Insights from the international workshop on "Adapting Agriculture to Climate Change and Air Pollution"

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Abstract

An international workshop on “Adapting Agriculture to Climate Change and Air Pollution” took place at Nanjing University of Information Science and Technology, Nanjing, China, during 23-27 October, 2023. Experts working in various multi-disciplinary areas of agroecosystem and environmental research gathered for academic communication and discussions. Two discussion groups focused on “agriculture under air pollution and climate change: Current challenges and priorities for the future” and “adapting agriculture to air pollution and climate change: current status and next steps”. Insights derived from the discussions are summarized in this article and include opinions about current issues, knowledge gaps identification, and potential priorities and actions that could be taken. The first discussion mainly addresses ozone impact estimates; ozone metrics for impact and risk assessments; ozone monitoring; air pollution impacts and policy; and pivotal role of agriculture and consumer choices. The second group covers adaptation and mitigation; greenhouse gases and energy efficiency; concerns about the link between adaptation and mitigation; local food, planetary-health diets and carbon footprint; irrigation and climate change adaptation; scientific evidence and policy-making; air pollution and crop adaptation; machine learning and crop modeling; and challenges faced by smallholder farmers and large-scale enterprises. Hence, this report could be useful for reseach, educational, and policy purposes, collating opinions of experts working in diverse research areas.

Keywords: air pollution; agriculture adaptation; agroecosystem health; climate change; crop production; impact mitigation

1 Introduction

Climate change presents a global issue of profound societal significance due to its widespread impacts on the biosphere (Wang et al., 2023). Agroecosystems face a wide range of climate change-related impacts, including agricultural nitrogen losses (Bowles et al., 2018), elevation of pathogen outbreak risk and expansion of plant disease spread (Singh et al., 2023), loss of pollinators (Millard et al., 2023), loss of nutritional quality (Myers et al., 2014), and suppression of crop yields (Rezaei et al., 2023). Concurrently, air pollution poses an additional threat to agroecosystems, particularly an increase in ground-level ozone, which is currently the most widespread and damaging air pollutant for vegetation (Wang et al., 2023). Air pollution effects on agroecosystems are also diverse, spanning from lowered crop yields (Feng et al., 2022; Gupta et al., 2022; Kobayashi, 2023) to impaired carbon and nitrogen cycling (Gu et al., 2022) as well as disrupted interactions between plants and microorganisms or insects (Agathokleous et al., 2020; Blande, 2021; Masui et al., 2023). In addition to the negative effects of air pollution on agroecosystem services and the threat to food security, air pollution is associated with profound economic losses, hampering the achievement of sustainable development goals at multiple levels (Feng et al., 2022; Pandey et al., 2023; Tai et al., 2014). Hence, strategies should be devised to address concurrent climate change and air pollution and their impacts on agroecosystems (Agathokleous et al., 2023; Clark et al., 2023; Pandey et al., 2023; Rezaei et al., 2023; Smith et al., 2023; Wang et al., 2023).

Quantifications of the impacts of climate change and air pollution on agriculture emphasize the severity of the problem (Hong et al., 2020; Sharps et al., 2024). For instance, assessment of the joint impacts of ozone and climate on perennial crops historical and future yields in California revealed a significant ozone-induced decrease, ranging from 2% for strawberries to 22% for table grapes, translated to approximately US$1 billion loses per year; and warming effects are non-significant for several perennial crops (Hong et al., 2020). Elevated ozone pollution during non-winter seasons is also estimated to decrease the agricultural total productivity in China by 18% over 2002–2015 (Chen et al., 2024). Moreover, analysis of data from 146 countries worldwide during 2010-2019 suggest that an 1% increase in ozone and fine particulate matter ($PM_{2.5}$) could decrease agricultural total productivity by 0.207% and 0.104%, respectively (Dong and Wang, 2023). Importantly, the detrimental impact of $PM_{2.5}$ pollution is stronger in cooler climates, indicating the potential of aggravated air pollution impacts by climatic changes (Dong and Wang, 2023). Despite that the inconsistencies in impact assessments due to different metric choices (Blanco-Ward et al., 2023; Emberson et al., 2000; Mao et al., 2024; Paoletti et al., 2022, 2007; Pleijel et al., 2004), research findings also indicate the promise of potential policies to mediate these impacts (Liu et al., 2024; Liu and Lu, 2023; Pandey et al., 2023). For example, if reduction of ozone concentrations is achieved in accordance with the WHO air quality standards, agricultural total productivity in China could increase by 60%, counteracting productivity losses that are expected based on a 2°C warming scenario (Chen et al., 2024). Moreover, if the air quality targets for ozone and $PM_{2.5}$ are met, China’s maize, rice and wheat yields could increase by 7.8, 4.1, and 3.4%, respectively (Liu et al., 2024). However, research and development are also crucial for air pollution-tolerance traits, while adaptation to air pollution and climate change can be facilitated by effective insurance enrollment rates and crop prices (Liu and Lu, 2023; Pandey et al., 2023).

An international workshop on “Adapting Agriculture to Climate Change and Air Pollution” was held at Nanjing University of Information Science and Technology (NUIST), Nanjing, China, from 23 to 27 October 2023 (organizers: Evgenios Agathokleous, Yansen Xu, Zhaozhong Feng). The aim of the workshop was to bring together experts from multiple disciplines working in these research areas, serving as a platform to share knowledge, exchange views and insights, and promote cooperation. A total of 54 participants from 18 institutions and 6 countries attended the workshop, which included 26 oral presentations and two discussion groups focused on overarching themes. The interactive discussions led to some important insights, which the main participants of the discussion groups wished to share with the broader scientific community, as they reflect expert opinions about current issues, identification of knowledge gaps, potential priorities for the research community, and possible actions that are needed.

2 Insights from Discussion Group A

Summary from the first discussion group A on “Agriculture under air pollution and climate change: Current challenges and priorities for the future”

Chairperson: Prof. Lisa Emberson, University of York, UK
Rapporteur: Prof. Evgenios Agathokleous, NUIST, China

The discussion session addressed a variety of aspects related to agriculture under air pollution and climate change, although the main factor discussed was ozone, the major air pollutant threatening vegetation (Emberson, 2020; Lin et al., 2020; Unger et al., 2020). The group discussed ozone impact estimates, ozone metrics used for the assessment of impact and risk, ozone monitoring, and the intersections between air pollution impacts and policy. The pivotal role of agriculture was also highlighted, and diet interventions were further discussed. Key points include:

- **Ozone impact estimates**:
    - The need for new dose-response relationships for a range of crops and cultivars to assess the magnitude of real-world ozone impacts was highlighted.
    - There is also a need to incorporate differences in agro-ecological zones (AEZs; zones defined based on combinations of climatic, landform, and soil characteristics) and agricultural management practices in ozone impact assessment. For example, experiments should be conducted under a range of conditions such as different AEZs, irrigated versus rainfed, different levels of fertilizer application and soil fertility, and use of region-specific cultivars, so that

    experimental results can be used to reliably inform impacts occurring under a range of conditions and management practice regimes.
  - The use of standardized experimental protocols could support experimental assessment of the influence of AEZ and management on ozone impacts. For example, in the 1990s there was a coordinated open-top chamber (OTC) effort in Europe, which helped to develop robust ozone metrics and associated dose-response relationships for the whole of Europe for a range of crops and cultivars. This was an excellent example of coordination, and a similar effort could be established within and across Asian countries.
  - More focus on multiple stresses is needed, especially air pollution together with climate change. A better understanding of the mechanisms by which air pollution and climate variables combine to cause stress to crops would improve impact assessments under future environmental conditions.
  - A key climate variable that interacts with ozone stress is drought. Drought is thought to exacerbate ozone impacts but will also reduce ozone uptake. More experiments are needed to improve our understanding of the interactive mechanisms and effects of drought and ozone damage.
- **Ozone metrics for impact and risk assessments**:
  - A large number of ozone metrics (e.g. M7/M12, W126, AOT40, PODy) have been developed to assess ozone impacts, but there is currently no scientific consensus on which of these metrics should be recommended for use in ozone impact assessment in Asia. This may be confusing for policymakers and is a question that should be addressed by the research community in the coming years. The next step for the research community would be to examine whether a consensus can be reached, providing an initial set of guidelines for which metrics to use for particular conditions. AOT40 (Accumulated Ozone exposure over a Threshold of 40 ppb) and PODy (Phytotoxic Ozone Dose above a flux threshold Y) are two of the most widely used metrics. The former is a concentration-based metric and the latter is a flux-based metric. The PODy metric is arguably the best metric to apply when environmental conditions (e.g. soil water or atmospheric water deficits) are likely to limit ozone uptake. In the presence of such stressors, PODy is biologically more relevant and would be recommended for use.
  - However, the PODy metric requires substantial data to be applied with confidence (i.e. hourly ozone concentration data and meteorological data as well as crop physiology data to develop the stomatal conductance model (gsto) to allow reliable estimates of stomatal ozone flux (PODy) to be calculated). There are only a limited number of sites in Asia that have all the data needed for the calibration of gsto models. Extending data collection to sites in a range of AEZs would be needed to ensure PODy can be reliably applied across regions.

    - There may be opportunities to work with other research communities (e.g. the agronomy community) who have data-driven knowledge of crop physiology and the influence of environmental conditions (e.g. irrigation and soil fertility) on crop growth and yield, and the environmental defense society. Cross-disciplinary collaboration with such data-rich communities would help to address data gaps and improve our understanding of combined stresses and the influence of crop management on abiotic stresses.
- **Ozone monitoring**
    - The lack of ozone data in Southeast Asian countries was noted. Moreover, in some cases, air pollution data are recorded but are not widely accessible to the public. This means there is often a lack of data to perform robust regional ozone impact assessments.
    - The type of air pollution monitoring stations is also an important factor affecting ozone impact estimates. Urban stations are widely used but sub-urban and remotely-sited stations are uncommon. Considering the difference in air pollution exposures (particularly for ozone) between urban and non-urban areas (Diaz et al., 2020; Malashock et al., 2022; McHugh et al., 2023), here is a need to expand air pollution monitoring to sub-urban and remote station locations, especially since low-cost sensors are also available nowadays (Carrari et al., 2021; De Marco et al., 2022; Frederickson et al., 2023; Saitanis et al., 2020). While remote-sensing, satellite data could contribute to this, their resolution is not as high as ground-measured data.
    - A major concern was expressed that modelled ozone concentration data (using atmospheric chemistry transport models) often differs from observational data. Further research is required to improve the diurnal and seasonal prediction of pollutant concentrations by chemical transport models (CTMs) and for pollutant concentration and pollutant impact communities to work more closely together to focus efforts on reducing the greatest uncertainties in impact assessment modelling.
- **Air pollution impacts and policy**:
    - The impact research community needs to think and better understand what information might be most useful to provide to policymakers. Previously, efforts have focused on developing air quality guidelines (AQGs) and yield loss estimates. The former can help to set targets for emission reductions whilst the latter can be used to monitor trends over time and therefore the success of policy interventions.
    - It may be that yield losses of 3-6% occurring in certain areas may be perceived as a relatively small impact on crop yield and may not be enough to attract the attention of policymakers. However, were such yield losses to be set within the

    context of food security, the implications of air pollution impacts could be more clearly understood.
  - It would therefore be useful to quantify air pollution impacts on yield and nutrition in terms of changes in price and hence cost to different stakeholders. It would also be useful to perform cost-benefit assessments to understand how the costs of air pollution mitigation compare with the costs of the existing air pollution burden.
  - A need was highlighted to create more connections and networks beyond the scientific community to better understand the consequences of air pollution impacts on different stakeholders.
  - The scientific consensus on the risk assessment methods to use to estimate ozone impacts on agriculture (e.g. reliable experiments, ozone metrics and dose-response relationships) along with suggested AQGs and an assessment of the current status and trends in how air pollution is affecting crop yields is likely to be extremely valuable to policymakers.
  - We should also consider aspects other than yield loss, such as biodiversity loss and nutrient and vitamin composition of grains, since these may also be important to consider in the development of policy. Such aspects gain high public and political attention, and may influence the public perception of the problem.
  - The importance of biodiversity loss and particularly effects on ecosystem service providers such as pest natural enemies and pollinators were highlighted. However, there remains a significant knowledge gap concerning the effects of ozone pollution on ecological interactions, especially at field or landscape scales.
- **Pivotal role of agriculture and consumer choices**:
  - Increased availability and access to food is needed; however, intensive agriculture is also part of the problem since it produces both air pollution and greenhouse gas (GHG) emissions. Consideration should be given to mitigation and adaptation measures for agriculture that might reduce emissions and improve yields and livelihoods.
  - The role of diet in air pollution emissions and consequent impacts was considered and specifically whether a diet transition could be achieved (i.e. reduced consumption of meat). Focusing on the human health benefits of such a diet transition could be a better way to encourage people to take action than a focus on the impacts of air pollution on food. For example, the North Karelia project in Finland has been a success story of diet intervention. Such examples provide promising evidence that the perception of the public to threats can result in action.
  - Facts may not be able to change people's minds, but prices can, especially in countries with lower standards. Taxes might be one way of changing consumer

behavior, but they should be deployed with complementary efforts in education. A combination of multiple strategies may be needed to support air pollution mitigation efforts.

3 Insights from Discussion Group B

Summary of the second discussion group B on “Adapting agriculture to air pollution and climate change: Current status and next steps”

Chairperson : Emer. Prof. Kazuhiko Kobayashi, The University of Tokyo, Tokyo, Japan
Rapporteur : Dr. Jie Pei, Sun Yat-sen University, China.

The session revolved around the impacts of climate change on agriculture, food security, and ways to mitigate and adapt to these changes. The participants discussed various topics such as soil quality, greenhouse gases, energy efficiency, irrigation, and air pollution, as well as the need for scientific evidence and predictions to inform policy-making. The key points include:

- **Adaptation and Mitigation**:
    - The significance of adapting agricultural practices to address climate change was underscored in the discussion (e.g., diversification, climate change resilient crops, water management, altering crop rotation and planting dates, integrated pest management), highlighting the necessity for integrative adaptation and mitigation strategies that not only focus on immediate responses but also on long-term sustainability. This includes enhancing soil quality through innovative agronomic practices and increasing resilience against environmental stressors. Such measures are essential for ensuring the continued productivity and sustainability of agricultural systems in the face of changing climate patterns and escalating air pollution challenges. Additionally, the integration of advanced technologies and research into climate-smart agriculture was identified as a critical step toward effectively managing and reducing the impacts of these environmental changes.
    - The discussion highlighted various adaptation strategies, such as modifications in tillage methods (e.g., no-tillage, direct sowing) and other agronomic practices (e.g., fertilizer and pesticide application). It was noted that these adaptation measures tend to offer greater flexibility and practicality compared to mitigation efforts. Furthermore, the array of stakeholders involved in implementing adaptation strategies is often more varied and extensive than those engaged in mitigation. This diversity in participation not only broadens the scope of knowledge and experience but also enhances the potential for innovative and context-specific solutions tailored to different agricultural environments and challenges.
- **GHGs and Energy Efficiency**:
    - The transition from conventional tillage practices to no-till farming was

extensively discussed as a proactive measure in mitigating climate change. This shift is particularly significant due to its potential to reduce greenhouse gas (GHG) emissions, a major contributing factor to global warming. No-till farming not only minimizes the disturbance of soil and hence the release of stored carbon, but it also promotes increased soil organic matter and carbon sequestration. Additionally, this approach can lead to improved soil health, increased water retention, and enhanced biodiversity. However, the adoption of no-till practices also requires consideration of various factors, including soil type, crop selection, and regional climatic conditions. The discussion also highlighted the need for supporting policies, educational initiatives, and incentives to encourage farmers to adopt these environmentally friendly practices more widely.

    - Energy efficiency improvements, such as the adoption of solar panels (e.g. agrivoltaics or agrophotovoltaics) and vertical planting, were highlighted for their potential to revolutionize agricultural practices. Solar panels help to reduce reliance on fossil fuels, thereby lowering GHG emissions and cutting costs. Vertical planting, on the other hand, optimizes space, particularly in urban areas, and can lead to more efficient resource use, including water and nutrients, while also reducing transportation needs while reducing air pollution. Together, these strategies represent significant steps toward more sustainable and energy-efficient agricultural practices.
- **Concerns about the link between adaptation and mitigation**:
    - The discussion around the potential negative impacts of solar panels on plant productivity acknowledged that while solar energy offers significant environmental benefits, it can also have unintended consequences for agricultural lands. One primary concern is the shading effect (and reduced rainfall beneath them) caused by solar panels, which can reduce the amount of sunlight (and water) available to crops, potentially impacting their growth and productivity. This effect could be particularly significant in agrivoltaic systems, where solar panels and agriculture coexist on the same land. However, this research area is still in its infancy, and the need for balanced measures and further research was emphasized to understand and mitigate these impacts fully. This includes exploring optimal configurations of solar panels to minimize shading, studying the effects of varying light intensities on different crops, and developing innovative agrivoltaic designs that can harmonize energy production with agricultural productivity. The goal is to ensure that the integration of solar energy into farming landscapes is done in a way that supports both sustainable energy goals and agricultural productivity.
    - A larger scale concern was also mentioned about the link of agriculture with the energy sector via the production of energy crops. When the food energy

production is compared with the total primary energy production at the global scale, the latter is one to two orders of magnitude larger than the former. The link of agriculture with the energy sector could therefore result in large fluctuations of food production driven by slight perturbations to the primary energy production. The nexus of food-energy-water-land has also attracted heated discussion and increased attention, and it is suggested that the issues can be more scientific and objective for the comprehensive development of the region; however, the current research methods and regional specificity are still being explored.

- **Local Food, Planetary-Health Diets and Carbon Footprint**:
    - Eating locally-produced food is often advocated as a strategy to reduce carbon footprints by minimizing the distance food travels from farm to consumer. This approach, known as reducing 'food miles', can significantly lower the emissions associated with transportation and agricultural activities. However, the discussion emphasized the need to consider the energy efficiency of various modes of transport in the food-mileage concept. Ship transport, for example, is much more energy-efficient than land transport particularly by tracks and trailors. Educating consumers about the environmental benefits of local diets not only supports lower emissions but also bolsters local economies and agricultural diversity. This approach, however, must consider that some means of international food transport are by far more efficient in energy consumption than local transport. For instance, shipping goods in bulk via sea or rail can be less energy-intensive per unit of food than transporting smaller quantities by road or air over shorter distances. Therefore, when evaluating the environmental impact of food transportation, it is crucial to assess the overall resource efficiency of the entire supply chain, rather than just the distance travelled. This nuanced understanding can help in formulating more effective strategies for reducing the carbon footprint of our food systems.
    - Another approach to reduce the carbon footprints of the food systems is dietary changes, especially the promotion of “eating lower on the food chain” to minimize energy loss during the transfer of energy up the trophic levels, as well as a shift toward a more plant-based diet and reduced consumption of high carbon-footprint foods such as red meat (especially meat from methane-emitting ruminants, e.g., beef and lamb). Such approaches can be encapsulated by the concept of “planetary health diet”, which is aimed to enhance the health of both people and the planet. However, it was noted that any promotion of dietary changes has to be culturally sensitive and locally relevant, recognizing different populations across the world might have divergent nutritional requirements and tolerances toward different foods. A “one diet fits all” approach should be avoided.

- **Irrigation and Climate Change Adaptation**:
    - The role of irrigation in climate change adaptation was discussed, particularly in Northern China. Irrigation does increase the adaptation capability to climate change at field to local scale, but it may increase vulnerability of agriculture to a large-scale change in climate. An example mentioned was the devastating impacts of the basin-scale drop of rainfall on rice production in Southeastern Australia for some continuous years.
    - The potential cooling effect of irrigation could reduce ozone uptake, although evidence is still being gathered. However, irrigation directly promotes stomatal opening and therefore increases ozone uptake. Hence, the effect of irrigation on ozone uptake is multi-dimensional and depends on the patterns of irrigation (amount, frequency, duration) and the genotype-specific hydrophilicity or hydrophobicity.
- **Scientific Evidence and Policy-making**:
    - The need for scientific evidence and predictions of crop yield impacts to inform policy-making and help people adapt to changes was highlighted.
    - The role of policy-making may somewhat differ between mitigation and adaptation to climate change. In mitigation, policymaking exerts direct impacts on the regulation of greenhouse gas emissions, whereas, in adaptation, policy-making needs to facilitate the transition of the plant and livestock production sector to a better-adapted means of production.
- **Air Pollution and Crop Adaptation**:
    - Adaptation to air pollution was a key topic, highlighting the necessity for developing crop varieties that are tolerant to such conditions. Alongside traditional breeding methods, emerging phenotyping technologies, e.g., LIFT (Light-Induced Fluorescence Transient) are gaining attention. Such innovative approaches include the active and passive retrieval of the chlorophyll fluorescence signal to identify plant stress. They allow for the rapid and non-destructive assessment of plant photosynthetic performance and health, which can be crucial in identifying varieties that are more resilient to air pollution and climate change. By providing detailed insights into plant responses under stress conditions phenotyping offers a powerful tool for developing crops that can better withstand the challenges posed by increasing air pollution levels.
    - Ethylenediurea (EDU; $C_4H_{10}N_4O_2$) is recommended for assessing the impacts of ozone on crops and potentially increasing yields. However, its specific mode of action against ozone phytotoxicity is unclear. and there is a lack of toxicological studies and food and chemical safety evaluations. EDU is known for its protective effects against ozone damage in plants. When applied, it can help to identify how ozone stress affects crop health and productivity, allowing

        researchers to better understand the specific impacts of ozone exposure under real field conditions. This information is crucial for developing strategies to mitigate ozone damage and improve crop yields in environments with high ozone levels.

- **Machine Learning and Crop Modeling**:
    - The discussion highlighted the promising role of machine learning in deciphering complex patterns and facilitating predictive analyses in agricultural contexts. The capacity of machine learning to process and analyze large datasets can uncover valuable insights into crop behavior under various environmental conditions. However, it was also noted that there are inherent uncertainties in machine learning predictions on crop responses to climate change and air pollution, particularly due to the variability in environmental factors and the limitations of available data.
    - To enhance the reliability of these machine learning insights, the integration of crop modeling was suggested. By combining the predictive power of machine learning with the detailed, process-based understanding provided by crop models, researchers can cross-verify findings and predictions. This synergy allows for a more comprehensive validation of results, ensuring they are not only data-driven but also grounded in agronomic principles. Such a combined approach could significantly improve the accuracy of forecasts and deepen our understanding of crop responses to environmental stresses.
- **Smallholder Farmers vs. Large Enterprises**:
    - The discussion touched upon the distinct challenges faced by smallholder farmers and large-scale enterprises in China in adapting to the stresses caused by climate change and air pollution, illuminating the ongoing transformation within the agricultural system. It was noted that large-scale enterprises often have more resources and access to advanced technologies, making it easier for them to implement adaptive measures and mitigate the impacts of environmental changes. In contrast, smallholder farmers, who may lack such resources and technology, often find it more challenging to respond effectively to these stresses. This disparity underscores the need for tailored strategies that address the specific needs and capabilities of different types of agricultural producers in the face of climate change and pollution.

4 Conclusion

The participants of the international workshop discussed diverse aspects related to climate change and air pollution impacts on agroecosystems and potential adaptation options, and the multi-disciplinary insights that are shared here will be useful to the broader research community.

Understanding damage and trends could also play an important role in establishing AQGs for policy formulation, such as emission reduction policy. Most of the participants focused on air pollution impacts (alone or in combination with climate factors), and thus the discussions mainly concerned air pollution, and primarily ozone pollution. Regarding impacts, much progress has been noted, but considerable uncertainties about air pollution impacts remain, consensus about key practices is lacking, and transfer of research outcomes to policy applications remains poor. Adaptation remains less studied and understood and, despite being promising, much needs to be done to achieve adaptation. Finally, although participants came from 6 countries, there was no participation from Africa, America, and Australia/Oceania, as well as from the southeast Asia. This limitation should be overcome in the near future for a more inclusive workshop and more representative geographic coverage, but inceptives are warranted to facilitate participation from ecomonically disadvantegous areas.

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Statements & Declarations

Ethical Approval

Not applicable.

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Authors contributions

Z. Feng, E. Agathokleous, Y. Xu: designed the activity.

E. Agathokleous, L. Emberson, J. Pei, K. Kobayashi: Writing-original draft.

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Competing Interests

The authors declare no competing interests.