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Interacting effects of urbanization and climate on atmospheric deposition of phosphorus around the globe: A meta-analysis

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HIGHLIGHTS

- Increasing interest in atmospheric phosphorus deposition over time.
- No significant urban enhancement of phosphorus deposition across sites.
- Higher temperatures increase deposition difference between urban and rural sites.

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ABSTRACT

Over half of the world's human population currently lives in cities, and population density in urban areas is projected to increase over the coming decades. Past studies have shown cities to be hotspots for atmospheric deposition of nitrogen and researchers have found individual cities to have elevated rates of atmospheric phosphorus deposition. However, it remains unknown whether atmospheric phosphorus inputs are elevated in urban areas around the world and how temperature and precipitation affects these inputs. We conducted a meta-analysis to compare atmospheric deposition of phosphorus in urban and rural sites across the globe. We hypothesized that atmospheric phosphorus deposition behaves similarly to atmospheric nitrogen deposition, with increased concentrations and rates of atmospheric phosphorus inputs in urban compared to nearby rural areas. We also hypothesized that the urban enhancement of atmospheric phosphorus inputs is positively influenced by mean annual temperature and precipitation. Data were compiled from 38 cities across 11 countries (i.e. Brazil, China, India, Japan, Pakistan, Spain, Taiwan, Tunisia, Turkey, Ukraine, and United States) and five continents (i.e. Africa, Asia, Europe, North America, and South America). Across the 16 cities that had paired urban and rural sites, there was not a statistically significant difference in atmospheric concentrations nor fluxes of phosphorus deposition between urban and nearby rural sites. However, we found that the difference between rates of atmospheric phosphorus deposition in urban vs. rural sites is positively related to mean annual temperature, though not total annual precipitation. Together these results demonstrate that climatic factors like temperature enhance the urbanization effect, such that sites with warmer temperatures experience a greater difference in urban vs. rural phosphorus deposition rates.

1. Introduction

Phosphrous is an essential element for all organisms and can limit primary productivity of many ecosystems, but in excess can leach from terrestrial to freshwater and marine ecosystems, leading to eutrophication that depletes dissolved oxygen for aquatic organisms (Duan et al., 2012 and EPA, 2022). There is increasing recognition that atmospheric inputs of phosphorus represent a significant source of phosphorus for terrestrial, freshwater, and marine ecosystems (Mahowald et al., 2008; Decina et al., 2018; Okin et al., 2011). Atmospheric deposition of phosphorus comes from natural sources, such as biogenic aerosols, as well as anthropogenic sources, such as fossil fuel combustion, flame retardants, waste production, dust from construction, and debris from roads (Mahowald et al., 2008; Decina et al., 2018; Saini et al., 2020; Violaki et al., 2021), all of which tend to be greater in cities than nearby rural areas (Dadashpoor et al., 2019; Liu et al., 2015). Over half of the world's population currently lives in cities and this proportion is expected to rise to over 70% by the year 2050 (UN DESA, 2018). As urban

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development increases (Briber et al., 2015), it is important to understand how urbanization may impact atmospheric deposition of nutrients, such as phosphorus. Cities tend to have large amounts of impervious surface and are often located along rivers and coastlines (Arnold and Gibbons, 1996; Grimm et al., 2008; Hobbie et al., 2017), making them vulnerable to nutrient run-off to nearby waterways. Therefore, it is crucial to determine whether rates of atmospheric phosphorus inputs are higher in cities compared to nearby rural areas.

Past studies have shown relationships between urbanization and increased rates of atmospheric deposition of both nitrogen (Decina et al., 2019; Conrad-Rooney et al., 2023) and phosphorus (Casartelli et al., 2008; Decina et al., 2018; Yadav and Pandey, 2017). A recent study by Decina et al. (2018) found increased rates of atmospheric deposition of inorganic phosphorus in the greater Boston, MA area compared to nearby rural areas. The contribution of phosphorus from atmospheric deposition to the Boston Harbor was estimated to be 1.2-fold greater than phosphorus inputs from sewage effluent, but the mechanism for elevated atmospheric phosphorus inputs in Boston is unknown (Decina et al., 2018). Casartelli et al. (2008) documented enhanced rates of inorganic phosphorus deposition in the city of Rio Grande, Brazil compared to a nearby rural area. The authors attribute the observed difference to anthropogenic influence from a large fertilizer production site located in the city. Additionally, Yadav and Pandey (2017) observed higher rates of bulk inorganic phosphorus deposition in Rajghat, India compared to its nearby rural site, which was attributed to urban land use and biomass burning (Yadav and Pandey, 2017). Researchers have attributed enhanced urban atmospheric phosphorus inputs in other studies to fertilizers containing phosphate from mined rocks (Vitousek et al., 2010) and combustion of fossil fuels, plant biomass, and municipal waste (Wang et al., 2015).

In addition to urbanization, variation in climatic conditions has been shown to affect atmospheric concentrations of phosphorus. For example, Furdui et al. (2022) found a positive relationship between air temperature and atmospheric total phosphorus concentrations in the city of Hamilton (Ontario, Canada). Varenik et al. (2016) found a positive relationship between atmospheric inorganic phosphorus concentrations in Katsiveli, on the northern shore of the Black Sea, during the warmest period of the year (April–September), which they attribute to decreases in precipitation at that time of the year. Tipping et al. (2014) compiled data of total phosphorus, filtered total phosphorus, and inorganic phosphorus across open land, lakes, and ocean coasts across 250 sites around the globe. They found a weak significant relationship between temperature and phosphorus concentrations, but no significant relationship between mean annual precipitation and phosphorus concentrations. Climatic variables are particularly important to examine as a significant portion of the world is experiencing changing precipitation (Contractor et al., 2021) and warming temperatures (NOAA National Centers for Environmental information, 2022).

Despite the fact that past studies have demonstrated that cities around the globe are hotspots for atmospheric deposition of nitrogen and individual studies have shown elevated rates of phosphorus deposition in urban areas and with temperature, we are unaware of a systematic review of studies examining phosphorus deposition comparing urban and rural areas, nor the potential impacts of climate on the possible urban enhancement of phosphorus concentrations or deposition rates, around the globe. The goals of this study were therefore (1) to compare atmospheric phosphorus concentrations and rates of deposition in cites and nearby rural areas and (2) to examine potential relationships between climatic variables, such as mean annual temperature (MAT) and precipitation (MAP), with a possible urban enhancement of both atmospheric phosphorus concentrations and deposition. We conducted a data synthesis from peer-reviewed publications that reported concentrations and fluxes of phosphorus deposition. For studies that included a nearby rural site, we compared phosphorus concentrations and/or fluxes between these sites. We hypothesized that concentrations and rates of atmospheric phosphorus inputs are greater in urban than nearby rural areas around the globe and that this urban enhancement of phosporus deposition is positively related to MAT and MAP.

2. Methods

We conducted a Web of Science search on April 28, 2022 using the following keywords: "phosphorus or phosphate", and "atmospher* or air", and "throughfall or deposit* or bulk or precipitation concentration or precipitation chemistry", and "urban* or city or cities or metropolitan or rural or suburban." This search produced 308 publications in which authors measured atmospheric concentrations or fluxes of bulk (i.e. sample collectors left in the open at all times), throughfall (beneath canopy), wet (rain or snow), and/or dry (particles or aerosols of phosphorus delivered via dust) atmospheric phosphorus deposition across urban and rural sites or exclusively in cities.

Publications that did not show up in the Web of Science keyword search were not included in our analysis. It is possible additional publications did not show up in our keyword search because the studies were conducted at the watershed scale and therefore did not explicitly include the aforementioned urban and/or rural keywords from our search. Additionally, some publication titles and/or abstracts mentioned a city or town only by its designated name (e.g. "Boston") and so they may not have been included in our initial 308 publications based on our keyword search that did not include specific city names. Two publications were excluded from our analysis because an urban or rural designation was not explicitly mentioned, and sites were determined to be rural based on location and description of the study sites within the publication.

A site was deemed as urban or rural based on the authors' explicit designations. When a study had multiple urban and/or rural locations, all towns and cities were included in our meta-analysis. When a city or town had more than one site within the same city or town, data from the location designated as the most urban (e.g., closest to the center of the city) and the most rural (e.g., furthest location from the city) were used in the analysis for comparison. Publications with exclusively urban study sites and/or publications with urban and rural counterparts were included in this meta-analysis. Rural-only publications were excluded in this study because our main goal was to determine if there is a difference between phosphorus deposition in urban vs. nearby rural areas and not to characterize atmospheric deposition of phosphorus in rural areas around the globe.

From the initial set of 308 publications, we excluded those (1) that solely measured atmospheric phosphorus inputs in rural areas and study sites characterized by authors as industrial sites (e.g., mining areas and areas of large construction work), (2) where flux and/or concentration units were ambiguous and the author did not respond when contacted for clarification, (3) where fluxes and/or concentrations were estimated based on models rather than empirical measurements, (4) that conducted airborne concentrations of phosphorus in clouds, and (5) that only measured snow that had already fallen to the ground.

With our criteria for inclusion and exclusion applied, the search yielded 30 publications to be included in this meta-analysis (Table 1). Five (i.e. Casartelli et al., 2008, de Conceicao et al., 2016; Luo et al., 2007, Pandey et al., 2016, and Pey et al., 2020) out of the 30 publications included more than one city, making a total of 38 cities in our meta-analysis (Fig. 1). Two publications included studies in Beijing (Hou et al., 2012; Zhai et al., 2013) and two included studies in Shanghai (Haiping et al., 2011; Zheng et al., 2019). Values from the two publications within both Beijing and Shanghai were analyzed independently and were not combined within each city. These were the only two cities in which concentrations or fluxes for an individual city were reported in two separate publications.

The 38 cities span eleven countries, including Brazil, China, India, Japan, Pakistan, Spain, Taiwan, Tunisia, Turkey, Ukraine, and United States. Twenty-three cities included in the analysis had no rural counterpart and 16 cities had paired urban and nearby rural sites. One city, Shanghai, was included in one publication as an urban site alone (Zheng et al., 2019) and in another publication with paired urban and rural sites (Haiping et al., 2011).

For all 30 publications, data were extracted for reported atmospheric phosphorus concentration and fluxes in cities, as well as in paired rural sites within 16 publications. Publications reported phosphorus as organic phosphorus, inorganic phosphorus, and/or total phosphorus (inorganic + organic). Inorganic phosphorus was reported as phosphate. All wet and bulk concentration data were reported as milligrams of phosphorus per liter (mg P L^{-1}) and dry concentration data were reported as nanograms of phosphorus per meter cubed (ng P m^{-3}). All wet, bulk, and dry deposition flux values were reported in kilograms of phosphorus per hectare per year (kg P ha^{-1} yr^{-1}). When publications did not report concentration and/or flux values in these formats, the data were converted to these units for consistency in our analysis. For publications reporting more than one year of data for atmospheric phosphorus concentrations or fluxes, we averaged reported values across all years. When investigators provided median concentration and/or flux values instead of mean values, the median values were used in this meta-analysis. For Beijing, China, the authors (Hou et al., 2012; Zhai et al., 2013) reported two values for wet phosphate deposition and therefore the median and 95% CI bars were reported rather than each value alone (Supplemental Fig. 1G). Five publications included figures and not numeric values in their text or tables (i.e. Dillon and Chanton, 2005; Heindel et al., 2020; Ling et al. 2022; Wang et al., 2018; Yadav and Pandey, 2017). For these papers, we extracted data from figures using WebPlot Digitizer (Version 4.6; Ankit Rohatgi, July 2022).

Table 1
List of 30 publications included in our meta-analysis. Studies included different forms of deposition: wet (W), bulk (B), dry (D), and/or throughfall (T). Studies also included concentrations (C) or flux (F) data, as well as different forms of phosphorus (T = total = organic + inorganic; O = organic; I = inorganic).

Continent	Country	City	Measured Phosphorus Type (W, B,D,T)	Concentration and or Flux (C,F)	Analyzed Phosphorus Type (T, O, I)	Reference
Africa	Tunisia	S fax	D	C	I	Saad et al., 2018
Asia	China	Nyingchi	B	C,F	T	Wang et al., 2018
Asia	Taiwan	Keelung	D	C	I	Chen and Chen, 2008
Asia	China	Beijing	W,B,D	C,F	T,I	Hou et al., 2012
Asia	India	Visakhapatnam	D	C	I	Yadav et al., 2016
Asia	China	Shanghai	W	C	T,I	Haiping et al., 2011
Asia	India	Rajghat	B	F	I	Yadav and Pandey, 2017
Asia	India	Haridwar	B	F	I	Pandey et al., 2016
Asia	India	Varanasi	B	F	I	Pandey et al., 2016
Asia	India	Harbour	B	F	I	Pandey et al., 2016
Asia	China	Beijing	W	C	I	Zhai et al., 2013
Asia	Pakistan	Saddar	D	F	I	Begum and Tabassum, 1991
Asia	Turkey	Mersin	W	C,F	I	Ozsoy and Ornektekin, 2009
Asia	China	Chengdu	B	C,F	T,O,I	Ling et al., 20022
Asia	Japan	Fukuoka	B	F	T	Chiwa, 2020
Asia	China	Wuxi	W	C,F	T	Luo et al., 2007
Asia	China	Suzhou	W	C,F	T	Luo et al., 2007
Asia	China	Changzhou	W	C,F	T	Luo et al., 2007
Asia	China	Jintan	W	C,F	T	Luo et al., 2007
Asia	Japan	Kyoto	B	F	T,I	Kunim atsu and Sudo 2006
Asia	China	Qingdao	D	C	T,I	Shi et al., 2019
Asia	China	Shanghai	B	F	T	Zheng et al., 2019
Europe	Ukaine	Sevastopol	W,B	C	I	Varenik and Konovalov, 2021
Europe	Spain	Pamplona	B	F	I	Pey et al., 2020
Europe	Spain	Zaragoza	B	F	I	Pey et al., 2020
Europe	Spain	Barcelona	B	F	I	Pey et al., 2020
Europe	Spain	Palma	B	F	I	Pey et al., 2020
North America	USA	Boston	B,T	F	O,I	Decina et al., 2020
North America	USA	Charleston	B	C	I	Lindner and Frysinger, 2007
North America	USA	Jersey City	W	C,F	T	Koelliker et al., 2004
North America	USA	Detroit	W	C	I	Cable and Deng, 2018
North America	USA	Boulder	W,B,D	F	I	Heindel et al., 2020
North America	USA	Sarasota	W	C	I	Dillon and Chanton, 2005
South America	Brazil	Rio Grande	B,D,T	C,F	I	Casartelli et al., 2008
South America	Brazil	Porto Alegre	B,D,T	C,F	I	Casartelli et al., 2008
South America	Brazil	Paranagua	W	F	I	Mizerkowski et al., 2012
South America	Brazil	Cuiaba	W	C	I	de Moraes Dias et al., 2012
South America	Brazil	Catalao	W	C,F	I	da Conceicao et al., 2016
South America	Brazil	Tapira	W	C,F	I	da Conceicao et al., 2016
South America	Brazil	Ipiranga	W,D	C,F	I	Bocuzzi et al., 2021

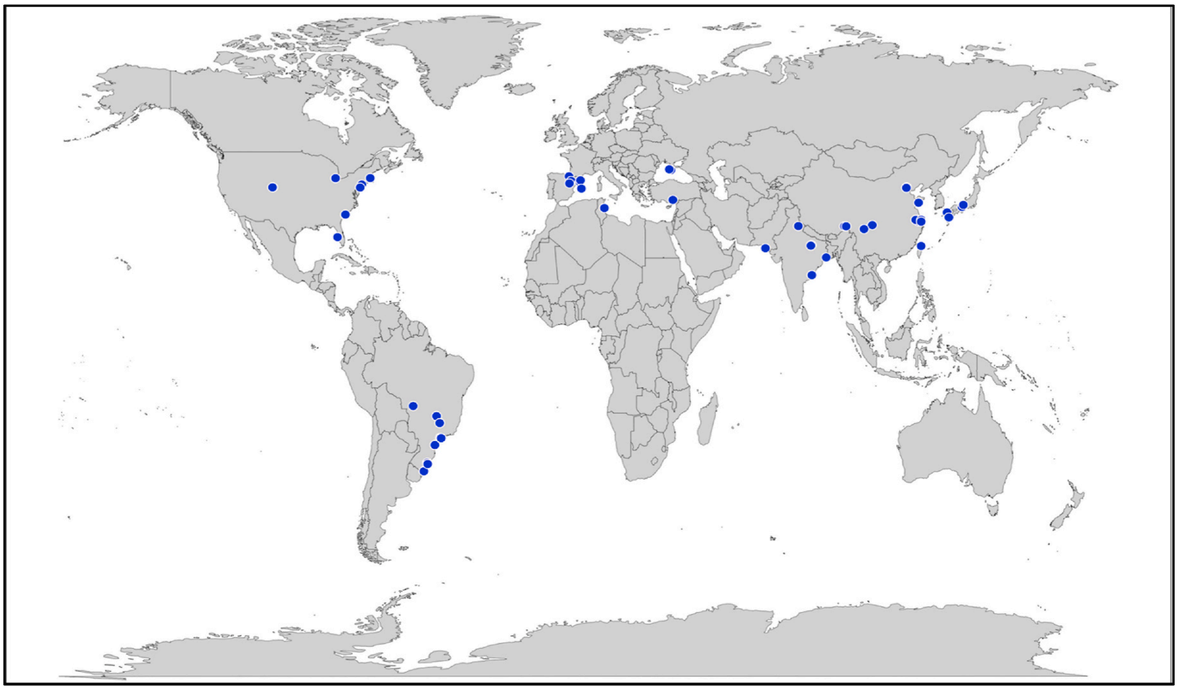

Fig. 1. Map showing locations of thirty-eight cities included in the meta-analysis. Of these thirty-eight cities, twenty-three contained urban sites only and sixteen included a nearby rural site, with Shanghai, China serving as location with both an urban-only and urban-rural site. The sixteen cities and their adjacent rural areas are located in Rio Grande and Porto Alegre in Brazil, Nyingchi and Shanghai in China, Sevastopol in Crimea, Boulder, Charleston, and Jersey City in USA, Rajghat, India, and Fukuoka and Kyoto in Japan, and Pamplona, Zaragoza, Barcelona, and Palma in Spain.

2.1. Climatic data

MAT and MAP values were assembled for each site using the most recent data available from WorldClim (version 2.1), an online database that contains high spatial resolution (i.e. 10-minute) global climate data across the years 1970–2000 (https://www.worldclim.org/data/worldclim21.html). We utilized the average values across the 31 years (1970–2000) for MAT and MAP at each site that was calculated by WorldClim. Even though our atmospheric deposition data spanned the years 1995–2018, we were not able to use climate data for the years 2001–2018 since these were not available. We chose to utilize WorldClim because it provides both MAT and MAP data on a global scale and covers most of our urban and rural sites. We used the bioclimatic MAT and MAP variables provided by WorldClim, identified as BIO1 and BIO12 in their database, at a resolution of 10 min (https://geodata.ucdavis.edu/climate/worldclim/2_1/base/wc2.1_10m_bio.zip).

We selected the WorldClim MAT and MAP data based on latitude and longitude coordinates or site names included within each publication. To our knowledge, there were no climate (i.e. MAT or MAP) data provided in the WorldClim BIO1 and BIO12 variables for urban Saddar, Pakistan (Begum and Tabassum, 1991), nor for the rural counterpart of the urban Nyingchi, China site (Sejila Mountain; Wang et al., 2015). These sites were therefore excluded from our MAT and MAP analysis. The data from the WorldClim database were imported directly to RStudio using the package "raster", which allows analysis and manipulation of spatial data. MAT values were reported in degrees celsius and MAP values in millimeters.

2.2. Statistical analyses

All statistical analyses were conducted in R Studio statistical software (version 1.3.959; R Studio, PBC, 2020). We calculated the natural log response ratio for each of the 16 pairs of urban and rural sites to quantify the effect size of atmospheric phosphorus inputs in urban versus rural sites. The log respose ratio for urban and rural sites was calculated for all forms of atmospheric inputs (bulk, dry, and wet) and analysis type (total, organic, inorganic). We examined log response ratio values for (1) all flux values, (2) all concentration values, and (3) all concentration and flux values combined. We also examined potential relationships between MAT and MAP and the log response ratio for fluxes and concentrations of atmospheric phosphorus deposition. The package "ggpubr" was used in RStudio to report R^2 and p-values using the *stat_cor* function under the package "ggpubr". We also ran simple linear regression models to examine these potential relationships.

3. Results and discussion

3.1. Trends in phosphorus deposition in cities around the globe

Thirty publications yielded phosphorus deposition data for 38 cities globally. Although eleven countries are represented in this meta-analysis, over half of the cities are in three countries: China, Brazil, and USA, emphasizing the need for greater research about atmospheric phosphorus deposition in cities globally. Publications span the years 1991–2022 and have increased over time, demonstrating the rising interest in phosphorus deposition in cities over time (Fig. 2). Among the various forms of phophorus deposition measured, wet phosphate concentration and bulk phosphate deposition were reported in the greatest number of cities (n = 8 cities and n = 15, respectively; see Table 1 and Supplemental Figs. 1 and 2). In contrast, there was only one city for each of the following concentration and deposition types and therefore we could not compare these values across cities: dry total phosphorus concentration (Qingdao, China only) and deposition (Beijing, China), bulk organic phosphorus concentration (Chengdu, China) and deposition (Boston, USA), and throughfall deposition for total phosphorus (Shanghai, China) and organic phosphorus (Boston, USA). It is possible most authors chose to measure phosphate more than organic (or total) phosphorus because phosphate is less labor intensive to measure and it is the most common form of phosphorus taken up by vegetation (Filippelli, 2008). Phosphate is also an important form of phosphorus that leads to

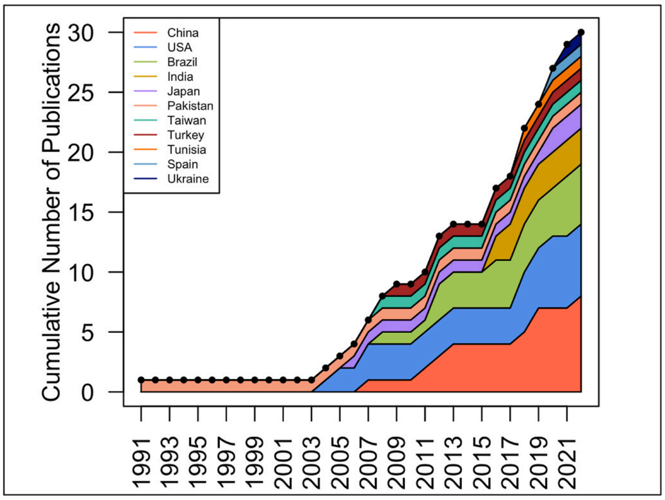

Fig. 2. Cumulative number of publications over time (1991–2022) that measured atmospheric phosphorus inputs in cities around the globe. Solid black circles represent the cumulative number of publications in any given year and the colored bands represent specific countries.

eutrophication in coastal and freshwater ecosystems (Duan et al., 2012 and EPA, 2022) and can impact productivity of the open ocean (Okin et al., 2011).

3.2. Comparing urban and nearby rural sites

When we examined the grand log response ratio for atmospheric concentrations and fluxes for the paired urban-rural sites across all studies, we did not find a statistically significant urban enhancement of phosphorus concentrations nor fluxes as we expected. In other words, the 95% confidence intervals for the grand log response ratios between urban and rural sites across all sites overlapped with zero across all forms (inorganic phosphate and total phosphorus; inorganic + organic phosphorus) and measured sample types of phosphorus (wet, bulk, dry, and throughfall) when analyzed for phosphorus concentration, fluxes, and combined (concentration and fluxes; Fig. 3). The grand median effect sizes for phosphorus concentrations, deposition, and combined (concentrations and deposition together) were 0.1 with 95% confidence interval equal to −0.65 and 2.08, zero with 95% confidence interval equal to −1.12 and 1.44, and zero with 95% confidence interval equal to −0.90 and 1.99, respectively (Fig. 3).

The lack of significantly greater atmospheric phosphorus inputs in urban than rural sites when examining sites around the globe is distinct from past findings for nitrogen deposition. In a meta-analysis of 174 publications with 69 paired urban and rural sites, Decina et al. (2019) found significant enhancement of nitrogen deposition in cities, with almost two-fold the amount of nitrogen deposition in cities compared to nearby rural areas. The lack of difference in atmospheric phosphorus inputs between urban and rural sites is surprising given that nitrogen and phosphorus deposition have overlapping sources, including fossil fuel combustion. However, a greater amount of phosphorus comes from non-anthropogenic sources, such as dust and bioaerosols, compared to nitrogen. Therefore, despite the documented increase in phosphorus in many cities around the globe (e.g. Casartelli et al., 2008; Decina et al., 2018; Yadav and Pandey, 2017), we conclude there is not a broad urban enhancement of phosphorus deposition evident from the data we examined. However, we caution that for most measured types and forms of phosphorus measurements we had too small a sample size to detect differences, demonstrating the paucity of studies comparing atmospheric phosphorus inputs in urban and nearby rural areas and the need for more research in this area.

While we did not find a significant difference in atmospheric concentrations nor deposition when examining all sites together, we found that out of the 16 cities with paired urban-rural sites, the log response ratio was greater than zero for five individual cities for phosphorus concentrations (i.e. Chengdu, Rio Grande, Porto Alegre, Shanghai, and Nyingchi) and for seven individual cities for rates of phosphorus deposition (i.e. Porto Alegre, Chengu, Rajghat, Rio Grande, Chengdu, Fukuoka, and Kyoto; Fig. 3A and B), which was often attributed by authors to fossil fuel combustion and biomass burning. In locations where authors found greater phosphorus inputs in rural than urban sites they often attributed this to application of phosphorus-containing fertilizer and biomass burning, both related to agricultural activity (Casartelli et al., 2008; Koelliker et al., 2004). Pey et al. (2020) attributed increased rural levels of phosphorus fluxes to a severe dust storm that occurred over their period of study. Heindel et al. (2020) specifically recorded significantly greater phosphorus inputs via dust in rural than urban areas in Boulder, USA due to springtime pollen deposits enriched in phosphorus. Dust likely impacted phosphorus inputs greatly in rural areas in our analysis, as observed in Zaragoza, Spain (Fig. 3B), Sevastopol, Ukraine (Fig. 3A and C), and Boulder, USA (Fig. 3B and C; Pey et al., 2020; Varenik and Konovalov, 2021; Heindel et al., 2020).

3.3. Relationships between climate and atmospheric phosphorus inputs

We found a statistically significant positive relationship between MAT and the log response ratio for paired urban-rural fluxes ($R^2 = 0.42$, $p = 0.002$) and combined data (both concentration and flux data; $R^2 = 0.27$, $p = 0.0016$; Fig. 4D and F). In contrast, we found no statistically significant relationships between MAP and log response ratios for the paired urban-rural phosphorus concentrations, fluxes, and combined (both concentration and flux) across all forms (inorganic phosphate and total phosphorus; inorganic + organic P) and measured types of phosphorus (wet, bulk, dry, and throughfall; Fig. 4). These results are in line with past studies that showed positive relationships between air temperature and atmospheric phosphorus concentrations, but not precipitation (Furdui et al., 2022; Varenik et al., 2016; and Tipping et al., 2014). In a study examining air particulate samples from Hamilton (ON, Canada), phosphorus levels peaked in April–June (Furdui et al., 2022). In a similar study in Katsiveli, on the northern shore of the Black Sea, atmospheric phosphate concentrations peaked in the warmest months (Varenik et al., 2016), which was attributed to these also being the driest months of the year. While it would have been ideal to examine seasonal variation in the potential urban enhancement of atmospheric phosphorus deposition in our meta-analysis, this analysis was outside the scope of our study due to the relatively small sample size among measurement types and forms of phosphorus.

While the mechanism behind the relationship between air temperature and atmospheric phosphorus is not yet known, together these results demonstrate that climatic factors like temperature enhance the urbanization effect, such that sites with warmer temperatures experience a greater difference in urban vs. rural phosporus deposition rates. These results indicate that climatic factors, like temperature, impact atmospheric phosphorus deposition on a global scale more than urbanization alone, which is important considering that temperatures are rising around the globe (NOAA National Centers for Environmental information, 2022).

3.4. Limitations of this study

Despite the large geographic extent and increasing interest over time in the number of studies examining atmospheric phosphorus deposition in cities around the globe (Figs. 1 and 2), we find there are still a limited number of studies examining atmospheric phosphorus inputs in cities and for many forms of phosphorus deposition. The three countries (China, Brazil, and USA) represented most dominantly in this analysis are also three of the largest countries in the world by population and area (World The World Factbook, 2021), yet many cities within each of

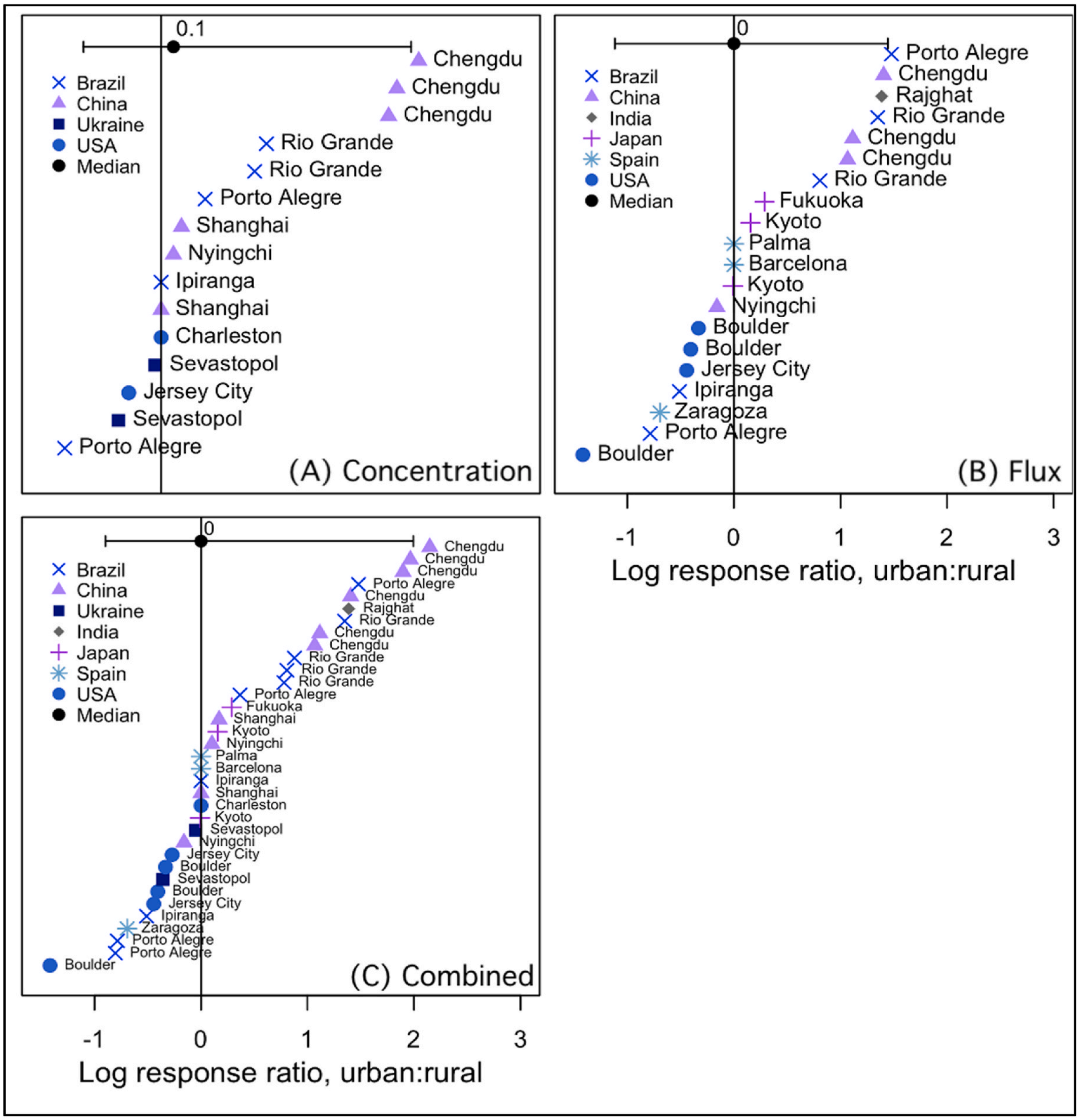

Fig. 3. Log response ratio comparing urban to rural sites for (A) concentrations, (B) fluxes, and (C) combined (both concentration and fluxes) across all forms (inorganic phosphate and total phosphorus; inorganic + organic P) and measured types of phosphorus (wet, bulk, dry, and throughfall). City names are listed next to each value and countries are designated by different shapes and colors. Multiple cities had more than one concentration or flux value for different measured types of phosphorus, which is why some city names appear more than once. The grand median effect size with 95% confidence intervals across all studies are shown at the top of each figure for (A) concentration, (B) flux, and (C) combined values. Values greater than zero indicate an urban enhancement.

these countries lack measurements of phosphorus in atmospheric deposition. Because these countries contain a large percentage of the world's population combined (Pew Research Center, 2022), it is crucial to further understand how anthropogenic activities in these countries influence atmospheric phosphorus inputs. In terms of form of phosphorus deposition, there are a limited number of studies that have measured organic phosphorus in atmospheric deposition in cities (Supplemental Fig. 2). Boston, USA and Chengdu, China are the only cities that included measurements of organic phosphorus deposition (Decina et al., 2018 and Ling et al. 2022), limiting our ability to compare organic phosphorus deposition in urban vs. rural areas around the globe.

4. Conclusions

While there was not a significant difference in atmospheric phosphorus inputs between urban and nearby rural sites when examining all sites together, we found that the difference in atmospheric phosphorus inputs between urban and rural sites was enhanced with higher air temperatures, demonstrating that climate interacts with urbanization to impact atmospheric phosphorus inputs around the globe. Because atmospheric phosphorus inputs are likely to continue to increase over time in cities from sources such as fossil fuel combustion, flame retardants, waste production, construction, and biomass burning, we recommend future studies continue to measure atmospheric phosphorus inputs and examine potential relationships with climate in cities and nearby rural areas.

CRediT authorship contribution statement

Kylie Blake: Conceptualization, Methodology, Software, Formal

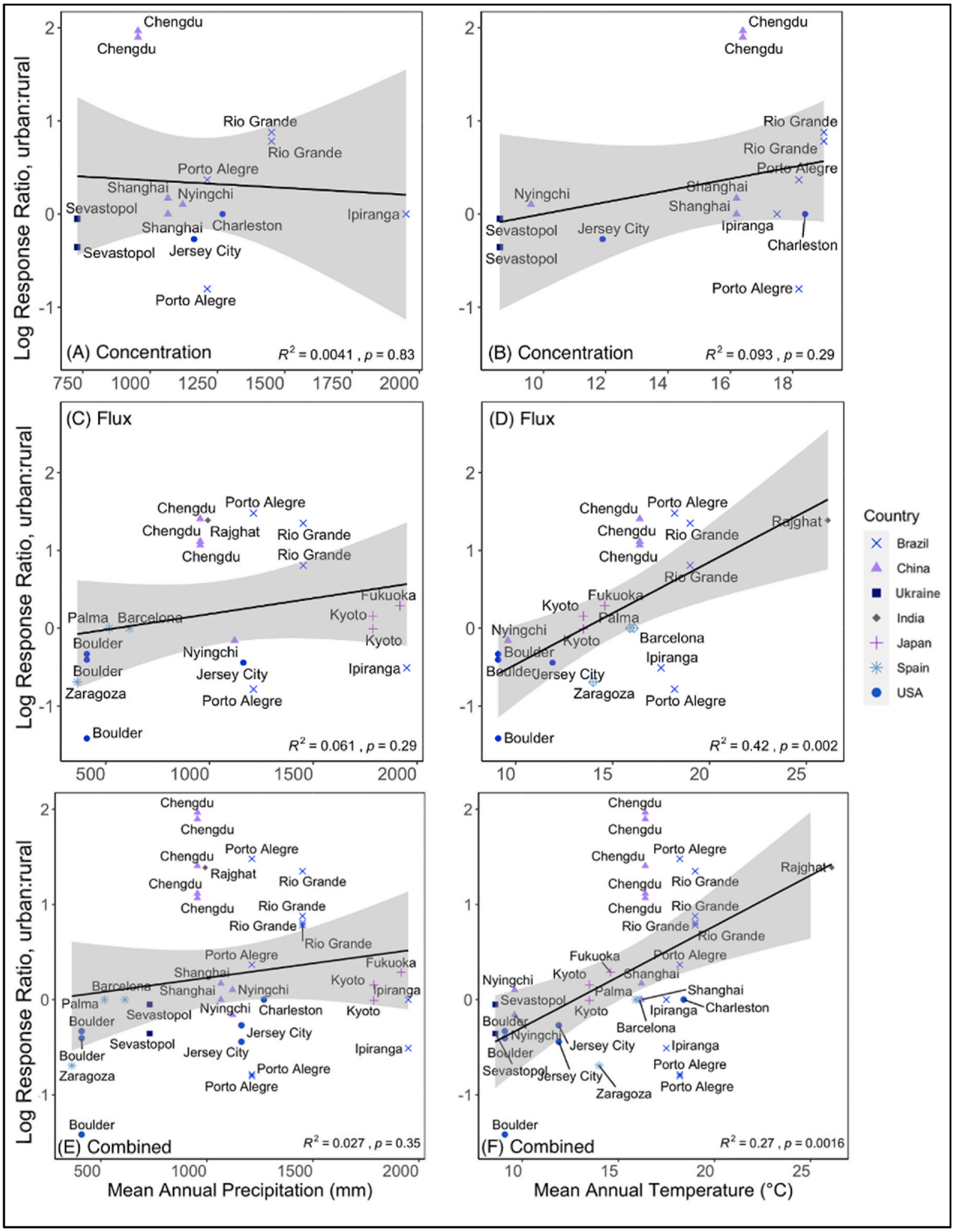

Fig. 4. Relationships between atmospheric phosphorus deposition and climatic variables for (A and B) concentrations, (C and D) fluxes, and (E and F) combined (both concentration and fluxes) across all forms (inorganic phosphate and total phosphorus; inorganic + organic P) and measured types of phosphorus (wet, bulk, dry, and throughfall). City names are listed next to each value and countries are designated by different shapes and colors. Some cities had more than one concentration or flux value for different measured types of phosphorus, which is why some city names appear more than once.

analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **Pamela H. Templer:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Pamela Templer reports financial support was provided by National Science Foundation. Pamela Templer reports a relationship with

National Science Foundation that includes: funding grants.

Data availability

Data will be published.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2023.119940.

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