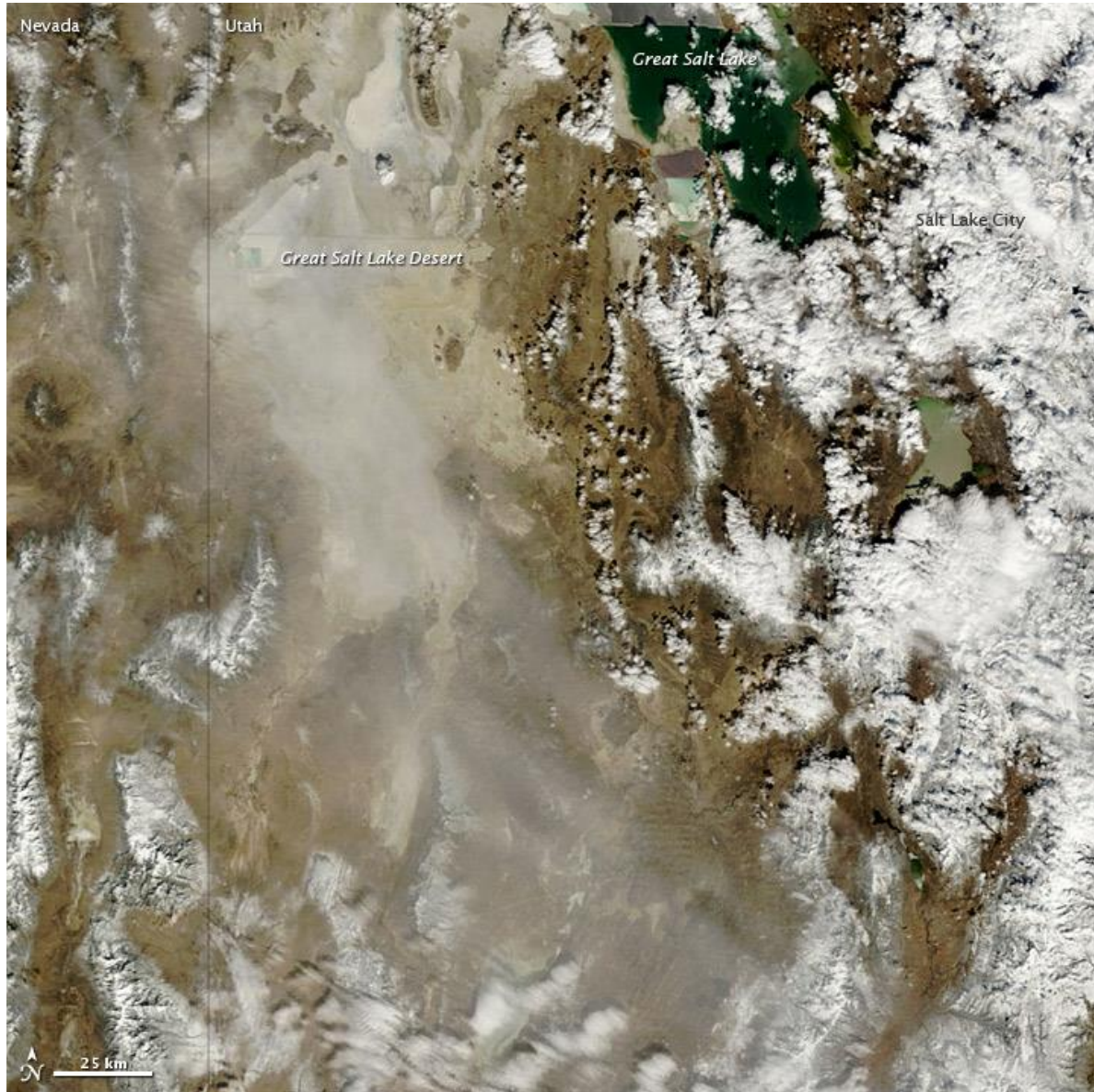


Estimating total and bioavailable nutrient loading to Utah Lake from the atmosphere

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NASA image courtesy Jeff Schmaltz

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Table of Contents

Table of Tables	3
Table of Figures.....	3
Abstract.....	4
1.0 Background and Scope	4
2.0 Introduction	5
2.1 Dust mediated transport of nutrients	5
2.1.1 Dust: composition	5
2.1.2 Dust: transport of nutrients to lake systems	6
2.2 Wet deposition of nutrients	8
3.0 Methods	8
4.0 Results	9
4.1 Particulate/dust deposition	9
4.1.1 Urban dust deposition rates in northern Utah	9
4.1.2 Urban dust phosphorus concentrations and deposition rates	9
4.1.3 Urban dust nitrogen concentrations and deposition rates	11
4.1.4 Regional dust deposition rates in northern Utah.....	11
4.1.5 Regional dust phosphorus concentrations and deposition rates.....	12
4.1.6 Regional dust nitrogen concentrations and deposition rates.....	15
4.2 Wet Deposition.....	16
4.2.1 Urban wet phosphorus deposition rates	16
4.2.2 Regional wet phosphorus deposition rates.....	16
4.2.3 Urban and regional wet and particulate nitrogen deposition rates.....	17
4.3 Estimating nutrient loading to Utah Lake	19
4.3.1 Estimating total and bioavailable phosphorus deposition to Utah Lake	19
4.3.2 Estimating total nitrogen deposition to Utah Lake	20
5.0 Recommendations for measuring the atmospheric deposition of nutrients to Utah	21
5.1 Option 1(preferred). Comprehensive spatial analyses using active sampling techniques.....	21
5.1.1 Dry fluxes	21
5.1.2 Wet fluxes	22
5.2 Option 2. Point sampling of deposition using passive sampling techniques.....	22
5.2.1 Sampler Location.....	22
5.2.2 Dry fluxes	24
5.2.1 Wet fluxes	25
References	26

Table of Tables

Table 1 Contemporary urban dust deposition rates in northern Utah (2016-2018)	9
Table 2 Total phosphorus deposition rates as measured in urban cites around the world and in Utah	10
Table 3 Estimated total and water-soluble deposition rates for urban dusts in northern Utah	11
Table 4 Regional dust deposition rates around Utah.....	12
Table 5 Phosphate concentrations from regional dusts east of the major regional dust producing sources	13
Table 6 Water soluble and organic phosphorus fractions for regional dusts in the intermountain west.	15
Table 7 Calculated mean and range of soluble and "bioavailable" (soluble + organic) P deposition	15
Table 8 Measurements of urban TP deposition rates from around the world and Utah estimates.....	16
Table 9 Wet phosphorus deposition rates from remote locations around Utah as measured by the NADP.	17
Table 10 Summary of all estimated P deposition rates and estimated loading to Utah Lake in metric tons per year.	19
Table 11 Estimated range of wet, dry, and total N deposition to Utah Lake from the CMAQ model and TDep working group from NADP and other affiliated monitoring networks.....	21

Table of Figures

Figure 1 Locations of phosphate rock in Utah. Source: Utah Geological Survey https://geology.utah.gov/map-pub/survey-notes/todays-and-tomorrows-phosphate/	14
Figure 2 Wet, Dry, and total estimates of all nitrogen species. The location of Utah Lake is shown on each map. Dry deposition estimates are based on aerosol concentrations and modeled deposition rates whereas wet deposition rates are based on measured deposition rates combined with the CMAQ model. Total deposition rates include all forms of nitrogen species, please see text for full details. 18	18
Figure 3 Image from Google Earth. Utah Lake with mean annual wind roses for five locations surrounding the lake. Also shown is an active mine and housing development on the western shores of the lake.	20
Figure 4. 2a (top left) From Pye 1987 showing a generalized scheme of erosion and entrainment from a dust producing surface, 2b (top right) a tractor producing dust in northern Utah (photo credit: Patrick Strong, 2c (bottom left) an ATV producing dusts in Utah (photo credit: David G. Paul, 2d (bottom right) a car producing dust in Utah.....	24

Abstract

Anthropogenic activities have led to increases in the emission, atmospheric transport, and deposition of key nutrients. In addition, climate change along with anthropogenic soil disturbance has led to recent increases in the mobilization and transport of soils and other particles through the atmosphere, collectively described here as dust. These increased emissions have led to growing interest and concern over the composition of atmospheric deposition and total loading of nutrients to aquatic systems. In the last several decades, much effort has been directed towards the measurement and modeling of nitrogen deposition through wet and aerosol deposition. Less is known about the capacity for regional dusts to transport nutrients in meaningful quantities in space and time. This paper summarizes the state of knowledge on dust deposition, composition, and potential effects on aquatic ecosystems. More specifically, this paper focuses on the potential for atmospheric aerosol, dust, and wet deposition to contribute phosphorus and nitrogen to Utah Lake in Provo, Utah. As part of this effort I, a) summarize recent estimates of dust deposition from Utah and elsewhere in the Great Basin, b) summarize current knowledge on total and soluble phosphorus loading from dusts, and c) summarize atmospheric deposition rates of nitrogen from wet, gaseous, and particulate sources. I use the above information to generate estimates of total (urban + regional) nutrient loading to Utah Lake. Based on the compiled information of observed deposition rates, we arrive at a minimum of 1.4 to a maximum of 13.4 metric tons of Total Phosphorus (TP) that may be deposited on Utah Lake per year. The annual deposition rate of the bioavailable fraction, here defined as the soluble plus organic fraction, of phosphorus is estimated at a minimum of 1.1 to a maximum of 7.9 metric tons. Because there is an interest in determining the maximum possible deposition flux of P to Utah Lake, we determined the maximum loads based on the maximum measured deposition rates and phosphorus concentrations applied over the full year, and, extended the urban zone of influence to 2 and 4 times that observed at Lake Tahoe. Total nitrogen loading is estimated between 153 and 288 metric tons per year. Recommendations on best practices for the measurement of particulate deposition onto a large lake are also provided.

1.0 Background and Scope

The Utah Lake Water Quality Study Science Panel commissioned this white paper to a) summarize existing knowledge on the atmospheric transport and deposition of nutrients in Utah and the Great Basin, specifically phosphorus (P) and nitrogen (N), and b) use this current knowledge and regional measurements of wet and dry nutrient deposition to provide estimated loading rates to Utah Lake. The information will support ongoing efforts to model nutrient budgets in Utah Lake. New analyses and modeling are beyond the scope of this effort. However, recommendations on the measurement and monitoring of nutrient deposition to Utah Lake are provided.

The atmospheric transport of nutrients to aquatic systems can occur as particulate (dust), wet, or gaseous deposition. Because phosphorus does not have a stable gaseous form it is typically transported through the atmosphere in association with particulates. Particulate deposition is heterogeneous in space and time and not routinely measured. Accordingly, much of this summary is directed towards estimating the dust-mediated transport of phosphorus. Nitrogen is transported in significant quantities through wet, gaseous, and particulate deposition. Because there is substantially more information and data on the transport and deposition of reactive nitrogen (Nr) in various forms,

estimated deposition rates to Utah Lake presented here are based on the combined measurement and modeling efforts of US national networks (TDep, 2019).

2.0 Introduction

Utah Lake is a large shallow lake in north-central Utah. Though the lake covers an area of 385 km², the mean depth is only 4 feet. The lake is near a large urban center (Provo, population: 117,000) and downwind from major southwestern dust-producing regions including the Great Basin, Mojave, and Sonoran deserts. The lake is currently eutrophic and recent frequent harmful algal blooms have led to urgency in quantifying the nutrient budget for the lake including the atmospheric contribution of phosphorus and nitrogen. Here I use existing data and literature to develop a first-order estimate of nutrient loading to Utah Lake from the atmosphere. Additionally, I provide recommendations on the measurement and monitoring of nutrient deposition to this large lake.

2.1 *Dust mediated transport of nutrients*

Atmospheric or aeolian dust typically refers to the mineral particulate mass eroded from the Earth's surface and subsequently transported through the atmosphere. However, particulate aerosols are generated from a number of natural and anthropogenic sources not limited to soil erosion, and include industrial emissions (e.g. mining, fossil fuel burning, cement production), transportation, civil engineering, biomass burning and residential heating sources, plant products (e.g. pollen), and volcanic emissions (Monks et al. 2009, Mahowald et al. 2017). Because all of the above have the capacity to influence receiving lakes (Mas howald et al. 2008b, Brahney et al. 2015b), for the purpose of this white paper, all atmospheric particulates will be considered as dust.

Dust deposition rates have increased in recent centuries and decades (Brahney et al. 2013, Clow et al. 2016) linked both to human activities (Neff et al. 2008, Brahney et al. 2019) and to climate (Munson et al. 2011, Flagg et al. 2014). Land-use activities can reduce threshold wind velocities required to produce dust (Belnap and Gillette 1998) and drought can reduce the amount of soil-stabilizing vegetation on the landscape (Field et al. 2009, Munson et al. 2011). However, dust events are episodic and controlled by stochastic factors. As a result, deposition rates are highly variable across space and time. To illustrate, fifteen years of dust on snow data from the intermountain west has shown as little as 3 events to as many as 12 events through the winter season with corresponding mass deposition rates ranging from 1.65 to 64.3 g m⁻² y⁻¹ (CODOS 2019).

At a global scale, dust deposition rates range from 0 to 450 g m⁻² y⁻¹ with the highest deposition rates influenced by proximal (<10 km) sources (Lawrence and Neff 2009). Lawrence and Neff (2009) partitioned dusts into broad categories based on the distance from source including “Local” dust sources originating from 0-10 km away, “Regional” from 10-1000 km, and “Global” from greater than 1000 km that align with general dust properties. Distance will influence the deposition rate and also the spatial heterogeneity in deposition, the chemical composition, and the particle size distribution.

2.1.1 *Dust: composition*

The composition of dust varies with source region as well as factors that alter composition during transport. The primary controls on dust composition are parent geology and degree of soil

development and/or land use (Moreno et al. 2006). For example, dusts from the Sahara tend to be minerogenic with only a minor (few percent) contribution from organic material (Eglinton et al. 2002). In contrast, dusts generated from semi-arid and agricultural regions tends to contain a greater fine organic and nutrient-rich fraction leading to dust material with >60% organic material (Malm et al. 2004). As a result, dusts from these regions may be enriched in rock-derived nutrients, such as phosphorus and calcium, as well as plant fixed nutrients, such as nitrogen. Because the wind erosion of soil removes the fine nutrient-rich fraction (Neff et al. 2005), dusts can be relatively enriched in plant nutrients compared to their source region. Dusts may also change appreciably in composition during atmospheric transport due to sorting, scavenging, and chemical reactions (Marx et al. 2008). The progressive loss of larger size fractions can lead to a decline in heavier and larger minerals such as zircons and silicates. Various gaseous and particulate emissions in urban areas can also be scavenged by dust during transport through adsorption, coagulation, nucleation, and precipitation reactions (Marx et al. 2008). As a result, dusts produced in or passing through urban centers will have a composition influenced by combustion sources (fossil fuels, incinerators), volatile metals, and organic contaminants (Han et al. 2004, Mahowald et al. 2008a, Xiong et al. 2017).

2.1.2 Dust: transport of nutrients to lake systems

Psenner, in 1999 was one of the first to identify the capacity for dust to affect nutrient subsidies in mountain lakes systems. Since then, other studies elsewhere in mountain regions of Europe, Asia, and the US have shown the effects of dust associated P deposition in controlling lake water nutrient chemistry, productivity, and species composition (Sickman et al. 2003, Morales-Baquero et al. 2006, Pulido-Villena et al. 2008a, Vicars et al. 2010, Ballantyne et al. 2011, Tsugeki et al. 2012, Brahney et al. 2015a). For example, there is a growing amount of evidence suggesting dust may transport ecologically significant quantities of nutrients to pristine oligotrophic freshwater ecosystems where catchment sources of nutrients are sparse (Morales-Baquero et al. 2006, Pulido-Villena et al. 2008b, Ballantyne et al. 2011, Mladenov et al. 2012, Brahney et al. 2014). The transport of the key limiting nutrients nitrogen and phosphorus via dust to aquatic systems may occur in both the organic and inorganic fractions. However, the bioavailability of nutrients from dusts may vary with dust composition. For example, organic phosphorus in dusts is likely more readily available than inorganic apatite phosphorus. Conversely, nitrogen may be more readily available in the soluble inorganic fraction than the total organic fraction. Understanding the bioavailability of nutrients from dust is an active area of research.

The dust-mediated transfer of phosphorus to aquatic systems has primarily focused on oligotrophic mountain lake systems as they have few alternative watershed sources of nutrients (Morales-Baquero et al. 2006, Vicars and Sickman 2011, Camarero and Catalán 2012, Brahney et al. 2014). Similarly, the atmospheric deposition of N and its effect on aquatic systems is pronounced in mountain watersheds where natural concentrations are low and abatement through catchment uptake is limited (Baron et al. 2000, 2011, Wolfe et al. 2001, Nydick et al. 2003, Elser et al. 2009). Thus, in mountain systems, a small change in atmospheric loads can result in a large change in absolute nutrient concentrations causing mountain lakes to be more susceptible to the influence of atmospheric deposition than lakes with large watersheds (Moser et al. 2019). For example, in the Sierra-Nevada Mountains of Spain, dust associated P deposition ranged from 24-38 $\mu\text{g P m}^{-2} \text{d}^{-1}$, a seemingly small contribution, yet this deposition rate had measurable effects on productivity, nutrient ratios, bacterial

abundance, and plankton diversity (Morales-Baquero et al. 2006, Pulido-Villena et al. 2008b, Reche et al. 2009, Camarero and Catalán 2012).

Nitrogen deposition via rain and gaseous aerosol deposition is well monitored and modeled (NADP 2019). Less is known about the contributions of nitrogen from dry dust material as this fraction is rarely analyzed, however, particulate N deposition is modeled based on atmospheric aerosol concentrations. In some areas, this fraction could potentially be an underappreciated component of the atmospheric nitrogen depending on the composition of the dust (Neff et al. 2002, Cornell 2011). The form and bioavailability of nitrogen associated with particulates will likely vary by biogeoclimate and land-use. For example, in the Mediterranean region, the organic fraction has been tied linearly to calcium deposition, indicating a dust source of organic N (Mace et al. 2003b) whereas agriculture and biomass burning significantly contribute to the particulate N flux in other areas (Mace et al. 2003a). The water-soluble organic nitrogen fraction has been shown to contribute approximately 25% of the flux of total nitrogen to Europe (Mace et al. 2003b, Cornell 2011), 2/3 of the flux to areas in North America (Neff et al. 2002), and up to 45% of the total nitrogen flux in the Amazon basin (Mace et al. 2003a, Cornell 2011).

In contrast to atmospheric nitrogen, phosphorus has no stable gaseous form and thus, atmospheric transport largely occurs as particulates (Tipping et al. 2014). The most important sources of phosphorus-containing dusts are soil emissions, biomass burning, and to some extent industrial and mining emissions (Crutzen and Andreae 1990, Ginoux et al. 2012, Wang et al. 2015). On average, dusts are enriched in phosphorus over average crustal composition by a factor of 1.6 (Lawrence and Neff 2009) and therefore dusts generally have the capacity to fertilize receiving environments. A recent study showed that oligotrophic (low phosphorus) lakes and streams are disappearing in the continental US; the sites most affected tended to be the most remote with the least amount of human influence within the catchment (Stoddard et al. 2016). This strongly suggests that phosphorus is likely entering these catchments via the atmosphere potentially as dust. Biomass burning may also transport significant quantities of P to alpine lakes in particulate form (Newman 1995). In regions with intense burning, lakes have been eutrophied due to large atmospheric contributions (Tammatamah et al. 2005, Boy et al. 2008). However, the concentration of P in emitted ash may vary with both the type of vegetation burning and the intensity of the fire (Maenhaut et al. 1996, Vicars et al. 2010, Vicars and Sickman 2011)

The effect of dust on phosphorus concentration in lakes is likely to vary widely with both particulate source and catchment geology. For many minerogenic dusts, the majority of P is bound in apatite, a mineral with a slow phosphorus leaching capacity. In contrast, dust from agricultural regions may have larger concentrations of bioavailable P in the organic form. Additional considerations are the extent and type of vegetation in the catchment as well as the catchment geology. These catchment characteristics will determine the capacity for dust, and dust leached phosphorus, to be transported to lake basins. In steep mountain catchments, dust material can be mechanically focused into lake basins by either wind redistribution, or overland flow. However, catchment geology will play a role in the transport of phosphate as it binds tightly to Al and Fe minerals. An abundance of these minerals within catchments may effectively immobilize phosphorus on the landscape (Kopáček et al. 2011, Kopáček et al. 2015). Conversely, watersheds with poor soil development and a low abundance of Al and Fe bearing minerals may allow for the effective transport of dust-phosphorus to lake basins (Sickman et

al. 2003, Morales-Baquero et al. 2006, Pulido-Villena et al. 2008b, Vicars and Sickman 2011, Tsugeki et al. 2012, Brahney et al. 2014).

2.2 *Wet deposition of nutrients*

Several comprehensive reviews on atmospheric aerosols and wet deposition of nutrients have been written in recent years (e.g. Aneja et al. 2001, Mahowald et al. 2017, TDep 2019) and will not be discussed in detail here. With respect to broad trends in emission and deposition, the Clean Air Act has led to substantive decreases in the amount of NO_x emitted to the atmosphere over the last several decades. However, in many regions of the West and Midwest, the atmospheric emission of ammonium aerosols has substantively increased. The spatial and temporal variability is accounted for in the models produced annually by joint national networks (please see section 4.3.2).

3.0 Methods

To determine the potential for atmospheric deposition to contribute P and N to Utah Lake, I compiled data from both published literature and ongoing studies at Utah State University and the University of Utah on the following,

1. Dust deposition rates in Utah, the Great Basin, and the Southwestern US with comparisons to other similar systems.
2. The phosphorus composition of dusts from Utah compared to other regions as total phosphorus, water-soluble phosphorus, and organic phosphorus
3. The nitrogen composition of dusts from the southwest
4. The wet deposition of phosphorus from Utah and elsewhere in the world
5. The wet deposition of reactive nitrogen species around Utah Lake

The data summarized above was then used to derive both local and regional dust deposition rates as well as total, organic, and dissolved nutrient fluxes. As has been demonstrated elsewhere, local sources are not expected to contribute significantly beyond the shoreline of Utah Lake (Cole et al. 1990, Dolislager et al. 2012, VanCuren et al. 2012a, 2012b) whereas regional sources, such as the semi-arid and arid regions of the Colorado Plateau, are assumed to contribute uniformly to the lake. Because there is no current data on the attenuation of urban atmospheric deposition onto Utah Lake, I apply three different attenuation equations. The Lake Tahoe study indicated that the zone of influence diminished to 10% at 200m. I applied first order rate decay equation that mimicked that observed at Lake Tahoe. In an attempt to calculate the maximum deposition to Utah Lake, and because there is only one example from a large lake, we apply first order rate decay equations where the urban influence would extend to 2 and 4x that observed at Lake Tahoe, i.e. 10% of the urban deposition rate at 400 and 600m. The potential effect of inversions is not accounted for here as there is no available data to do so. Note that inversions in Utah County make up between 3 and 7% of the year. Regional loading rates are applied to the remainder of the lake to derive total annual loads of nutrients to Utah lake in metric tons.

4.0 Results

4.1 Particulate/dust deposition

4.1.1 Urban dust deposition rates in northern Utah

Dust deposition rates in the urban regions of northern Utah ranges from 24.7 to 56.7 g m⁻² yr⁻¹, with an average of 39 g m⁻² yr⁻¹ (Table 1). These rates are larger than those observed in the desert regions of California and Nevada (3.92 - 20.98 g m⁻² yr⁻¹), which include sites near the urban areas of Las Vegas (Reheis and Kihl 1995, Reheis 2003, 2006), but are similar to rates measured in other urban areas of the southwestern USA, e.g. Phoenix, Arizona at 54.5 g m⁻² yr⁻¹ (Péwé and Science 1981). For reference, the largest recorded urban deposition rates are from Kuwait City, in the Arabian Desert at 600 g m⁻² yr⁻¹ (Al-Awadhi and AlShuaibi 2013).

Table 1 Contemporary urban dust deposition rates in northern Utah (2016-2018)

Region	Site	Method	Dust Source	Class	Deposition Rate g m ⁻² yr ⁻¹	Data Source
Utah	Provo	Bulk Marble	Urban	Local	28.7	Goodman et al In rev.
Utah	SLC	Bulk Marble	Urban	Local	24.9	Goodman et al In rev.
Utah	Ogden	Bulk Marble	Urban	Local	33.8	Goodman et al In rev.
Utah	Logan	Bulk Marble	Urban	Local	24.7	Goodman et al In rev.
Utah	Provo	Bulk Marble	Urban	Local	49.0	Scholz et al. 2019
Utah	SLC	Bulk Marble	Urban	Local	55.5	Scholz et al. 2019
Utah	Ogden	Bulk Marble	Urban	Local	56.7	Scholz et al. 2019
Utah	Logan	Bulk Marble	Urban	Local		Scholz et al. 2019
Utah Urban Average					39.0	
Utah Urban Range					24.7-56.7	

4.1.2 Urban dust phosphorus concentrations and deposition rates

4.1.2.1 Total Phosphorus in Urban Dusts and Deposition Rates

Urban total phosphorus deposition rates in urban areas were determined from dust deposition rates and corresponding dust phosphorus concentrations. For reference on expected phosphorus deposition rates, a compilation of total phosphorus (TP) deposition (wet and dry) from around the world found measurable deposition rates ranged from 4 mg P m⁻² yr⁻¹ of to 400 mg P m⁻² yr⁻¹ (Brahney et al. 2015b). The highest deposition rates were found in the southern hemisphere close to areas of biomass burning (400 mg TP m⁻² yr⁻¹) or near industrial sources, eg. Jena, Germany at 200 mg TP m⁻² yr⁻¹.

Two methods were used to calculate and estimate urban TP deposition rates around Provo, Utah,

- 1) The average of two data points of observed dust concentrations and masses from urban centers of northern Utah (Goodman et al. in review). Using this data, the mean urban dust TP deposition rate for northern Utah was 139.3 mg TP m⁻² yr⁻¹ (Table 2).
- 2) The average concentrations of P in urban dusts from multiple regions applied to the average urban dust deposition rate determined for northern Utah. Average percent TP concentrations in the fine fraction (<2.5 μm) is 1% for coal, oil boiler, gasoline and diesel engines, and incinerator sources of dusts and 0.5% for the coarse (>10 μm) fraction of the same (Mahowald et al. 2008b). I use average

grain size distributions for local and urban dusts to derive an estimated deposition rate of 93.6 mg TP m⁻² yr⁻¹ (Table 2).

I note that Olsen et al. 2019 measured TP deposition on the shores of Utah Lake and found deposition rates between 1.26 and 31.38 (average 8.1) mg P m⁻² day⁻¹, up to two orders of magnitude higher than has been measured anywhere else in the world (Tipping et al. 2014, Brahney et al. 2015b). The study did not consider point sources of atmospheric contamination including open pit mines, the construction of housing developments, agricultural activities, roads, and urban centers. Though a considerable effort on the part of the authors, at present, I elect not to include these data points until they can be confirmed or refuted by a study that follows established protocols outlined by the NADP and the atmospheric deposition community. Please see the section on recommendations (5.0).

Table 2 Total phosphorus deposition rates as measured in urban cites around the world and in Utah

Region	Site	Method	Dust Source	Class	Deposition Rate mg TP m ⁻² yr ⁻¹	Data Source
China	Lake Taihu 2007	Bulk	Urban/Lake	Local/Regional	84.0	Zhai et al, 2009
China	Lake Taihu (2002-2003)	Bulk	Urban/Lake	Local/Regional	395.0	Zhai et al, 2009
Soudi Arabia	Riyadh City	Bulk	Urban	Local	104.0	Modaihsh et al 1997
Germany	Jena	Bulk	Urban	Local	200.0	Oelmann et al 2007
Poland	(central Poland)	Bulk	Urban/Forest	Local	181.0	Kram 2010
Singapore	Marina	Active Sampler	Urban	Local	140.0	He et al 2011
Utah	Provo	Bulk Marble	Urban	Local	189.6	Goodman et al In rev.
Utah	Logan	Bulk Marble	Urban	Local	88.9	Goodman et al In rev.
Utah Average	Urban	Bulk Marble	Urban	Local	139.3	Goodman et al In rev.
Utah	Urban	Estimate	Urban	Local	93.6	This review

4.1.2.2 Soluble Phosphorus from Urban Dusts and Deposition Rates

Few studies quantify leachable phosphate from deposition samples and even fewer studies have attempted to examine the bioavailable component. The exact fraction of leachable or bioavailable forms of P in dusts will vary significantly with dust composition. Tipping et al. 2014 summarized TP, total dissolved P (TDP) and soluble reactive P (SRP) globally and found mean TP, TDP, and SRP deposition rates of 27, 19, and 14 mg P m⁻² yr⁻¹. On average TDP was 75% of TP, but very few sites contained both measurements. Apart from our own studies (data not yet available), I only found only a few studies where leachable phosphates were measured from dusts that are partially derived from urban sources. In China, Luo et al 2011 found that soluble phosphate accounted for ~50% of the total aerosol phosphate load to Lake Taihu with deposition rates that ranged from 2 to 22 mg SRP m⁻² yr⁻¹ (Luo et al. 2011). Two nearby coal-fired power plants appeared to be the dominant source of aerosol P (Luo et al. 2011). Similarly, in a mixed urban-forested catchment Gao et al. 2017 measured SRP and PO₄³⁻ deposition rates at 19.6 and 25.6 mg P m⁻² yr⁻¹. If I assume a minimum of 50% and a maximum of 75% of the deposited phosphorus is leachable, I arrive at estimated leachable phosphorus deposition rates of 45 to 142 mg P m⁻² yr⁻¹ in urban areas (Table 3).

Table 3 Estimated total and water-soluble deposition rates for urban dusts in northern Utah

Urban P depositin in $\text{mg m}^{-2} \text{ yr}^{-1}$	Total P	Mean (50%)	Max (75%)
		Water Solbule	Water Solbule
Minimum	88.9	44.5	66.7
Mean	139.3	69.7	104.5
Maximum	189.6	94.8	142.2

4.1.3 Urban dust nitrogen concentrations and deposition rates

Estimates of nitrogen concentrations from urban dusts are not available. However, please see section 4.3.2 on estimating nitrogen deposition loading rates to Utah Lake, which includes this fraction.

4.1.4 Regional dust deposition rates in northern Utah

The Colorado Plateau, and the Mojave and Sonoran deserts are the primary sources of regional dusts to southwestern USA. Regional dust deposition rates as determined from mountain regions east of the Colorado Plateau during the years 2011 through present (June 2019) range from 1.4 to 15.6 $\text{g m}^{-2} \text{ yr}^{-1}$ with an average deposition rate of 6.2 $\text{g m}^{-2} \text{ yr}^{-1}$ (Table 3). Dust deposition rates in southeastern Utah (Canyonlands) are generally higher averaging 28.9 $\text{g m}^{-2} \text{ yr}^{-2}$ while sites on the western edge of the Colorado Plateau are lower at 3.6 $\text{g m}^{-2} \text{ yr}^{-1}$.

Table 4 Regional dust deposition rates around Utah.

Deposition Region	Site	Method	Years	Class	Deposition Rate $\text{g m}^{-2} \text{yr}^{-1}$	Source
Utah	Uinta (D1)	Bulk Marble	2011-2012	Regional*	4.7	Munroe 2014
Utah	Uinta (D1)	Bulk Marble	2012-2013	Regional*	2.3	Munroe 2014
Utah	Uinta (D2)	Bulk Marble	2011-2012	Regional*	3.6	Munroe 2014
Utah	Uinta (D2)	Bulk Marble	2012-2013	Regional*	2.9	Munroe 2014
Utah	Uinta (D3)	Bulk Marble	2011-2012	Regional*	5.5	Munroe 2014
Utah	Uinta (D3)	Bulk Marble	2012-2013	Regional*	4.1	Munroe 2014
Utah	Uinta (D4)	Bulk Marble	2011-2012	Regional*	3.9	Munroe 2014
Utah	Uinta (D4)	Bulk Marble	2012-2013	Regional*	1.4	Munroe 2014
Utah	Uinta East	DSI (Brahney)	2018	Regional	8.8	Brahney unpublished
Utah	Uinta East	DSI (Brahney)	2019	Regional	3.2	Brahney unpublished
Uinta Average					4.0	
Utah	CM2 (CanyonInds)	Bulk Marble	1998-2007	Regional	14.9	Reheis and Urban 2011
Utah	CM3 (CanyonInds)	Bulk Marble	1998-2007	Regional	21.9	Reheis and Urban 2011
Utah	CM4 (CanyonInds)	Bulk Marble	1998-2007	Regional	33.6	Reheis and Urban 2011
Utah	CM8 (CanyonInds)	Bulk Marble	1998-2007	Regional	19.8	Reheis and Urban 2011
Utah	CP1 (CanyonInds)	Bulk Marble	1998-2007	Regional	15.1	Reheis and Urban 2011
Utah	CP2 (CanyonInds)	Bulk Marble	1998-2007	Regional	20.4	Reheis and Urban 2011
Utah	CP3 (CanyonInds)	Bulk Marble	1998-2007	Regional	23.8	Reheis and Urban 2011
Utah	CP4 (CanyonInds)	Bulk Marble	1998-2007	Regional	51.4	Reheis and Urban 2011
Utah	Canyonlands	DSI (Brahney)	2018	Regional*	47.4	Brahney unpublished
Utah	Canyonlands	DSI (Brahney)	2019	Regional*	40.4	Brahney unpublished
Canyonland Average					28.9	
Utah	Bryce Canyon	DSI (Brahney)	2018	Regional	4.11	Brahney unpublished
Utah	Bryce Canyon	DSI (Brahney)	2019	Regional	3.03	Brahney unpublished
Bryce Canyon Average					3.57	
Colorado	SASP	Dust on Snow	2004-2008	Regional	6.53	Lawrence et al 2010
Colorado	Loch Vale	Dust on Snow	2017-2018	Regional	5.83	Brahney unpublished
Colorado	Lake Fork	Dust on Snow	2017-2018	Regional	6.96	Brahney unpublished
Colorado	Grizz Ridge	Dust on Snow	2017-2018	Regional	5.5	Brahney unpublished
Colorado	Grand Mesa	Dust on Snow	2017-2018	Regional	13.5	Brahney unpublished
Colorado	University Camp	Dust on Snow	2017-2018	Regional	10.5	Brahney unpublished
Colorado	Molas Lake	Dust on Snow	2017-2018	Regional	15.6	Brahney unpublished
Colorado Mountain Average					9.2	
Mountain West Average					6.2	

*Because samplers are not always > 2m above the surface I assume some local contribution

4.1.5 Regional dust phosphorus concentrations and deposition rates

4.1.5.1 Total Phosphorus in Regional Dusts of Utah and Deposition Rates

Measured total phosphorus concentrations from Utah and Colorado mountain ranges, east of the dominant regional sources of dusts, ranged from 0.56 mg g^{-1} to 5.08 mg g^{-1} , with a mean of 1.56 mg g^{-1} . Some of the highest measured total phosphorus concentrations occur in the Uinta Ranges (Table 4), which is proximal to several geologic sources of apatite including active mining operations (Figure 1).

Table 5 Phosphate concentrations from regional dusts east of the major regional dust producing sources

Deposition Region	Site	TP mg/g	Source
Utah/Uinta	DI 2011-2012	4.05	Munroe 2014
Utah/Uinta	DI 2012-2013	3.32	Munroe 2014
Utah/Uinta	D2 2011-2012	4.33	Munroe 2014
Utah/Uinta	D2 2012-2013	3.29	Munroe 2014
Utah/Uinta	D3 2011-2012	5.08	Munroe 2014
Utah/Uinta	D3 2012-2013	2.92	Munroe 2014
Utah/Uinta	D4 2011-2012	2.83	Munroe 2014
Average Uinta		3.69	
Utah/Wasatch Front	Lower Red Pine	0.92	Reynolds et al. 2014
Utah/Wasatch Front	Upper Red Pine	0.95	Reynolds et al. 2014
Utah/Wasatch Front	Upper Mill B	0.96	Reynolds et al. 2014
Utah/Wasatch Front	Lower Mill B	0.95	Reynolds et al. 2014
Utah/Wasatch Front	Blind Hollow	0.81	Reynolds et al. 2014
Utah/Wasatch Front	SOLA	0.79	Reynolds et al. 2014
Utah/Wasatch Front	Wasatch 209	1.03	Reynolds et al. 2014
Utah/Wasatch Front	Guardsman 1	0.57	Brahney & Skiles unpublished
Utah/Wasatch Front	D1 2017	0.89	Brahney & Skiles unpublished
Utah/Wasatch Front	Guardsman 2	0.99	Brahney & Skiles unpublished
Utah/Wasatch Front	DI 2017 2	1.15	Brahney & Skiles unpublished
Utah/Wasatch Front	Atwater	0.85	Brahney & Skiles unpublished
Average Wasatch Front		0.90	
Colorado	SASP	0.91	Lawrence et al 2010
Colorado	Rappit Ears	0.80	Zhang et al. 2018
Colorado	WillowCreek	0.65	Zhang et al. 2019
Colorado	Berthoud	0.60	Zhang et al. 2020
Colorado	Grizzly	0.66	Zhang et al. 2021
Colorado	Hoosier	0.56	Zhang et al. 2022
Colorado	Grand Mesa	0.68	Zhang et al. 2023
Colorado	McClure	0.63	Zhang et al. 2024
Colorado	Independence	0.57	Zhang et al. 2025
Colorado	ParkCone	0.56	Zhang et al. 2026
Colorado	SASP	0.60	Zhang et al. 2027
Colorado	SCP	0.68	Zhang et al. 2028
Colorado	Wolf Creek	0.63	Zhang et al. 2029
Average Colorado		0.66	
Average intermountain excluding Uinta		0.78	

**Uinta is excluded in the calculation of average concentrations due to the proximity of open pit phosphate mines around this mountain range (Figure 1). Apatite is not expected to be readily bioavailable and concentrations of phosphorus from dusts measured on the Wasatch Front are more likely representative of regional dust composition*

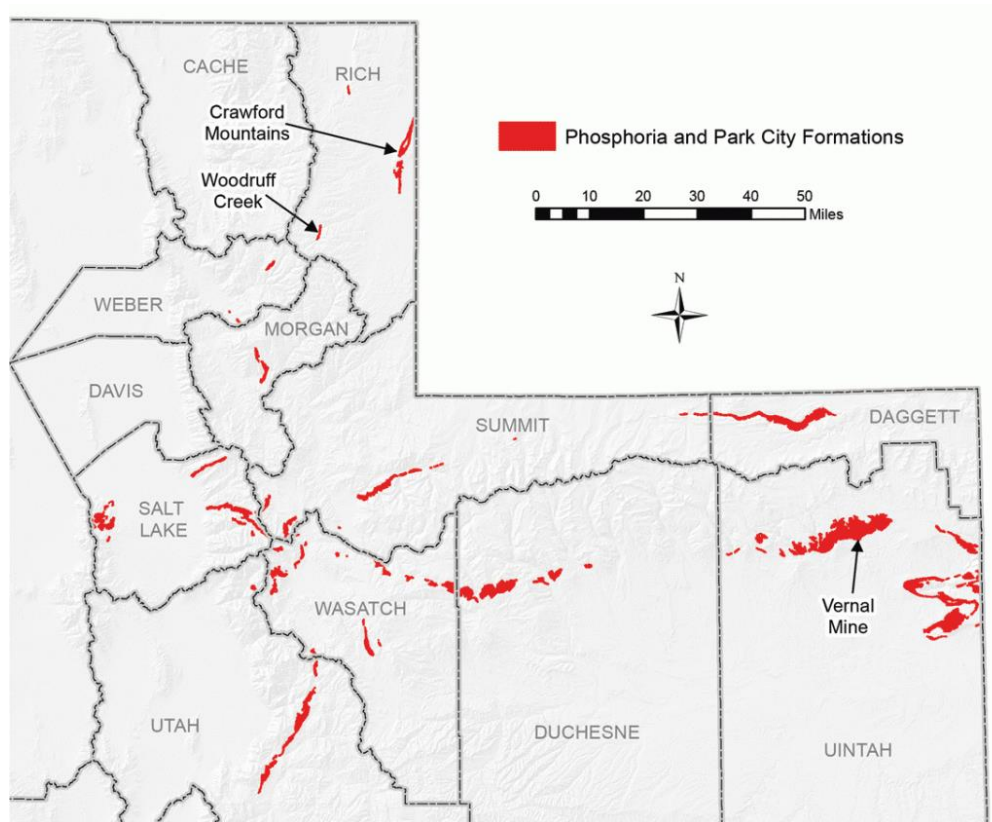


Figure 1 Locations of phosphate rock in Utah. Source: Utah Geological Survey <https://geology.utah.gov/map-pub/survey-notes/todays-and-tomorrows-phosphate/>

Assuming minimum to maximum and mean deposition rates observed regionally (1.4 - 15.6, mean $6.2 \text{ g m}^{-2} \text{ yr}^{-1}$) and phosphorus concentrations as measured in these dusts (0.56 – 1.15, mean 0.78 mg/g), total phosphorus deposition can be expected to range from 0.78 to $17.9 \text{ mg TP m}^{-2} \text{ yr}^{-1}$, with an average deposition rate of $4.8 \text{ mg TP m}^{-2} \text{ yr}^{-1}$.

4.1.5.2 Leachable Phosphorus in Regional Dusts of Utah

Several studies have examined the exchangeable/leachable and or organic phosphorus concentrations in regional dusts from the intermountain west (Lawrence et al. 2010, Zhang et al. 2018, Brahney and Skiles. in preparation). On average water soluble concentrations were 2.7% of total phosphorus while organic phosphorus made up on average 31% of total phosphorus (Table 6).

Table 6 Water soluble and organic phosphorus fractions for regional dusts in the intermountain west.

Deposition Region	Site	TP mg/g	Water Soluble	% Water Soluble	Water Soluble + Organic	% Water Soluble + Organic	Data Source
Utah	Guardsman 2	0.99	0.04	3.6			Brahney & Skiles unpublished
Utah	DI 2017 2	1.15	0.02	1.7			Brahney & Skiles unpublished
Utah	Atwater	0.85	0.03	3.5			Brahney & Skiles unpublished
Colorado	SASP	0.89	0.08	8.4			Brahney unpublished
Colorado	SASP	0.91			0.8	85.4	Lawrence et al. 2010
Colorado	Rappit Ears	0.80	0.05	6.4	0.5	67.7	Zhanget al. 2018
Colorado	WillowCreek	0.65	0.03	4.7	0.3	41.7	Zhanget al. 2018
Colorado	Berthoud	0.60	0.02	2.8	0.2	30.5	Zhanget al. 2018
Colorado	Grizzly	0.66	0.01	2.0	0.1	21.6	Zhanget al. 2018
Colorado	Hoosier	0.56	0.02	3.6	0.2	27.0	Zhanget al. 2018
Colorado	Grand Mesa	0.68	0.03	4.2	0.2	25.5	Zhanget al. 2018
Colorado	McClure	0.63	0.02	2.9	0.2	34.6	Zhanget al. 2018
Colorado	Independence	0.57	0.01	2.1	0.1	17.8	Zhanget al. 2018
Colorado	ParkCone	0.56	0.01	2.3	0.1	20.7	Zhanget al. 2018
Colorado	SASP	0.60	0.01	2.0	0.1	18.7	Zhanget al. 2018
Colorado	SCP	0.68	0.02	3.4	0.2	24.8	Zhanget al. 2018
Colorado	Wolf Creek	0.63	0.03	5.0	0.2	25.4	Zhanget al. 2018
Average		0.73	0.03	3.7	0.24	33.95	

Assuming the above range in total phosphorus deposition rates, and that leachable and organic phosphorus make up the “bioavailable” fraction, I can calculate water-soluble deposition rates between 0.02 – 0.48 mg P m⁻² yr⁻¹ with an average of 0.13 mg P m⁻² yr⁻¹, and the “bioavailable” fraction between 0.3 and 6.1 mg P m⁻² yr⁻¹ with an average of 1.9 mg P m⁻² yr⁻¹ (Table 7).

Table 7 Calculated mean and range of soluble and "bioavailable" (soluble + organic) P deposition

Regional P deposition in mg m ⁻² yr ⁻¹	Total P	Water Soluble P	Bioavailable (Wat. Sol + Org) P
Minimum	0.78	0.02	0.27
Mean	4.80	0.13	1.63
Maximum	17.90	0.48	6.09

4.1.6 Regional dust nitrogen concentrations and deposition rates

Only two studies were found from the mountain west, including work in the Brahney lab, that look at organic nitrogen concentrations in regional dusts. Lawrence et al. (2010) found organic nitrogen made up 0.29% of the dusts deposited in the San Juan Mountains of Colorado. On the Wasatch Front, Brahney et al (in prep) found dust organic nitrogen concentrations ranged from (0.07 – 0.53%). This information is provided for reference only as estimates of nitrogen loading to Utah Lake as all fractions are accounted for by US national network modeling efforts (please see section 4.3.2).

4.2 Wet Deposition

4.2.1 Urban wet phosphorus deposition rates

I estimate urban wet P deposition rates by taking an average of the few measurements that have been made globally. The lack of information on wet P deposition rates in urban centers is a significant limitation on the estimation of wet P deposition rates. The minimum was from Logan, Utah, where the sampler is in a rural agricultural region near the urban area of Hyrum. The maximum was from Singapore, a city with approximately 5.6 million inhabitants and a population density of 7,909 people per km². In comparison, Hyrum, Utah has a population density of 624 people per km² and Provo 1,025 people per km². Based on the range provided by this information, I estimate that deposition around Provo would be between 5 and 15 mg P m⁻² yr⁻¹ (Table 8). Note that assuming TP in wet deposition is entirely bioavailable may not be accurate as several man-made phosphate compounds are not bioavailable.

Table 8 Measurements of urban TP deposition rates from around the world and Utah estimates

Region	Site	Method	Class	Population Density	Deposition Rate mg TP m ⁻² yr ⁻¹	Data Source
Singapore	Marina	Wet-only	urban	7909	50.6	He et al singapoere
China	Lake Taihu	Rain guage	urban/lake	3000	30.0	Lyo et al 2007
New Jersey	Jersey City	Wet-only	urban	6930	5.2	Koelliker et al. 2003
New Jersey	Camden	Wet-only	urban	1227	8.2	Koelliker et al. 2003
Logan (Hyrum)	Collage Ward	Wet-only	urban/ag	624	4.7	NADP
Average					19.7	
Range for northern Utah					5-15	

4.2.2 Regional wet phosphorus deposition rates

I estimate the regional or background wet deposition rate of phosphorus from data collected at four NADP sites around Utah over the last five years (NADP 2019). Because phosphorus does not have a gaseous form, these values are expected to be low. The measurement of phosphorus within the NADP network is used to determine contamination from birds, along with high concentrations of potassium. Vegetation, insect, and dust contamination can also influence measured P concentrations. Note that if the dust mediated transfer of nutrients to Utah Lake is determined by the total mass flux of dust and mean P concentrations, rain contaminated by dusts should not be used to establish a wet deposition rate since dust deposition is independently accounted for. Since rain effectively scrubs the atmosphere of particles, I recommend instead measuring wet and dry particulate deposition separately. Regional wet phosphorus deposition rates are determined as an average of the four NADP locations in remote locations. I do not include Logan due to the proximity to urban and agricultural locations. Because 65% of the measurements were below detection, I use half the detection limit (3 PO₄³⁻ μg L⁻¹) in these instances. The mean concentration was 10.9 μg P L⁻¹. Deposition rates ranged from 2 to 4.1 mg P m⁻² yr⁻¹, with a mean of 2.9 mg P m⁻² yr⁻¹ (Table 9).

Table 9 Wet phosphorus deposition rates from remote locations around Utah as measured by the NADP.

NADP site	Site Name	Class	PO ₄ ³⁻ µg/L	total ppt (mm)	mg PO ₄ ³⁻ m ⁻² yr ⁻¹
UT98	Green River	Rural	13.5	996.2	2.7
UT09	Canyonlands	National Park	9.5	1073.9	2.0
UT99	Bryce	National Park	6.0	2432.2	2.9
UT95	East McKee	Mountain	14.5	280.3	4.1
<i>Average</i>			<i>10.9</i>		<i>2.9</i>

*Note East McKee is a new site and thus only has one year of data.

4.2.3 Urban and regional wet and particulate nitrogen deposition rates

As with phosphorus, I could estimate reactive nitrogen deposition fluxes based on available data for urban and regional sites. However, considerably more effort has been allocated towards the estimation of reactive nitrogen fluxes to ecosystems with the United States. As a result, maps of reactive N deposition data are available at high spatial resolution. The maps are produced using both wet deposition measurements as well as dry deposition estimates that are based on ambient atmospheric concentrations and the output from the Community Multiscale Air Quality (CMAQ) model (TDep 2019). The model combines monitoring data from the Clean Air Status and Trends Network (CASTNET), National Atmospheric Deposition Program (NADP), Atmospheric Integrated Research Monitoring Network (AirMoN) and the NADP National Trends Network (NTN). More details on this modeling effort including caveats can be found in the Total Nitrogen Documentation produced annually by TDep, more information can be found on the NADP TDep website <http://nadp.slh.wisc.edu/committees/tdep/reports/nrDepWhite-Paper.aspx>

Atmospheric inputs of reactive nitrogen (Nr) occur via wet or dry deposition. Wet deposition includes aerosols and particulates dissolved in or carried by precipitation to an ecosystem. Dry deposition includes the deposition of gases as well as particulates that are deposited to ecosystems directly. The CMAQ model estimates the deposition of common aerosols measured in both wet and dry deposition including nitrate (NO₃⁻), nitrite (NO₂⁻), and ammonium (NH₄⁺). In addition, the CMAQ model estimates the deposition of nitrogen species that are rarely measured but are likely to contribute Nr to ecosystems including peroxyacetyl nitrate (PAN), dinitrogen pentoxide (N₂O₅), nitric oxide (NO), nitrogen dioxide (NO₂), nitrous acid (HONO), and organic forms of nitrogen (ON). Note, unlike organic phosphorus, organic nitrogen is not completely bioavailable. Wet deposition of nitrate ions is estimated to be between 200 and 300 mg m⁻² yr⁻¹ and dry deposition of aerosols between 200 and 400 mg m⁻² yr⁻¹. Total Nitrogen deposition, all forms, wet and dry is estimated to be between 400 and 750 mg m⁻² yr⁻¹ (Table 11, Figure 2).

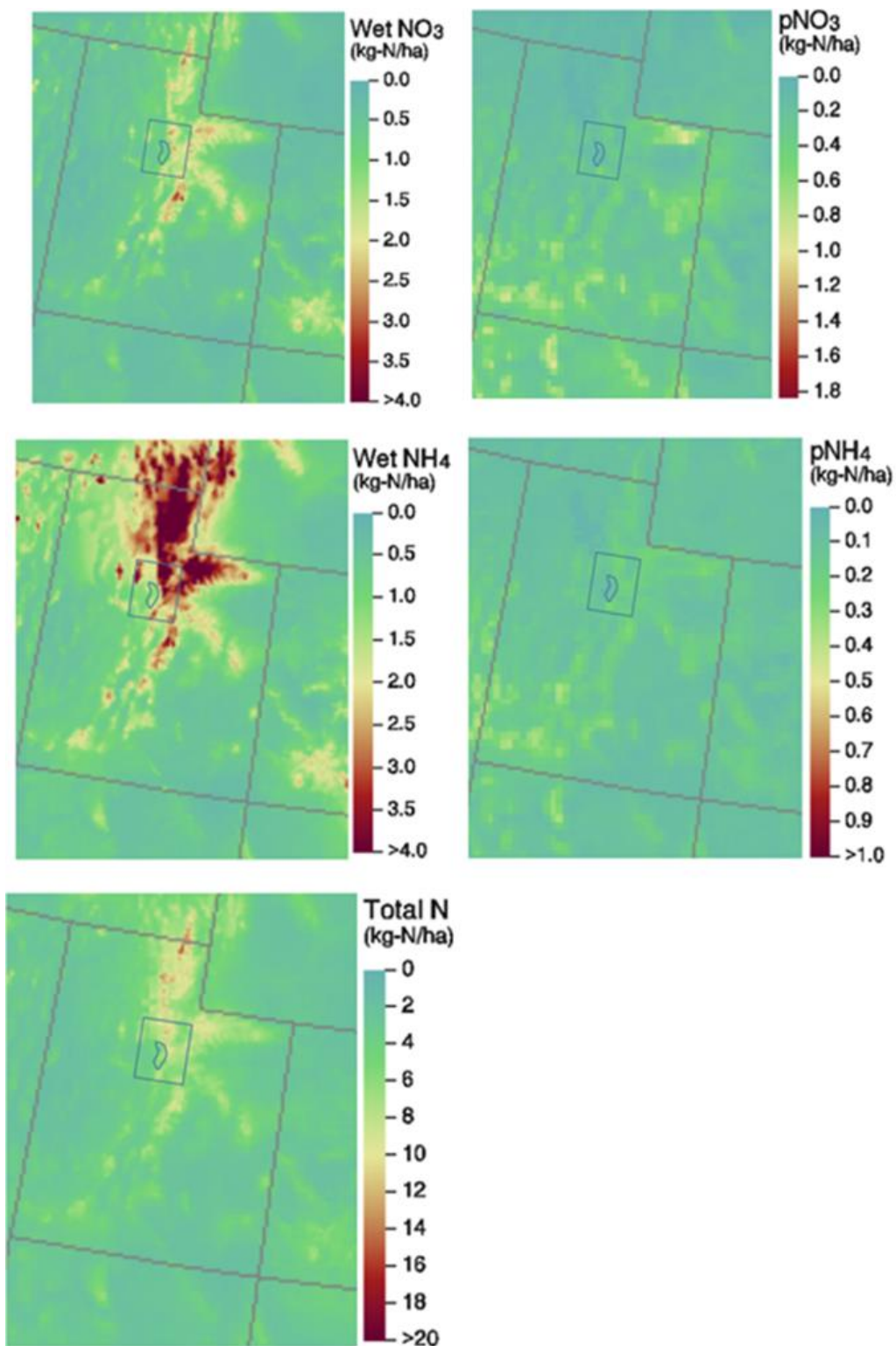


Figure 2 Wet, Dry, and total estimates of all nitrogen species. The location of Utah Lake is shown on each map. Dry deposition estimates are based on aerosol concentrations and modeled deposition rates whereas wet deposition rates are based on measured deposition rates combined with the CMAQ model. Total deposition rates include all forms of nitrogen species, please see text for full details.

4.3 Estimating nutrient loading to Utah Lake

4.3.1 Estimating total and bioavailable phosphorus deposition to Utah Lake

Approximately 56.6 km of the Utah Lake perimeter is bordered by urban or agricultural regions. To determine the lake area potentially influenced by urban activities, we applied a first order decay equation mimicking similar observations at Lake Tahoe where urban influence had diminished to 10% by 200m (VanCuren et al. 2012a, VanCuren et al. 2012b). Because we only had one study to draw from and local winds surrounding Utah Lake are different than those observed at Lake Tahoe (Figure 3), we included two more estimates at 2 and 4 times the radius of influence observed in Lake Tahoe.

Given our estimated areas affected by urban or regional influences and our estimated urban and regional deposition rates, I arrive at estimated minimum to maximum loading to Utah Lake at 1.4 to 13.4 metric tons of total phosphorus (TP) per year. Considering the ‘bioavailable’ fraction, here defined as

- 75% of urban dust TP deposition rates (see text for justification)
- Water-soluble + organic fraction of regional dust TP deposition rates
- Urban wet TP deposition rates
- Regional wet phosphate deposition rates

I calculate a range of bioavailable P deposition between 1.1 and 7.9 metric tons per year (Table 10). If we assume an urban deposition rate throughout the entire lake during inversions, which may occur 10 to 25 days of the year, this may add 1 to 2.5 metric tons per year. Option 1 below in the recommendations provides a mechanism for determining the actual potential deposition associated with an inversion.

Table 10 Summary of all estimated P deposition rates and estimated loading to Utah Lake in metric tons per year.

Summary deposition rates	mg P m ⁻² yr ⁻¹			Tons of P to Utah Lake (assuming 10% urban influence at 0.2 km)			Tons of P to Utah Lake (assuming 10% urban influence at 0.4 km)			Tons of P to Utah Lake (assuming 10% urban influence at 0.6 km)		
	Min	Mid	Max	Min	Mid	Max	Min	Mid	Max	Min	Mid	Max
Urban dust TP deposition Rate	88.9	139.3	189.6	0.3	0.5	0.7	1.3	2.1	2.8	2.4	3.7	5.1
Water Soluble (50% on average TP)	44.5	69.7	94.8	0.2	0.3	0.4	0.7	1.0	1.4	1.2	1.9	2.6
Water Soluble (75% maximum TP)	66.7	104.5	142.2	0.3	0.4	0.5	1.0	1.5	2.1	1.8	2.8	3.8
Regional dust TP deposition Rate	0.8	4.8	17.9	0.3	1.8	6.8	0.3	1.8	6.6	0.3	1.7	6.4
Water Soluble	0.0	0.2	0.6	0.0	0.1	0.2	0.0	0.1	0.2	0.0	0.1	0.2
Water Soluble + Organic	0.3	1.6	6.1	0.1	0.6	2.3	0.1	0.6	2.2	0.1	0.6	2.2
Urban wet TP deposition rates	5.0	10.0	15.0	0.0	0.0	0.1	0.1	0.2	0.2	0.1	0.3	0.4
Regional wet P deposition rates	2.0	2.9	4.2	0.8	1.1	1.6	0.7	1.1	1.6	0.7	1.0	1.5
Sum TP				1.4	3.5	9.2	2.4	5.0	11.2	3.5	6.7	13.4
Sum maximum' bioavailable'				1.1	2.1	4.5	1.9	3.4	6.1	2.7	4.7	7.9



Figure 3 Image from Google Earth. Utah Lake with mean annual wind roses for five locations surrounding the lake. Also shown is an active mine and housing development on the western shores of the lake.

4.3.2 Estimating total nitrogen deposition to Utah Lake

Estimated deposition rates of N to Utah Lake in metric tons are here based solely off the estimated deposition rate as determined above ($400\text{-}750 \text{ mg m}^{-2} \text{ yr}^{-1}$). The acquisition of high-resolution spatial datasets for deposition data combined with an aerial estimate is beyond the scope of this study, however, clearly a more accurate estimated could be determined using the available spatial data. Total estimated deposition to Utah Lake is between 153-288 metric tons per year.

Table 11 Estimated range of wet, dry, and total N deposition to Utah Lake from the CMAQ model and TDep working group from NADP and other affiliated monitoring networks.

	Utah Lake		Total N
	Wet	Aerosol	
	mg N m ⁻² yr ⁻¹		
NO ₃ ⁻	90-125	100-400	
NH ₄ ⁺	100-150	50-150	
Total N	200-300	200-400	400-700

5.0 Recommendations for measuring the atmospheric deposition of nutrients to Utah

Very few studies have attempted to monitor the atmospheric deposition of particles across a large lake basin. However, several studies have been conducted on Lake Tahoe, which can be viewed as a reasonable analog. These studies have indicated that the contribution of urban dusts and aerosols to the lake have a very narrow zone of influence nearshore dictated by dominant wind strengths and directions (Engelbrecht et al. 2009, Dolislager et al. 2012, VanCuren et al. 2012a, 2012b). The primary zone of urban influence around Utah Lake is on the eastern shore and given that regional wind patterns are variable surrounding the lake (Figure 3) wind transport may also vary by time of day with early morning land-breezes. Particles generated by urban activities can be expected to vary by time of day and season alongside variation in human activity. Similarly, regional deposition rates will vary by season (Reheis 2003, Steenburgh et al. 2012, Hahnenberger and Nicoll 2012, Hand et al. 2016) and by year according to climate variables such as drought, wind speeds, and storm patterns (Okin and Reheis 2002, Brahney et al. 2013, Flagg et al. 2014). Thus any program designed to monitor atmospheric deposition to Utah Lake should occur over a several year period to establish diurnal, seasonal, and yearly variation.

5.1 Option 1 (preferred). Comprehensive spatial analyses using active sampling techniques

5.1.1 Dry fluxes

Because open bucket samplers in urban and agricultural areas are subject to localized contamination, my primary recommendation is to use atmospheric aerosol concentrations in conjunction with well-established theoretical deposition velocities as a function of grain size (Brook et al. 1999a, 1999b, Smith et al. 2000, Wesely and Hicks 2000, Lu et al. 2003). This method has a distinct advantage because data with a high spatial resolution can be obtained using portable samplers. High-resolution sampling will minimize erroneous extrapolation that can occur from point sources of urban aerosols and dusts.

Several commercially available products for are now offered for real-time monitoring of size-fractionated aerosols. Many of these systems can be used with cassette impactors (filters that capture dusts) to collect samples for analyses. I do not recommend using real-time sensors that only capture particles <PM10 (eg purple air) as this size fraction is not well represented in many Utah dust events (Reynolds et al. 2016). Real time samplers can be used to establish:

1. The perimeter around Utah Lake that is influenced by urban aerosols. This information can be used to establish sites where permanent aerosol samplers can be placed.
2. The zone of influence of urban aerosols (here assumed to be 1 km into the lake, which is potentially excessively large).
3. The total mass of dust deposition and associated nutrients at a high resolution across the lake basin. Periodic cruises in transects across the lake using the portable real-time sampler can determine the concentrations of aerosols above different areas of the lake. This data, combined with deposition velocities for size fractions, can then be used to calculate deposition rates at sites across the lake. If total suspended particulate impactors are used in conjunction, the sample generated can be used to determine the concentration of relevant nutrients and therefore their deposition rates across different regions of Utah Lake

While several stationary stations can be established around the perimeter of the lake using information from (1) above, cruises can be undertaken during different times of day and different seasons. The combined data will provide a comprehensive understanding of particle and nutrient deposition to Utah Lake and associated spatial and annual variability.

5.1.1.1 Sample analyses

Captured particles should be analyzed to distinguish between biologically available and unavailable forms. Unavailable forms that can be determined by common chemical leaching methods are mineral and occluded (Fe-,Mn-,Al-bound) forms. The soluble and exchangeable fraction can be considered readily available while the organic fraction potentially available over time. Organic phosphorus should not be determined by difference with total phosphorus since a proportion of total phosphorus from dusts in Utah are likely from minerals such as apatite. Similar analyses can be conducted for nitrogen including the leaching and exchangeable fraction. The organic fraction should also be determined with the caveat that not all forms of organic nitrogen are readily bioavailable. Total organic nitrogen can be analyzed using a CHN analyzer.

5.1.2 Wet fluxes

Standard tipping bucket rain gauges can be used to acquire precipitation samples for phosphorus analyses using standard wet chemistry methods. Existing spatial data sets on reactive nitrogen deposition should be used to estimate the total loading of nitrogen.

5.2 Option 2. Point sampling of deposition using passive sampling techniques

Option 2 is a less suitable option because sampling locations will be few and far between requiring considerable extrapolation between sites. In addition, it is not possible to determine the zone of influence from point sources of materials that may end up in the sampler. Because open bucket samplers similar to the Aerochem Metrics sampler in urban and agricultural areas are subject to contamination, care should be taken to minimize the potential for contamination and strict protocols on whether samples should be kept or discarded should be enforced.

5.2.1 Sampler Location

The sampler should be placed at minimum 2 m above the ground to avoid contamination by saltating materials (Figure 4a), requirements laid out by the NADP for their only current dry

deposition network (AMoN) require minimum 2 m sampling heights, and, many NADP Aerochem Metrics samplers are placed on towers > 5 m above the ground surface, with each site's height determined at a case by case basis. Samplers should not be located near point sources of atmospheric pollution including but not limited to open pit mining and housing developments on the western shores of Utah Lake (Figure 2), agricultural areas where either soils (Figure 4b) or irrigation spray can reach the sampler, construction sites or roads in urban areas (Figure 2, Figure 4c,d). Point sampling methods do not allow one to determine the zone of influence and thus contamination of samples by point sources can lead to erroneous extrapolation and inflation of actual deposition rates. To avoid these errors, the NADP uses the following guidelines to determine a sampler location which is typically followed by a site visit to assess site suitability:

Samples must not be placed

- Where there is potential for contamination from irrigation;
- Where there is potential for contamination by fugitive dusts;
- <100 m from roads, paved or unpaved;
- <10 meters from access roads, though in Utah I recommend this be increased to at least 30 m (Figure 4c,d);
- <5 m from objects greater than 1 m tall (including a solar panel);
- Within a 5 m radius of vegetation.

5.2.2 Dry fluxes

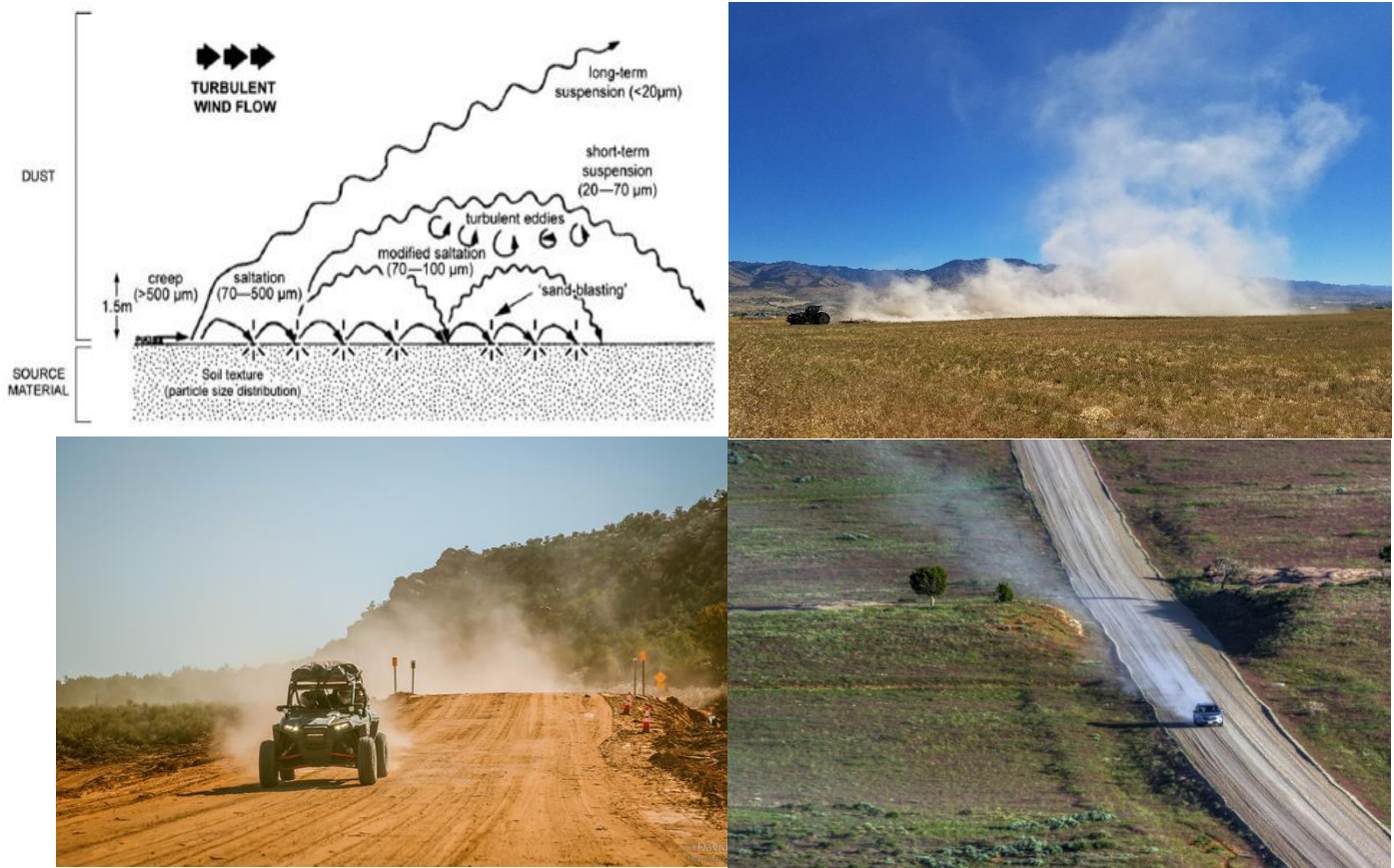


Figure 4. 2a (top left) From Pye 1987 showing a generalized scheme of erosion and entrainment from a dust producing surface, 2b (top right) a tractor producing dust in northern Utah (photo credit: Patrick Strong, 2c (bottom left) an ATV producing dusts in Utah (photo credit: David G. Paul, 2d (bottom right) a car producing dust in Utah

I recommend using the dry side to capture dry deposition of particulates only and not to use them in an attempt to capture aerosols and ions. I recognize that early studies used ‘dry side’ buckets filled with water to simulate the water surface environment, which can capture ions at a higher rate than dry surfaces (Lewis Jr 1983). However, studies examining the efficiency of the Aerochem Metrics dry side buckets for capturing acid and ion deposition deemed these buckets unsuitable for these measurement, e.g. nitric and sulfuric acids that may evaporate or react with cations (or deposited dust) (Hicks 1980, Dasch 1985, Feely et al. 1985, Knapp et al. 1986, Wesely and Hicks 2000). An extensive critique on dry deposition methods by Hicks et al. 1980, recommended estimating dry deposition rates of acids and gases from atmospheric concentrations, as is now done by IMPROVE and CASTNET.

SensorSpace and myself have developed a dry deposition sampler (DDS or DSI) to work either in conjunction with the NADP Aerochem Metrics sampler or as a standalone unit. The sampler effectively eliminates wind excavation of material while preventing sample contamination. A simpler, less expensive alternative, would be to cover each bucket with a 100 - 250 μm Nitex screen. This can help protect the sample from contamination by bugs, vegetation, and from the use of samplers by birds as baths, particularly if the sampler is full of water. Because the precipitation samplers are not

always triggered by light rain or snow, the dry side can become damp or wet in some instances. Once collected, I recommend drying the sample prior to collection, weighting, and chemical analyses. Dry side samples can be collected monthly or seasonally and split for nutrient composition analyses. Contaminated samples should not be included. Obvious signs of contamination include bird feces on or near the sampler as well as fragments of vegetation or bugs. Keeping water in the dry side buckets can encourage the use of buckets as a bird bath, which is a form of contamination that is difficult to discern.

5.2.2.1 Sample analyses

Please see section 5.1.1.1 on particulate sample analyses.

5.2.1 Wet fluxes

I recommend discarding wet samples when visible contamination from bird feces, bugs, vegetation, and dusts are present. The latter may sound counter-intuitive if one is attempting to determine the dry and wet deposition of phosphorus. Note, however, that since phosphorus does not have stable gaseous forms the wet deposition of phosphorus should be low. If dust contaminated samples are present and kept, the mass of dusts delivered in wet deposition should be kept separate from any calculations using dry side masses to establish nutrient loadings so as not to double count this fraction. All samples should be double filtered through a 250 μm mesh screen and a 0.45 μm filter. The $>250 \mu\text{m}$ fraction should be discarded. The filter should be weighed pre- and post- filtration to determine the mass of dust deposited with rain. The filtered sample can be analyzed for dissolved ions using standard chemical analyses. There is no standardized method to determine contamination, however, phosphate, potassium, and ammonium measurements higher than expected can indicate contamination. As above, there are also physical signs of contamination.

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