Near-term climate mitigation by short-lived forcers

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Emissions reductions focused on anthropogenic climate-forcing agents with relatively short atmospheric lifetimes, such as methane (CH_4) and black carbon, have been suggested as a strategy to reduce the rate of climate change over the next several decades. We find that reductions of methane and black carbon would likely have only a modest impact on near-term global climate warming. Even with maximally feasible reductions phased in from 2015 to 2035, global mean temperatures in 2050 would be reduced by 0.16 °C, with a range of 0.04–0.35 °C because of uncertainties in carbonaceous aerosol emissions and aerosol forcing per unit of emissions. The high end of this range is only possible if total historical aerosol forcing is relatively small. More realistic emission reductions would likely provide an even smaller climate benefit. We find that the climate benefit from reductions in short-lived forcing agents are smaller than previously estimated. These near-term climate benefits of targeted reductions in short-lived forcers are not substantially different in magnitude from the benefits from a comprehensive climate policy.

Mitigation focused on short-lived climate forcers (SLCFs) is a potentially attractive option to reduce the magnitude of anthropogenic climate change, given the potential for a shorter-term influence on climate compared with carbon dioxide mitigation (1–4). These proposals have focused on methane (CH_4) and black carbon (BC), which are thought to be the two most important positive forcing agents after carbon dioxide (5, 6).

Current forcing from methane, including its effect on tropospheric ozone and stratospheric water vapor, is of the order 0.65 W/m^2, and the impact of BC was recently assessed to be 1 W/m^2, although with very high uncertainty (6). A forcing reduction of 0.5 W/m^2, less than a third of the central estimate for total BC and CH_4 forcing, would result in a long-term temperature decrease of 0.4 °C, for a central equilibrium climate sensitivity of 3.0 °C per CO_2 doubling. As discussed in *SI Appendix*, section 2, however, only a portion of this reduction would be realized in the short term.

Although this simple calculation points to the potential benefit from SLCF mitigation, this potential is subject to many uncertainties, including the impact of coemitted pollutants and the large uncertainty in both aerosol forcing and carbonaceous aerosol emissions. With respect to BC mitigation, a critical constraint is that there is strong evidence that net aerosol forcing is negative (*SI Appendix*, section 6) (7–10).

In addition, the potential for SLCF-focused policies must be examined within a consistent, evolving context. This is particularly true for the so-called developing world, where, in many regions, incomes are growing, and, as a result, pollution control polices are rapidly changing. In the parlance of scenarios research, this means that potential SLCF polices need to be evaluated against a consistent reference scenario, as described below. Any near-term reductions will take place within a context of an expected overall reduction in aerosol emissions over this century that will ultimately increase climate change. The finite time over which mitigation would take place and the finite timescale for atmospheric and climatic responses also need to be taken into account in a realistic manner.

Two sets of previous analyses have explored the potential for SLCF policies: one originally published by the United Nations Environment Programme (UNEP) (1, 3) and a second analysis recently updated to examine sea-level rise (2, 4). We perform a similar analysis of idealized SLCF-reduction pathways using a well-developed, integrated-assessment model that consistently considers future socioeconomic and technological developments, focusing on energy and land use, together with greenhouse gas and pollutant emissions, radiative forcing, and global mean-temperature change. Using a consistent scenario and modeling framework, we find that earlier work appears to have overestimated the potential impact of SLCF mitigation.

Scenarios and Methods

We examine here the potential climate benefit of a SLCF strategy using the Global Change Assessment Model (GCAM) (*SI Appendix*, section 3) (11). A previous version of the same model produced the representative concentration pathway (RCP) 4.5 emissions scenario being used as part of the fifth climate model intercomparison exercise (12, 13). We consider the climate impact of focused BC- and CH_4-emission reductions, the effects of these reductions on coemitted pollutants and energy-system response, and the time evolution of atmospheric concentrations, forcing, and temperature change relative to a consistent reference scenario. To take account of the relevant response timescales, atmospheric concentrations, radiative forcing, and global mean-temperature change are estimated using a simple climate model that is sufficiently realistic to be able to replicate the global-mean results from coupled global 3D ocean–atmosphere models (14–16).

We first present results from a central reference-case scenario and then focus on uncertainties in aerosol emissions and forcing. The starting point for the analysis is the GCAM reference scenario, which is an internally consistent description of the evolution of the global energy and land-use system over the 21st century in the absence of explicit policies to control greenhouse gases. The use of a consistent modeling framework for these scenarios that covers the entire 21st century is an important aspect of this work. The reference-case, pollution-control assumptions are described elsewhere and were developed so that surface pollutant concentrations over time are broadly consistent with the assumed regional income levels in this scenario (17). Given evidence that BC emissions are underestimated, we assume in our central case that BC- and organic carbon (OC)-emission factors for the building and road-transportation sectors are 50% higher than used previously (*SI Appendix*, sections 3 and 4).

We assume in the reference case that economically attractive methane-emission reductions—largely the use of potential methane emissions as an energy source—are taken in the future (18). The emissions characteristics of biomass and coal cookstoves are also assumed to improve over time as countries develop economically and energy systems mature (*SI Appendix*, section 4). Although the future magnitude of both of these trends are uncertain, substantial changes are likely over the 100-y timescale of

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these scenarios, given, for example, the successes of current efforts to promote economically efficient methane mitigation (19). Over the long term, improvements in living conditions and incomes in developing regions, particularly in Asia, will result in the increased penetration of modern technologies in the residential sector. Technological advances over time will also increase the financial attractiveness of methane abatement and availability of particulate-pollution controls. However, these efforts are not assumed to achieve their full technical potential in the reference scenario, leading to continued impacts on climate and air quality. Traditional biomass, for example, continues to be used through late in the century in some regions. Methane emissions increase from 330 megatons (Tg) in 2005 to 420 Tg in 2050 in the reference scenario.

For context, we also present a counterfactual scenario, in which no economically attractive methane-emission reductions occur and the carbonaceous aerosol-emission characteristics of residential sector biomass and coal technologies and road vehicles do not improve over time. We use the term "counterfactual" given that economically driven methane reductions are already occurring (19) and that policies are in place in many world regions to reduce particulate emissions, including BC. Although the counterfactual scenario is not a realistic future pathway, this allows quantification of the improvements in methane- and aerosol-emission factors assumed in the reference scenario.

We focus on the impact of SLCF mitigation by constructing a scenario that assumes three sets of emission reductions starting in 2016, broadly following the UNEP SLCF analysis (1). The GCAM SLCF scenario has three elements. First, methane emissions are reduced to the maximal extent technically feasible in all sectors, based on published estimates (20, 21). This results in a reduction in 2030 of 170 Tg of CH_4 relative to the counterfactual case with no methane reduction and a 120-Tg reduction of CH_4 relative to the reference scenario, where some economically driven reductions in CH_4 emissions already occur (*SI Appendix*, section 4). The reference case methane reductions occur largely through capture of methane from landfills and coal mines and reductions in natural gas leakage and flaring.

Second, by 2035, there is a complete phase out of wood and coal use for heating and cooking in the residential sector for all countries, including all direct and indirect emissions changes. A more realistic policy would, at least in part, substitute advanced stoves with far lower emissions, but for simplicity, we assume full deployment of modern technologies. We assume that this phase-out applies to both coal and biomass stoves.

The third element of the SLCF-reduction scenario is the strict imposition of particulate controls, such as the Euro VI standards, on all light cars, light trucks, and heavy trucks in all regions by 2035. To enable this level of control, full desulfurization of road diesel is also assumed to take place, which results in a reduction in sulfur emissions in the SLCF scenario relative to the reference case. As in the UNEP scenarios, all superemitting vehicles are also assumed to meet the emissions standard.

The SLCF scenario represents a set of idealized policies that are implemented in addition to the background improvements assumed in the reference scenario. Although many of the changes in the reference scenario also require some policy action, the policies implicitly assumed to be in place follow historical trends for the imposition of air pollution standards (17) and the adoption of modern technologies in developing regions. The SLCF policies would require substantial additional effort. We note that the SLCF polices envisioned in this scenario are not strictly achievable as stated. Although, for example, it may be possible to reduce the fraction of superemitting vehicles, it is not possible to eliminate them entirely, and not all regions are likely to be able to strictly enforce emission control policies. It will likely take longer than 25 y to completely phase out traditional cookstoves, for example, given the complexity of this endeavor and the mixed results of such efforts to date (22). Some of these policies might also be costly in some cases. This SLCF-reduction scenario, however, provides a bounding case for the benefits of potential actions.

Results—Central Case

We first examine results under central values for aerosol forcing (Table 1) and emissions. Aerosol forcing per unit of emissions are taken from a recent assessment (6). We use central carbonaceous aerosol emission factor values that are 50% larger than used previously because of evidence of a significant under prediction of BC in the atmosphere (6). A detailed description of the reference-case emission scenario, SLCF-emission reduction and climate-forcing assumptions are provided in *SI Appendix*.

Fig. 1 shows the central result for forcing reduction from the SLCF-mitigation scenario broken out by forcing agent. Methane, including its indirect effects through ozone and stratospheric water vapor, is the largest contributor to temperature reduction in the central case. Note that ozone reductions occur through both reductions in methane and reductions in ozone-precursor emissions in the buildings sector because of the coal and biomass phase-out (*SI Appendix*, section 4). The methane reductions provide the largest contribution to ozone reductions after 20 y. BC provides the second-largest contribution, although this is far more uncertain, as examined below. The BC-forcing reduction is offset slightly by reductions in organic carbon and sulfur dioxide from both the building and transportation sectors.

Global temperature change, relative to the reference scenarios, is shown in Fig. 2. Under central assumptions for climate response, emission factors, and aerosol forcing, we find that the SLCF-policy scenario reduces temperature change by 0.16 °C by 2050 relative to the reference case (Fig. 2). The impact of the SLCF reductions is slow to be realized because of the finite time for implementation of the specified reductions, the finite lifetime of methane in the atmosphere, and the impacts of negative forcing from reductions in coemitted SO_2 and OC, particularly in early years. Because of these effects, the temperature reduction in 2050 is only 56% of the equilibrium-temperature reduction for the forcing change of 0.33 W/m^2 at this point (*SI Appendix*, section 7). Methane reductions provide much of the climate benefit in the central scenario.

Global temperatures in the counterfactual scenario, relative to the reference case, increase in 2050 by an absolute value similar to the reduction seen in the SLCF scenario (Fig. 2). It is important to distinguish the changes seen in the reference case from the additional actions called for under a SLCF scenario. There is, of course, uncertainty as to the reference-case trajectory; however, the range of impact of a SLCF policy is roughly bounded, at least for this particular reference scenario, by the counterfactual and SLCF scenarios shown in Fig. 2.

The impact of the methane-emission reductions assumed to take place in the reference case are also shown. Methane reductions are about one-third of the increase in the counterfactual scenario relative to the reference case by 2050. If some portion of these reductions did not occur in the reference case, then the impact of the idealized SLCF policy would be that much larger.

Table 1. Historical aerosol radiative forcing assumptions used in this work

Aerosol component	Year 2000 aerosol forcing		
	Strong	Central	Weak
Sulfate direct	−0.55	−0.40	−0.20
Sulfate cloud indirect	−0.85	−0.61	−0.25
Black carbon (direct plus indirect)	0.97	0.48	0.08
Organic Carbon (direct plus indirect)	−0.29	−0.24	−0.02
Nitrate and mineral dust	−0.2	−0.2	−0.2

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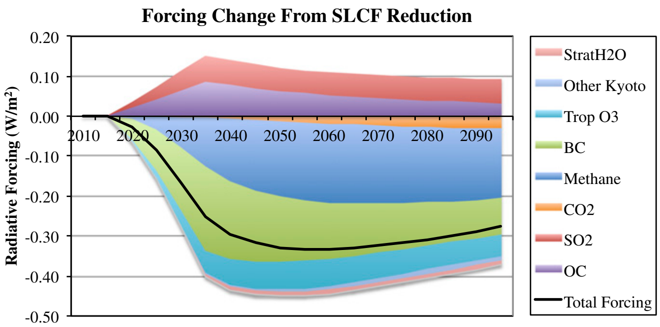

Fig. 1. Radiative-forcing change attributable to SLCF reduction (SLCF – reference scenario forcing) under central-case emission factor and radiative-forcing assumptions.

As a contrasting policy case, we also show a climate policy scenario whereby an efficient, global pathway is followed to stabilize total anthropogenic forcing at 4.5 W/m^2 by 2100 (Fig. 2 and *SI Appendix*, section 3) (12). Under this climate policy scenario, emissions of all greenhouse gases are reduced over time using a global, economically efficient carbon price pathway. This is a standard, idealized, climate policy scenario to which the, also idealized, SLCF-policy scenario can be compared. We see that a comprehensive climate policy provides a greater global mean-temperature reduction by 2050 than the SLCF policy, with even larger reductions in the second half of the century (*SI Appendix*). However, the 4.5 W/m^2 stabilization policy also results in a small additional temperature increase in 2020 because of a larger reduction in SO_2 cooling. Substantial early methane-emission reductions occur as part of a comprehensive climate policy (18), as well as some reductions in BC emissions. This means that much of the reductions envisioned under a SLCF policy would also occur under a comprehensive climate policy.

Results—Uncertainty Analysis

Although the central result is instructive, the sensitivity of SLCF climate response to a number of uncertain aspects of the climate system must be considered. We find that the major uncertainties over the next few decades are related to aerosol emissions and forcing. We examine this uncertainty space by repeating the above experiment using a bounding exercise whereby all permutations of high, medium, and low assumptions for the following parameters are used: building biomass BC- and OC-emission factors; transportation BC- and OC-emission factors; and forcing from BC, OC, SO_2 direct, and SO_2 cloud indirect, all as forcings per unit of emission, for a total of 1,458 cases, with the same BC/OC ratio retained in all cases (6).

The forcing bounds are shown in Table 1 and are drawn from a recent assessment (6). Drawing from estimates of uncertainty in historical BC emissions (23) and evidence for a substantial underestimate of current BC emissions (6), we take currently used emission factors for road-transportation and building-sector biomass and coal combustion as our low bound, a 50% increase in these emissions factors for the central case and a 100% increase in these emission factors as our high bound.

Cases where total aerosol radiative forcing in 2005 that are outside of observationally estimated bounds, liberally estimated to be inclusive, are excluded (*SI Appendix*, section 6). We conduct a combinatorial sensitivity analysis to examine a wide range of potential results. A formal uncertainty analysis is not warranted and could be potentially misleading, because central values and probability distributions for BC and OC emissions, and many components of aerosol forcing, are not well constrained.

The results of this analysis are shown in Fig. 3. Temperature reduction in 2050 ranges from 0.04 to 0.35 °C, with a median value of 0.15 °C in 2050. Because the impact of methane reductions are identical in all scenarios, these ranges are entirely attributable to differences in aerosol-forcing and emission assumptions. This means that, in many of these scenarios, BC-emission reductions provide a larger fraction of the temperature change benefit compared with the central scenario (e.g., Fig. 2).

Building-sector reductions range from a small increase to a 0.14 °C reduction in 2050. Reductions from the transportation sector result in a smaller range. In contrast to previous work, we find that a substantial number of net-positive forcing outcomes (e.g., warming) for the transportation sector attributable to the less-than-complete, near-term desulfurization of liquid fuels in the GCAM reference case. This points to the need to consider the full energy system and not each sector in isolation.

Not shown here are impacts from uncertainty in methane lifetime and forcing, which has only a small impact on the near-term results. Also not included is uncertainty in climate sensitivity which would add an additional uncertainty of ±23% to the central case 2050 temperature reduction (*SI Appendix*, section 6).

Fig. 3 also shows results if total year 2000 aerosol forcing is constrained to the 1σ range of −1.5 to −0.7 W/m^2, which is the range estimated from observational constraints (assuming a central forcing of −0.2 W/m^2 for nitrate aerosols and mineral dust) (7). The highest values for temperature reduction are not present in this case. The highest temperature reductions from SLCF mitigation are, therefore, predicated on relatively small total global aerosol forcing (e.g., less than −0.7 W/m^2).

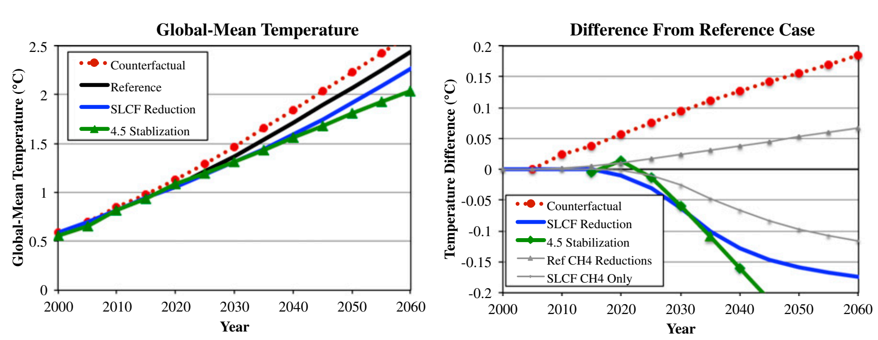

Fig. 2. (*Left*) Global temperature change relative to preindustrial conditions for the reference scenario, a counterfactual scenario with no economically attractive methane-emission reductions or improvements in building and road-transportation BC and OC emissions, the SLCF-reduction scenario described in the text, and an idealized climate policy scenario that stabilizes at 4.5 W/m^2. (*Right*) Difference from reference scenario for the counterfactual, SLCF, and 4.5 W/m^2 stabilization scenarios. The impact of only changes in methane emissions are also shown (gray lines).

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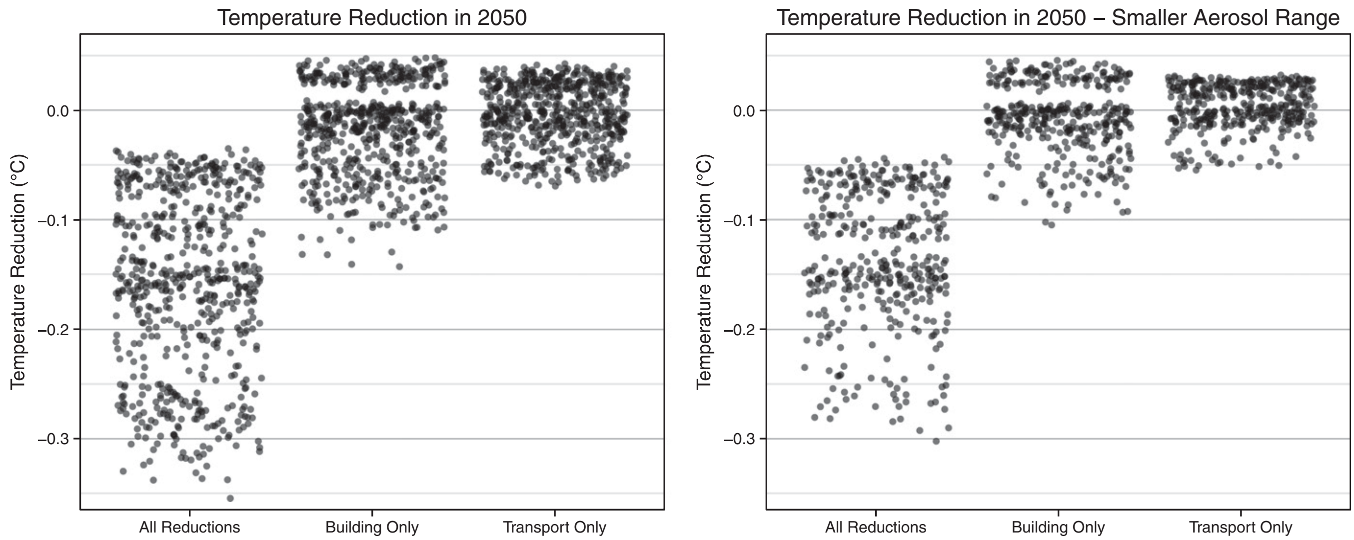

Fig. 3. (*Left*) Sensitivity analysis showing the temperature reduction in 2050 attributable to all reductions, building-sector reductions, and road-transportation reductions (jitter added so all points are visible). Note that the "All Reductions" results also include a temperature decrease of 0.09 °C attributable to the assumed methane-emission reduction by 2030. (*Right*) Results screened for cases where total aerosol forcing is between −0.7 and −1.5 W/m^2.

Discussion

The SLCF-reduction policy presented here, as in previous work (1, 3), is a bounding case where control of pollutant and CH_4 emissions is assumed to take place to the maximal extent currently thought to be technically possible. Actual policy impacts are likely to be lower than those illustrated here, given that any real world policy will not be maximally effective, for example, given difficulties in implementing cookstove programs (22) and the inevitable presence of some superemitting vehicles (24). Furthermore, the climate impact of any SLCF policy, even if successful, is highly uncertain because of our lack of understanding of carbonaceous aerosol emissions and aerosol forcing.

The climate impact of methane-control policies is more certain. The extent to which methane-emission reductions could or will be implemented is the greater source of uncertainty in this case. We assumed that economically attractive methane-reduction options are taken up in the reference scenario. There is uncertainty in this assumption, given that, in general, not all economically attractive energy-saving options are actually adopted. The impact of a methane-focused policy could be larger if some of the reference-case reductions did not occur. We note, however, that most these economically attractive methane-reduction opportunities are focused in large, industrial sectors (e.g., landfills, coal mines, and natural gas systems), where barriers to adoption can be lower than in end-use sectors.

In any event, some level of additional economically attractive reductions in CH_4 emissions are likely to occur in the future as methane-capture technologies mature. Reductions that are not attractive on purely economic grounds are likely to require policy intervention. Given that many, if not most, of these reductions would also take place under a comprehensive climate policy (18), the scope for large methane reductions outside of, or in addition to, such a policy, is unclear, particularly if financial incentives are limited.

The impact of SLCF reduction on temperature seen here is far lower than the ~0.5 °C year 2050 reduction reported as a central value in the UNEP study (1). The largest reasons for this difference are the use of a more realistic climate and atmospheric-system response and inclusion of methane reductions in the reference case, with smaller differences attributable to a more gradual phase-in of emission reductions, larger sulfur dioxide emission reductions, and a slightly lower central net forcing reduction (*SI Appendix*, section 7). When the impact of the UNEP emission reductions are replicated with the climate model used here, we find only half the temperature reduction (0.27 °C) reported in the UNEP study, a difference that is apparently attributable to more realistic climate and atmospheric-concentration responses to the imposed emission changes. The reference-case methane reductions also contribute to the difference in results. Assuming the same reference-case methane reductions as modeled here, we find that the UNEP emission scenarios result in a 0.2 °C temperature reduction in 2050, only slightly higher than the central value found here and well within the uncertainty range of our results.

The temperature response seen here is also smaller than that found in ref. 4. As discussed in *SI Appendix*, in addition to an apparent underestimate of climate lag times in that work, the larger response in ref. 4 also appears to be attributable to the assumption of a BC-forcing reduction that continues to increase even after the BC SLCF policy is fully in effect. In contrast, as shown here, the BC-forcing reduction decreases after 2035, once the assumed BC SLCF policy is fully in place (*SI Appendix*, Fig. S12). This is because the impact of, for example, eliminating traditional cookstoves decreases past 2035 because use of traditional cookstoves naturally decreases globally as incomes increase through the century. This highlights the importance of consistently treating all aspects of the problem, including socioeconomics, emission control assumptions, and aerosol forcing assumptions.

We note that both of these previous works compare SLCF reductions with a scenario where only CO_2 emissions are reduced. This is an inconsistent comparison, however, because actions to reduce CO_2 emissions will also result in reductions in methane and pollutant emissions because of many common sources of these emissions (18, 25).

Both reductions in methane emissions, which will result in a decrease in background tropospheric ozone levels, and reductions in particulate matter, such as BC, will have substantial global health benefits and could potentially be justified on this basis alone (3, 26, 27). The near-term climate benefits of an idealized SLCF-reduction policy, however, are relatively modest, uncertain, and similar to those from an idealized climate policy in the near-term. As expected, there is little additional impact of a SLCF policy in the second half of the century, whereas a comprehensive climate policy reduces climate changes substantially

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by 2100. Although there is likely to be a climate benefit from a SLCF-focused policy, much of this benefit would also be obtained from a comprehensive climate policy. This implies that reductions in greenhouse gas emissions, both long- and short-lived, need to remain the central focus of any climate-mitigation policy that aims to stabilize the climate system.

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