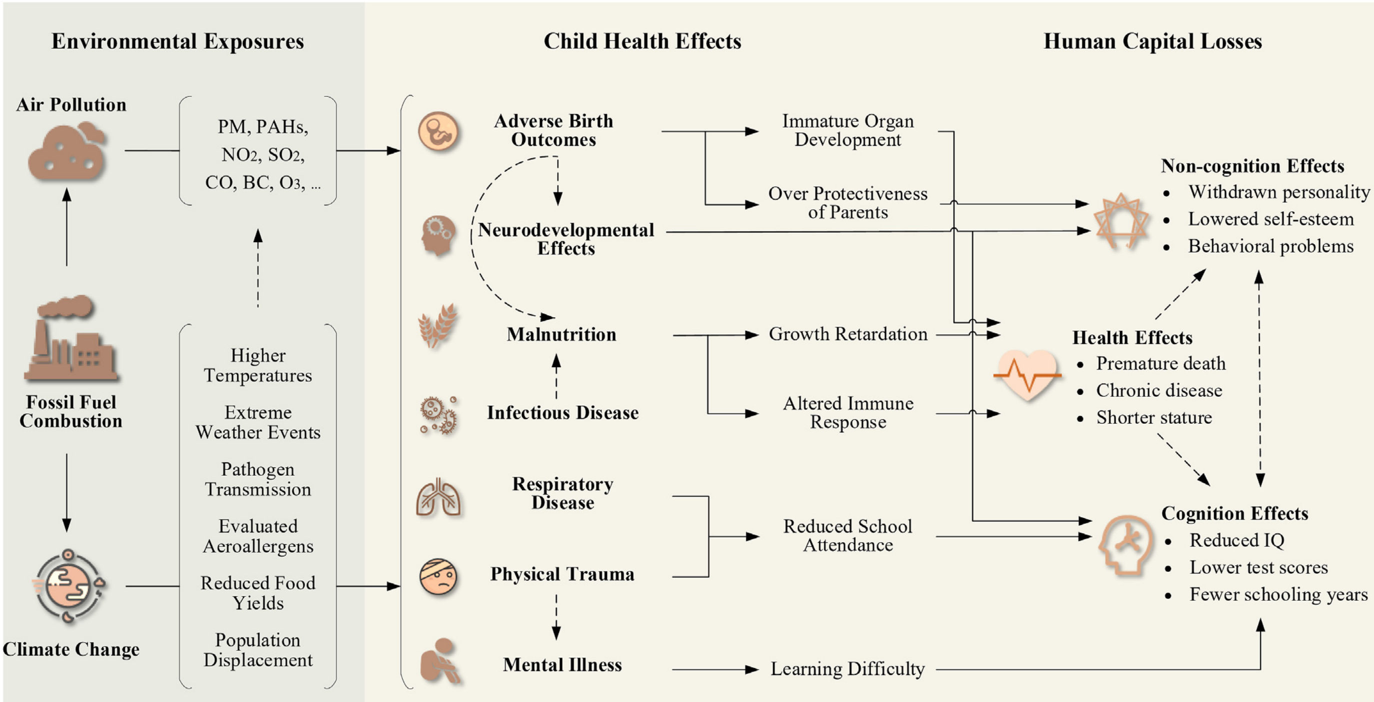

Fig. 1. Pathways from fossil fuel combustion to the possible impacts on child health outcomes and associated human capital losses. Black carbon (BC); carbon monoxide (CO); nitrogen dioxide (NO_2); ozone (O_3); polycyclic aromatic hydrocarbons (PAHs); particulate matter (PM); sulfur dioxide (SO_2); the dashed line represents the inherent relationship between elements in the same category.

storms [26], indirectly increasing risks of adverse birth outcomes [27].

2.2. Neurodevelopmental effects

Most human brain neurons start to grow starting before birth and continue into early childhood and adulthood, which can set the stage for future health. Prenatal environmental pollutants exposure may induce oxidative stress and neuroinflammation that disrupt the differentiation and organization of the fetal brain and central nervous system (CNS) [28], causing permanent cognitive deficits and neurodevelopmental disorders diagnosed in childhood. Additionally, it was proved that prenatal air pollutants exposure is linked with reduced intelligence quotient (IQ), anxiety, depression, inattention of children, and autism spectrum disorder (ASD) [29–31]. Besides, postnatal exposures can impair brain development through similar mechanisms. Researchers found that reduced attention spans of primary school students were associated with increased levels of daily ambient traffic-related air pollutants in Barcelona, Spain [32].

Data over long-time scales are still limited for the neurodevelopmental effects of climate change. Currently, prenatal heat exposure may impair permanent neurodevelopmental and neurological outcomes. For example, studies from China and Ecuador found that those experiencing higher temperatures during in-utero attained fewer years of schooling as adults [33,34]. Notably, heat exposure in childhood can also directly causes cognition impairment. Graff et al. [35] found that students' performance on math tests was significantly diminished on days with an average temperature above 26 °C, even though air conditioning is widespread in the study region. Besides, rising temperatures with a decrease in precipitation area can also result in the volatilization of POPs and pesticides, which circulate globally and accumulate in areas to affect the development of nervous systems in children [36].

2.3. Malnutrition and infectious disease

The WHO estimates climate change increases diseases, including malnutrition, diarrhoea, and malaria, mainly in poor children under ten [37]. Warmer climates are suitable for the rapid spread of viruses and bacteria. They thus could lead to an increase in dengue and malaria, which are endemic in many regions of the world [38]. Children with immature systems are more susceptible to pathogens from crop and water contamination due to increased storms and floods [9]. In recent decades, floods and hurricanes have risen in Africa, Asia, and the Americas [38], which will continue with climate change.

Therefore, the prevalence of infectious diseases, including pneumonia, diarrhoea, malaria and sepsis will increase among children. In many developing countries, children under-5 years old are overwhelmingly affected by malnutrition [39]. The Lancet Countdown indicated that crop production is being threatened by heat in many ways, including the altered incidence of pests and pathogens, increasing water scarcity, and increases in frequency and strength of extreme weather conditions that can reduce crop yield [38]. Additionally, elevated concentrations of CO_2 reduce the nutritional values of plant foods, such as wheat, barley, rice, and potato et al. [40]. Climate change could also increase the frequency and intensity of extreme weather events, thus raising the prices of essential foods and commodities. As a result, this will increase in undernutrition among the most food-insecure populations, particularly in poor children.

2.4. Respiratory effects

Children are more vulnerable to breathing in polluted air because of the immune lungs' capacity to detoxify air toxins and more outdoor activities than adults [41]. Previous studies have confirmed that children with air pollutants exposure are associated with poor lung function or rhinitis/asthma [41–43]. Furthermore, substantial evidence suggests that exposure to pre-gestational and gestational air pollutants is associated with decreased pulmonary function, increased respiratory symptoms, and wheezing/asthma in childhood and later life [44], and the underlying mechanisms include changes in maternal physiology and DNA alterations in the fetuses [44].

Climate change can harm respiratory health through multiple routes. First, extreme temperatures, including extreme heat, extreme cold, and temperature variations, were observed to increase hospital visits for asthma in childhood [41]. In a recent cohort study, long-term heat and cold exposure from the second trimester until four weeks after birth was associated with newborn lung volumes, especially among female newborns [45]. Second, the changed climate enhances the severity and frequency of air pollution episodes and thereby directly and indirectly causes many pulmonary diseases. Increased extreme weather events, including heatwaves, wildfires, and dust storms, can contribute to elevated levels of air pollutants such as PM, O_3, and black carbon (BC), potentially exposing plenty of children [9]. Third, most importantly, global warming has promoted the growth of aeroallergens such as pollens and molds, which causes more respiratory allergic diseases for children [41].

2.5. Physical trauma and mental illness

Air pollution exposure also negatively affects children's mental health. A cohort study indicated that high prenatal exposure to PAH has associations with anxious/depressive symptoms in children aged 6–7 years [46]. Underlying mechanisms include endocrine disruption, DNA damage of fetuses, and binding to receptors for placental growth factors [46]. It is reported that increased neuroinflammation levels and neurodegeneration markers in the brains of children and young adults exposed to high levels of air pollution indicate a potential for higher risk of mental health problems due to postnatal exposure. Another study suggested that childhood exposure to high levels of NO_2 and $PM_{2.5}$ is significantly associated with an increased risk of major depressive disorder in adolescence and later life [47].

Recently, global warming is worsening some extreme weather events, particularly hurricanes, and flooding, which could directly cause physical trauma or death for children. For example, during the first 24 h after Hurricane Ike in Camaguey, Cuba, there were approximately 500 emergency cases appeared at the Children's Hospital with 96% needing admission [48]. Climate change and related disaster worsen children's physical health and cause chronic and severe mental health disorders [49]. Children exposed to weather-related disasters and the ensuing family stress, social network disruptions and population displacement are at higher risks of developing sleep disorders, depression, post-traumatic stress disorder, and panic et al. [49]. Moreover, climate change-related droughts and sea-level rises may cause displacement, violence, and crime, further threatening children's mental health in less developed and developing countries [9].

3. Multi-dimensional impacts on human capital

Human capital refers to the intangible resource a country's citizens possess, namely individual's health, knowledge, skills, judgment, and other attributes [14,50]. Human capital facilitates contemporary economic growth [50] and is conducive to long-term sustainable development [51]. Early childhood has been considered a sensitive and critical period for human capital development [52]. The fetal programming literature demonstrates that early-life health conditions predict later adult health [52], and adult health is an essential element for human capital. Early childhood health status and development are crucial for human flourishing and human capital formation by influencing learning, idea production, and interpersonal contact [53,54]. Therefore, health insults on a developing fetus and child due to air pollution and climate change are more likely to profoundly impacts human capital development over the life span.

Although human capital is a broad concept of multiple dimensions and there is no consistent measurement, previous studies mainly focused on education outcomes as proxies of human capital, such as years of schooling, academic attainment, enrollment rate and illiteracy rate [33,50]. One crucial reason is education's vital position in human capital research, while easy access to education data is another reason. With more remarkable methodological development to measure intangible attributes of individuals and more attention paid to the functions of health and non-cognitive abilities, some studies have studied health and non-cognition dimensions in recent years [52,55–57]. However, only a few considered these dimensions simultaneously [52,56]. This section summarizes the human capital effects due to climate change and air pollution, which are mainly mediated by children's health damages, in terms of three dimensions: health (represented by mortality and morbidity), cognitive ability (measured by IQ and education outcomes), and non-cognitive/socio-emotional ability (including psychological characteristics and behavioral tendencies). Pathways from child health impacts of climate change or air pollution to long-term human capital are in Fig. 1.

3.1. Impacts on health status in adulthood

Early-life experience and health status significantly predict later survival and diseases. Hence, climate change and air pollution due to fossil fuel combustion may cause additional mortality or morbidity in the long-term through their early-life health damages. As the most severe health consequences of air pollution and high temperatures, PTB and LBW are likely to cause relatively immature organs and immune system, potentially resulting in severe complications for newborns and they are at increased risk of premature death [58,59]. Malnutrition and infectious diseases associated with the changing climate are also important causes of child premature deaths. Among the causes of global under-5 mortality in 2019, diarrhoea and malaria accounted for 17% of premature deaths [60]. Child undernutrition can further increase the risks of mortality and morbidity from infections via its negative impacts on the epithelial barrier function and altered immune response [61]. During 1991–2018, approximately 37% of deaths related to heat exposure due to anthropogenic climate change, and the increased mortality is evident on every continent while burdens vary geographically [62].

Moreover, many early-life health impairments associated with climate change or air pollution predict illness or disability in adulthood [16,63]. As noted previously, PTB/LBW infants tend to have relatively immature organs and impaired vascular growth later in life, thus having a higher risk for an array of chronic diseases as adults, such as COPD and psychiatric illness [64]. Intrauterine malnutrition caused by poor maternal diet, placental insufficiency, and impaired fetal usage of nutrients will lead to children stunting, and the adult heights will be determined by the setting where they developed childhood undernutrition [65]. Previous studies indicated that poor fetal growth or stunting in the first 2 years of life leads to irreversible damage, including shorter adult height, lower attained schooling, reduced adult income, and decreased offspring birthweight [65]. Besides, chronic respiratory and mental diseases in childhood, such as asthma, anxiety, and depression can persist throughout childhood and even into adulthood [66]. All these disabilities, chronic diseases, and even reduced height for adults caused by climate change and air pollution may directly or indirectly cause substantial economic losses due to medical costs or impaired labor productivity [67–70].

3.2. Impacts on cognitive ability

Cognition encompasses a range of complex neurological and psychological processes and is vital for individual earnings and economic productivity. Cognitive development occurs through many complex developmental processes, which a single test cannot ultimately reflect. Currently, two broad but complementary constructs—intelligence quotient (IQ) scores and academic performance—are generally used measures of cognition in previous research. Although only a few studies explored associations between early-life exposure to high temperatures or air pollutants and cognition or education in adulthood [33,34], we could still speculate that climate change or air pollution may influence lifetime cognition through multiple health damages summarized above [10,71].

Children with a lower level of IQ are associated with a higher risk of health in later life and could even persist throughout their lifetime. Among multiple health damages of air pollution or climate change, PTB/LBW could have severe and long-term negative cognitive consequences. A meta-analysis on IQ scores of children born preterm and at ages 5–16 years found that the average IQ scores of PTB-born children were 11–12 points lower than peers born typically [72]. Another meta-analysis focusing on LBW found similar reductions (10 points) in IQ scores of LBW children [73]. Incomplete perinatal brain development will result in widespread disruptions in the frontoparietal network of PTB/LBW-born children. Climate-related undernutrition and infections will also impede cognitive development. A plausible mechanism indicated that prenatal/childhood infections might alter neurodevelopment which measured by IQ or school grades through inflammatory cytokines [74].

Academic achievement is another reflection of cognitive ability and can be significantly affected by early-life health damages due to air pollution and climate change. Few studies have found that those who experience higher temperatures in utero will attain fewer years of school and achieve lower standardized word-test scores as adults [33,34]. In addition to the direct neurodevelopmental effects of high temperatures, heat-related adverse birth outcomes are also possible mechanisms. Due to a recent review involving 23 studies worldwide, PTB and LBW are significantly linked to lower educational qualifications and an increased rate of receipt of social benefits in adulthood [75]. Besides, diseases in schoolchildren due to air pollution and climate change can significantly influence childhood academic achievement. For example, child malnutrition due to climate change can directly impede brain development and hence affect school-age children's academic performance [76,77]. Respiratory diseases in childhood can affect academic performance by reducing school attendance. Children's mental health problems can lead to difficulties in learning and social contact and increase the risk of dropping out. These lags in children's academic performance may accumulate, eventually leading to failures in the entrance examinations and less education for adults.

3.3. Impacts on non-cognitive ability

Emerging evidence shows that, besides health and cognitive ability, other skills (so-called non-cognitive skills) are also crucial to individual earnings and different economic outcomes [55]. Non-cognitive skills, called socio-emotional and soft skills, refer to personality, character, motivation, and preferences that are highly appreciated in the labor market, schools, and other fields [78]. Although personality traits are strongly hereditary, socio-emotional skills are also affected by early-life experiences and environmental conditions [79]. Although the term "non-cognitive" is controversial, we still use "non-cognitive" here because it is a familiar term in studies and a superior alternative has not emerged. Also, there no constant and standard measurements for non-cognitive skills yet. Based on current studies relevant to non-cognitive skills [52,56,57,79], we divide non-cognitive impacts into two groups, including psychological characteristics (defined as personality traits, self-esteem, and other stable psychological activities) and behavioral tendencies (such as social interactions, relationship establishment and behavioral problems).

Although no direct evidence supports climate change or air pollution associated with adulthood psychological characteristics, indirect impacts may still exist through the effects on adverse birth outcomes. Several authors have described "specific" personal traits in PTB/LBW-born adults, with have a trend toward introversion, shyness, caution, and risk avoidance [80,81]. This withdrawn personality may be due to genetic influences, alterations in the brain structure, biological mechanisms, and environmental consequences such as early experience, parenting, and peer interactions [80,82]. This personality can prevent people from participating in social activities or competitions to acquire achievement and self-confidence, leading to lowered income and self-esteem. For example, a study in Canada showed that survivors with very low birth weights will have lower levels of self-esteem, employment, and revenues compared with the control group in their fourth decade [83].

PTB/LBW induced by air pollution and climate change could further lead to specific behavior tendencies in children. Shortened gestational age also predicts offspring morbidity across the lifespan, including academic problems, attention and social difficulties, and adaptive competencies [84,85]. A meta-analysis found that compared with full-term, those who were born with PTB/LBW were linked to having less experience in a romantic partnership or to have become parents [86], which may be due to their poorer health status, lower income and self-esteem, more emotional and behavioral problems, and worse academic performance [83,87]. PTB/LBW-born adults are also more likely to have internalized behaviors including anxiety, depression, and social withdrawal [81,88], which their tendency toward a withdrawn personality may explain [80]. In addition, VLBW/VPTB born children have a higher risk of emotional and behavioral disorders because of their impaired neurodevelopment [58]. These severe neuro-behavioral problems are often costly due to the substantial medical and non-medical expenditures over the life course.

4. Call for a holistic assessment

A child born today will go through a series of vulnerable windows from the fetal period to childhood and beyond and suffer from multiple health impacts in these periods due to air pollution and climate change. These health impairments can further affect the entire human capital (i.e., health, cognition, and non-cognition) in the long run. However, such profound effects of climate change or air pollution on children have not been comprehensively evaluated. These knowledge gaps must be filled with high-quality health-relevant data, so we call for a holistic assessment of the direct impacts of health damages on children, as well as the indirect impacts of long-term human capital and associated economic costs, to reflect the profound effects of fossil fuel combustion on current and subsequent generations.

First, as for the holistic assessments on the impacts of child health, health care professionals need to consider more health outcomes related to climate change and air pollution from the stage of fetuses to adolescence. Current health assessments mainly depend on the selected health outcomes of adults, such as mortality, and only very limited child health impacts are considered [5]. Given that children experience extended periods vulnerable to environmental risks and are more likely to experience severe health impacts, the absence of complete assessments of child health may lead to policymakers underestimating the full health burdens that are borne by children. Some health effects from early-life exposure to air pollution or climatic events have been well quantified, such as PTB and LBW. To build a solid foundation for a comprehensive assessment, we need to evaluate more health impacts of children, particularly on mental health and neurodevelopment.

Second, we urge public health researchers to work across disciplines and beyond academia to understand a holistic life course assessment better. Experts climate change and health should be aware that the long-term human capital impacts of adverse birth outcomes and child health damages are an essential part of the health impact assessment for fossil fuel combustion. High-quality birth cohort studies are encouraged for such exploration, and outcomes relevant to human capital can be added to the existing birth cohorts for additional monitors. Given that human capital is a comprehensive broad concept of human attributes and closely related to early-life experience, this framework can be a valuable reference for future research.

Third, health economists should be motivated to estimate the economic costs in a holistic assessment of the impact on health and human capital. Child health effects undoubtedly cost a lot, either from medical care expenses or from parents' work loss. Compared to health damages to children, human capital's latent cognition and non-cognition impairments may have more long-lasting economic losses due to reduced lifetime earnings. However, the micro-economic losses from child human capital impairments, and the macroeconomic losses from their potential productivity loss have not been fully estimated. Appropriate methodologies to comprehensively monetize human capital impacts need to be developed to evaluate the economic losses of fossil fuel burning due to its impediment on future human capital accumulation. The basis of this process must be the robust interchange and collaboration of multiple disciplines and sections.

In the 21st century, humans will inevitably be exposed to and continue to live in a rapidly changing environment caused by the fossil fuels burning. Previous research have proven that the effects of fossil fuel-driven climate change and air pollution on children are giant and still growing. Health professionals and policy makers are responsible for identifying children and pregnant women with relevant health consequences as early as possible and reducing health inequities caused by fossil fuel combustion by educating them and their guardians more widely about these risks and effective intervention measures. Therefore, we proposed several priorities for future research. The first is to conduct more empirical studies to clarify the relationships between environmental risks, child health and future human capital impacts. Collaborative and interdisciplinary efforts are vital for further studies to monetize child health and human capital impacts, and to capture the broad socio-economic consequences of the damages to offspring. Second, a comprehensive assessment that involves child health damages, long-term human capital impacts, and the associated economic costs is urgently needed. However, this will inevitably result in some uncertainties in the estimates, mainly coming from the three stages of assessment: exposure-response relationship, exposure assessment, and human capital measurement. Additionally, future studies should consider that many measures have been taken by parents to protect children from extreme weather events or air pollution, and the estimated of the impact could be misestimated. Finally, assessing the profound effects of fossil fuel use on human health and their future potential is essential to determine political will and policy development, especially in the Paris Agreement and the Sustainable Development Goals.

5. Conclusions

Fossil fuel combustion can cause multiple health effects on children, which can further affect a range of health, cognitive and non-cognitive outcomes (e.g., human capital) in people's adulthood, resulting in possibly more substantial socio-economic losses in the future. This paper provides a complete picture of the profound impacts of fossil fuel use on the current and future generations, and provides additional impetus to reduce people's dependence on fossil fuels and facilitate the transition to clean energy. We call for a holistic assessment of the full range of impacts of fossil fuel combustion borne by children; hence more concerted global efforts can be motivated to protect our environments and the health of the next generations. In addition, our discussion of how to conduct a comprehensive assessment of child health, human capital impacts, and associated economic costs may spark additional ideas for future research.

Contributors

CH conceived this study. YZ, AH and SD wrote the first draft of the manuscript with support from CH. AH and SD lead the process of revision, with contributions from XW, HZ, SH, JJ, WL, CH, including critical feedback. CH supervised the development of the manuscript. All authors approved the final version of the submitted manuscript.

Declaration of competing interest

All authors declare that they have no competing interests. Cunrui Huang and Wannian Liang are the Editors-in-Chief of the journal, but they were not involved in the peer review procedure. This paper was handled by another Editorial Board member.

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