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More concerns about atmospheric methane removal efforts

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1 Introduction

The National Oceanic and Atmospheric Administration reported record-high global atmospheric carbon dioxide levels (419.3 ppm) in 2023, alongside atmospheric methane levels (1922.6 ppb) now over 160% above pre-industrial levels.[1] The World Meteorological Organization predicts 2024 could surpass 2023 as the warmest year on record, with more frequent and severe extreme weather events.[2] Meeting the Paris Climate goal of limiting global warming to well below 2°C—or ideally 1.5°C—above pre-industrial levels is becoming increasingly difficult.

To address these challenges, efforts are expanding beyond reducing greenhouse gas emissions. While carbon dioxide removal (CDR) technologies have been the focus, attention is now turning to atmospheric methane removal (AMR).[3] While ARM technologies promise a number of benefits, few concerns have been raised about them.[4] This article identifies and lists several new and important, ethical, social, and governance-related concerns about AMR, which have been overlooked in existing literature. As they reveal, greater scrutiny of AMR is urgently needed to ensure that future research and its implementation, if pursued, is both effective and ethically sound.

The article is structured in five parts: first, a discussion of why AMR is being proposed alongside mitigation and CDR efforts, including its potential benefits; second, a review of the concerns about AMR that have appeared in literature to date; third, the presentation of several new, important, additional concerns that have been missed; and finally, a summary and concluding remarks.

2 Some benefits

Although atmospheric methane is less abundant than carbon dioxide, its significantly higher global warming potential (GWP) makes it a major contributor to climate change, accounting for about 0.5°C of the 1.1°C warming above pre-industrial levels.[5] Due to its high

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1 See National Oceanic and Administration (2024).

2 See World Meteorological OrganizationWorld Meteorological (2024).

3 See, for example, Abernethy and Jackson (2024), Abernethy et al. (2023), Abernethy et al. (2021), Boucher and Folberth (2010), Edwards et al. (2024), Gaucher et al. (2024), Hickey and Allen (2024), Jackson et al. (2021), Jackson et al. (2019), Ming et al. (2022), Mundra and Lockley (2024), Nisbet-Jones et al. (2021), de Richter et al. (2017), Sawyer et al. (2022), Smith and Mathison (2024), and Wang and He (2023).

4 See the references listed in the previous footnote.

5 See, for example, Harmsen et al. (2020), Ocko et al. (2018), and Solomon et al. (2007).

GWP, removing methane could have a substantial climate impact, potentially slowing global warming significantly over the next few decades.[6] This could be critical in avoiding irreversible climate tipping points, such as Arctic permafrost melting, which could release vast amounts of methane and carbon dioxide into the atmosphere.[7]

Reducing methane emissions could also "buy time" for adaptation, mitigation, and the deployment of carbon dioxide removal (CDR) technologies. Importantly, a small quantity of methane removal can achieve notable temperature reductions; for example, removing 300 Mt of CH_4 (equivalent to 25.8 billion tons of CO_2 over 20 years) could lower warming by 0.21 – 0.22°C by 2050, making it economically advantageous compared to CO_2 removal.[8]

Methane removal is particularly appealing for sources that are difficult or inappropriate to mitigate, such as scattered agricultural emissions (e.g., rice paddies and ruminants) and natural emissions from wetlands and permafrost (Nisbet-Jones et al., 2021). Additionally, mitigation efforts like altering rice farming practices sometimes increase nitrous oxide (N_2O) emissions, another potent greenhouse gas. Atmospheric methane removal (AMR) technologies could address these emissions and remain useful even after international climate goals are met.[9]

Beyond reducing warming, AMR could improve air quality by lowering tropospheric ozone concentrations, which contribute to respiratory illnesses causing around one million premature deaths annually.[10] A 1 ppb reduction in ozone could prevent an estimated 50,000 premature deaths per year and improve crop yields and vegetation productivity.[11]

Unlike CDR technologies, which require storing and managing captured carbon, methane can be removed by oxidizing it to CO_2, a thermodynamically favorable process [$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ ($\Delta H_r = -803$ kJ mol^{-1})].[12] While this generates additional CO_2, its significantly lower GWP results in a net temperature reduction (Jackson et al., 2019). Furthermore, AMR processes could potentially target other greenhouse gases, such as N_2O, expanding their environmental benefits.[13]

3 Some concerns

As interest in AMR grows, several concerns have been raised. This sections lists and describes the concerns that have appeared in the AMR literature to date.

Methane's low atmospheric concentration and stable chemical structure make it challenging to capture, particularly in open-air settings far from point sources.[14] The energy and resources required for its removal may be prohibitively costly, given the vast amounts of air that would need processing.[15] These challenges impact the technical feasibility, economics, and scalability of AMR technologies.[16] With limited resources, decisions must be made about their prioritization. Additionally, like other negative emissions technologies, AMR's commercial viability may depend on public funding, policy support, or inclusion in greenhouse gas pricing schemes, as private sector incentives are often insufficient (Jackson et al., 2021, p.11).[17]

Environmental impacts are another major concern, with potential effects on temperature, air quality, air and ocean chemistry, and ozone cited frequently.[18]

Public perception also poses a challenge, as negative responses could hinder research, development, and deployment of AMR technologies.[19]

4 Some additional concerns

This section identifies and lists several new and important, ethical, social, and governance-related concerns about AMR that have been overlooked in existing literature. They highlight that greater scrutiny of AMR is urgently needed.

The first concern is the side-effects of AMR technologies. While this concern is (roughly) noted in the literature, as the previous section acknowledged, it is worth elaborating a little bit more on it here. While their primary aim is to remove methane from the atmosphere, each technology comes with its own unique consequences. None can perfectly restore the climate to a previous state, nor can they replicate the effects of methane never

6 See, for example, Ocko et al. (2021), Harmsen et al. (2020), Collins et al. (2018), Alvarez et al. (2012), and Rogelj et al. (2015).

7 See, for example, Lee et al. (2023), p.5.

8 See, Jackson et al. (2019) and Wang and He (2023), Abernethy et al. (2021), and Ocko et al. (2021).

9 See, for example, Abernethy et al. (2021), Nisbet-Jones et al. (2021), and Warszawski et al. (2021).

10 See, for example, Abernethy et al. (2023), p.3, Jackson et al. (2021), p.10, Ming et al. (2022), p.6, Collins et al. (2018), Fiore et al. (2008), and Shindell et al. (2012), and Staniaszek et al. (2022).

11 See, for example, Abernethy et al. (2021), p.2, Collins et al. (2018), Jackson et al. (2021), p.9–10, (Malley et al., 2017; West et al., 2012), and Shindell et al. (2012).

12 See, for example, Jackson et al. (2021) and Jackson et al. (2019).

13 See, for example, Jackson et al. (2021), p.11 and Jackson et al. (2019).

14 Most proposed AMR methods target methane in the gas phase, either through catalytic surfaces (e.g., in engineered reactors) or via atmospheric oxidants like hydroxyl radicals or iron-salt aerosols. These approaches face significant kinetic and thermodynamic challenges due to methane's low reactivity, which complicates its oxidation under ambient conditions. See Ming et al. (2022) for a comparative overview of such mechanisms. See also Jackson et al. (2021), Jackson et al. (2019), Nisbet-Jones et al. (2021), and Wang and He (2023).

15 See, for example, Jackson et al. (2021), p.11, Lackner (2020), Ming et al. (2022), p.6, Nisbet-Jones et al. (2021), and Wang and He (2023), p.410.

16 Nisbet-Jones et al. (2021) and Wang and He (2023), p.411.

17 See also Bui et al. (2018), Durmaz (2018), and Shindell et al. (2017).

18 See, for example, Abernethy et al. (2021), Jackson et al. (2021), Nisbet-Jones et al. (2021), Ming et al. (2022), and Wang and He (2023).

19 See, for example, Jackson et al. (2021) and Wang and He (2023).

having been emitted. For instance, oxidizing methane results in carbon dioxide, which adds to the existing carbon load. These side-effects raise questions about their overall impact on humans, animals, and ecosystems, and whether they could inadvertently cause harms as severe as the problems they aim to solve. For example, keeping global mean temperatures under 1.5°C could cause side effects that are as bad as those in a world that is 2°C warmer—such as through environmental damage caused by changes to air chemistry through AMR.

Another concern arises from the distribution of AMR's impacts, which will create "winners" and "losers." The effects of AMR will vary across regions and communities, benefiting some while harming others. Vulnerable populations, future generations, and non-human species are particularly at risk, as they will bear the consequences without having a say (or likely having a say) in decision-making. Ensuring fair participation in decisions—such as where and how AMR is deployed—is critical. Questions also arise about compensating those burdened by its impacts and ensuring equitable distribution of risks and benefits. Of notable concern here are those who are already being harmed by anthropogenic climate change but that have not contributed to the problem in any meaningful sense, and, again, vulnerable communities, non-human life forms, and future generations. It will also be important to bear in mind the historical responsibilities and capabilities of various groups to determine how, if at all, that should be incorporated into decision making, and into the distribution of burdens and benefits that come with AMR research, its deployment, and the appropriateness of it as a response relative to other non-AMR options. Furthermore, there is a risk of AMR being used for political or military advantage, with groups acting unilaterally to prioritize their own interests. Also, since it is likely that different groups will prefer different climates, it seems as though challenges will naturally arise about what climate settings should be set to at local, regional, and global levels—if, in fact, the idea of designer climates should be entertained at all. How should these preferences and differences be managed?

A third issue is that AMR might discourage mitigation and adaptation efforts. Roughly, the concern is that the prospect of possessing a technical solution that prevents or remedies catastrophic climate change might encourage risky behaviour, or influence, or worse, mask, the willingness of parties to engage in mitigation and adaptation. It may even encourage the explicit, deliberate obstruction of mitigation and adaptation projects. This is especially dangerous in light of climate tipping points, where delays could render even ambitious AMR plans ineffective.

A related but distinct worry is the moral corruption that AMR could foster, particularly among affluent, industrialized nations.[20] Faced with the immense complexity of climate change, it may be easier for some to embrace AMR as a way to maintain current lifestyles rather than pursuing more transformative, and potentially just, solutions. Here the idea is that the prospect of developing and utilising AMR at scales corrupts our moral reasoning, and undermines moral clarity and responsibility.

A fifth worry is the hubris inherent in AMR. History is filled with examples of environmental harm caused by human attempts to control nature, and AMR could repeat these mistakes. Confidence in AMR's success may reflect arrogance rather than a cautious, humble approach, perpetuating attitudes that have historically led to environmental degradation. In fact, it may even make us culpably arrogant.

A sixth worry concerns the governance of AMR research and its deployment. Here are just a few of the many questions that stem from this concern: since some AMR technologies work locally (e.g., biological methanotrophic technologies), while others work in international spaces (e.g., photochemical oxidation via the release of iron-salt aerosols), what kinds of principles ought govern AMR research and its deployment at local, regional, and international levels? What justifies these principles? What bodies ought to govern AMR research and its deployment at these levels? And what justifies their authority? Without clear frameworks, AMR efforts risk being disorganized, inequitable, and politically and legally troublesome.

The boundary between research and deployment is another concern. Large-scale tests of AMR technologies may effectively amount to their deployment, blurring lines of oversight and governance. This makes careful management of research activities critical to avoid unintended consequences.

An eighth worry concerns path dependency. Once resources and effort are invested in AMR, it becomes harder to pivot away, even if better solutions arise. Institutional and human structures supporting AMR may create pressure to deploy it regardless of caution. This lock-in effect could limit exploration of alternative strategies and exacerbate the risk of crossing climate tipping points.

A ninth set of concerns surround ending the use of AMR technologies. If emissions are not sufficiently reduced, stopping AMR could worsen climate conditions. Even with emission reductions, knowing when to end AMR use is complicated by the delayed responses of climate systems, such as the ocean's heat capacity, which could sustain harmful impacts even after methane levels drop.

A 10th set of worries concern the sustainability of AMR efforts. Many AMR technologies require significant energy and resources, and their effectiveness depends on a transition to renewable energy and sustainable practices. Without these, AMR could exacerbate rather than mitigate climate problems, dispelling the notion that geoengineering is a viable "Plan B" in the absence of robust mitigation efforts.[21] What's more, given the fraught history of mitigation efforts, one might be pessimistic to think that the development and deployment of AMR technologies will fair any better given that they seem to depend so heavily on effective mitigation schemes. As these points hope to make clear, AMR cannot be viewed as an independent course of action. Rather, AMR is better viewed as a response that is only possible when utilised in conjunction with good mitigation efforts. It is not merely complementary, as some [e.g., Jackson et al. (2019), p.437] have suggested. It is, at best, an additional, secondary tool that can be utilised to achieve international climate goals.

Finally, public perception of AMR could significantly shape its development and deployment. This kind of concern has been gestured to in the literature, as noted in the previous section, but

20 This worry, within the SRM context, has been noted by Gardiner (2010).

21 For a good and extensive discussion, and criticism of framing geoengineering as a "Plan B" see Fragniere and Gardiner (2016).

it is worth elaborating on it in different, new ways here. Opposition might arise not only from the concerns outlined here but also from other sources. For example, there is data to suggest that some people are wary of geoengineering for entirely ideological reasons, while other people's perceptions of it are dependent on how it is framed, whether such efforts are endorsed by their preferred political party or authority figure, and by the levels of trust they have in the actors and processes involved.[22] As the Royal Society (2018), p.86 has noted, if people feel that solutions are being "imposed" on them from above, or that solutions are being primarily driven by a profit motive, then, this too leads to negative perceptions. As the Royal Society (2018), p.86 also suggests, public reactions will also be driven by the perceived compatibility of [geoengineering] techniques with people's visions of how the world "should" look in the future. So then, the general worry here is that public perceptions of AMR technologies may shape the form and scale of their development and deployment independently (or somewhat independently) of facts and expectations about the technologies and their consequences.

5 Conclusion

This article collated and described the potential benefits and concerns arising from AMR that have appeared in the literature to date. It also added many new concerns to the list and implicitly, *ipso facto*, suggested that current discussions of AMR concerns are impoverished and in urgent need of updating. While it is not the intention of this article to pass judgment on the permissibility or suitability of researching, developing, and deploying AMR technologies, it is hoped that by collecting concerns, and flagging several new ones, it encourages others to think more carefully about them at all of these stages. It is also hoped that this article encourages others to identify other concerns, since the collection presented here is not assumed to be exhaustive. Finally, this article also hopes to encourage others to establish how troubling these considerations are for the future of AMR, and to make determinations about the place of AMR in local, regional, and international responses to climate change.

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