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Deep mitigation of CO_2 and non-CO_2 greenhouse gases toward 1.5 °C and 2 °C futures

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Stabilizing climate change well below 2 °C and towards 1.5 °C requires comprehensive mitigation of all greenhouse gases (GHG), including both CO_2 and non-CO_2 GHG emissions. Here we incorporate the latest global non-CO_2 emissions and mitigation data into a state-of-the-art integrated assessment model GCAM and examine 90 mitigation scenarios pairing different levels of CO_2 and non-CO_2 GHG abatement pathways. We estimate that when non-CO_2 mitigation contributions are not fully implemented, the timing of net-zero CO_2 must occur about two decades earlier. Conversely, comprehensive GHG abatement that fully integrates non-CO_2 mitigation measures in addition to a net-zero CO_2 commitment can help achieve 1.5 °C stabilization. While decarbonization-driven fuel switching mainly reduces non-CO_2 emissions from fuel extraction and end use, targeted non-CO_2 mitigation measures can significantly reduce fluorinated gas emissions from industrial processes and cooling sectors. Our integrated modeling provides direct insights in how system-wide all GHG mitigation can affect the timing of net-zero CO_2 for 1.5 °C and 2 °C climate change scenarios.

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The Paris Agreement aims to strengthen the global response to climate change mitigation by keeping a global temperature rise this century well below 2 °C above pre-industrial levels and "pursue efforts to limit the temperature increase to 1.5 °C" (Article 2). Achieving these goals implies a tight limit on cumulative greenhouse gas (GHGs) emissions, which should "reach global peaking of GHG emissions as soon as possible", followed by rapid reductions "to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century" (Article 4). The emission trajectories are consistent with the recent net-zero emissions pledges, including China's 2060 net-zero pledge[1], EU's 2050 climate neutrality pledge[2], and California's 2045 carbon neutrality pledge[3]. Recent studies have emphasized the importance and urgency of reaching net-zero CO_2 emissions to achieve stringent climate targets[4–7].

Modeling scenarios avoiding global warming >1.5 °C, as stipulated in the Paris Agreement, requires combined mitigation of CO_2 and non-CO_2 GHG emissions[8,9]. Non-CO_2 GHGs accounted for about one quarter of total CO_2-eq emissions in 2015[10]. Thus, cuts in their emissions could potentially lessen future climate forcing[11]. The present literature indicates that the ultimate level of surface temperature warming depends both on driving CO_2 emissions to zero but also on the residual level of non-CO_2 emissions[5,9,12–20]. Although these studies have in some way accounted for the climate benefits for non-CO_2 mitigation, different representations and non-CO_2 mitigation options, as well as the economic structure of the models, can lead to a fairly large variation in the reported remaining carbon budget or net-zero commitment years that aim to achieve the same 1.5 °C or 2 °C goals[21–23].

A comprehensive evaluation of the climate benefits for system-wide non-CO_2 GHG mitigation is challenging due to the difficulties of identifying and parameterizing the numerous possible mitigation options for different gases emitted from various sectors. In addition, some CO_2 mitigation and non-CO_2 mitigation actions are intertwined across sectors[24]. For example, phasing out fossil fuels can both reduce direct CO_2 emissions from fuel combustion and upstream methane emissions from fossil fuel extraction. Furthermore, the techno-economic mitigation potential for each source and mitigation technology is also evolving, affected by technology innovation. These dynamics can further complicate the comprehensive non-CO_2 representation in long-term mitigation analysis. Therefore, a robust analysis of all GHG mitigation must combine sectoral and regional detail of mitigation data with an integrated representation of the entire economic system, including energy, industrial processes, buildings, transport, urban process, and agriculture sectors.

Here we combine the latest region-, sector-, and year-specific EPA non-CO_2 abatement datasets with the Global Change Analysis Model (GCAM)[25] to explore how CO_2 and non-CO_2 GHG mitigation pathways jointly affect the ultimate level of temperature change. Specifically, we investigate to which degree a comprehensive non-CO_2 mitigation scheme covering all GHGs (CH_4, N_2O, HFCs, PFCs, and SF_6) (Supplementary Table 1) and all sectors (energy, industrial processes, buildings, transport, urban process, and agriculture) (Supplementary Table 2) can affect the timing of net-zero CO_2 required to achieve 1.5 °C and 2 °C targets. We construct 90 mitigation scenarios pairing 30 CO_2 abatement pathways with three non-CO_2 abatement levels to evaluate the mitigation potential of each non-CO_2 GHG to the overall stabilization efforts (Supplementary Fig. 1) through both reduced fossil fuel use and adoption of specific non-CO_2 abatement measures endogenously driven by societal carbon prices. Our research aims at better disentangling and assessing the interactions between non-CO_2 GHG mitigation and net-zero CO_2

commitments toward 1.5 °C and 2 °C goals and is an extension of the conceptual framework in ref. [22].

Results

Effects of non-CO_2 abatement on climate response. We developed 90 mitigation scenarios by combining 30 alternative years in which global net-zero CO_2 emission levels are achieved with three levels of non-CO_2 abatement. The CO_2 abatement pathways are split into two levels of negative CO_2 assumptions. The 2 °C pathways linearly reach net-zero CO_2 emissions between 2030 and 2100 in 5-year increments, followed by zero CO_2 emissions afterwards, and the 1.5 °C pathways linearly reach −8 $GtCO_2$ yr^{-1} CO_2 emissions between 2030 and 2100 in 5-year increments (so their net-zero CO_2 years are slightly earlier), followed by −8 $GtCO_2$ yr^{-1} CO_2 emissions afterwards. The endpoints of 0 and −8 $GtCO_2$ yr^{-1} CO_2 are generally on the conservative side of negative CO_2 emissions required for 2 °C and 1.5 °C pathways[26], respectively. For non-CO_2 GHG mitigation, CO_2 abatement only assumes the same non-CO_2 emissions as the Reference scenario while reducing CO_2 emissions alone, which is a counterfactual scenario aiming at isolating the climate impact of CO_2 mitigation alone. CO_2-driven GHG abatement includes CO_2 abatement and the non-CO_2 emission reductions associated with fuel switching and demand reduction driven by CO_2 abatement. Comprehensive GHG abatement additionally includes specific non-CO_2 abatement measures driven by increased societal carbon prices. Figure 1 illustrates how non-CO_2 abatement levels are combined with carbon budgets to jointly determine the end-of-century temperature changes.

The temperature increase (°C) since pre-industrial times is linearly associated with the remaining carbon budget[27], consistent with literature[22], which is determined by peak cumulative CO_2 emissions and in this analysis, the timing of the year in which net-zero CO_2 emissions are achieved. The transient climate response to cumulative emissions of CO_2 are similar across different non-CO_2 abatement levels, falling within the IPCC reported range of 0.2–0.7 °C per 1000 Gt CO_2 (66% probability)[27]. However, the ultimate level of temperature change is jointly affected by both the timing of net-zero CO_2 and the stringency of non-CO_2 GHG abatement. In Comprehensive GHG abatement scenarios, the timing of net-zero CO_2 could be two decades later to achieve the same temperature change levels, compared with CO_2-driven GHG abatement that only considers emission reductions from fuel switching and service demand reduction (Table 1).

Among all 90 mitigation scenarios explored, the same 1.5 °C and 2 °C targets can be achieved with different combinations of net-zero CO_2 commitment and non-CO_2 abatement levels (thick lines in Fig. 2). Per 2007 IPCC Fourth Assessment Report (AR4)[28], Global Warming Potentials (GWPs) based on a timeframe of 100 years (GWP-100) are used to estimate CO_2-eq emissions for non-CO_2 GHGs. In Reference, global CO_2 and non-CO_2 GHG emissions continue to grow throughout the century, reaching 69 Gt CO_2-eq yr^{-1} and 25 Gt CO_2-eq yr^{-1}, respectively, driven by increasing population and GDP. The mean temperature increases by 3.8 °C by 2100. In 1.5 °C scenarios (Fig. 2a), the CO_2 abatement only is infeasible, and CO_2-driven GHG abatement requires net-zero CO_2 emissions to be reached by ~2032 (and −8 $GtCO_2$ yr^{-1} in 2035). The timing of reaching net-zero CO_2 here emphasizes the urgency of transitioning to net-zero emissions for the 1.5 °C target[29]. In the CO_2-driven GHG abatement scenario, non-CO_2 emissions decrease by 28% relative to Reference, reaching 18 Gt CO_2-eq yr^{-1} in 2100. However, non-CO_2 emissions still show a growing trend in the CO_2-driven GHG abatement scenario, suggesting a significant amount of residual
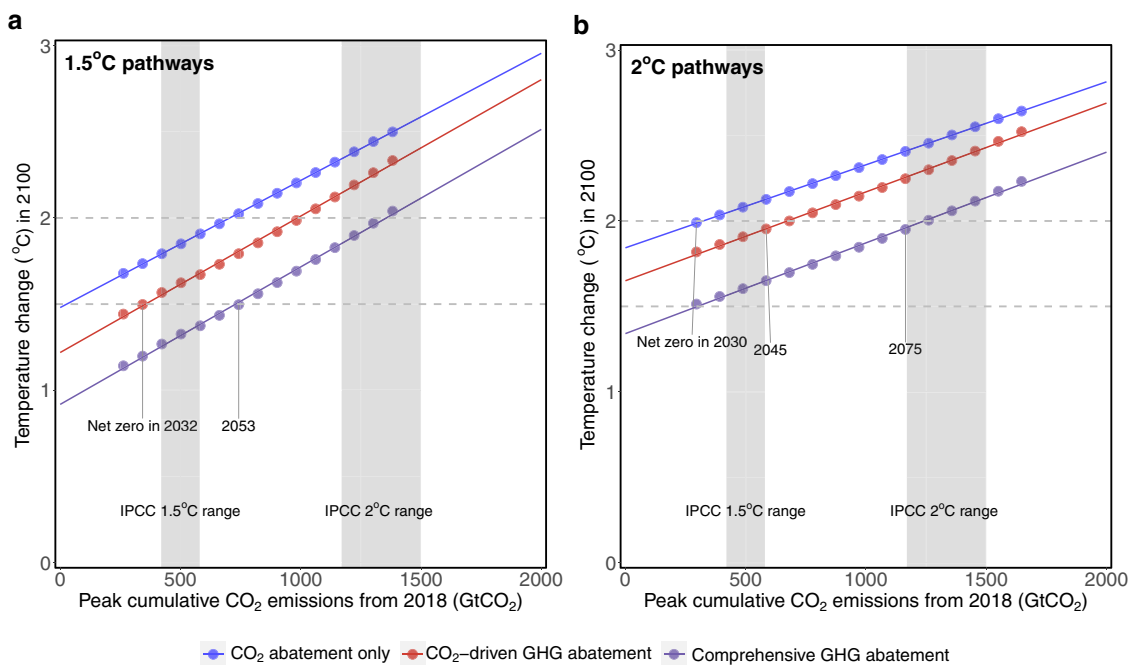
Fig. 1 Transient climate response to cumulative emissions of CO_2 for different non-CO_2 abatement levels. a 1.5 °C pathways and (**b**) 2 °C pathways, assume CO_2 emissions linearly reduce to −8 and 0 $GtCO_2$ yr^{-1} and stay constant, correspondingly. CO_2 abatement only assumes the same non-CO_2 emissions as the Reference scenario while reducing CO_2 emissions alone; CO_2-driven GHG abatement includes CO_2 abatement and the non-CO_2 abatement associated with fuel switching and demand reduction driven by CO_2 abatement; Comprehensive GHG abatement additionally considers various non-CO_2 abatement options based on their technical feasibility and cost-effectiveness. For (**a**) net-zero years are interpolated based on the linear CO_2 emission trajectories.

Table 1 Net-zero CO_2 emission years necessary to achieve 1.5 °C and 2 °C future.		
Mitigation pathway	**1.5 °C**	**2 °C**
CO_2 abatement only	Unsolvable	2030
CO_2-driven GHG abatement	2032	2045
Comprehensive GHG abatement	2053	2075

In 1.5 °C pathways, CO_2 emissions linearly reduce to −8 $GtCO_2$ yr^{-1} and stay constant. In 2 °C pathways, CO_2 emissions linearly reduce to 0 $GtCO_2$ yr^{-1} and stay constant.

non-CO_2 emissions when reductions are driven solely by CO_2 mitigation actions. In the comprehensive GHG mitigation scenario that further accounts for non-CO_2 abatement measures, non-CO_2 emissions show a decreasing trend, reducing to 9.8 Gt CO_2-eq yr^{-1} in 2100. As a result, the 1.5 °C target is viable by reaching net-zero CO_2 in ~2053 (and −8 $GtCO_2$ yr^{-1} in 2060). Figure 2b shows the same results for the 2 °C scenarios, in which CO_2 abatement only and CO_2-driven abatement scenarios would need to reach net-zero CO_2 by 2030 and 2045, respectively. In contrast, Comprehensive GHG abatement allows net-zero CO_2 to be achieved by 2070 without jeopardizing the 2 °C goal. Notably, net negative CO_2 emissions are not required in 2 °C scenarios.

We further conducted three sets of sensitivity analysis for the 1.5 °C scenario with comprehensive GHG mitigation (red line in Fig. 2a), additionally exploring three alternative technology change assumptions (Supplementary Fig. 2), five shared socioeconomic pathways (SSPs) (Supplementary Fig. 3), and four alternative GWP assumptions (Supplementary Figs. 4–6). While the 2019 EPA mitigation report[10] estimates used here represent non-CO_2 mitigation measures and technology innovation to 2050, assumptions of technology change after 2050 have limited

impact on the end-of-century forcing and temperature changes (Supplementary Fig. 2). Even without technology changes after 2050, our comprehensive GHG mitigation scenario can still achieve the 1.5 °C target. However, the underlying socioeconomic pathways have a fairly significant impact (Supplementary Fig. 3), and some SSP scenarios would fail to achieve the 1.5 °C target, while all SSP scenarios can still achieve the well-below 2 °C target.

Non-CO_2 emission abatement actions. Future non-CO_2 reductions are determined by the level of CO_2 mitigation as well as non-CO_2 abatement measures. Here we focus on the CO_2 mitigation pathways reaching net-zero by 2053, which achieves the 1.5 °C target in Comprehensive GHG abatement (Fig. 3). Without additional non-CO_2 abatement measures, reductions in non-CO_2 GHG emissions are achieved by cuts in fuel extraction and other energy sector activity due to the lower reliance on fossil fuels driven by CO_2 mitigation (Supplementary Fig. 7). However, cooling-related HFC emissions and industrial process emissions (PFCs and SF_6) are barely affected by fuel switching. Agriculture CH_4 and N_2O emissions from livestock population, rice cultivation, and fertilizer application, are also slightly reduced from the Reference (Supplementary Fig. 8) due to the overall demand reduction from decarbonization actions, which increases the overall prices of services and goods.

When additionally including system-wide non-CO_2 mitigation measures in Comprehensive GHG abatement, industrial and cooling-related HFCs emissions are heavily reduced (Fig. 3a–b). In 2050, 68% of HFCs are reduced from the Reference, whereas only 6% are reduced in the CO_2-driven GHG abatement scenario (Table 2). In 2100, 92% of HFCs are reduced from the Reference, leading to an 85% reduction in HFC forcings. HFCs are mainly used as alternatives to several classes of ozone-depleting substances required to be phased out under the Montreal Protocol. Among different HFC species, HFC134a, HFC143a,
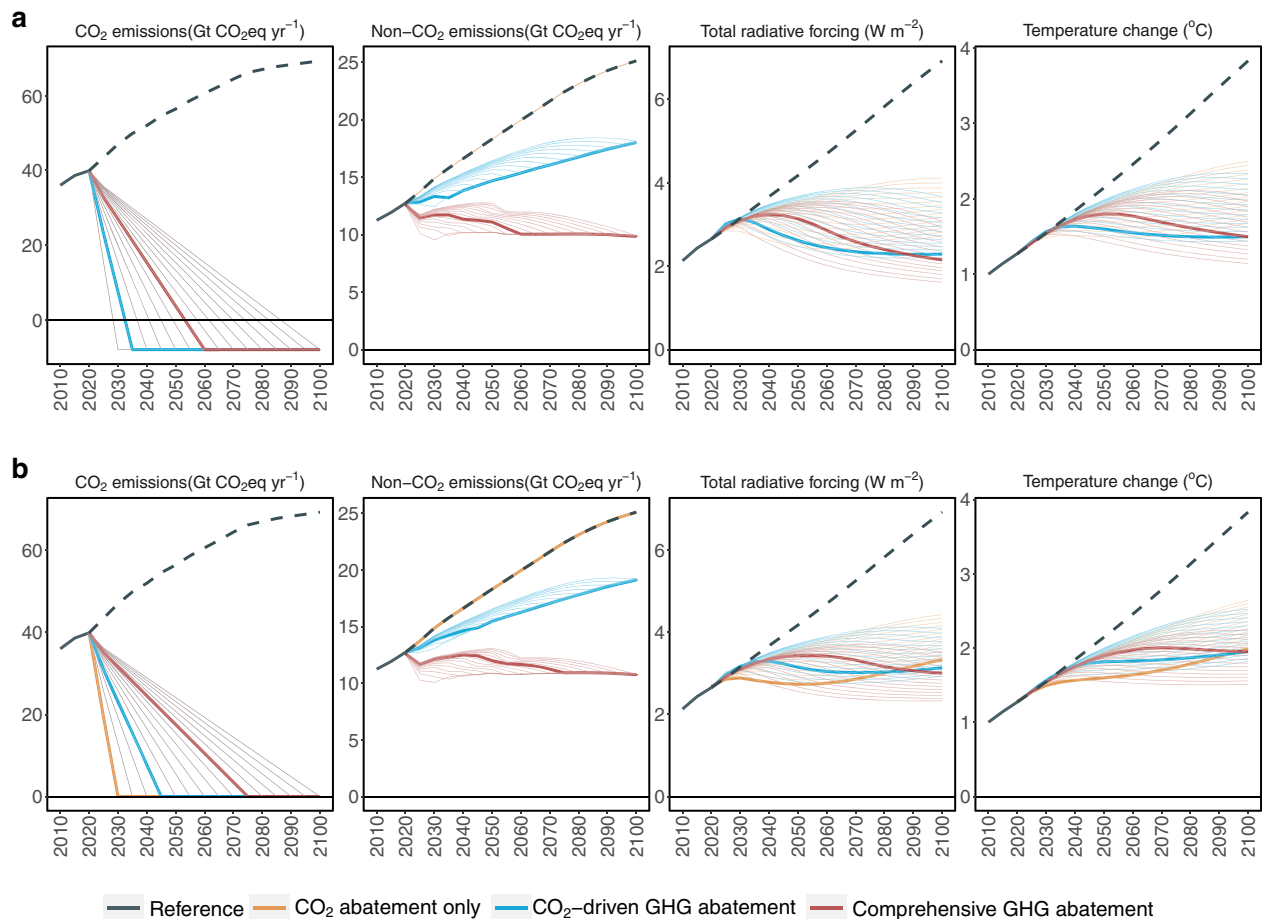
Fig. 2 Global emission and climate results. a 1.5 °C and (**b**) 2 °C scenarios, including total CO_2 emissions from fossil fuels and land-use changes, total non-CO_2 GHG (CH_4, N_2O, HFCs, P.F.C.s, and SF_6) emissions, total radiative forcing, and global mean surface temperature change. Reference assumes no GHG mitigation. CO_2 abatement only cannot achieve the 1.5 °C target under all modeled 1.5 °C pathways but achieves the 2 °C target if reaching net-zero CO_2 by 2030 under 2 °C pathways; CO_2-driven GHG abatement achieves the 1.5 °C target if reaching net-zero CO_2 by 2032 under 1.5 °C pathways or achieves the 2 °C target if reaching net-zero CO_2 by 2045 under 2 °C pathways; Comprehensive GHG abatement achieves the 1.5 °C target if reaching net-zero CO_2 by 2053 under 1.5 °C pathways or achieves the 2 °C target if reaching net-zero CO_2 by 2075 under 2 °C pathways. The faint lines are colored based on non-CO_2 mitigation pathways, representing scenarios with CO_2 emission constraints reaching net-zero in alternative years. Non-CO_2 GHG emissions were aggregated with GWP-100 from ref. [28].

and HFC125 accounts for over 90% of the total F-gas emissions in both Reference and CO_2-driven GHG abatement scenarios, while they are all effectively reduced in Comprehensive GHG abatement (Fig. 3c), accounting for a large share of total forcing reductions in Comprehensive GHG abatement (Supplementary Fig. 9). These HFCs are used in various industrial and building applications, including refrigeration and air-conditioning equipment, aerosols, solvent cleaning, fire extinguishing, foam production, and sterilization. These sources have considerable mitigation potential, such as leak repair for existing requirements, refrigerant recovery at disposal for existing refrigeration with AC equipment, and the adoption of other non-GHG cooling agents to replace current HFCs[10]. The Kigali Amendment to the Montreal Protocol requires global HFC emissions to be heavily reduced by 2050 relative to the present levels[30]. In Comprehensive GHG abatement, most regions continue to reduce their HFCs after 2050, and the average HFC reductions across all GCAM regions achieve 90% by 2065 relative to their present levels.

SF_6 emissions are even higher in the CO_2-driven GHG abatement scenario than in Reference due to greater electrification. SF_6 is mainly used in electrical transmission and distribution systems as an insulating medium. In Comprehensive GHG abatement, SF_6 emission decreases by 68% in 2100 and its climate

forcing decreases 48%. Note that SF_6 has an extremely long lifetime of 800–3200 years, so early SF_6 reduction can result in substantial long-term climate benefits even beyond the current century. Similarly, PFCs also have very high GWPs and can be much more effectively reduced in Comprehensive GHG abatement.

While non-CO_2 abatement measures effectively reduce cooling and industrial process emissions, agriculture emissions are barely affected by these measures because the cost-effective mitigation options are comparatively limited at current estimation. Agriculture is the largest non-CO_2 emission source, contributing to half of the total non-CO_2 emissions throughout the century. A previous work[31] suggested that the economic potential of mitigation measures in the livestock sector is less than 10% of what is technically possible. In addition, agriculture CH_4 emissions mostly from enteric fermentation are projected to constitute an increasingly larger share of total anthropogenic CH_4 emissions even under direct CH_4 mitigation scenarios[32]. The residual emissions from these sources would ultimately limit the ability to further reducing non-CO_2 emissions and achieving additional climate benefits.

Spatially, Comprehensive GHG abatement achieves greater non-CO_2 reductions in 2050 across all regions, especially in
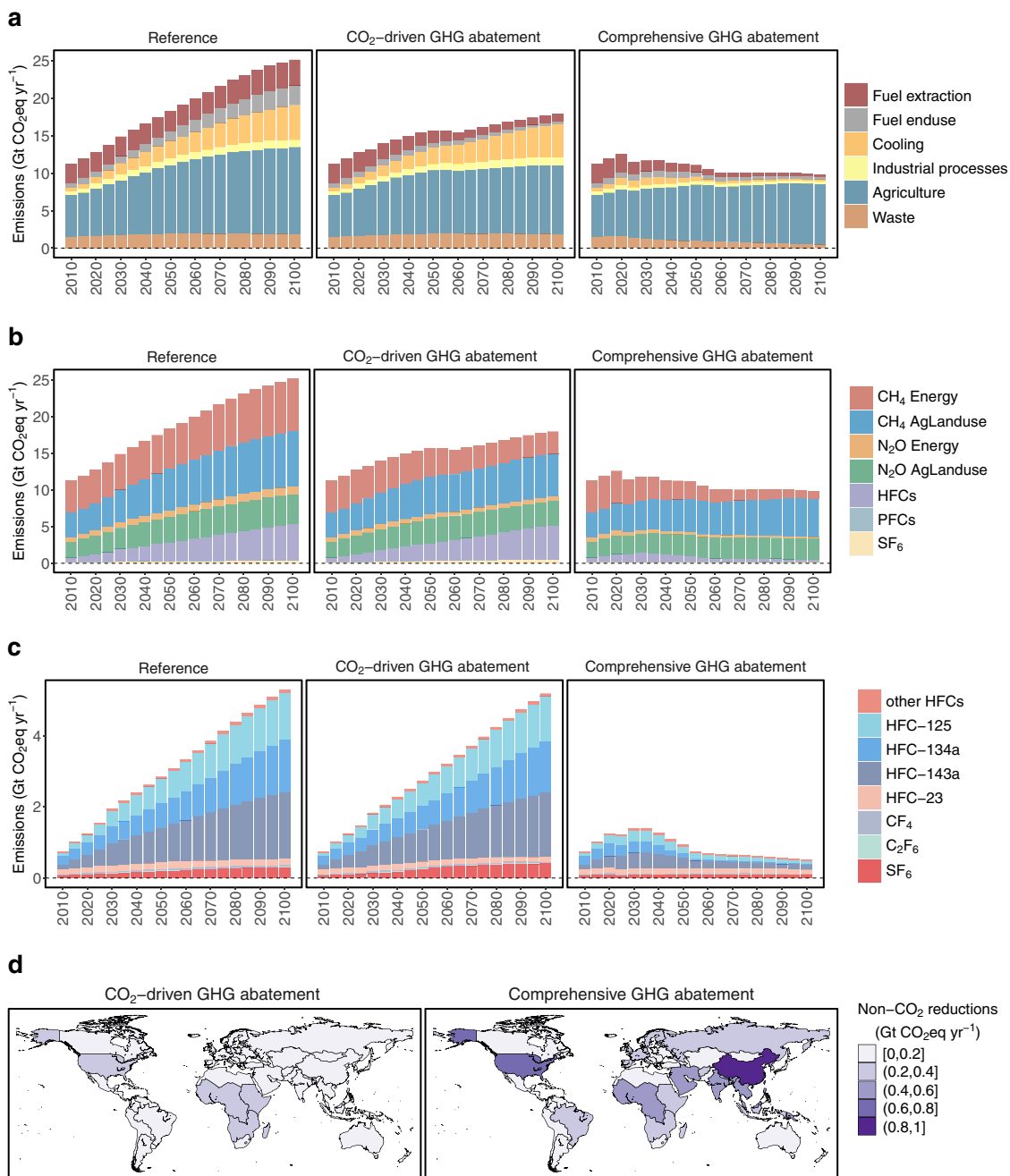
Fig. 3 Global non-CO$_2$ GHG emissions. Emissions by (**a**) sector and (**b**) species, (**c**) F-gas emissions by species, and (**d**) reductions in 2050, when reaching net-zero CO$_2$ emissions by 2053 (and −8 GtCO$_2$ in 2060) for a 1.5 °C scenario. Other HFCs include HFC-32, HFC-43, HFC-152a, HFC-227ea, HFC-236fa, HFC-245fa, and HFC-365mfc. Non-CO$_2$ GHG emissions were aggregated with GWP-100, from ref. [28]. Global maps in this figure are created using an open-source R package. [55] and documented in ref. [56].

China and the U.S. (Fig. 3d). Greater non-CO$_2$ reductions are also achieved in growing economies such as Brazil, South Asia, and Western Africa, where industrial process and cooling demands are projected to increase rapidly (Fig. 3d). Compared with the Reference, HFCs are reduced by over 80% in 2050 for most regions under Comprehensive GHG abatement. In contrast, limited reductions could be achieved purely due to the demand reductions under CO$_2$-driven GHG abatement (Supplementary Fig. 10). Notably, for all regions, CO$_2$-driven GHG abatement results in significant additional SF$_6$ emissions, while such side effects of greater electrification to replace fossil fuels can be turned entirely into net benefits with SF$_6$ abatement measures under Comprehensive GHG abatement. In addition, non-CO$_2$

abatement can also help reduce agriculture CH$_4$ and N$_2$O emissions, especially for the U.S., Central Asia, and Northern Africa, partially offsetting the increased agriculture emissions in these regions due to the high biomass energy production (Supplementary Fig. 7). All trends above are consistent in 2100 (Supplementary Fig. 11), with greater additional benefits achieved in Comprehensive GHG abatement.

Discussion
Scenarios avoiding global warming >1.5 °C and 2 °C require the combined mitigation of CO$_2$ and non-CO$_2$ GHG emissions. Coupling the latest global non-CO$_2$ emission projection and

Table 2 Non-CO$_2$ emission and climate forcing changes in mitigation scenarios relative to Reference in 2050 and 2100 when CO$_2$ emissions reach net-zero by 2053 under 1.5 °C pathway (percentage reductions are shown in parentheses).

Scenario	CH$_4$ Energy	CH$_4$ AgLanduse	N$_2$O Energy	N$_2$O AgLanduse	HFCs	PFCs	SF$_6$
2050 Emission (Gt CO$_2$-eq yr^{-1})							
CO$_2$-driven	−1.58 (−29.3%)	−0.51 (−8.9%)	−0.26 (−31.2%)	−0.19 (−5.3%)	−0.16 (−6.2%)	−0.01 (−15.1%)	0.06 (31.8%)
Comprehensive	−3.09 (−57.2%)	−1.10 (−19.2%)	−0.52 (−61.9%)	−0.59 (−16.8%)	−1.77 (−68.2%)	−0.04 (−53.4%)	−0.10 (−52.6%)
2100 Emission (Gt CO$_2$-eq yr^{-1})							
CO$_2$-driven	−4.11 (−57.8%)	−1.58 (−21.1%)	−0.57 (−52.1%)	−0.80 (−19.4%)	−0.20 (−4.1%)	−0.01 (−16.0%)	0.11 (36.0%)
Comprehensive	−6.10 (−85.8%)	−2.22 (−29.6%)	−0.91 (−83.4%)	−1.26 (−30.7%)	−4.52 (−91.7%)	−0.06 (−79.8%)	−0.20 (−67.9%)
2050 Forcing (W m^{-2})							
CO$_2$-driven	−0.046 (−11.1%)	−0.001 (−0.3%)	−0.007 (−5.3%)	0.000 (0.0%)	−0.007 (−5.3%)	0.000 (−1.7%)	0.000 (6.4%)
Comprehensive	−0.128 (−31.0%)	−0.022 (−10.6%)	−0.020 (−14.3%)	−0.005 (−4.2%)	−0.062 (−46.3%)	−0.001 (−6.4%)	−0.002 (−23.6%)
2100 Forcing (W m^{-2})							
CO$_2$-driven	−0.170 (−32.3%)	−0.034 (−12.5%)	−0.041 (−18.1%)	−0.019 (−10.5%)	−0.018 (−5.4%)	−0.001 (−5.1%)	0.005 (27.0%)
Comprehensive	−0.285 (−54.1%)	−0.067 (−24.9%)	−0.075 (−33.3%)	−0.037 (−20.7%)	−0.287 (−85.0%)	−0.003 (−21.1%)	−0.008 (−47.7%)

Non-CO$_2$ GHG emissions were aggregated with GWP-100 from ref. [28].

mitigation data with a state-of-the-art integrated assessment model, we find that non-CO$_2$ emission reductions associated with decarbonization-driven fuel switching and specific abatement measures can significantly contribute to climate change mitigation and greatly help to ease the burden of CO$_2$ mitigation toward 1.5 °C and 2 °C targets. In particular, CO$_2$ emissions would have to reach net-zero by two decades earlier to achieve the same climate target without specific non-CO$_2$ abatement measures disentangled from major decarbonization actions. While it is critical to reach net-zero CO$_2$ to stabilize global temperature change, our results emphasize that underestimating the role of non-CO$_2$ mitigation measures can lead to substantial bias in lower carbon budgets and premature net-zero CO$_2$ commitment.

Our research highlights the importance of comprehensive GHG abatement that fully accounts for non-CO$_2$ mitigation measures in conjunction with CO$_2$ emissions in deep mitigation scenarios. We incorporate the updated marginal abatement cost (MAC) curves for all major non-CO$_2$ GHG species across economic sectors and global regions, and our year-specific parameterization considers future technological innovation in mitigation measures. In addition to fuel-related CH$_4$ and N$_2$O reductions from fuel switching and demand reduction driven by decarbonization, our results highlight the significant mitigation potential of F-gases from industrial processes and cooling sectors, which can be cost-effectively achieved for all global regions. Furthermore, our results also identify major sources of residual non-CO$_2$ emissions that call for additional technological innovation and structural changes to reduce, following in line with the previous literature[21,33,34]. For example, agriculture non-CO$_2$ emissions are barely affected under mitigation scenarios for most regions because of the relatively limited economic mitigation options available at current cost estimates. Without disruptive technological innovation that can significantly expand the affordable mitigation potential or leverage economic feedback of directly pricing CH$_4$ that can lead to lifestyle changes[21], it will be challenging to reduce non-CO$_2$ emissions from agriculture. Future research in better understanding the technical and economic potential for all GHGs and technological/institutional innovation in further mitigating residual non-CO$_2$ emissions can further contribute to the growing body of literature supporting the transformation needed to achieve ambitious climate stabilization.

The following sources of uncertainty should be noted. First, our 90 mitigation scenarios are examined within the same modeling framework sharing the same socioeconomic pathway, economic structure, and climate modeling assumptions, so the effect of non-CO$_2$ emission reductions can be isolated. To examine the robustness of our findings, we further conducted two sets of sensitivity analyses to demonstrate the impact of alternative socioeconomic pathways and alternative technological change assumptions for non-CO$_2$ abatement (Supplementary Figs. 2-3). For the main 1.5 °C scenario, socioeconomic and technological change assumptions can influence the ultimate level of non-CO$_2$ emissions by up to −34% (SSP1) and +44% (no technological change), respectively.

Second, alternative assumptions in modeling structure, non-CO$_2$ mitigation parameterization, and climate modeling choices that characterize the physical effects of climate forcers, can certainly affect the ultimate temperature changes[21,32,35]. Although other climate forcers such as black carbon, aerosols, and ozone, can also contribute to temperature change[36] and interact with CO$_2$ and non-CO$_2$ GHG forcings through complex atmospheric processes[5,37], their emissions are primarily affected by the level of CO$_2$ mitigation[24] instead of specific non-CO$_2$ GHG mitigation measures. Third, while our climate results are unaffected by the GWP choices (Methods), the GWP assumptions can affect the

relative contributions of different GHG species to the total GHG reductions when presenting. If a longer GWP timeframe were chosen, the long-lived CO_2 emissions would show a greater share of the cumulative GHG reductions in terms of CO_2-equivalent amount (Supplementary Figs. 4–6). Lastly, uncertainty in emission factors, derived from historical emissions, may influence the relative mitigation potential from some sectors and major emitting regions (Fig. 3). For example, several studies suggested a considerable underestimation of U.S. methane emission from oil and gas supply chain in some inventory data compared to ground-based, facility-scale measurements[38,39], due to challenges in quantifying abnormal operating conditions, leakages, and emerging gas production techniques. Similarly, existing inventories provide divergent estimates in China's coal mining methane emissions[40,41], as methane emissions are not necessarily directly related to coal production but can also occur even if coal production is ceased[42]. Given that fossil fuel production is a major source of CH_4 emissions, future work would benefit from more accurate estimation methodologies that better account for operational details and geologic factors of fossil fuel production. Nevertheless, key qualitative insights still hold: Comprehensive GHG abatement that fully incorporates non-CO_2 mitigation measures in addition to a net-zero CO_2 commitment facilitates a more moderate decline in emissions on the pathway to Paris stabilization goals.

The CO_2 mitigation in our study is modeled with an economy-wide carbon price, and increased societal carbon prices also drive non-CO_2 abatement through MAC curves (see Methods). Here we do not attempt to address the question of how likely a uniform, economy-wide carbon price would be applied in the real world[43], but rather focus on to which degree the expected emission changes in all GHGs would collectively shape climate consequences. However, it should be noted that CO_2 abatement often requires large technological shifts and demand reductions, which typically need high mitigation costs[44–47]. Conversely, many non-CO_2 abatement technologies reflected in the MACs do not require radical changes in technologies from a user standpoint, making them potentially easier to widely adopt if appropriate incentives and information are provided. Thus, future work should seek to better understand the barriers and potential of both CO_2 and non-CO_2 reductions to devise more realistic mitigation scenarios to inform scientific modeling and decision-making. With increasing numbers of major economies announcing or indicating ambitious net-zero targets to pursue the path of net-zero emissions targets under the Paris Agreement, it is critical to understand the mitigation potential and specific abatement actions for all greenhouse gases.

Methods

Non-CO_2 GHG data. Our emission data are based on the Community Emissions Data System (CEDS v_2020-09-11), which provides annual historical (1750–2019) anthropogenic chemically reactive gases (CO, CH_4, NH_3, NO_x, SO_2, NMVOCs), carbonaceous aerosols (black carbon—BC, and organic carbon—OC), and CO_2. First published in ref. [48], the latest CEDS (DOI: 0.5281/zenodo.4025316) is updated with more recent inventory data, updated emission factors in selective sectors, and updated country-level emission inventories.

For non-CO_2 GHGs (CH_4, N_2O, HFCs, PFCs, and SF_6), we further harmonize our current CEDS emissions with the 2019 EPA Global Non-CO_2 Greenhouse Gas Emission Projections and Mitigation Potential report[10]. This report provides country-, sector-, and year-specific emissions projections and estimates of mitigation potential for non-CO_2 GHGs through a comprehensive global analysis using a combination of country-reported inventory data supplemented with EPA-estimated calculations consistent with inventory guidelines of the Intergovernmental Panel on Climate Change (IPCC)[27]. Historical emission estimates were incorporated from country-reported data from 1990 to 2015, and emissions were projected through 2050. Here we scaled our non-CO_2 emissions to EPA historical emissions by region, sector, and species from 1990 to 2015, derived emission factors using historical activity data, and then projected future emissions being consistent with EPA's emission projections.

The detailed non-CO_2 GHG mitigation estimates in EPA report[10] employ a bottom-up, engineering cost approach that analyzed the costs of a wide range of mitigation technologies and incorporated them into an economic estimate of MAC curve (Supplementary Fig. 12). MAC curves were estimated by the break-even price at which the present-value benefits and costs for each mitigation option equilibrate. Mitigation potential and cost also account for country differences in industry structures and availability, labor, nonenergy materials, and energy across countries. In addition, MACs incorporate the effects of technology change on mitigation costs, representing cost savings of mitigation measures due to technology learning over time.

For each region and species, mitigation cost and corresponding emission reductions achievable are summarized into source categories covering all sectors (Supplementary Tables 3–5). For example, CH_4 mitigation includes control measures in resource production (coal mining activities, natural gas and oil system, and combustion of fossil fuels and biomass), agriculture (livestock and rice cultivation), and waste management (landfill of solid waste and wastewater). While HFC mitigation mainly happens in industrial processes and cooling sectors, such as electronics manufacturing, the use of substitutes for ozone-depleting substances, and HCFC-22 production. Major abatement measures for each source category are listed in Supplementary Table 6.

The Global Change Analysis Model. GCAM (jgcri.github.io/gcam-doc/) is a multi-sector integrated assessment model that links the global economy, energy supply and demand, agriculture, land use, water, and climate systems[25]. GCAM is designed to explore long-term interactions between human and earth systems, which has been widely used to produce global emission scenarios, including the IPCC Special Report on Emissions Scenarios[49], the Representative Concentration Pathways[50], and quantification of the Shared Socioeconomic Pathways[51]. GCAM 5.3 used in this analysis includes 32 geo-political regions, and linked land allocation, water use, and agriculture production across over 300 subregions and 235 water basins.

GCAM simulates the evolution of the energy, land, water, climate, and economic systems driven by exogenous assumptions regarding population and labor productivity, determining energy and service demands for each region and each sector. CO_2 emissions are estimated by tracking the carbon content of various fuels embedded in energy flows. Historical emissions of other GHGs (CH_4 and N_2O), short-lived forcing agents (BC and OC), and air pollutants (CO, SO_2, NO_x, and $PM_{2.5}$) are adopted from the latest CEDS, which is then used to develop emission factors (emission per energy input or service output of a specific technology). Future emissions are estimated as the product of the projected economic activity and the corresponding emission factor for a given technology.

In this study, we harmonize historical emissions with the EPA non-CO_2 report so that future non-CO_2 emission trends are consistent with the baseline scenario in the EPA report. In addition, we incorporate MAC curves for non-CO_2 emissions, mapped from the EPA mitigation scenario (Supplementary Note). Based on the maximum reduction potentials reported from 2015 to 2050 (Supplementary Table 7), we derived year-specific technological change (TC) parameter for 2020–2050, allowing GCAM to simulate the EPA MAC in these future years and to extend the current MAC after 2050 (Eq. 1). In the main analysis, we assume the TC after 2050 is the average TC for pre-2050 periods. Supplementary Fig. 12 qualitatively illustrates the effect of technological change on MACs.

$$E(t_1, p) = E(t_0, p) \times \prod_{i=t_0}^{t_1} (1 + TC^i) \qquad (1)$$

Where $E(t_1, p)$ and $E(t_0, p)$ represent the emission reductions corresponding to mitigation cost of p in the MAC of year t_1 and t_0, TC^i represents the technology change in year i relative to year t_0. Therefore, any future year's mitigation potential is cumulatively determined by the TCs of all previous years. To avoid unrealistically abrupt emission reductions in the first several modeling periods due to the implementation of MAC (which does not necessarily reflect the delays in stock turnover), we phase in the maximum reduction potential from 2020, linearly reaching their reported maximum mitigation potential by 2040. In the sensitivity analysis, we further examine the effect of different TC assumptions, which do not substantively alter our findings.

These MACs allow non-CO_2 GHG emissions to respond to increased carbon prices (Supplementary Fig. 13) by considering the application of various control measures in addition to fuel switching and adopting more efficient technologies, based on both technological feasibility and cost-effectiveness reflected in MACs. For example, due to the limited economic mitigation measures in agriculture, CH_4 emission is much more challenging to reduce relative to resource extraction. In GCAM, both MAC and direct pricing can be applied to non-CO_2 GHG emissions. For our analysis, we assume that only the MAC affects non-CO_2 emissions, reflecting the difficulties in transferring the emission pricing on non-CO_2 GHG emissions to the final goods. If considering direct pricing, these emission penalties will likely be transferred to the corresponding economic activity and consumers, leading to economic feedbacks on technology shifts and behavioral changes[21].

GCAM is coupled with Hector v2.5 (https://github.com/JGCRI/hector), an open-source, reduced-form global climate model[52,53], to estimated various climate outcomes such as radiative forcings and global temperature. At every GCAM modeling period, GCAM supplies Hector with global emissions of fossil fuel and

industrial CO_2, LULUC, CH_4, N_2O, BC, OC, CO, NMVOC, and halocarbons. Next, emissions are interpolated into yearly estimations in Hector to calculate the corresponding future concentrations of GHGs from the input emissions. Then Hector calculates global mean radiative forcing from GHG concentrations and short-lived climate forcers and finally converts the radiative forcing to global mean temperature[52]. It should be noted that GWP-100 is only used to aggregated GHG emissions in our results, while our climate results (Fig. 1) are unaffected by GWP choices.

Scenarios. In this study, we model a Reference scenario and 90 mitigation scenarios pairing 30 CO_2 abatement pathways with three non-CO_2 abatement levels. The Reference scenario is harmonized with the baseline scenario in the EPA mitigation report, assuming projected emission rates consistent with historical levels without future effects of policy changes beyond GCAM's final calibration year (2015). However, future emissions are determined by both emission rates and projected activity. The Reference scenario in the current work projected slightly higher non-CO_2 emissions compared with EPA's baseline scenario, mainly from agriculture CH_4 emissions driven by rapid growth in agricultural demand in developing countries. Reference also includes a small portion of non-CO_2 GHG reductions at no cost that are readily available without abatement costs (Supplementary Table 8). Reference and all mitigation scenarios share the same socioeconomic growth trajectory based on a middle-of-the-road socioeconomic pathway (SSP2)[54]. Regional non-CO_2 GHG emissions in the Reference scenario are shown in Supplementary Tables 9–15.

The CO_2 abatement pathways are characterized by two levels of annual CO_2 emissions as endpoints (0 and -8 $GtCO_2$ yr^{-1}), representing different societal expectations on negative CO_2 emissions necessary to achieve 2 °C and 1.5 °C targets, respectively. The 2 °C pathways linearly reach net-zero CO_2 emissions between 2030 and 2100 in 5-year increments, followed by zero CO_2 emissions afterwards, and the 1.5 °C pathways linearly reach -8 $GtCO_2$ yr^{-1} CO_2 emissions between 2030 and 2100 in 5-year increments (so their net-zero CO_2 years are slightly earlier), followed by -8 $GtCO_2$ yr^{-1} CO_2 emissions afterwards. The endpoints of 0 and -8 $GtCO_2$ yr^{-1} CO_2 are generally on the conservative side of negative CO_2 emissions required for the corresponding 2 °C and 1.5 °C pathways in existing literature[26].

Each CO_2 abatement pathway is further evaluated under three non-CO_2 abatement levels. CO_2 abatement only assumes the same non-CO_2 emissions as the Reference scenario while reducing CO_2 emissions alone. This is a counterfactual scenario aiming at isolating the climate impact of CO_2 mitigation alone. CO_2-driven GHG abatement includes CO_2 abatement and the non-CO_2 abatement associated with fuel switching and demand reduction driven by CO_2 abatement without explicit non-CO_2 abatement measures. Finally, Comprehensive GHG abatement includes specific non-CO_2 abatement measures, such as repairing leaks in existing large cooling systems to reduce HFC emissions and methane reductions from natural gas and oil systems with flaring. This is achieved by fully integrating country, sector, and year-specific MAC data from the EPA report into GCAM's non-CO_2 module, allowing non-CO_2 emissions to respond to increased GHG prices by explicitly considering various control measures based on their technical feasibility and cost-effectiveness. The implementation of MACs allows us to fully evaluate the mitigation potential of non-CO_2 emissions and its contribution to climate stabilization toward 1.5 °C.

Data availability

Code availability

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Author contributions

H.M., Y.O., S.J.S., and A.F. designed the study. Y.O., C.R., J.A., J.C., K.N., P.O., S.R., S.J.S. compiled and processed the data. J.E., P.P., P.K., K.C., and S.J.S. developed the modeling platform. Y.O. modeled all scenarios. Y.O. and H.M. wrote the paper with input from all co-authors.

Competing interests

The authors declare no competing interests.

Additional information

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