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Sustainable policy—key considerations for air quality and climate change

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Air quality and climate change are inexorably linked from their emission sources to their impacts on climate, human health, and ecosystems, including agriculture. However, in global environmental change and sustainability policies the link between air quality and climate change is often ignored. To facilitate including the link between air pollution and climate change in the policy process, three key considerations (1) mix of emissions, (2) lifetime, and (3) benefits and trade-offs should be taken into account. These three key considerations will help decision makers understand how proposed policies may impact the emissions of air pollutants and greenhouse gases and their resulting impacts on climate, human health, and ecosystems, thus reducing unintended consequences and likely resulting in additional economic and environmental benefits.

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Introduction

In 2012, the Organization for Economic Co-operation and Development (OECD) projected that by 2050 air pollution will be the top environmental cause of mortality worldwide [1]. However, the World Health Organization (WHO) reported shortly thereafter in 2012 that seven million people died as a result of exposure to air pollution, making it the world's largest single environmental risk [2••]. In response, the United Nations Environment Assembly (UNEA) in 2014 made improving air quality a top priority for sustainable development, recognizing that clean air is critical to protect human health and simultaneously benefit climate and ecosystems, including food security [3]. These areas – climate, human health, and ecosystems – also have broader implications for socio-economic development which we consider associated impacts.

Furthermore, 2015 was the warmest year on record, reaching 1 °C above the pre-industrial average (1850–1900 reference period) [4]. Including 2015, 15 of the 16 warmest years on record have occurred in the 21st century [5]. Global carbon dioxide emissions from fossil fuels and industry in 2014 were 9.8 ± 0.5 GtC (billion tonnes of carbon), 60% above 1990 emissions [6]. The continued increase in carbon dioxide emissions and the resulting warming of the planet are impacting extreme events, water resources, coastal erosion, ecosystems, wildfires, food production, human health, amongst many others. In response, 195 nations as part of the United Nations Framework Convention on Climate Change (UNFCC) adopted The Paris Agreement, which aims to limit the global temperature increase below 2 °C above pre-industrial levels [7].

Increasingly, air quality and climate change are seen as two issues that are inexorably linked and should be addressed in a coordinated manner. On one level, there is growing recognition of this through the development of international organizations, such as the Climate and Clean Air Coalition (CCAC) or the Global Alliance for Clean Cookstoves that are working to reduce emissions of air pollutants that both warm the climate and negatively impact human health and ecosystems [8,9]. National and regional governing bodies, out of recognition of the linkages, are also taking action to address air quality and climate change simultaneously [10–12].

On another level, for most decision makers there is little guidance on how to best address the linkages between air quality and climate change within the policy process to understand how the emissions of air pollutants and greenhouse gases (GHGs) will impact climate, human health and ecosystems, including agriculture. Guidance on how to incorporate air quality and climate change into the policy process could result in more comprehensive policies. For example, although the air quality and climate change linkages are not explicitly stated as a United Nations Sustainable Development Goal (SDG), there is a great opportunity to contribute to meeting the SDGs by including the air quality and climate change linkages in designing policies to address them. To address this challenge, the International Geosphere-Biosphere Programme (IGBP) and the International Global Atmospheric Chemistry (IGAC) project launched the Air Pollution & Climate: A Science-Policy Dialogue initiative in 2010. As a first step, the initiative released *Time to Act: The Opportunity to Simultaneously Mitigate Air Pollution and Climate Change* that summarized the linkages between air quality and climate change [13] and stated that "an integrated approach to addressing air pollution and climate change is essential if society desires to slow the rate of climate change and to protect human health, food/water security and ecosystems."

Here, as part of the Air Pollution & Climate: A Science-Policy initiative, we present three key considerations to include in an integrated approach to addressing air quality and climate change as part of the policy process. These three key considerations can be used for policies not only specifically addressing air quality and/or climate change but for a broad range of policies from how a municipality designs a waste treatment system to the United Nations Sustainable Development Goals, for example. The main goal of the policies does not need to change, but by addressing the following three key considerations in the development of global environmental change and sustainability policies, more comprehensive policies can result that maximize the benefits for air quality and climate change.

Background

Both in the scientific and policy world, air pollutants and greenhouse gases (GHGs) are often defined, researched, and politically addressed independently of one another. Therefore, their impacts on climate, human health, and ecosystems are also often considered independently. However, the scientific evidence linking emissions of air pollutants and GHGs and their associated impacts is well established [14,15,16•,17•]. Increasing the incentive for coordination, a number of studies have also shown clear economic benefits resulting from integrated air quality and climate change policies [18–20].

Air pollutants are most often defined (from a human health perspective) as particulate matter (PM), ground-level ozone (O_3), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) [21]. In addition, carbon monoxide (CO) and volatile organic compounds (VOCs) are also often considered when addressing air quality as they are precursors in the formation of ozone and particulate matter. Greenhouse gases are most often defined as carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and fluorinated gases (F-gases) [22]. Methane is also often considered when addressing air quality as it is a volatile organic compound, and a precursor to the formation of ozone.

More recently, the focus for addressing air quality and climate change simultaneously has been through short-lived climate-forcing pollutants (SLCPs), which are air pollutants that typically have a warming impact on the climate as well as negative impacts on human health and ecosystems. SLCPs are generally defined as black carbon (BC, which is a component of particulate matter), methane, ozone and hydrofluorocarbons (HFCs) [8]. Research indicates that by reducing emissions of SLCPs significant benefits to human health and to ecosystems would result such as the prevention of millions of premature deaths and an increase of crop yields on the order of tens of millions of tons annually on a global scale [14,15,16•,17•,23–25,26•,27]. In addition, mitigation of SLCPs using existing measures has been projected to be able to reduce global warming by 0.5 °C by 2050 if full implementation of these measures occurs by 2030 [15]. The 2 °C warming limit in the UNFCCC Paris Agreement relies on extensive carbon dioxide emission reductions as well as technological innovation to remove carbon from the atmosphere (e.g., carbon capture and storage) to achieve the limit. However, extensive carbon dioxide emission reductions and sufficient technological innovation are unlikely to happen to the extent IPCC scenarios project [28]. Therefore, reductions of SLCPs are a complementary way to reduce the rate of warming as carbon dioxide emission reductions come online [29].

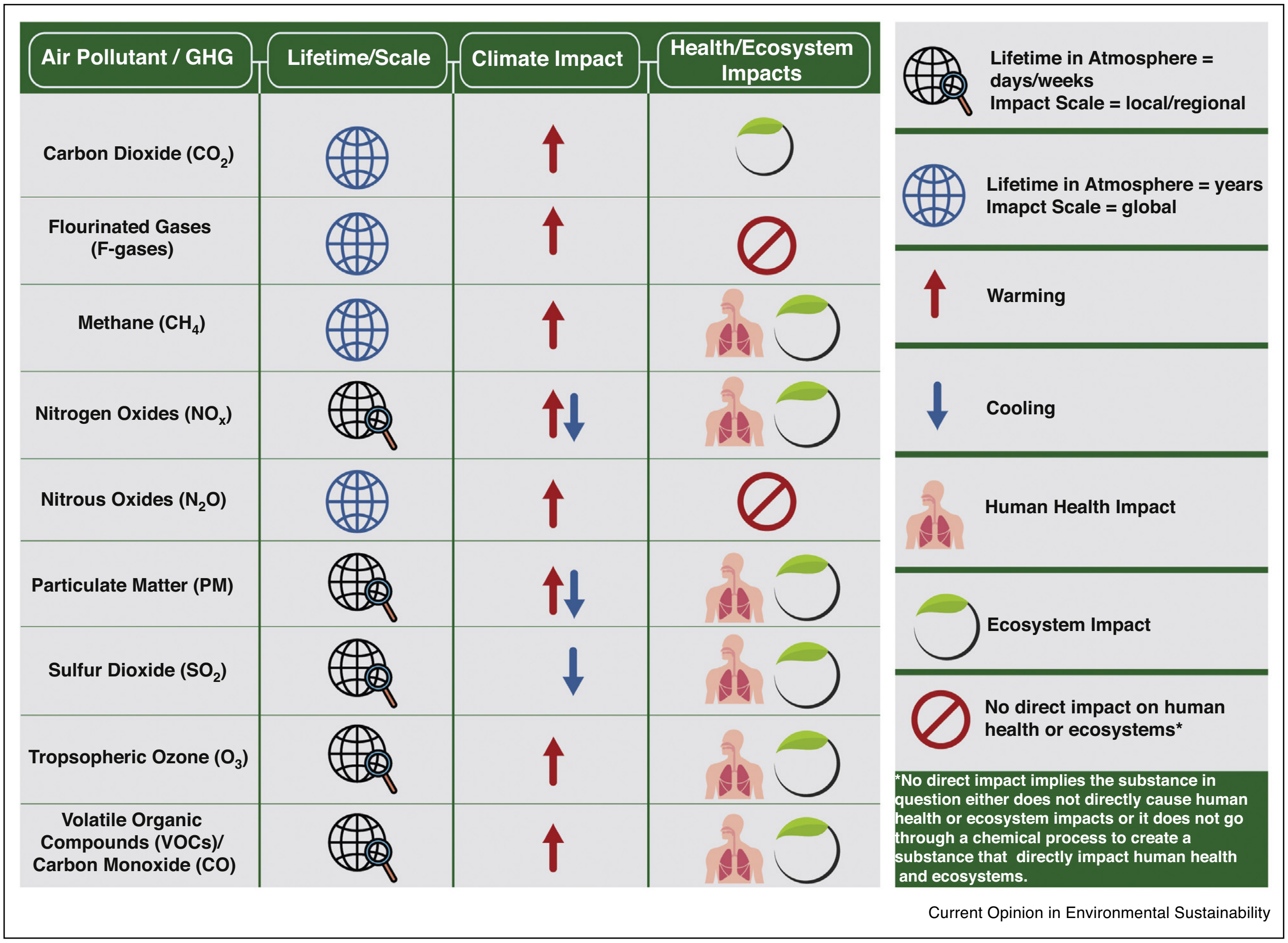
However, the focus on only those SLCPs that contribute to warming falls short of truly understanding and addressing the links between air pollutant and GHG emissions and their impacts. A more comprehensive view is required (Figure 1 and Section "Key Considerations").

Common GHGs are very effective at absorbing thermal and terrestrial radiation and thus warming the climate. However, due to the relative inertness of common GHGs such as carbon dioxide, nitrous oxide, and chlorofluorocarbons, and hydroflourocarbons, these gases have no direct impact on human health, with the exception of methane, which can react to form ozone. Methane also reacts to form carbon dioxide which can directly impact the photosynthesis process for plant growth.

Air pollutants cause human health and ecosystem impacts at the local to regional scale. Some of these air pollutants, such as ozone, are also effective at absorbing solar radiation and warming the climate. On the other hand, some of these pollutants, for example sulfur dioxide, go through chemical and physical processes to form sulfate particles that reflect sunlight and have an overall cooling impact on the climate. Other pollutants, for example volatile organic compounds, are a precursor for ozone and secondary organic aerosol and therefore can have either a warming or cooling impact.

Whether an air pollutant warms or cools the climate, they all directly impact human health and ecosystems on the local to regional scale. Nitrogen oxides and sulfur dioxide cause eutrophication and acidification of lakes and streams, damaging ecosystems. In addition, nitrogen

Figure 1



Common air pollutants and greenhouse gases and their impacts on climate, human health and ecosystems, including agriculture.

oxides and sulfur dioxide go through processes in the atmosphere to form particles, contributing to the particulate matter burden [30]. Particulate matter, especially under 2.5 μm in diameter (50 times smaller than the diameter of a human hair) penetrates deeply into our lungs and can cause both respiratory and cardiovascular diseases [2••,31]. Particulate matter can also directly interact with cloud formation processes and may impact both the amount and location of precipitation [32], for example the interaction of high concentrations of particulate matter in Asia and their influence on the Asian Monsoon [33]. Breathing in ozone exacerbates respiratory illnesses such as asthma. The deposition of ozone on vegetation weakens plants and stunts their growth, including reduction of agricultural crop yields [34,35]. Methane, through the production of ozone as well as its warming impact, significantly reduces crop yields more than any other air pollutant or greenhouse gas [36].

Figure 1 summarizes this more comprehensive view of air pollutants, GHGs and their direct impacts on climate, human health, and ecosystems. Indirect impacts, such as how a warming climate increases the likelihood of heat waves that result in human health impacts, were not considered as they rely on feedback mechanisms in the system that are difficult to predict. Using this table as a guide, policies can be designed to more comprehensively account for the impacts emissions of air pollutants and GHGs will have by taking into account several of the key considerations.

Key considerations

An integrated approach to addressing air quality and climate change in order to understand the impacts on climate, human health and ecosystems should take into account three key considerations: (1) mix of emissions, (2) lifetime, and (3) benefits and trade-offs.

Mix of emissions

The particular mix of emissions determines their actual effect on air quality and climate change. When you drive your car down the road or light a fire in your fireplace, it is not just carbon dioxide *or* air pollutants that are emitted, but rather both. This is almost always the case; air pollutants and GHGs are emitted from the same sources as a mixture. For example, any source involving combustion will emit not only carbon dioxide, but air pollutants such as nitrogen oxides, carbon monoxide, and particulate matter. Therefore, it is nearly impossible to reduce emissions of one pollutant at a source without affecting the co-pollutants also emitted by the source. For example, the U. S. Clean Air Act focuses on reducing the concentration of six common pollutants (ozone, particulate matter, sulfur dioxide, lead, carbon monoxide, and nitrogen dioxide), but the actions to decrease the concentration of these pollutants also resulted in a modest associated decrease in carbon dioxide emissions [10]. Another example from the green energy sector shows the opposite. As combined heat and power plants as well as decentralized power generation were promoted in the European Union as a measure to reduce carbon dioxide emissions, the number of small combined plants in urban areas increased [37]. As small plants with relatively low power generation do not fall under the strict air pollutant emission guidelines of larger plants, urban air pollution increased [38]. Therefore, in the policy process, the mixture of air pollutants and GHG emissions at the source should be considered to determine how the policy will impact climate, human health and ecosystems.

Lifetime

The atmospheric lifetime of GHGs and air pollutants determines on which geographical scales the impacts will be felt. Carbon dioxide, a long-lived greenhouse gas, is essentially chemically non-reactive and therefore remains in the atmosphere on the order of centuries or longer. This long lifetime results in a large buildup of carbon dioxide in the atmosphere over time causing an incremental increase in warming for each kilogram emitted. In addition, the long lifetime of carbon dioxide in the air also means that it becomes well mixed in the atmosphere, making the location of the source of the emissions irrelevant to its impact on warming the climate globally. For example, emissions of carbon dioxide from a coal fired power plant in China and carbon dioxide emitted from vehicle tailpipes in the US will become well mixed in the atmosphere and have the same impact on warming the climate globally. Generally, GHGs have a lifetime in the atmosphere on the order of decades to centuries resulting in a global scale impact. This, however, is not the case for the air pollutants.

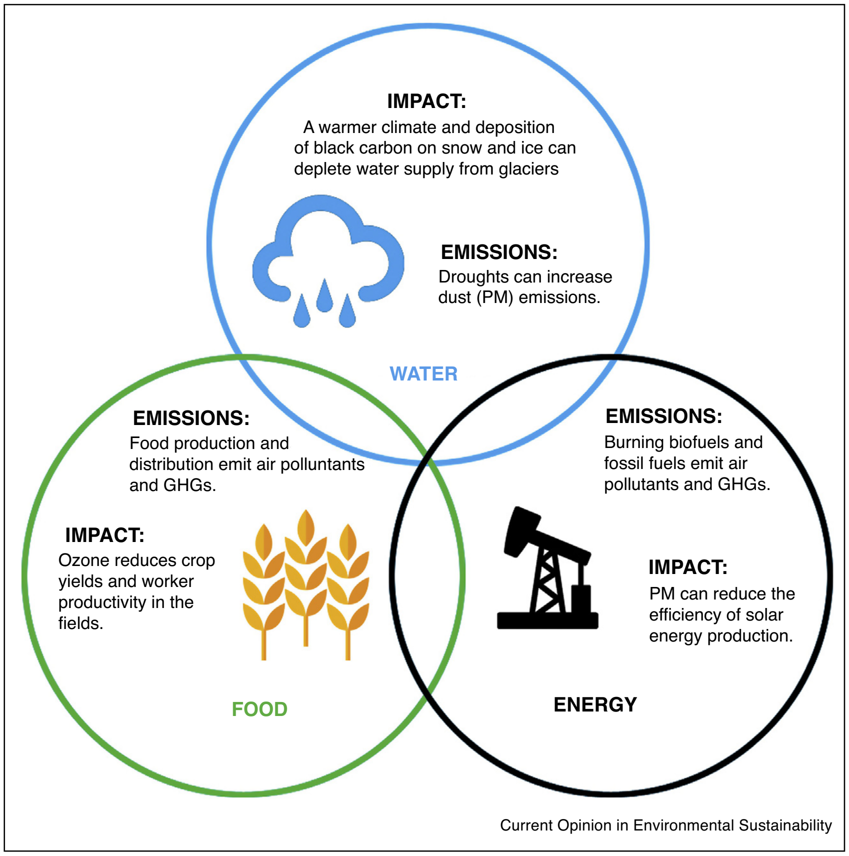
Air pollutants typically have lifetimes that last from hours to months resulting in local to regional scale impacts. In the case of the open burning emissions in south Asia, the associated air pollutant emissions (nitrogen oxides, volatile organic compounds, particulate matter) contribute, for example, to the tremendously high levels of air pollution reported in Asia. Similarly, vehicle tailpipe emissions in the US will be most noticeable in the adverse air quality impacts they exert close to their location of emission, for example smog in Los Angeles. This also holds for the climate change impacts of air pollutants. In Asia, the high concentration of particulate matter, which contains a significant amount of sulfate, has a cooling impact on the region. Reducing particulate matter concentrations in Asia, which is likely to occur to improve air quality, could therefore result in warming the region by 2 °C by the end of the century [39]. In other words, the impact of air pollutants on air quality and climate change is closer (local to regional) to the source of their emissions.

Benefits and trade-offs

Policy options aiming to address a single issue, such as climate change, may have unintended benefits and trade-offs that should be taken into consideration. For example, as countries look at options for reducing their carbon dioxide emissions to mitigate climate change as part of the UNFCCC Paris Agreement, these options will impact air quality. Therefore, a coordinated approach considering both climate change and air quality could lead to significant synergies and economic benefits. Another example, biofuels are often considered a carbon neutral way to produce energy. While the burning of fossil fuel blended with 5–85% ethanol, a biofuel from corn and sugarcane typically used in cars, can decrease the emission of certain air pollutants such as carbon monoxide, total hydrocarbons and particulate matter, it increases the amount of acetaldehyde and other unregulated toxic air pollutants [40]. Emissions of nitrogen oxides compared to normal gasoline or diesel vary, with studies reporting a decrease [41] or increase [42]. Increased nitrogen oxide emissions from biofuels can lead to increased ozone levels, reducing air quality in urban areas as seen in Sao Paulo, Brazil [43]. Some mitigation options to improve air quality, such as diesel particulate filters on vehicles can result in slightly greater carbon dioxide emissions [38,44]. Burning biomass in our homes as a heat source is also often considered a 'green' option as the net carbon dioxide emissions are lower compared to fossil fuels. However, burning biomass can also result in significant emissions of air pollutants (nitrogen oxides, volatile organic compounds, particulate matter) and have local/regional impacts on climate, human health and ecosystems [23]. This is especially true in regions of the world that use biomass for cooking indoors with open fires. Considering the possible implications for benefits and trade-offs of such options can lead to improved policies.

To fully understand how a policy option will impact climate, human health and ecosystems the mix of emissions, lifetime, and benefits and trade-offs of air pollutants and GHG emissions should be considered. This can occur at various levels of detail depending on the specific policy

Figure 2



Air quality and climate change are integral to the Water-Energy-Food Nexus. The figure provides some examples of how the domains of the nexus can cause air pollutant and greenhouse gas emissions and in return how water, energy and food can be impacted by air pollution and greenhouse gases.

context, ranging from a general mention in a strategy document down to the required application of integrated assessment tools [45] or even incorporation of scientific support for detailed model simulations [46]. Following, we provide one example as to how the three key considerations can be integrated on a general level in a broad sustainability global environmental change and policy approach.

Example of integrating air quality and climate change into the Water-Energy-Food Nexus

Recently, the Water-Energy-Food Nexus has been a topic of much discussion both within the science and policy communities. This nexus is considered a useful "conceptual approach to better understand and systematically analyze the interactions between the natural environment and human activities, and to work towards a more coordinated management and use of natural resources across sectors and scales" [47]. The importance of providing fresh water, energy and food for all should not be understated. However, considering this nexus solely in terms of water, energy, and food ignores the impact this nexus has on multiple other parts of natural and human systems, such as land and soil, climate change and air quality.

Here we discuss how in the context of the Water-Energy-Food Nexus, if the emissions of air pollutants and GHGs as well as their impacts are taken into account, a more comprehensive policy design would result. Figure 2 shows how the domains of the nexus contribute to air pollutant and GHG emissions, and vice versa how water, energy, and food domains can be affected by air quality and climate change. For example, the production of energy from both biofuels and fossil fuels emit substantial quantities of air pollutants and GHGs. Food production and distribution also emit substantial quantities of air pollutants and GHGs. During drought conditions, air quality can decrease due to increased soil dust (particulate matter) emissions [48••]. In addition, it has been shown that air pollutants, specifically particulate matter, impact alternative energy production options such as solar power [49]. Ozone reduces crop yields and worker productivity in the fields. Climate warming will lead to increased melting of seasonal snow pack and glaciers in winter and spring resulting in a decrease in the summer and fall run-off [50], which makes water management for agriculture more complex. These examples of emissions of air pollutants and GHGs and their impacts are an integral part of the Water-Energy-Food Nexus. Therefore, policies in relation to water, energy, and food should consider the three key aspects, the mix of emissions, lifetime, and benefits and trade-offs of air pollutants and GHGs throughout nexus.

Conclusions

Future research agendas and programs should recognize the broader connections of environmental issues, such as was shown here for the links between air quality and climate change within the water-food-energy nexus, and foster research investigating the wider implications of an issue rather than limiting research to artificially bounded issues. This would help to build the scientific foundation to support integrated policies. In addition, if there is political resistance to addressing an environmental issue, recognizing the broader connections of environmental issue and implementing integrated policies could help to overcome these political barriers. International NGO's such as the Climate and Clean Air Coalition (CCAC) already make use of this strategy by focusing on improving public health through better air quality, which has resulted in consensus-finding policies that benefit other environmental issues such as climate change and food security.

The number of national, regional, and global agreements and policies to address environmental change and sustainability issues is likely to increase. In many cases, these agreements will result in changing emissions of air pollutants and GHGs and their associated impacts. Although improving air quality and mitigating climate change may not be the primary goal of some of these policies, by taking into account the three key considerations, (1) mix of emissions, (2) lifetime, and (3) benefits and trade-offs, more comprehensive sustainable policies can be developed to maximize the benefits for air quality and climate change mitigation.

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