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PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

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Highly contrasting effects of different climate forcing agents on terrestrial ecosystem services

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Many atmospheric constituents besides carbon dioxide (CO_2) contribute to global warming, and it is common to compare their influence on climate in terms of radiative forcing, which measures their impact on the planetary energy budget. A number of recent studies have shown that many radiatively active constituents also have important impacts on the physiological functioning of ecosystems, and thus the 'ecosystem services' that humankind relies upon. CO_2 increases have most probably increased river runoff and had generally positive impacts on plant growth where nutrients are non-limiting, whereas increases in near-surface ozone (O_3) are very detrimental to plant productivity. Atmospheric aerosols increase the fraction of surface diffuse light, which is beneficial for plant growth. To illustrate these differences, we present the impact on net primary productivity and runoff of higher CO_2, higher near-surface O_3, and lower sulphate aerosols, and for equivalent changes in radiative forcing. We compare this with the impact of climate change alone, arising, for example, from a physiologically inactive gas such as methane (CH_4). For equivalent levels of change in radiative forcing, we show that the combined climate and physiological impacts of these individual agents vary markedly and in some cases actually differ in sign. This study highlights the need to develop more informative metrics of the impact of changing atmospheric constituents that go beyond simple radiative forcing.

Keywords: global warming; ecosystem services; climate change; methane; carbon dioxide; photosynthesis

1. Atmospheric radiative forcing

A commonly used metric to compare the contributions that different factors make to climate change is global mean radiative forcing, ΔQ (W m^{-2}). Radiative forcing corresponds to the change in net radiation entering the atmosphere [1]. Increases

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in greenhouse gases such as carbon dioxide (CO_2) produce a positive radiative forcing, which warms the planet, whereas increases in reflective sulphate aerosols result in a negative value, and therefore a cooling. Humankind is known to be changing the concentration of greenhouse gases, such as CO_2, methane (CH_4) and nitrous oxide (N_2O). At the same time, anthropogenic activities have also modified the atmospheric loading of microscopic 'aerosol' particles.

Individual radiative forcings may be combined to give an overall value for ΔQ, to which the climate system will respond. Global temperature change ΔT (K) adjusts to this combined radiative forcing, and if ΔQ is positive then 'global warming' occurs. Given sufficient time at a fixed forcing change, the Earth system will approach a new thermal equilibrium satisfying $\Delta Q = \lambda \Delta T$. Here, $\lambda\,(\mathrm{W\,m^{-2}\,K^{-1}})$ determines the change in radiative forcing required to produce 1 K of warming. Climate scientists often consider the related inversely linked equilibrium temperature sensitivity to a doubling of atmospheric CO_2, $\Delta T_{2\times}$ (K). At present there remains major uncertainty in the value of $\Delta T_{2\times}$ (e.g. [2]), although the uncertainty in radiative forcing for greenhouse gases is generally much smaller [1].

The additive nature of radiative forcings to give a single, time-varying $\Delta Q(\tau)$ can provide policymakers with significant manoeuvrability. A particular pathway in $\Delta Q(\tau)$ may be recommended to avoid an expected level of dangerous climate change, but the precise composition of changing greenhouse gas concentrations is free to be determined. Given the different sources of greenhouse gases, it may be decided to take a more aggressive stance on reducing CO_2 emissions to allow for larger increases in atmospheric CH_4 and N_2O—or vice versa. Anthropogenic CO_2 emissions are largely due to the burning of fossil fuels and deforestation, whereas the largest contributions to CH_4 and N_2O increases are associated with agriculture. The balance can also take account of changes in levels of atmospheric ozone (O_3) concentrations or aerosols as important clean air policies are implemented. Reduction in cooling aerosols will actually require more aggressive reductions in atmospheric greenhouse gases as sulphate aerosols are believed to have masked the full extent of current global warming (e.g. [3,4]).

2. Impacts of different atmospheric constituents on ecosystem services

Recent research shows that different radiative forcing agents have markedly contrasting physiological effects on terrestrial ecosystems. Hence for ecosystem services, the dimensionality of the climate change problem may not reduce simply to pathways in the single quantity $\Delta Q(\tau)$. We analyse these differences through changes to four different atmospheric constituents, all of which are expected to alter markedly through the twenty-first century. First, increases in CO_2 will influence vegetation not just through climate change but also by 'CO_2 fertilization' of photosynthesis (e.g. [5]). Second, increases in other atmospheric greenhouse gases (such as CH_4 or N_2O) will affect terrestrial ecosystems only through climate change—it is believed that there is no significant physiological response of vegetation to changes in surface concentrations of these gases. (CH_4 emissions can have an indirect physiological effect by O_3 formation, but this is small and can be neglected here as tropospheric O_3 chemistry is mostly limited by nitrogen oxide (NO_x). N_2O is inert in the troposphere and so has no

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indirect effect.) Third, we consider raised levels of near-surface O_3 concentrations, which are known to damage vegetation and reduce the ability to photosynthesize [6–8]. Besides this direct effect, O_3 is also a greenhouse gas. Fourth, changed concentrations of atmospheric aerosols alter levels of surface photosynthetically active radiation (PAR) and its partitioning into direct and diffuse radiation [9]. This influences ecosystem net primary productivity (NPP), and in a slightly surprising way; it has been demonstrated that the increased levels of atmospheric aerosols since pre-industrial periods have actually enhanced photosynthesis, primarily owing to vegetation canopy interactions with higher levels of diffuse light [10]. Increasing aerosol levels also have a climatological influence on the land surface, although in this case through an overall cooling effect.

We characterize physiological and climate responses for these four atmospheric constituents, in each case for concentration changes that would lead to a radiative forcing of $\Delta Q = +1\,\mathrm{W\,m^{-2}}$. In this idealized experiment, the effect of these prescribed changes on global warming is, therefore, equal according to the radiative forcing equivalence paradigm. To place this in context, the pre-industrial to present forcing for CO_2 is estimated to be $1.66\,\mathrm{W\,m^{-2}}$, other long-lived greenhouse gases (which include CH_4 and N_2O) to be $0.98\,\mathrm{W\,m^{-2}}$, tropospheric O_3 to be $0.35\,\mathrm{W\,m^{-2}}$ and the direct effect of aerosols to be around $-0.5\,\mathrm{W\,m^{-2}}$ [11]. To estimate the ecosystem responses, we use the Joint UK Land Environment Simulator (JULES) land surface model, a modelling system suitable for prediction at large spatial scales. The JULES model has two components. The first calculates heat, water and carbon fluxes [12,13]. This has recently been extended to include a multi-layer canopy description as needed to capture the PAR responses recently identified [14]. The second component (called TRIFFID—Top-down Representation of Interactive Foliage and Flora Including Dynamics) predicts global vegetation distributions and associated carbon content. Five plant functional type (PFT) classes are represented: broadleaf trees, needleleaf trees, shrubs and C_3 and C_4 grasses. The model determines fractional coverage of each PFT based on the available resources using Lotka–Volterra equations.

We run the JULES model for all land regions (excluding Antarctica) on a 2.5° latitude by 3.75° longitude grid, and, unless otherwise stated, we use the same methodology as in the previous published studies [6,10,15]. An initial control simulation is forced with gridded mean climatological data representative of the period 1980–1999 [16]. Direct and diffuse short-wave fluxes were reconstructed using aerosol distributions simulated by the Hadley Centre Global Environment Model, HadGEM2-A, and radiative transfer calculations [10]. The effect of the major volcanic eruptions of El Chichón (Mexico) and Mount Pinatubo (The Philippines) are excluded from the means for 1980–1999 (i.e. periods 1982–1984 and 1991–1993, respectively). Atmospheric CO_2 concentration is set to the 1980–1999 average (354 ppm). Fields of surface O_3 are prescribed to be representative of year 1990. For each land point, gridbox averaged values of NPP ($\mathrm{kg\,C\,m^{-2}\,yr^{-1}}$) and runoff (R) ($\mathrm{m^3\,m^{-2}\,yr^{-1}}$) are calculated. Global values of these quantities for this control simulation (in units of $\mathrm{Gt\,C\,yr^{-1}}$ and $10^{12}\,\mathrm{m^3\,yr^{-1}}$, respectively) are plotted in black in figure 1*a*,*b*. Global values of soil plus vegetation carbon are given as the single number (1613 Gt C) in table 1.

In order to compare the impacts of different radiative forcing agents we make simulations of the equilibrium state of the vegetation and soil for each of the physiological or climate drivers outlined above (note this differs from [15], which

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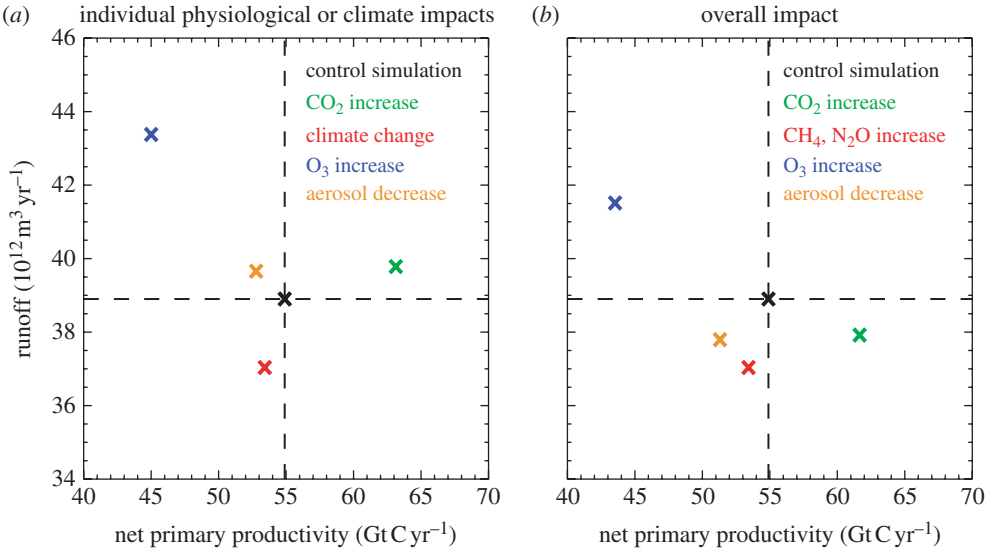

Figure 1. (*a*) Simulations of global values of NPP and R for the control simulation (black), and for the *physiological response* to alterations in different atmospheric constituents that would represent $+1\,\mathrm{W\,m^{-2}}$ increase in radiative forcing. The green cross shows the physiological-only response to raised levels of CO_2 (the climate is assumed to be the same as the control simulation). Similarly, the physiological-only responses to increased O_3 and decreased sulphates are given by the blue and orange crosses, respectively. For comparison, the red cross represents the impact of climate change only (i.e. no physiological response) on NPP and R through altered surface meteorological conditions associated with $+1\,\mathrm{W\,m^{-2}}$ of radiative forcing. Hence this plot allows comparison between the impact of individual physiological responses and climate change *per se*. (*b*) The combined influence of both *physiological and climate change* effects on global NPP and R for $+1\,\mathrm{W\,m^{-2}}$ radiative forcing, which provides information on the overall implications of changing particular atmospheric constituents. We achieve this simply by adding the calculated climate change perturbation to the physiological responses in (*a*). Hence the difference between the red and black crosses in (*a*) is added to each of the three physiological effects, also as given in (*a*), to obtain their new overall position in (*b*). The red cross in (*b*) represents greenhouse gases, such as CH_4 and N_2O, which have no known direct physiological effects on vegetation, but which, when changed, do alter the atmospheric radiative balance. Hence the red cross in (*b*) is in the identical position to that of (*a*).

used fixed vegetation cover). Land-use changes are excluded so as to focus on changes due to the different atmospheric pollutants. A rise in atmospheric CO_2 concentration from 354 to 426 ppm corresponds to an increase in radiative forcing of $+1\,\mathrm{W\,m^{-2}}$, and so, to capture the associated physiological effects, a new simulation is made for this higher concentration. All other model components, including climate forcing conditions, are as in the control simulation. Global NPP and R for this new simulation are given by the green cross in figure 1*a*. The increased CO_2 concentration generates both higher NPP and runoff (owing to reduced transpiration) in this model. This is broadly consistent with experimental evidence of CO_2 fertilization of photosynthesis [17] and CO_2-induced stomatal closure [18]. In common with other global vegetation models [5], JULES produces an increase in water use efficiency under elevated CO_2, which implies an

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Table 1. Total terrestrial carbon content (vegetation and soil) for each of the five simulations presented in figure 1*a*. The percentage differences away from the control simulation are given in the third column, and the absolute changes in terrestrial carbon content are presented in the last column. Under the assumption of linearity, terrestrial carbon contents corresponding to figure 1*b* would be found by subtracting the difference between control and climate change simulations (i.e. subtract 116 Gt C) away from the other three altered atmospheric constituent simulations.

simulation	terrestrial carbon (vegetation + soil) (Gt C)	% change from control simulation	change in terrestrial carbon (Gt C)
control	1613		
increased CO_2	1819	+12.8	+206
climate change	1497	−7.2	−116
increased O_3	1365	−15.4	−248
decreased aerosol	1548	−4.0	−65

increase in photosynthesis, a reduction in transpiration, or a combination of both. Models differ in the balance between these manifestations of increasing water-use efficiency, in large part because they disagree on the extent to which increasing leaf area index offsets the reduced water use by each leaf [19]. However, the almost universal agreement that plant water-use efficiency increases under elevated CO_2—and in most models this is associated with increased runoff [5]—implies a high degree of confidence that CO_2 fits uniquely into the higher NPP and higher R quadrant of figure 1*a*. This is despite the remaining uncertainties in the exact magnitude of CO_2 effects on photosynthesis and stomatal conductance.

From table 1, this new equilibrium simulation with atmospheric CO_2 now at 426 ppm also corresponds to an increase of 12.8 per cent in terrestrial carbon content when compared with the control state. Geographical maps of these changes for NPP and R are given in figures 2*a* and 3*a*, respectively. There is an increase in NPP for most regions, whereas the runoff map is patchier, with a few regions experiencing reduced runoff where increases in water-use efficiency per leaf are counteracted by increases in leaf area index.

The climate change simulation describes the impact of altered surface climate on terrestrial ecosystems due to an increase in global mean radiative forcing of $+1\,\mathrm{W\,m^{-2}}$. For greenhouse gases such as CH_4 and N_2O, to which ecosystems have no direct physiological response, this represents the only changes to impact on them. To calculate the altered surface climate conditions, we employ a pattern-scaling approach (calibrated against the HadCM3 climate model) in which the local changes in surface climate are scaled proportional to the mean warming over land [20]. Climate change alone is predicted to reduce both global NPP and R, as shown by the red cross in figure 1*a*, and terrestrial carbon content is predicted to decrease by over 7 per cent (table 1). Geographical differences are given in figures 2*b* and 3*b*. Climate change is predicted to lead to major geographical changes in NPP, with particular reductions in the Amazon rainforest. Decreases in NPP are also predicted in mid-Northern latitudes, but further north global warming increases NPP as a result of an extended growing season and the

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northward propagation of boreal forest. From figure 3*b*, climate change alone reduces runoff in many regions because evaporative demand increases more rapidly than precipitation. This increase in evaporative demand is particularly large over Amazonia, which therefore dominates the global signal in runoff reduction for this climate change simulation.

We can estimate the combined effect of each change by simply adding the climate impact (the difference between the black and red crosses in figure 1*a*) to the direct physiological impact. The new values are given in figure 1*b*. Hence for our prescribed increase in CO_2 concentration, we estimate an overall increase in NPP as the positive impacts of CO_2 fertilization outweigh the negative impacts of climate change. However, in these particular simulations we still see a slight reduction in runoff owing to the overall (climate plus physiological) effect of the CO_2 increase.

The O_3 simulation is achieved by forcing the gridded JULES model with prescribed surface fields of O_3. We use monthly mean surface O_3 concentrations for year 1990 (as in the control simulation) and year 1860, both as simulated by the Met Office's Lagrangian tropospheric chemistry model STOCHEM [6,21]. It is estimated that the difference in radiative forcing associated with surface O_3 changes between these two dates is $+0.32\,\mathrm{W\,m^{-2}}$ [22]. Hence to estimate a further increase in atmospheric O_3 concentration consistent with $+1\,\mathrm{W\,m^{-2}}$, we add to the year 1990 O_3 values that are the difference between the year 1860 and 1990 fields, multiplied by factor (1.0/0.32). In all other respects, the simulation is identical to that of the control simulation. From figure 1*a*, such O_3 damage would give a significantly lower global NPP, although raised R because the less productive vegetation uses much less water for transpiration. Indeed, we simulate a 13.2 per cent reduction in leaf stomatal conductance for woody vegetation between the elevated O_3 and present-day control simulation, which is broadly consistent with observed reductions from manipulation experiments [8]. When combined with the associated climate change (blue cross in figure 1*b*), there is a further reduction in NPP, and slightly smaller increase in runoff. O_3 physiological damage in this simulation corresponds to a 15.4 per cent reduction in terrestrial carbon (table 1). Where O_3 concentrations increase there is almost always a reduction in NPP (figure 2*c*) and an increase in R (figure 3*c*).

The physiological influence of changes in atmospheric aerosols is through variation in the amount and quality of the PAR to which plants are exposed. Higher levels of aerosols generally reduce total surface PAR, but they also cause more scattering of that radiation, thereby increasing the ratio of diffuse to total radiation (called diffuse fraction, F_d). These two effects are found to be competing: lower light levels will generally reduce NPP at any particular leaf surface, but this is counteracted and even overtaken by a higher diffuse fraction, which acts to distribute the PAR more evenly through the canopy [10]. In the control simulation, average distributions of tropospheric aerosols (sulphate, soot, biomass-burning, mineral dust, sea-salt and biogenic) and known cloud cover for 1980–1999 (again ignoring major volcano years and 2 years after) are used within radiative transfer look-up tables to obtain surface PAR fluxes. This follows the method described in Mercado *et al.* [10]. The direct effect of scattering aerosols, such as sulphate aerosols, is to exert a negative radiative forcing by scattering incoming solar radiation back to space. Hence a positive value for ΔQ implies a reduction in the amount of sulphate aerosols.

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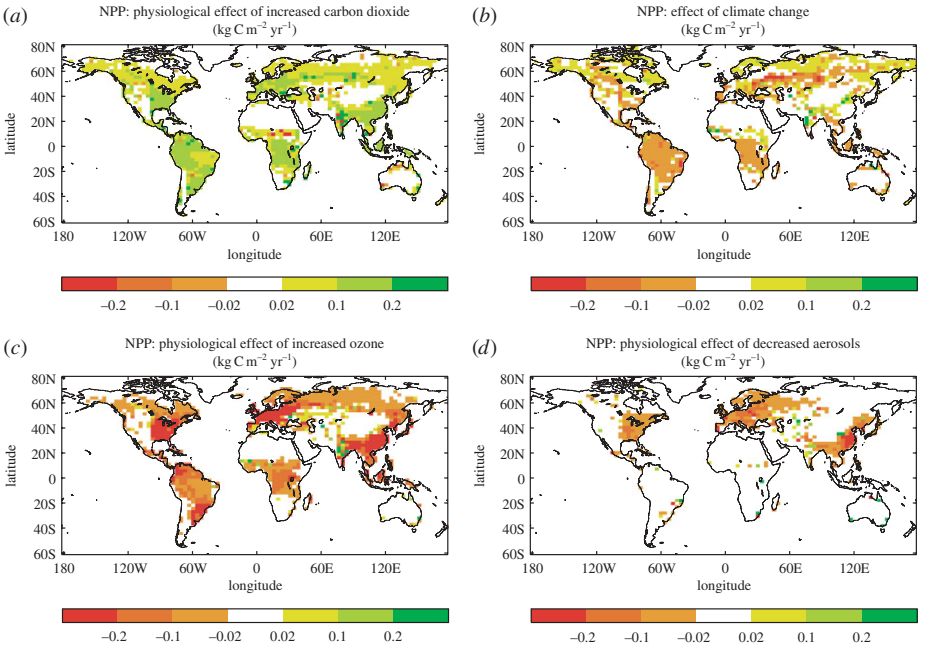

Figure 2. Calculated geographical changes in NPP by our simulations for altered atmospheric constituents minus the control simulation: (*a*) physiological effect of raised CO_2, (*b*) impact of climate change, (*c*) physiological effect of raised O_3 and (*d*) physiological effect of decreased aerosols.

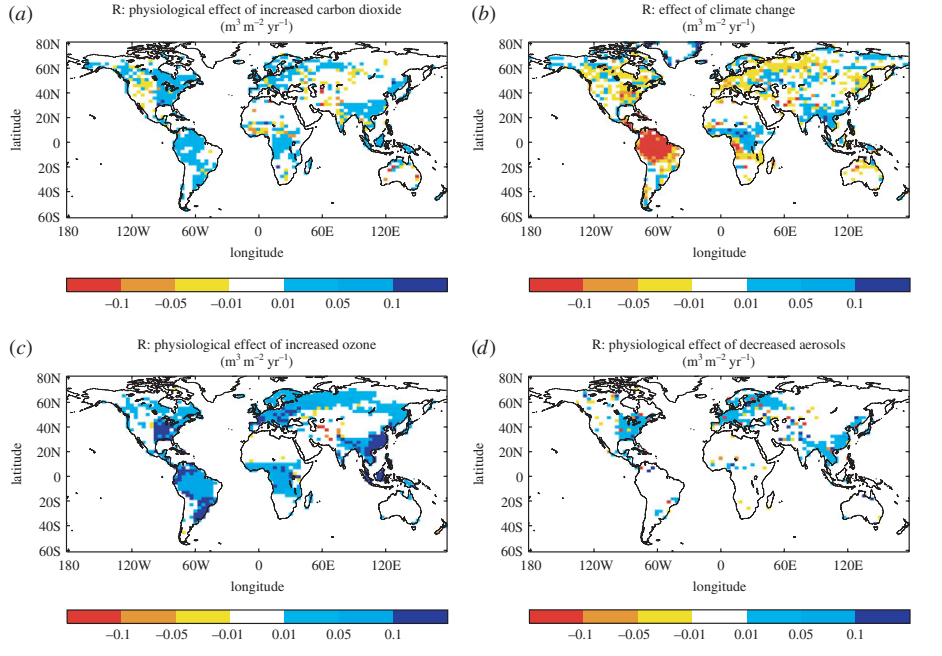

Figure 3. Calculated geographical changes in runoff (R) by our simulations for altered atmospheric constituents minus the control simulation: (*a*) physiological effect of raised CO_2, (*b*) impact of climate change, (*c*) physiological effect of raised O_3 and (*d*) physiological effect of decreased aerosols.

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Sulphate aerosol concentrations in particular increased throughout the twentieth century. Hence to simulate a positive aerosol radiative forcing, we replace the distribution of sulphate aerosol for the period 1980–1999 (as used in the control) with those believed to be appropriate for year 1901. This provides a forcing of $+0.26\,\mathrm{W\,m^{-2}}$ at the top of the atmosphere. Surface PAR fluxes are then recomputed with this revised distribution of sulphate aerosol, and a new global equilibrium simulation is undertaken. Differences in ecosystem response from the control simulation are then normalized by the forcing of $+0.26\,\mathrm{W\,m^{-2}}$ (i.e. we multiply differences by 1.0/0.26) to allow comparison with the other climate agents on the basis of an equivalent radiative forcing of $+1\,\mathrm{W\,m^{-2}}$. However, this may neglect some nonlinearity in the response of ecosystems to changes in direct and diffuse radiation. Cloud cover and concentrations of the other tropospheric aerosol species remain unchanged at their 1980–1999 average. In agreement with the analysis of Mercado *et al.* [10], a major reduction in atmospheric aerosols yields a significant decrease in NPP (figure 1, orange cross), and from table 1 there is also a 4 per cent decrease in total terrestrial carbon content. Global mean runoff is modelled to increase, as the less productive vegetation uses less water for transpiration. Short-lived aerosols are far less well mixed in the atmosphere than long-lived greenhouse gases, and as a result diffuse radiation effects are most obvious near to the industrial areas that dominate the sulphur emissions (figures 2*d* and 3*d*). When the physiological impacts are combined with climate change, the orange cross in figure 1*b* implies that aerosol reduction will overall cause an actual decrease in both NPP and R. However, the precise values here should be treated carefully, as the climate change associated with changes in aerosols will be more regionalized than that of our climate change simulation associated with well-mixed greenhouse gases.

3. Discussion

Climate change caused by changes in atmospheric constituents is usually expressed in terms of radiative forcing. Advice to policymakers working to avoid levels of unwelcome or even dangerous climate change is often presented in terms of upper limits to such forcing. This is sometimes translated into 'equivalent CO_2 concentrations', with the implication that there is significant freedom in constituent changes as long as total radiative forcing stays within prescribed limits. However, some of the greatest impacts on humankind will occur through changes in food and water availability [23] rather than through climate change *per se*. NPP and runoff levels are indicators of such availability, and a set of recent research papers have shown that the direct physiological effects of changing different atmospheric constituents on these ecosystem services is large and varied. This implies that consideration should be given to going beyond the single 'radiative equivalence' metric when addressing the overall impacts of different atmospheric pollutants. For equivalent radiative forcing (of $+1\,\mathrm{W\,m^{-2}}$), we calculate changes in NPP and R for (i) increases in CO_2, (ii) increases in greenhouse gases with no physiological effects and hence only climate impacts such as CH_4 or N_2O, (iii) increases in ground-level O_3, and (iv) decreases in

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sulphate aerosols. The global overall effects (physiological plus climate) are presented in figure 1*b* for both NPP and R, and most importantly are found to have different signs.

The fertilization effect of higher CO_2 levels, which is not present for other greenhouse gases, offsets the detrimental influence of imposed climate change. This suggests that a greater emphasis should be placed on also dealing with non-CO_2 causes of global warming. On the basis of our calculations, the difference between the overall impact of a $+1\,W\,m^{-2}$ increase in atmospheric CO_2 as compared with a $+1\,W\,m^{-2}$ increase in the concentration of a physiologically inactive atmospheric constituent such as CH_4 amounts to about 5 per cent higher values of global runoff and 10 per cent higher values of NPP. Another interpretation of figure 1 is that higher levels of atmospheric sulphates may actually be beneficial in the context of NPP and R, owing to the higher diffuse fraction aiding photosynthesis along with an overall cooling effect (i.e. offsetting global warming). This also has implications for the geoengineering option being considered, using deliberate aerosol increases to counteract climate change. However, such gains from raised NPP and R values should be balanced against the uncertain but potentially very damaging effects of ocean acidification associated with higher CO_2 on coral reefs, shell-forming marine organisms [24] and fish populations [25].

While trusting the qualitative features of our analysis, there do remain important uncertainties in the size of direct physiological effects of different atmospheric constituents. This is particularly true of CO_2 fertilization [17,26] and this represents a critical limitation for the comparison of different mitigation options. The magnitude of this effect may be altered in mid- and high-latitude ecosystems by plant nitrogen availability, and possibly by phosphorus cycling in tropical ecosystems [27,28], although these processes are not yet fully understood. The nitrogen cycle is only now beginning to be depicted in general circulation modelling (GCM) land surface models suitable for global-scale simulations [29]. Further studies are required to determine the overall impact of alternative aerosol types. We have analysed the response to sulphate aerosols because of their large concentrations and ubiquitous nature. However, emerging understanding of how changed levels of black carbon and biomass-burning affect the atmosphere will allow the implications of these aerosols also to be incorporated in a similar framework. Our study has also only considered equilibrium climate states for changes to NPP and runoff. In a transient climate, the precise magnitude of climate versus physiological effects may differ.

This study argues for metrics to compare different atmospheric pollutants that go beyond radiative forcing and global warming. Here, we have considered impacts on the vital terrestrial ecosystem services related to the availability of food and water, but we accept that there will be other alternative metrics to radiative forcing that could provide insights into the overall impacts of different climate mitigation options. Key among these are metrics related to air quality and human health [30], and the impacts of ocean acidification on marine ecosystem services [25].

Although the largest anthropogenic change to radiative forcing, and thus contribution to climate change, has been through increases in atmospheric CO_2 concentration, without such metrics there is the risk that action on climate change mitigation will become overly concerned with reducing CO_2 emissions.

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This could have potentially counterproductive consequences for human well-being and also risks missing other co-benefits associated with the abatement of non-CO_2 greenhouse gases [31]. We have highlighted the differentiated impacts (including regional variation) that climate forcing agents have on ecosystem services, and argue that they require consideration in both mitigation and adaptation measures proposed to minimize the effect of climate change on society.

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