Title: Eutrophication will increase over the 21st century due to precipitation changes

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Abstract: Eutrophication, or excessive nutrient enrichment, threatens water resources across the globe. Here we show that climate-change-induced precipitation changes alone will substantially increase (19±14%) riverine total nitrogen loading within the continental US by the end of the century for the "business-as-usual" scenario. The impacts will be especially strong for the Northeast and the corn belt of the US, and are driven by projected increases in both total and extreme precipitation. Offsetting this increase would require a 33±24% reduction in nitrogen inputs, presenting a massive management challenge. Globally, changes in precipitation are especially likely to also exacerbate eutrophication for India, China and Southeast Asia. It is therefore imperative that water quality management strategies account for the impact of projected future changes in precipitation on nitrogen loading.

One sentence summary: Future changes in total and extreme precipitation will increase riverine nitrogen loading for the continental US and beyond.

Main Text: Nutrient enrichment of water bodies, or eutrophication, is a growing global problem. While phosphorus is the leading concern for freshwater systems, excessive nitrogen is the primary cause of eutrophication in estuaries and coastal waters (*1*). Associated water quality impacts, including but not limited to the occurrence of harmful algal blooms (*2*, *3*) and hypoxia (*4*, *5*) have been widely documented and are on the rise (*4*, *6*). Ecosystem and human impacts are severe (*7*, *8*). Population growth and changes in land management practices are projected to further increase total nitrogen export globally (*9*) and for the continental US (*10*), as is anticipated agricultural adaptation to climate change (*11*). Various publications have suggested that the water quality impacts of nitrogen loading may also increase in frequency and intensity due to future changes in precipitation(*5*, *12*, *13*). Clear evidence substantiating these concerns is lacking, however, because very little is known about the impact of changes to the physical climate itself, and especially precipitation, on nitrogen export and therefore on eutrophication. This is despite the fact that precipitation amount, frequency, and intensity are major controls on riverine nitrogen load (*14*–*17*). The impact of changes in future precipitation patterns on nitrogen loading have only been examined for individual watersheds, and have relied on only one to three global climate models (*14*, *18*–*20*), or a single average across an ensemble of climate models (*21*–*24*). These studies therefore do not provide a basis for understanding impacts at regional to continental scales, or for examining the robustness of conclusions to uncertainty in future climate. At the same time, emerging strategies aimed at managing eutrophication focus on setting nutrient loading targets (*25*, *26*). Because loading is most directly influenced by nitrogen inputs and by precipitation patterns, it is imperative to understand how changes in precipitation might in turn impact loading (*27*), thereby confounding management efforts.

Here, we fill this knowledge gap by providing spatially extensive and contiguous estimates of changes in riverine total nitrogen loading (henceforth, nitrogen loading) for the continental US resulting from anticipated changes in precipitation across 21 Climate Model Intercomparison Project Phase 5 (CMIP5) models, three climate scenarios (RCP2.6 ‘mitigation’ scenario, RCP4.5 ‘stabilization’ scenario, RCP8.5 ‘business-as-usual’ scenario), two future time periods (‘near future’ 2031-2060 and ‘far future’ 2071-2100), and 2,105 subbasins within the continental US. We use bias corrected and spatially downscaled (1/8°) climate model projections (*28*), and report changes at scales ranging from the eight-digit hydrologic unit (HUC8) ‘subbasin’ scale (henceforth, watershed scale; Fig. S1) to the continental US. The analysis is made possible by a recently-developed empirical model linking net anthropogenic nitrogen inputs into a watershed (e.g., fertilizer application), total annual precipitation, extreme springtime precipitation, and land use to annual nitrogen flux (*17*) (see supplementary materials). While we recognize that a number of factors will impact future riverine nitrogen fluxes, we focus here specifically on impacts of changes in precipitation in the absence of other concurrent changes, because these impacts cannot be avoided through management within the affected regions. We therefore keep net anthropogenic nitrogen inputs (henceforth, nitrogen inputs) and land use constant at existing levels throughout the analysis (2007 and 2006, respectively; see supplementary materials). We use the approach proposed by Tebaldi et al. (*29*) to assess the significance of observed changes and their consistency across the CMIP5 models; we use the term *robust* to denote results where at least 80% of models are *consistent* on the direction of change and where the change is statistically *significant* (p<0.05) for at least 50% of models.

We find that anticipated changes in future precipitation patterns alone will lead to large and robust increases in watershed-scale nitrogen fluxes by the end of the century for the business-as-usual scenario (stippling in Fig. 1C), especially within the Upper Mississippi Atchafalaya River Basin, the Northeast continental US, and the Great Lakes basin. Watersheds across much of the Northeast continental US show a robust increase even under the stabilization scenario by the end of the century. These spatial patterns are especially noteworthy because these regions also have high historical nitrogen fluxes (Fig. 1A) and they discharge to coastal regions with documented water quality impairments resulting from eutrophication (*7*, *30*). We further find that, at the watershed scale, only a small fraction of areas experience a robust increase in fluxes in the near future for any of the examined scenarios (Fig. 1B, Fig. S2A,C), due to inter-model differences and internal climate variability (i.e., natural climate fluctuations that arise even in the absence of changes in radiative forcing).

For large aggregated regions (see supplementary materials) including the continental US as a whole, models agree with high consistency (>80%) that nitrogen loading will increase across all three examined climate scenarios and for both the near future and far future periods (Fig. 2, Table S1), with the only exception being the lower Mississippi Atchafalaya River Basin. These changes are robust for the far future periods and the mitigation and business-as-usual scenarios, with significant changes observed for the majority of models and for most regions including the continental US as a whole (filled boxplots in Fig. 2). Although the projected changes in nitrogen flux at watershed scale for mitigation scenario are within the range of natural variability (colored regions with no stippling in Fig. S2), aggregation to large regions yields a robust increase. For the stabilization scenario, a smaller projected overall increase in total precipitation relative to the other scenarios leads to less robust changes in nitrogen loading for most regions. In the near future, high interannual variability and the smaller projected magnitude of change lead to the observed consistent but not robust increases across scenarios.

For the remainder of the discussion, we focus primarily on the far future period under the business-as-usual scenario.

The across-model mean projected increase in nitrogen loading within the continental US is 19% (Fig. 2), with the Northeast (28%), the upper Mississippi Atchafalaya River Basin (24%), and the Great Lakes basin (21%) experiencing the largest increases (Fig. 2). To put these numbers in context, the United States Environmental Protection Agency recently promulgated a 20% load reduction target relative to 1980-1996 levels for the Mississippi Atchafalaya River Basin as a whole (*26*), with the aim of reducing the size of massive annual hypoxic zone in the Gulf of Mexico (*31*). We find here that precipitation changes alone will instead lead to an 18% increase in loading within the Mississippi Atchafalaya River Basin as a whole. Offsetting this increase in loading would require a 30% reduction in nitrogen inputs for the region, while achieving a 20% loading reduction in light of the confounding effect of precipitation changes would require a 62% reduction in nitrogen inputs (see supplementary materials). For the continental US, a 33% reduction in nitrogen inputs would be required to offset the 19% nitrogen load increase attributable to changes in precipitation.

The large spread across models indicates that the magnitude of the change in nitrogen load is uncertain, presenting an additional risk for management (Fig. 2). Across-model differences in precipitation projections translate into large uncertainties in the magnitude of nitrogen load change. In addition, we find that a large fraction of this uncertainty is due to internal climate variability (see supplementary materials, Fig. S3), and therefore represents irreducible uncertainty. For large portions of the continental US, internal climate variability explains more than half of the total inter-model spread for both time periods and for all emission scenarios (results for business-as-usual shown in Fig. S3C & D). Because current global climate models have been shown to underestimate internal climate variability (*32*), the actual contribution may be even greater. Furthermore, precipitation downscaling of projected future climate is based on an assumption of climate stationarity (see supplementary materials), the limitations of which represent an additional uncertainty. This result implies that, not only are nitrogen loads expected to increase, but the magnitude of the increase is quite uncertain. For the far future under the business-as-usual scenario, the spread between the first and third quartiles for the continental US represents increases ranging from 9% to 24%, while for the Northeast this range spans an 18% to 39% increase. The full range is broader still (Fig. 2).

We further find that the magnitude of predicted changes in the nitrogen flux is explained by the compounding impacts of changes in the total annual and springtime extreme precipitation, but only the changes due to total precipitation are robust on their own (Fig. 3). The spatial patterns of change in future nitrogen flux (Fig. 1C) are comparable to those that would result only from future changes in total annual precipitation (see supplementary materials; Fig. 3A). Conversely, accounting only for projected changes in springtime extreme precipitation or changes to the correlation between total annual and springtime extreme precipitation does not lead to robust changes in future nitrogen flux at the watershed scale (Fig. 3B,C). This conclusion holds true even at regional scales, including for the continental US, where the magnitude of change is explained by changes to both total and extreme precipitation, with the change in total annual precipitation having the largest impact and leading to a robust increase on its own for most regions (Fig. S4). The larger contribution of change in annual precipitation to the change in mean annual nitrogen flux is attributable to the robustness of the projected changes in annual precipitation (Fig. S5B), and the larger sensitivity of nitrogen flux to total annual precipitation relative to extreme precipitation (see supplementary materials).

Overall, we find that regions with high historical loading (which correspond to regions with high nitrogen inputs and high precipitation) and a robust projected increase in precipitation are most likely to experience a large and robust future increase in nitrogen loading, both at the watershed and regional scale. The empirical model used here to relate nitrogen inputs, land use, and precipitation statistics to nitrogen flux is specific to the continental US, precluding its direct application to other regions of the globe. We may however seek analogues in other regions that meet certain criteria and use those as heuristics to identify other regions where similar conditions exist and similar outcomes may be expected. Namely, the general finding that large increases in nitrogen load are expected for regions with (i) high nitrogen inputs, (ii) high precipitation, and (iii) a robust projected increase in precipitation is likely to be true beyond the continental US. We therefore re-examine the business-as-usual far future precipitation projections across the 21 available CMIP5 models globally (bias corrected and spatially downscaled to 1/4°) to identify regions that exhibit all three risk factors (see supplementary materials). We find that identifying regions with robust projected precipitation increases (Fig. S6A) and high historical total annual precipitation (>75th percentile globally; 656 [mm yr^{-1}]; Fig. S6B), combined with data on historical fertilizer application rates (as a proxy for nitrogen inputs) (Fig. S6C), provides a good approximation of the regions within the continental US that are likely to experience a large and robust increase in nitrogen flux (stippled region in Fig. 1C vs. continental US area in Fig. 4).

Applying this heuristic approach globally makes it possible to identify other regions where changes in precipitation are likely to engender substantial increases in nitrogen load (Fig. 4); we find that large portions of East, South, and Southeast Asia, including India and eastern China, exhibit conditions that are directly analogous to those in the upper Mississippi Atchafalaya River Basin, Northeast, and Great Lakes regions of the continental US, and these regions are therefore likely to undergo large increases in nitrogen load as a result of projected changes in precipitation. These regions are also home to over half of the world's population (*33*), and are heavily dependent on surface water supplies (*34*). As a result, increased eutrophication would have widespread impacts. Among countries in this region, India is especially noteworthy because it exhibits all three risk factors across over two thirds of its area, is one of the fastest developing countries in the world, and has one of the fastest growing populations (*33*). The precipitation projections in this region are also highly sensitive to aerosol emission trajectories (*35*), which are themselves uncertain (*36*). Portions of Europe (e.g., Italy, southern France, Denmark, northern Germany) also display all three risk factors. Other highly agricultural regions (e.g. central Europe, eastern South America, southern Australia) have comparable fertilizer application rates (Fig. S6C) but have either lower historical precipitation or a less robust projected precipitation change. In general, this heuristic approach identifies global agricultural regions that are particularly susceptible to the impacts of precipitation changes.

Overall, we conclude that changes in precipitation patterns will have substantial impacts on nitrogen loading within the continental US. These trends will either compound changes due to anticipated intensification of land use (*9*, *10*), or may negate the benefits of strategies aimed at load reductions (*9*, *10*), thereby exacerbating water quality impairments (*37*). The same scenario is likely to play out in East, South, and Southeast Asia, and India and eastern China in particular, which have high precipitation and fertilizer application rates, and are projected to experience future precipitation increases. Our findings imply that strategies aimed at managing eutrophication and associated water quality problems must account for the impact of changing precipitation patterns on nutrient loading.

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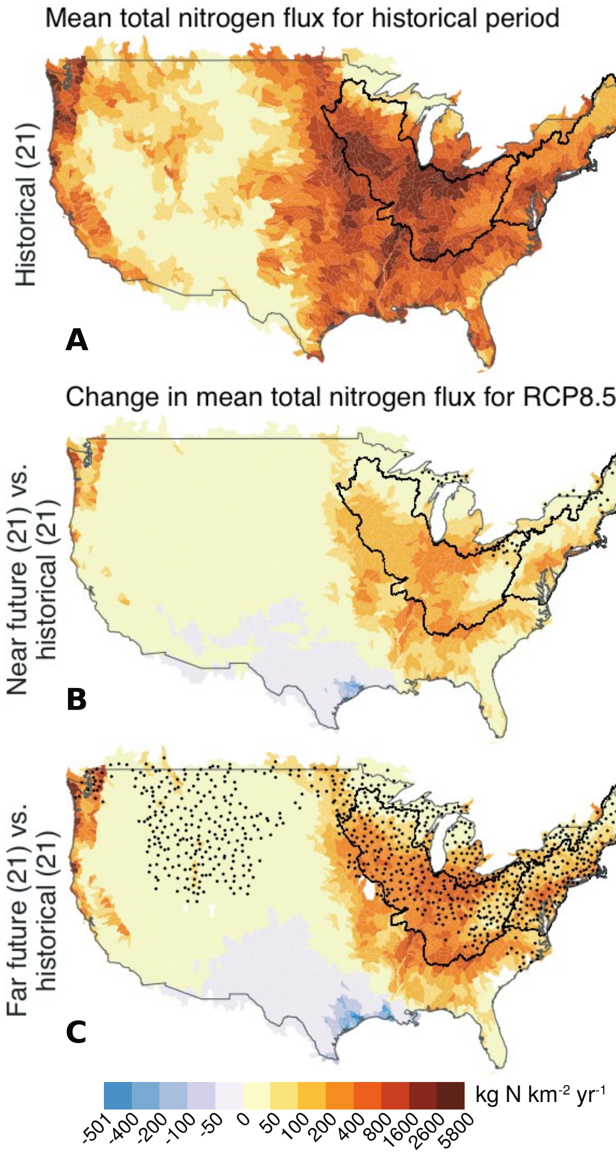

Fig. 1: Projected changes in mean total nitrogen flux for watersheds within the continental US for the RCP8.5 ‘business-as-usual’ emission scenario. (**A**) total nitrogen flux for the historical period (1976-2005), averaged across 30 years and 21 CMIP5 models. (**B,C**) Projected change in mean total nitrogen flux for near future (2031-2060) and far future (2071-2100) relative to historical period. For panels (**B**) and (**C**), stippling highlights watersheds with a robust change in total nitrogen flux (i.e., more than 50% of the models show a significant change and more than 80% of the models are consistent on the sign of change). Watersheds with inconsistent projections (i.e., more than 50% of the models show significant change but fewer than 80% of the models agree on the sign of change) are shown in white. Remaining watersheds are shown in color without stippling. The black polygons outline the upper Mississippi Atchafalaya River Basin and the Northeast region (Fig. 2).

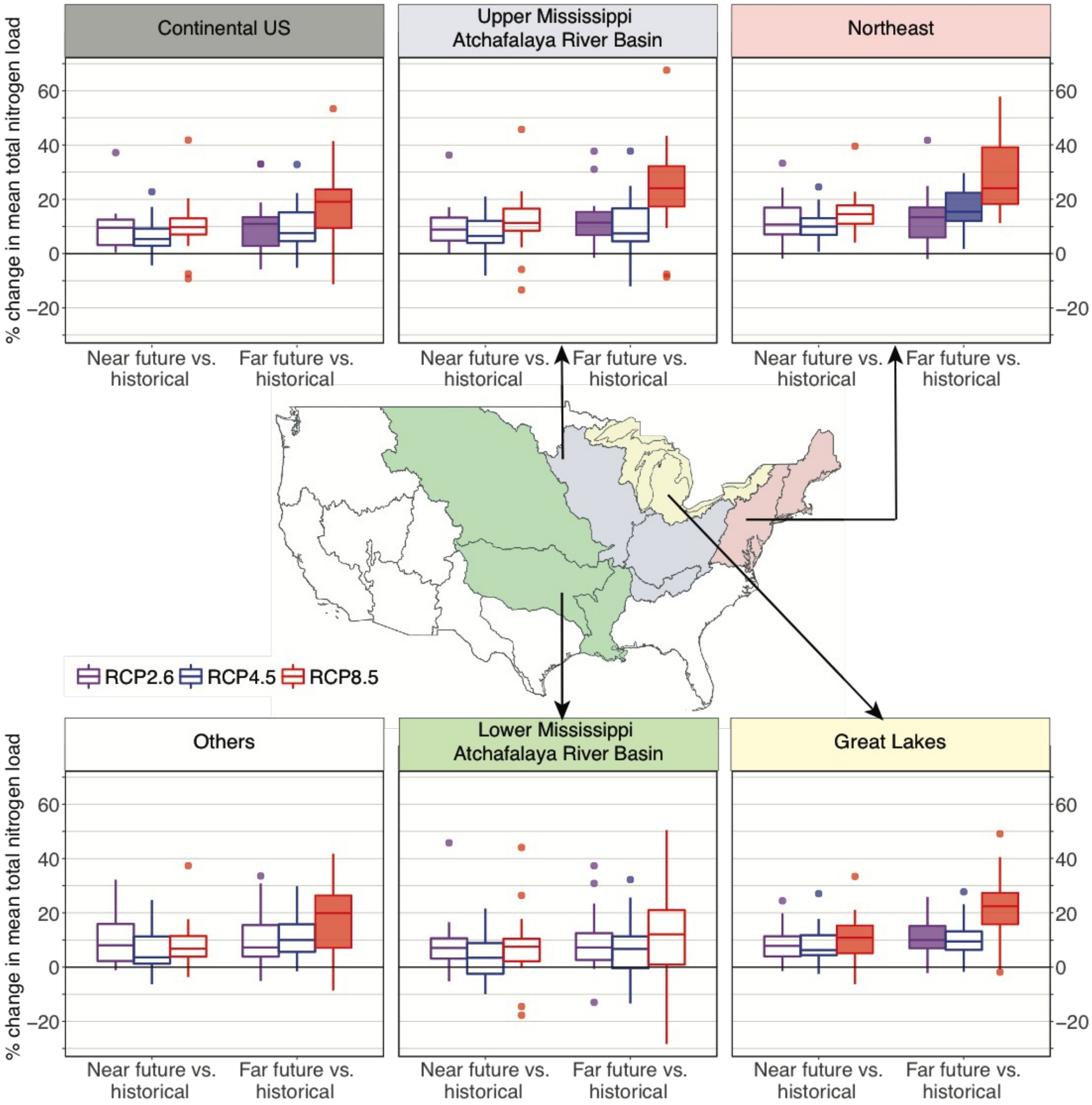

Fig. 2: Percent changes in mean total nitrogen load within large regions within the continental US for the RCP2.6 'mitigation', RCP4.5 'stabilization', and RCP8.5 'business-as-usual' emission scenarios. For a given model, total nitrogen load is first averaged for each 30-year period (historical, near future, far future), each scenario, and each region (using an area-weighted average of contributing watersheds), and these values are then expressed as a percent change in projected total nitrogen load within a given region, period, and model. Box plots represent the spread across the 21 examined models for specific periods and scenarios, with outliers marked as dots. Filled boxplot highlight regions with a robust change in total nitrogen load (i.e., more than 50% of the models show a significant change and more than 80% of the models are consistent on the sign of change). Grey outlines show HUC2 regions for reference (Fig. S1).

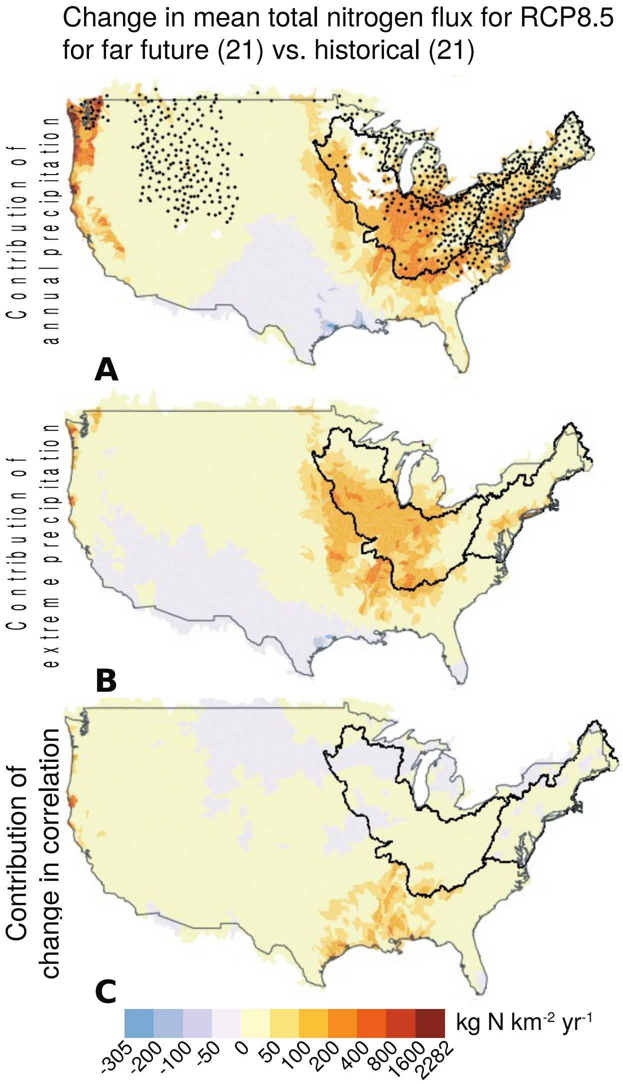

Fig. 3: Contribution of total annual precipitation (A), extreme springtime precipitation (B), and correlation between annual and extreme precipitation (C) to projected changes in mean total nitrogen flux for watersheds within the continental US for the business-as-usual emission scenario (Fig. 1C). The individual contributions of these three factors were calculated by eliminating the contribution of the two other factors to the total change in the total nitrogen flux (see supplementary material). Note that the contributions are not additive due to the nonlinearity of the total nitrogen flux model (see supplementary materials). Colors and stippling are as defined in Fig. 1.

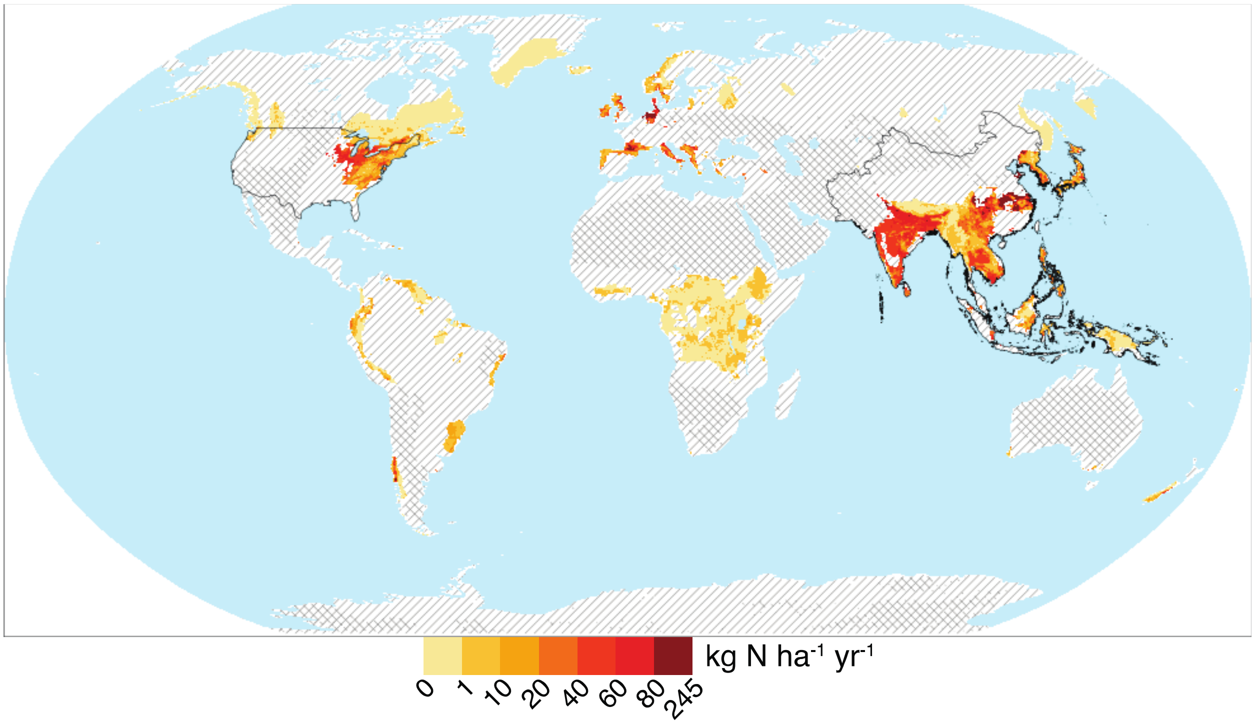

Fig. 4: Warm colors highlight global regions most likely to experience large increases in total nitrogen flux. Map shows 2015 fertilizer application rate for regions with historical (1976-2005) annual precipitation rates above the 75th percentile (averaged over 30-year period and 21 models) and projected robust increases in annual precipitation by the far future (2071-2100) for the business-as-usual emission scenario. Global regions in dark orange and red therefore exhibit all three risk factors for increased future loading. Regions in yellow and light orange meet the precipitation criteria but have low nitrogen inputs, while hatched regions do not meet one (diagonal hatching) or both (cross hatching) of the precipitation criteria. The black outlines highlight the continental US, and South, East, and Southeast Asia.