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Intraurban Nitrogen Pollution and Effects on Desert Ecosystems

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Intraurban Nitrogen Pollution and Effects on Desert Ecosystems

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by

Stephanie Jean Piper

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ABSTRACT OF THE DISSERTATION

Intraurban Nitrogen Pollution and Effects in Desert Ecosystems

by

Stephanie Jean Piper

Doctor of Philosophy, Graduate Program in Plant Biology
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Professor Darrel Jenerette, Chairperson

Urban systems, or socio-ecological systems, are complex on fine and coarse scales, and are important to humans through the effects of ecological processes. Nitrogen pollution is uniquely altered by humans and variable on fine spatial scales with understudied potential sources and sinks. We found local atmospheric nitrogen pollution concertation in Riverside correlated with traffic as a pollution source, but plant canopy did not act as a significant source. Atmospheric pollution does not remain within city limits, and effects in natural systems can be observed in the air, canopy, and soil. We observed a deposition gradient, with decreased atmospheric nitrogen further from urbanization. However the pattern was not consistent for nitrogen in the canopy and the soil, highlighting a disconnect in the gradient and the complexity of teleconnections. Urban ecology affects humans in socioecological systems and plays an important role in science policy. The Salton Sea is a hyper-resilient ecological crisis that fits within the framework of wicked problems. Through research on existing government policy and interviews with key stakeholders, we identified issues that potentially keep the sea in a degraded state and recommendation via resilience theory to address the wicked problem.

The dissertation as a whole seeks to improve understanding of socio-ecological systems across scales, and quantify variation in ecosystem processes and nitrogen patterns within and beyond urban areas.

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Introduction

Urban areas, or socio-ecological systems, are increasingly important to understand for ecologists and urban residents. Socio-ecological systems are complex, with patterns and processes varying across scales. Landscape ecology asks how ecosystems and processes differ through space. Local scale patterns are important in highly heterogeneous ecosystems, like cities (Pickett et al. 2017). Plants provide ecosystem services in both urban and natural areas (Pataki et al. 2011, Dobbs et al. 2021). Plants have the potential to improve air quality, sequester carbon, and provide cooling benefits, but how urban residents benefit from those services can vary spatially (Vos et al. 2013, Vieira et al. 2018). In this dissertation, patterns across scales and complexity are addressed within an urban system, along a gradient from an urban system, and at the site of an ecological crisis.

Air quality, and therefore atmospheric concentration of reactive nitrogen, is of particular concern in Southern California, a region known for high traffic volumes. Nitrogen pollution is an ideal process to understand intraurban heterogeneity; hot spots and hot moments are well documented with nitrogen pathways (McClain et al. 2003). Atmospheric concentrations of reactive nitrogen, specifically nitrogen oxides (collectively NO_X) and ammonia (NH_3), are elevated in cities, and are the main contributor to dry deposition (Bettez and Groffman 2013, Decina et al. 2019). NO_X and NH_3 negatively contribute to air quality in cities, and high concentrations mean increased exposure for human health (Frampton and Greaves 2009, Behera and Sharma 2010). Patterns of atmospheric pollution are well-documented on the regional level, but research within cities to understand local exposure is limited. There is evidence of local patterns of variable deposition within the city of Boston, showing seasonal peaks in spring and elevated wet deposition in urban areas compared to suburban (Raciti et al. 2012, Rao et al. 2014, Decina et al. 2017). However, Southern California is an arid ecosystem where dry deposition is a more important driver, and atmospheric concentration is a key variable in determining dry deposition (Sickman et al. 2019). Therefore, there is a major research need to understand local patterns of air pollution.

To quantify atmospheric concentrations of nitrogen in a city, we adopt a source-sink framework where traffic is the hypothesized source, and tree canopy is the hypothesized sink. Tailpipe emissions are a major source of atmospheric nitrogen in most cities (Xu et al. 2018), and the heterogeneity of urban road networks may have an effect on atmospheric concentrations on fine scales. Tree canopies capture particles when deposited (Bottalico et al. 2016), but whether that canopy capture can significantly improve air quality is uncertain (Eisenman et al. 2019). Quantifying local pollution and variation within a city provides insight into ecosystem processes within a complex system that have effects on human health.

Urban pollution is often described as a plume, where large amounts of pollution surround urban areas. While urban nitrogen pollution can vary on the local level, ecosystems are not discrete, and ecological processes are affected by urbanization even as we travel to natural areas. Far-reaching effects of cities on surrounding ecosystems are called teleconnections; land cover and use exist on a continuum of urban to rural rather than discrete systems (Seto et al. 2012). Anthropogenic NO_X and NH_3 can lead to elevated deposition in national parks (Ellis et al. 2013), including pollution from Los Angeles travelling over 200 kilometers to Joshua Tree National Park (NPCA Report, 2019). Deposition to and effects on desert areas are important, with increasing aridification (Ezcurra et al. 2006). Southern California's high amount of nitrogen pollution along with the importance of understanding ecological patterns in deserts makes this a prime area to understand teleconnections.

Nitrogen travels along a deposition gradient and effects patterns in the air, shrub canopy, and soil once it is deposited. Atmospheric NO_X and NH_3 is expected to decrease with increasing distance from urban areas (Allen et al. 2009). Nitrogen deposited to the canopy in collected via throughfall, which is what washes off the canopy during a rain event, in the form of nitrate (NO_3) and ammonium (NH_4). Throughfall nitrogen provides an estimate of particles the canopy captures, but capture varies so it is unclear how shrubs can alter deposition (Bortolazzi et al. 2021). Shrubs are interspersed in the desert, so deposition from the air to soil is a substantial input along with throughfall (Michalski et al. 2004). NO_3 and NH_4 can build up in dry soils, but can also be emitted after wetting, extending effects of nitrogen processes through natural areas (Krichels et al. 2022). Ecosystem inputs also vary seasonally, with dry and wet season affecting nitrogen processes (Notaro et al. 2010). Patterns across a gradient as well as within sites allow us to understand teleconnections as a driver of processes along the urban to rural continuum. Varying levels of urbanization along the deposition gradient, and ecosystem effects at each site, lead to a complex system where nitrogen processes may be understood via teleconnections.

Teleconnections and local patterns contribute to ecosystem complexity, and in a degraded socio-ecological system there are trans-disciplinary challenges. Human-nature interactions are important to human health, ecosystem functioning, and environmental policy. The Salton Sea is a socio-ecological system in crisis, as an evaporating, hypersaline lake has wide-ranging effects (Fogel et al. 2021). The ecosystem is unhealthy for flora and fauna, but also presents health risks to the residents surrounding the sea, who are underserved and under resourced.

The Salton Sea as a system continues to degrade, but stakeholders and decision-makers struggle to identify solutions and implement change. We view this socio-ecological system as one facing a "wicked problem", or a problem that cannot be definitively described and cannot have objective solutions (Rittel and Webber 1973, Craig 2020). Part of this problems is that, though degraded, the system is hyper-resilient and resistant to change. Addressing wicked problems through the context of resilience may include collaboration, improved community capacity, shifts in existing activities, but a single solution is unlikely. Policy can have negative or positive effects on resilience (Quandt 2023), and identifying the diverse stakeholders and needs connected to the sea may be foundational. Community engagement and policy research can inform the use of ecological theory on resilience to address a wicked problem and identify solutions.

Nitrogen patterns and processes within a city, effects travelling from a city, and wicked problems in a degraded system address questions of spatial differences along complex landscapes. Patterns are further affected by human needs and infrastructure, from traffic to health, and plants in and around cuties have the potential to offset disadvantages or provide service. Quantifying pollution effects and spatial pattern can provide an improved understanding of socio-ecological systems, based in ecological theory with potential for beneficial applications.

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Chapter 1: Local Atmospheric Pollution Driven by Traffic Sources, with Limited Protections by Tree Canopy Sinks

Abstract

Nitrogen pollution is a major issue for urban residents, but patterns of atmospheric reactive nitrogen concentrations within a city are not well-quantified spatially or temporally. We developed an urban pollution source-sink hypothesis, where traffic would be the source and tree canopy would be the sink. We measured atmospheric NO_X and NH_3 at different traffic levels and high and low canopy sites over a year in Riverside, CA. We found NO_X and NH_3 have an inverse relationship in seasonal concentrations, highlighting the need to understand multiple pollutants. We found distinct local patterns of pollution with traffic as a source but did not find that tree canopy acted reliably act as a sink. We measured canopy inputs of nitrogen, but fond that atmospheric concentrations are not reduced with increased tree canopy cover. This work highlights the need to address pollution directly and evaluate how we can best use ecosystem services.

Introduction

Urban areas have high levels of nitrogen pollution compared to rural areas (Bettez and Groffman 2013). Nevertheless, intraurban distributions of atmospheric nitrogen, which are crucial to exposure and total nitrogen input, are not well understood (King et al. 2014**.** Local patterns may differ from regionally derived expectations, in particular as urban development modifies nutrient cycling, mainly through increased magnitude of sources and sinks relative to rural areas (Kaye et al., 2006). Local variation in the magnitude of atmospheric reactive nitrogen may be important to pollution and its effects on people and ecosystems. In the US, approximately 60% of urban areas have regular air quality monitoring, but limited to an average of 2-5 monitors per million residents (Apte et al. 2017). Though nationwide networks like the National Atmospheric Deposition Program (NADP) collect a large amount of wet and dry deposition data (Lamb and Van Bowersox 2000), the focus on collecting in rural areas means estimates of urban exposure to nitrogen pollutants and their variability in time and space is limited. Both variability in emissions, primarily from vehicles (Festy, 2013; Wen, Zhang, Wu, & Hao, 2023), and sinks, potentially green spaces (Vos et al. 2013), may contribute to differences in atmospheric nitrogen concentrations and whose effects may vary seasonally.

Atmospheric concentration of reactive nitrogen is an important aspect of urban nitrogen cycles – it is a driver of deposition to ecosystems (Hertel et al. 2011), a key component of air pollutant exposure for health, and is important for many atmospheric chemical reactions (Roger Atkinson 2000). Atmospheric nitrogen is the predominant contributor to dry deposition in cities globally (Decina et al. 2019), especially in more arid climates like Southern California (Gillette et al., 1992; Fenn, Poth, & Johnson, 1996). The role of atmospheric reactive nitrogen concentration in arid climates is especially important for major nitrogen pollutants present in cities, including nitrogen oxides (NO and NO_2, collectively NO_X) and ammonia (NH_3), which are distinct in source and deposition. NO_X acts as a precursor to smog and ozone, leading to respiratory disease in humans when in the atmosphere at high amounts (Frampton and Greaves 2009). NH_3

also negatively contributes to air quality in cities (Behera and Sharma 2010). NH_3 is underestimated in on-road emission measurements compared to other nitrogen pollutants (Fenn et al. 2018a), leading to much more uncertainty about the magnitudes of NH_3 concentrations and drivers of their variability. NH_3 data and management has been focused on agricultural areas and their emissions (Liu et al. 2022, Wyer et al. 2022). In cities where NH_3 was monitored, NH_3 emissions were more than twice those described in the National Emission Inventory, and emissions from vehicles were greater than agricultural emissions for nearly half of the U.S. population (Sun et al. 2017). In places where dry deposition is the predominant pathway for ecosystem inputs, atmospheric concentration is a key driver of impacts (Bytnerowicz et al. 2005).

Atmospheric concentrations of NO_X and NH_3 pollutants vary seasonally, but we have limited data describing magnitudes and drivers of their variation on small spatial scales. Atmospheric nitrogen data is collected on annual and monthly time scales, but that is on a large spatial scale (NADP). The EPA has tracked national nitrogen pollutant patterns annually since the 1980s (EPA), but national patterns cannot resolve intra-urban heterogeneity that may vary interactively seasonally and spatially. On an annual scale, NO_X concentrations have been shown to be the highest during winter months (Roberts-Semple et al. 2012), but this may vary locally. Data on intra-urban seasonal patterns of atmospheric NO_X and NH_3 concentrations are lacking, leaving a gap in research on urban atmospheric nitrogen concentrations. To evaluate the temporal and spatial variation in urban atmospheric nitrogen concentration, we consider a source-sink hypothesis (Gravel et al. 2010). A source acts as an input of pollutants to the system while a sink would remove them. As traffic sources and tree canopy vary across a city, which we hypothesize will lead to variable concentrations atmospheric reactive nitrogen spatially and temporally.

Spatial distributions of atmospheric reactive nitrogen will be associated with sources, particularly traffic. The main source of atmospheric nitrogen concentrations in most cities are tailpipe emissions (Xu et al. 2018), compared to fertilizer application or emissions from household energy or appliances. Because of the distribution of road networks, intraurban patterns of nitrogen emissions have the potential vary substantially. NO_X concentrations have been the primary focus of pollution mitigation activities through implementation of vehicle catalytic converters (Czerwinski et al. 2010). However, NH_3 is produced by catalytic converters and recent studies show that NH_3 is underestimated and can potentially be important to atmospheric pollution patterns (Fenn et al., 2018). This creates a potential trade-off where reductions in NO_X emissions can result in increased NH_3 emissions, suggesting a need to account for both forms of atmospheric nitrogen.

While roads serve as nitrogen sources, urban tree canopies may act as a pollutant sink, trapping particles as they are deposited (Bottalico et al. 2016). However, this sink does not always reduce pollution and the magnitude of the sink may vary (Vos et al. 2013), and the degree to which tree canopy can improve air quality in uncertain (Eisenman et al. 2019). Measuring deposition and modelling air quality effects may be less informative than understanding dispersion; in some cases roadside urban vegetation increases local pollutant concentrations (Vos et al. 2013). Models have shown that trees remove air pollution and improve air quality, with the total estimated removal of multiple pollutants by US urban trees estimated at 711,000 metric tons (Nowak et al. 2006). This effect can be stronger in street canyons, where air has enhanced residence times, where vegetation can reduce street level NO_2 concentrations substantially, up to 40% (Pugh et al. 2012). However the success of tree canopies to reduce pollution varies among different subregions (Escobedo and Nowak 2009). Further, even if effective, the ability to trap pollutants may be limited based on the high amount of pollution produced (Nemitz et al. 2020). Cities are heterogeneous landscapes (Cadenasso et al. 2007) with differences in tree cover and density, which could mean varying effectiveness of sinks.

Sink differences can be exacerbated by differences in species, but also how deposition or nitrogen inputs affect atmospheric pollution. Differences between pollutant capture among species are clear in wind tunnel studies, with conifers collecting far more particles, possibly due to their more complex foliage patterns (Beckett et al. 2000). Modeling and laboratory research on canopy nitrogen deposition has focused largely on the physics and chemistry of the particles and how they deposit on leaves, but the consequences for outdoor atmospheric concentration may be influenced by many variables (Hicks et al. 2016). Results from field studies are more variable, and have shown differences among species, plant arrangement, and environmental conditions (Hagler et al. 2012) (Beckett et al. 2000). Selecting certain species that exhibit specific biophysical traits, like small leaf size and high leaf complexity at optimal height, can enhance pollution mitigation (Barwise and Kumar 2020). Other factors, like tree height or which particles we hope to capture must be considered; dilution of emissions with clean air above is helpful to reduce emissions and differently designed green space will trap different particles (Janhäll 2015). NO_X and NH_3 also differ in deposition velocity; NH_3 has a higher deposition velocity, meaning it more readily deposits onto plant canopies (Hanson and Lindberg 1991), so results may vary among pollutants. Deposition of NO_X and NH_3 is one source of nitrogen input to the system, but throughfall, the water rinsed from the canopy with rain, includes nitrate (NO_3) and ammonium (NH_4) is another substantial source (Xiao et al. 2000). Throughfall measurements help to understand nitrogen inputs, which may connect to pollution reduction. The role of vegetation capture on nitrogen inputs and atmospheric from a field setting remains an important research need.

To address the uncertainties associated with intra-urban atmospheric reactive nitrogen distributions, we ask how atmospheric nitrogen concentrations and inputs vary with sources and sinks within the city of Riverside, California over the course of a year. Riverside is a model city to evaluate local patterns of atmospheric nitrogen pollution driven by traffic and tree canopy. Southern California is known for heavy traffic, which is a major source of NO_X in this region (EPA GHG Inventory), and the large pollution plume from Los Angeles serves as a useful context for evaluating both local source and sink contributions. Riverside has high levels of local traffic heterogeneity, including freeways, main roads, and residential areas as well as large variation in urban vegetation density and tree species (Tayyebi & Jenerette, 2016) (Avolio et al. 2015). In this context, we used Riverside, CA to test predictions from the source-sink hypothesis, which predicts increased traffic will result in the highest atmospheric concentrations of NO_X and NH_3 within the city, and increased vegetation will lead to lower concentrations. We also predict that NO_X and NH_3 concentrations will vary seasonally and with increasing temperatures, atmospheric pollution will decrease. However, based on the trade-off between emissions, we also predict NO_X and NH_3 will vary inversely; based on the greater deposition velocity of NH_3, we predict it will be more sensitive to sink dynamics than NO_X. Further, we predict that species with complex leaf structure, like conifers, will collect the highest amount of pollutant particles. Evaluating these predictions in a dryland city, such as Riverside, will provide new information characterizing the distribution and dynamics of atmospheric nitrogen pollution and the potential roles of traffic and tree canopies.

Methods

Riverside, California is a city with an approximate population of 320,000 in inland Southern California. Riverside is 85 kilometers east of Los Angeles, located in the Inland Empire. The Inland Empire has recently become a hub for logistics and shipping companies, further contributing to atmospheric pollution from Los Angeles (Riverside Press Enterprise).

To measure atmospheric concentration of reactive nitrogen, we deployed a network of sixteen passive samplers in Riverside, California (Figure 1). Our passive samplers were placed across four traffic levels based on volume of traffic and two canopy cover types to estimate the range of variation of urban pollution sources. Two major freeways cross the city, CA-91 and CA-60, and these include the highest traffic volumes. The next highest level, called main streets, refers to major throughfares over four lanes across, which are common driving routes for locals. The next lower input are commercial-residential areas, which are roads with consistent, but lower traffic. The lowest level are residential neighborhoods, which are much lower traffic and farther from large roads. Each traffic level has sites in two neighborhoods, with a total of eight different neighborhoods in the city. Finally, for each neighborhood group there were paired high and low canopy cover sites. Canopy cover was based on pairwise comparison to its paired site in the same neighborhood and at the same traffic level. At high canopy sites, samplers were placed on structures surrounded by canopy, and at low canopy sites samplers were installed at least five meters from any present trees.

At each sampling location, we deployed Ogawa passive samplers (Fenn, Bytnerowicz, & Schilling, 2018) exposed continuously for every two weeks from July 2020 through October 2021. These observations provide an integrated concentration amount for each two-week period. Each sampler contained two Ogawa filters for each gas, which were averaged. Samplers were installed under weather shelters on telephone and light poles, approximately three meters above the ground, and measured atmospheric nitrogen at these sites. Seasons over the course of sampling were characterized as fall (October- December), winter (January- March), spring (April- June), and summer (July- September). We also use weather data from the Riverside Municipal weather station (Weather Underground). Using these hourly data, we calculated the average temperature for each sampling period.

Figure 1.1: a. Map of California with inset of Riverside, CA **b.** Map of Riverside, CA passive sampler network. Green points are high canopy cover sites and grey points are low canopy cover.

Ogawa samplers were processed at the United States Forest Service (USFS) Southwest Research Station. NO_X and NH_3 values from filters were converted to concentration values in parts per billion (ppb) and parts per million (ppm), respectfully using methods described in Fenn, Bytnerowicz, & Schilling, 2018. Traffic count data for residential, commercial-residential, and main street traffic levels was collected from the City of Riverside Public Works Department Traffic Volume Counts (Riverside DPW), and traffic counts were collected at cross streets where samplers were deployed in 2017. Freeway traffic count data was collected by California Department of Transportation as an annual average daily traffic count (CalTrans).

To evaluate the effects of species differences on deposition, we also conducted a shorter term throughfall study at the US Forest Service Southwest Research Station from November 2019 to May 2020 using ion-exchange resin collectors (IERs) under six species along with an unexposed blank, and a sample under open canopy. Species include canary island pine (*Pinus canariensis,* PICA15), chamise (*Adenostoma fasciculatum,* ADFA), canyon live oak (*Quercus chrysolepis,* QUCH2), coast live oak (*Quercus agrifolia,* QUAG), ghost gum (*Corymbia papuana,* COPA40), and Dutch elm (*Ulmus hollandica,* ULHO). These species represent the diversity of native trees that are also planted in Southern California cities. Throughfall data from IERs was collected at the USFS Southwest Research Station lab using a KCl resin extraction as outlined in (Fenn et al. 2018b).

Statistical analyses and visualization were performed using R 4.1.3 (2022) and RStudio. Data from this project will be stored in DRYAD. Temporal effects were quantified with one-way ANOVAs with the date the sampler was removed as a factor. To determine seasonal patterns, linear regressions were used to determine effect of temperature on atmospheric concentration. We compared concentrations at each site throughout the entire study to quantify spatial patterns. We used one-way ANOVAs to evaluate source effects, along with Tukey post-hoc tests. We looked at relationship between high and low canopy sites to evaluate the linearity of sink effects. We compared differences in throughfall between native tree species and used one-way ANOVAs and Tukey post-hoc tests to identify differences among species.

Results

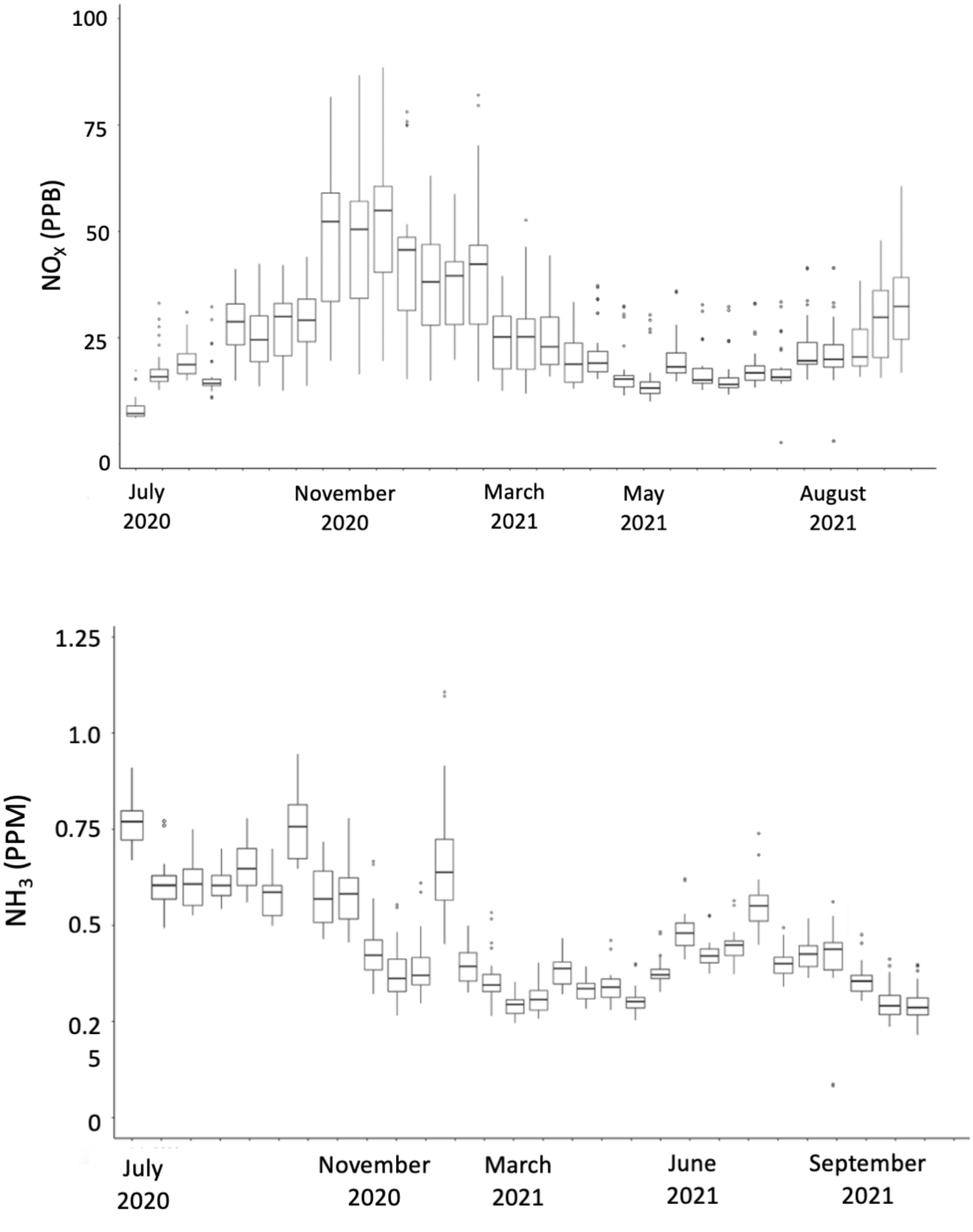

Figure 1.2: NO_X and NH_3 over full sampling period by date.

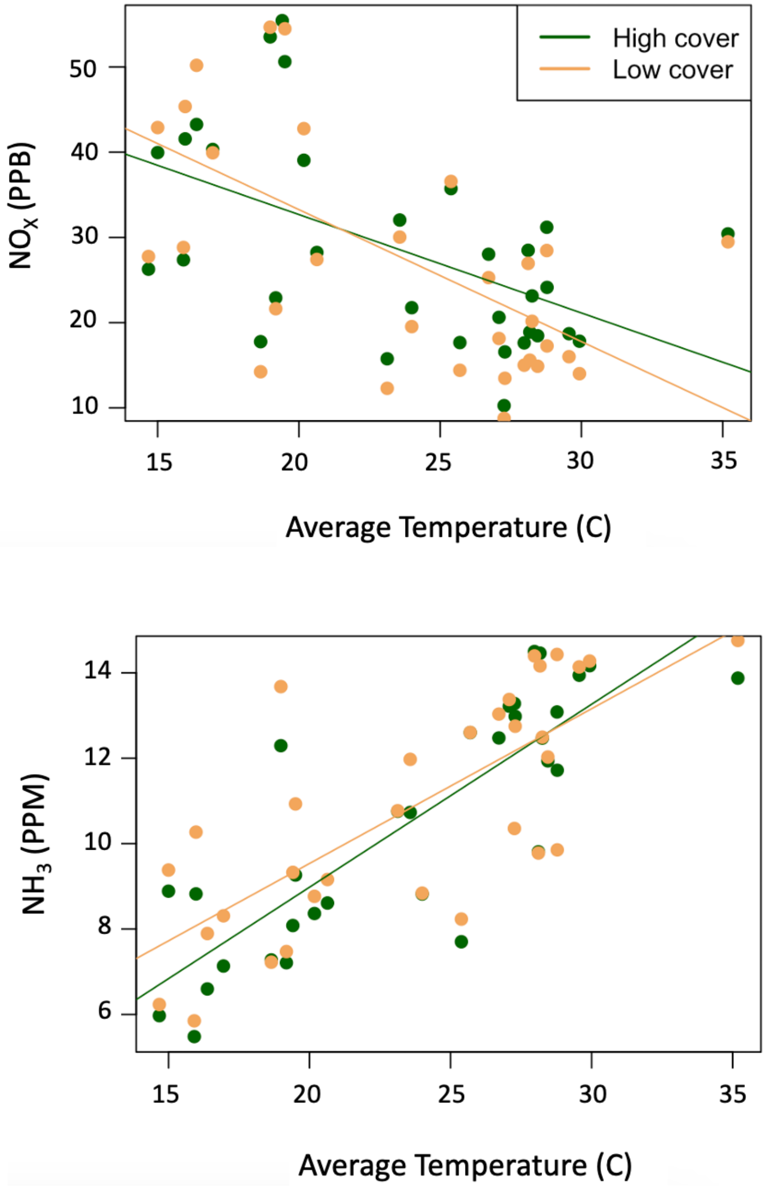

Figure 1.3: Atmospheric concentration of nitrogen with temperature over the sampling period. NO_X and NH_3 show opposite patterns with temperature, and NH_3 is more affected by temperature.

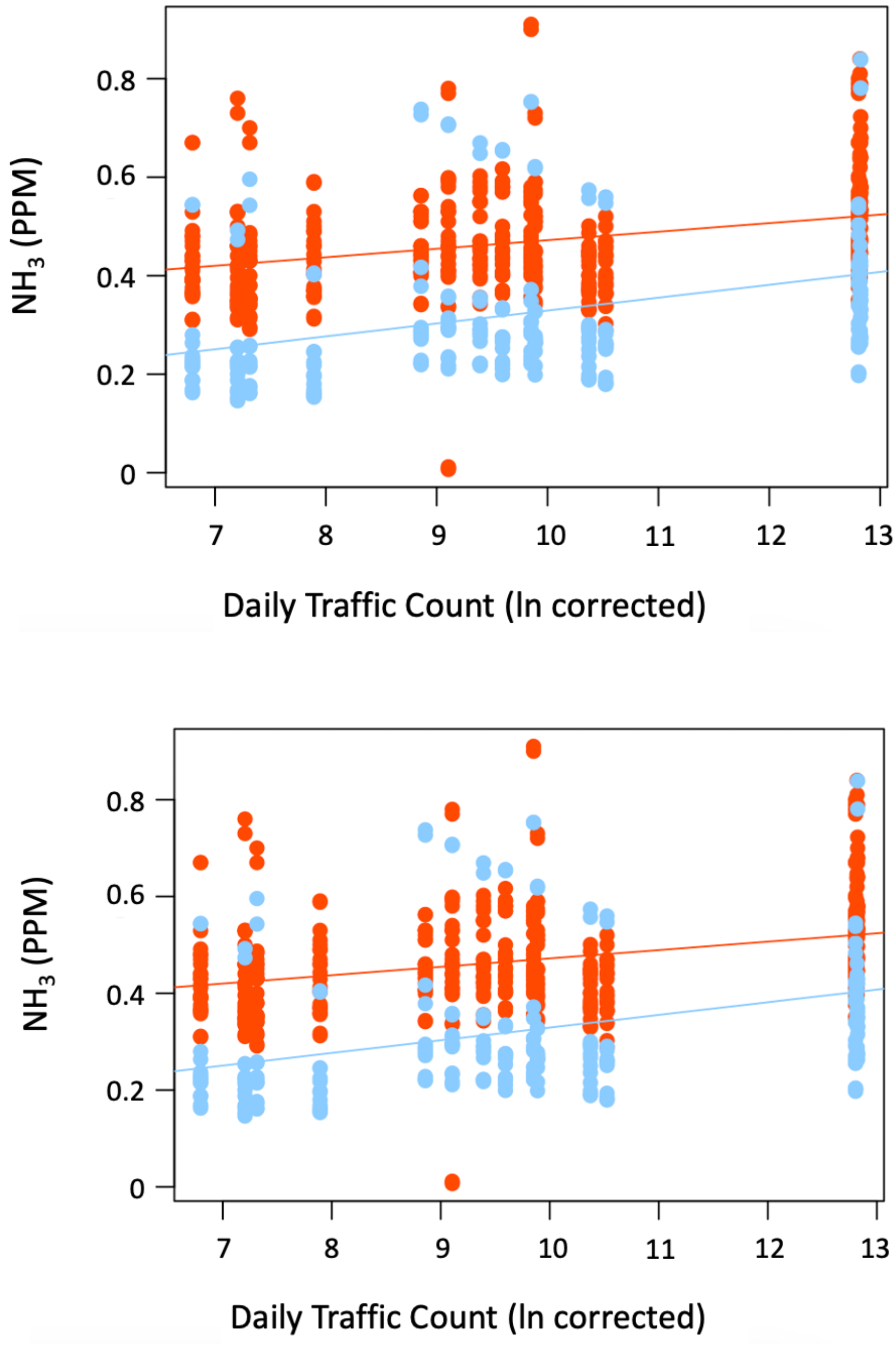

Figure 1.4: Traffic count relationship during summer and winter.

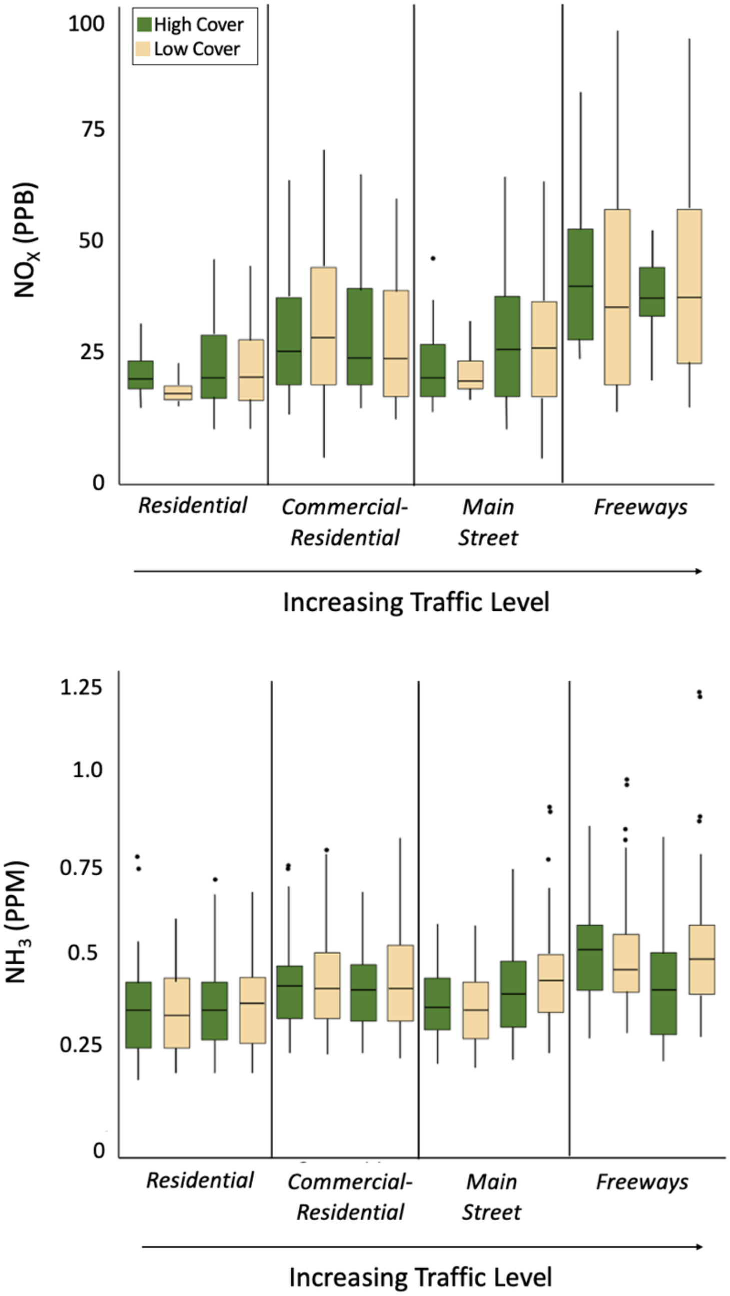

Figure 1.5: Concentrations of NO_X and NH_3 across the four traffic levels for the entire sampling period. Green boxes show concentrations at high canopy cover sites and tan show concentration at low canopy cover sites. Panel a shows NO_X and panel b shows NH_3.

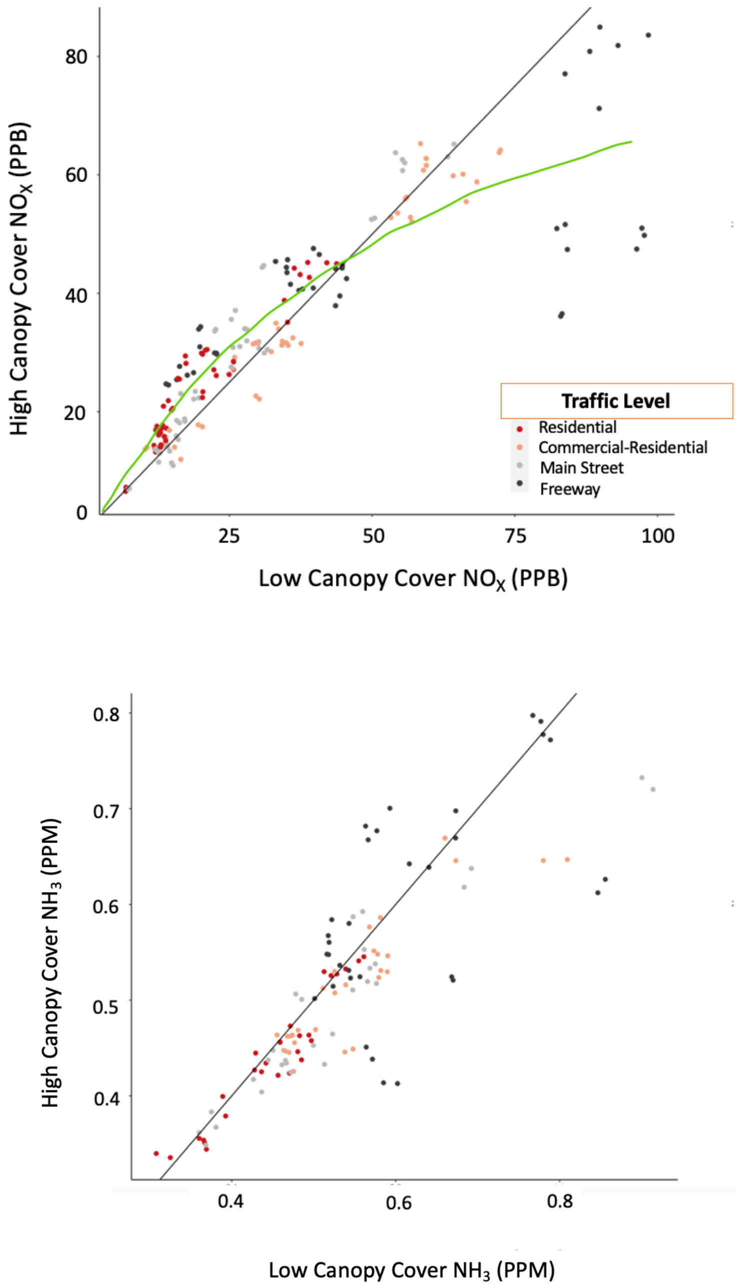

Figure 1.6: Concentrations of NO_X and NH_3 at high cover versus low cover sites with 1:1 line. Points are colored by traffic level. The green line shows the non-linear model of NO_X concentrations.

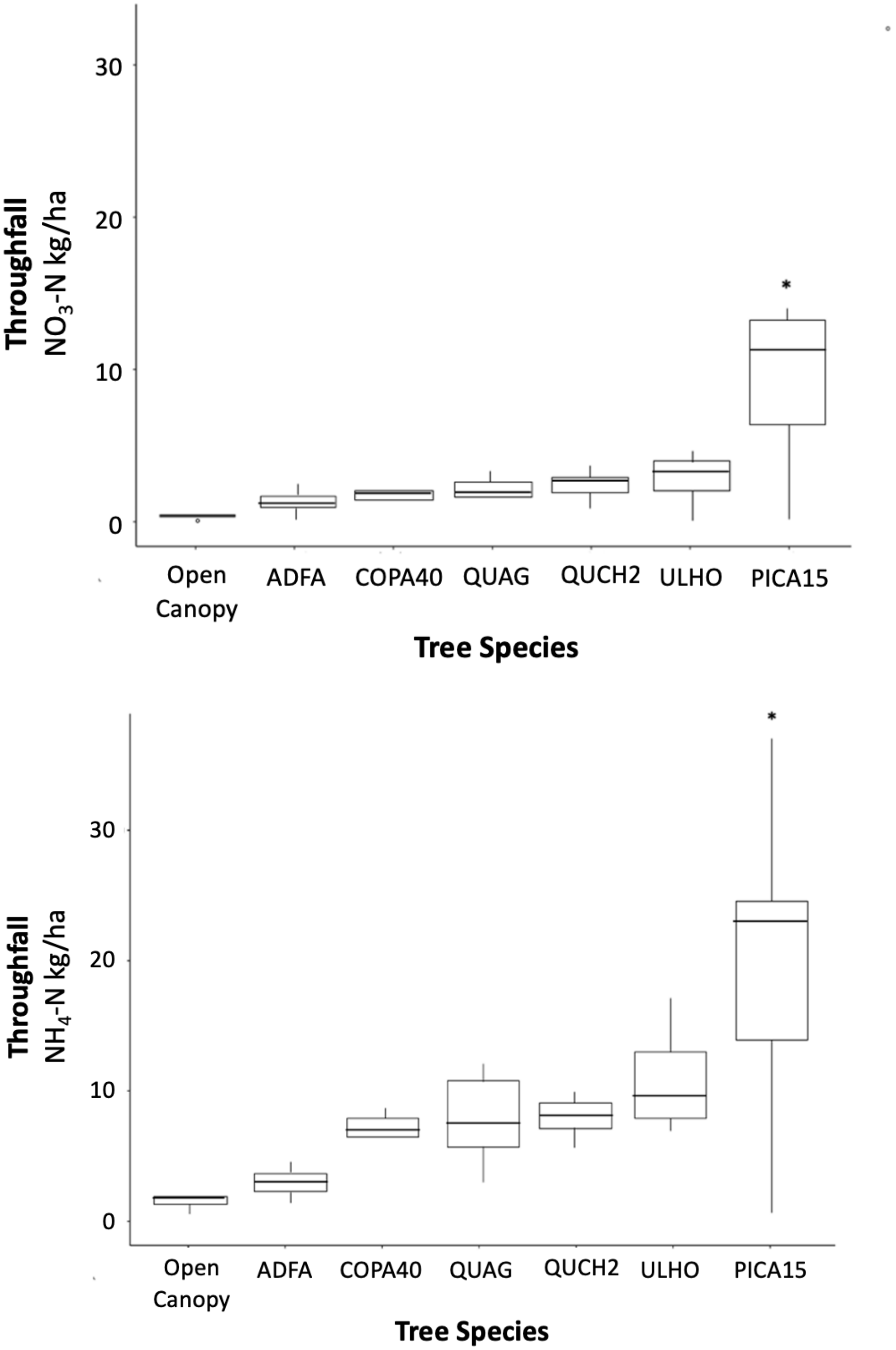

Figure 1.7: NO_3 and NH_4 throughfall under different tree species.

Temporal Patterns

Patterns of atmospheric concentration of NO_X and NH_3 across the sampling period showed differences across seasons (Figure 2). NO_X showed higher concentrations in winter months and lower concentrations in summer months ($F(1,30)= 14.21$, $p< 0.001$), while NH_3 had the opposite pattern ($F(1,30)= 48.16$, $p< 0.001$). In the summer months, NH_3 concentrations ranged from 5.83-13.33 mg/m^3, with the highest recorded value of 13.33 mg/m^3 in July 2021. NO_X concentrations were lowest during those summer months, ranging from 7.27- 43.51 ppb, with the lowest measurement of 7.27 ppb in July 2020. During winter months when NH_3 concentrations decreased, NO_X concentrations increased. NH_3 concentrations during this time period ranged from 2.7-8.39 mg/m^3 in the winter, with the lowest value observed in March 2021, while NO_X concentration ranged from 29.94- 98.39 ppb in the winter with the highest value of 98.39 ppb in December 2020.

Seasonal patterns are further supported by temperature relationships with NO_X and NH_3 concentrations. We compared atmospheric concentration to the average temperature during each sampling period (Figure 3). Temperature patterns mirror the seasonal patterns shown in figure 4: NO_X and NH_3 show opposite patterns. NO_X concentrations decrease with increasing temperature (NO_X at high cover sites: $F(1, 30) = 11.98$, $p = 0.002$, $r^2= 0.29$; and low cover sites: $F(1, 30) = 15.82$, $p < 0.001$, $r^2= 0.35$), while NH_3 concentrations increase with temperature (NH_3 at high cover sites: $F(1, 30) = 68.65$, $p < 0.001$, $r^2= 0.70$; and at low cover sites: $F(1, 30) = 37.24$, $p < 0.001$, $r^2= 0.55$).

Spatial Patterns

To quantify the effect of traffic sources, we compared traffic counts with atmospheric nitrogen concentration distributions (Figure 4). We compared both NO_X and NH_3 concentrations with traffic count during summer and winter months. Atmospheric concentrations of NH_3 were higher in the summer with a peak of 13.33 mg/m^3 in July 202 (NH_3 summer: F (1, 398) = 44.29, $p < 0.001$, $r^2 = 0.10$; NH_3 winter: F (1, 220) = 22.24, $p < 0.001$, $r^2 = 0.10$), while NO_X concentrations were higher in winter months, with a peak of 98.39 ppb in December 2020 (NO_X summer: F (1, 398) = 130.7, $p < 0.001$, $r^2 = 0.25$; NO_X winter: F (1, 184) = 109.8, $p < 0.001$, $r^2 = 0.37$;). For both gases, atmospheric concentration increased with traffic count, with that pattern most evident in winter NO_X concentrations.

Our study found evidence that urban atmospheric reactive nitrogen varies throughout the city of Riverside (Figure 5). The data show that traffic level and canopy cover affect atmospheric concentration of NO_X and NH_3, though the patterns diverge between the forms of reactive nitrogen. Both NO_X and NH_3 vary across the four traffic levels, but the endpoints of the traffic levels show the biggest differences, meaning freeways and residential areas within a single city have major differences in NO_X and NH_3 concentrations. The maximum concentrations were 97.47 ppb NO_X and 13.33 ppm NH_3, which occurred in December 2020 and July 2021, respectively. The minimum concentrations were 6.85 ppb NO_X and 2.7 ppm NH_3, which occurred in June 2020 and March 2021. Over the year-long sampling period, NO_X had an average concentration of 28.4 ppb and NH_3 had an average concentration of 7.4 ppm. Average concentrations by season mirror patterns with temperature: for NO_X average were 19.7 ppb in the summer, 43.2 ppb in the fall, 38.0 ppb in the winter, and 19.7 ppb in the spring, while for NH_3 averages were 8.9 ppm in the summer, 7.3 ppm in the fall, 4.9 ppm in the winter, and 6.5 ppm in the spring. NO_X concentration is much more variable, with a coefficient of variation of 96.8, than NH_3, with a coefficient of variation of 65.8. We also see little evidence of a canopy sink effect when we look at the full dataset.

When evaluating the effect of the tree canopy as a sink, no differences were detected in canopy cover across all sites and sampling periods ($p>0.1$, ANOVA). For both NO_X and NH_3, when all sites were combined for analysis, no canopy effect was detected. We then compared concentrations between high and low canopy sites (Figure 6). While NH_3 appeared to show a linear pattern, NO_X was non-linear. At the low concentrations of NO_X, there appears to be a concentrating effect with tree canopy less effective as a sink until it reaches higher concentrations, which is supported by the fit of a nonlinear model to the data ($p< 0.001$, AIC = 3171).

Throughfall measured under different tree species shows that pollutant capture or sink effect could be shifted depending on what trees make up the urban canopy (Figure 7). The highest throughfall measurements were under the conifer species. We used an ANOVA and Tukey post-hoc test and found that only canary island pine (PICA15) showed significantly increased throughfall NO_3 and NH_4 compared to the other species. Other species were also not significant from open canopy, or bulk throughfall, measurements.

Discussion

Atmospheric concentrations of NH_3 vary ten-fold and concentrations of NO_X vary twenty-fold within Riverside, highlighting the importance of local, intra-urban air pollution distributions. The large urban pollution plume from Los Angeles does not overwhelm local patterns. Over the course of a year, we found that NO_X and NH_3 peak in opposite seasons. This highlights an inverse pattern between NO_X and NH_3 over time which, along with local variation, contributes to observed atmospheric patterns. Atmospheric concentration is important for exposure to pollutants, and this work shows that sources and sinks contribute to local pollution distributions. Our findings highlight that in our hypothesized source sink framework, there is support for traffic sources, but not for tree canopy sinks.

Patterns in NO_X and NH_3 varied seasonally and were correlated to average temperature. We predicted lower pollutant concentrations at higher temperatures in a given sampling period, as shown in previous NO_X studies (Roberts-Semple et al. 2012), which was corroborated for NO_X but not for NH_3. NO_X was lowest at highest temperatures, while NH_3 was lowest at low temperatures. This pattern was consistent with both season and temperature. NH_3 peaks in summer have been shown atmospherically in Beijing (Xu et al. 2018), as well as over the North China Plain (Li et al. 2018) and other regions in China (Chen et al. 2020), which mirrors our results. Throughfall NH_3 peaked in the spring in a Boston study, associated with increased use of fertilizers during that time (Decina et al. 2017). While NH_3 patterns have been linked to fertilizer use or agriculture, seasonal patterns of NO_X may be explained by atmospheric chemistry. NO is the primary precursor for ozone (O_3), which also peaks in the summer months (Roberts-Semple et al. 2012); potentially, NO being transformed into O_3 in the summer may reduce its atmospheric concentration. Drivers of seasonal patterns of variation in atmospheric NO_X and NH_3, including fertilizer use or effects of catalytic converters, will provide tools to confirm these patterns and identify new hypotheses.

Local traffic acts a source within a city, affecting atmospheric reactive nitrogen concentrations. Traffic as a source is supported by both for categorical traffic data as well as quantitative traffic counts. Daily, NO_X concentrations increase with increased traffic in previous studies (Roberts-Semple et al. 2012), so traffic sources appear to be important on multiple time scales. NO_X had a wider range of variation across sites, while NH_3 shows more fine scale patterns. NO_X is often more affected by anthropogenic sources than meteorological patterns (CATC 2003), meaning the range of variation in NO_X may be connected more directly to daily human activities or traffic than NH_3. This study shows traffic is a major determinant of local patterns of atmospheric NO_X, and characterizing this source on the local level is crucial.

We found in Riverside, CA that, while tree canopy may be capturing particles, there is little evidence that trees are significantly reducing atmospheric reactive nitrogen concentrations or improving air quality. Urban trees in Beijing showed a potential to remove 1304 tons of NO_X in 2019 (Gong et al. 2021), but our study suggests removal capacity may depend on pollutant concentration. Trees provide a wide range of ecosystem services, like cooling, water regulation, habitat, and cultural services (Elmqvist et al. 2015), but may not provide air quality benefits in all locations. To improve air quality in a city like Riverside, reducing street emissions may be more effective than relying on trees or green infrastructure. Tree canopy does however act as a slight sink at lower NH_3 concentrations. This inverse relationship between NO_X and NH_3, mirrored in the seasonal data, highlights the need for monitoring multiple pollutants. Past studies acknowledge city-wide pollution reduction would need large scale green infrastructure (Nemitz et al. 2020), but our results show greening may not be the ideal solution for air quality problems.

We found evidence deposition varies with tree species, suggesting variation in capture of pollutant particles. Differences among tree species may be due to leaf micromorphology, leaf size, and longevity, as shown in previous studies (Li et al. 2019, Redondo-Bermúdez et al. 2021). From our common native species, the most effective sink in terms of particle capture is the conifer: canary island pine. The high throughfall from pine along with the peaks of NO_X during fall and winter months highlight the potential use of evergreen conifers for pollution capture. However, it is unclear if pollutant capture by trees affects atmospheric concentrations. While atmospheric concentrations can affect health (Jonson et al. 2017, Jacobson et al. 2019), deposition of pollutant particles to trees may not improve air quality. Tree canopy's ability to capture pollutants can be further affected by leaf uptake and nitrogen cycle processes in the canopy like fixation or volatilization (Bortolazzi et al. 2021). In another study tracking particle deposition from traffic, researchers found that traffic related NO_X, but not NH_3, affected nitrogen isotope compositions in roadside soil and plant tissues (Xu et al. 2019).

Urban emissions are being captured by trees and plant tissue, though it is unclear if atmospheric concentrations are reduced as a result.

This work shows that local characteristics affect atmospheric concentration of, and therefore exposure to, nitrogen pollutants. Riverside, CA has local pollution along with pollutants from the greater Los Angeles area. Riverside's proximity to poor air quality with increased logistic and freight facilities (American Lung Association 2023), along with fine scale local variation, makes it a unique system. Though states set the baseline requirements, cities are often responsible for their own progressive pollution reduction (Miller & Michalak, 2016). The concentrating effect we observed in NO_X appeared at concentrations below 55 ppb, which is the threshold identified by the Clean Air Act (H.R.5961, 117th Congress) Federal and state policy to improve air quality may be inaccurate when we consider uncertainties in effects of tree canopy on pollution. These results highlight the uncertainty of vegetation as a solution for mitigation, and in Southern California reducing traffic significantly is a challenge. Particle capture of nitrogen was most successful by conifers like pine trees, but reduction in air pollution was not observed. Whether particle capture by the canopy can offset atmospheric deposition remains unclear and casts doubt on tree canopy sink effectiveness. Adverse health effects near roadways have been observed (Festy 2013), but there is conflicting evidence whether residences near roadways have increased health hazards for N_2O specifically (Kobza and Geremek 2017). Understanding the most impacted areas and quantifying tree services is key for mitigation Local variation from traffic and limited success of tree canopy sinks makes cities a crucial system to quantify pollution effects and reduction for an ecosystem and its residents.

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Chapter 2: Urban Teleconnections Across Air, Canopy, and Soil Along a Nitrogen Deposition Gradient

Abstract

Atmospheric pollution is a major concern for urban residents, but pollution travels beyond city limits, affecting natural ecosystems through teleconnections. Atmospheric nitrogen from greater Los Angeles area reaches over 200 kilometers beyond the city limits, in Joshua Tree National Park. We hypothesized that the deposition gradient patterns would be similar across the air, canopy, and soil. We measured nitrogen in the air, shrub canopy, and soil to understand nitrogen dynamics along an atmospheric deposition gradient from Riverside, CA to the eastern edge of Joshua Tree from 2018-2020. Atmospheric nitrogen concentrations differ by site overall with decreased atmospheric concentration with increased distance from urban areas. Throughfall NO_3 and NH_4 varied significantly across the gradient, (NO_3: $p< 0.001$, NH_4: $p< 0,001$) but only the lowest deposition site was different when comparing sites in pairs. Soil NH_4 was significantly different at each site, while NO_3 was only different at the endpoints of the gradient. Seasonal patterns showed an inverse relationship between NO_X and NH_3 in the air, and NO_3 and NH_4 in throughfall mirrored that pattern, while NO_3 and NH_4 in the soil showed similar patterns to each other. The changing patterns in nitrogen as it moves through an arid system shine light on teleconnections between urban and natural areas, highlighting the long-range effects on urban pollution.

Introduction

Urban teleconnections describe far-reaching effects of cities on surrounding ecosystems, moving from a place-based to a process-based concept. Traditionally, understanding urbanization is focused on place and discrete classes like urban versus rural, while land cover and use can be more accurately described along a continuum (Seto et al. 2012). Teleconnections links places through processes, which allows us to capture patterns in non-urban places affected by urban places. Teleconnections leading to increased deposition in rural areas and even national parks has been shown to be 40-85% from anthropogenic NO_X or domestic NH_3 emissions, so human effects on nitrogen are far-reaching (Ellis et al. 2013). Increased nitrogen deposition from urban areas can affect ecosystem processes and alter natural systems.

Nitrogen pollution from the city to the hinterlands serves as a case study of teleconnections. Global reactive nitrogen production by humans generated three-fold more reactive nitrogen than natural terrestrial processes from 1950 to 2010, much of which comes from urban areas (Galloway et al. 2014). Urban pollution is substantial, but that pollution travels beyond the city limits (Sickman et al. 2019). Los Angeles, for example, produces a large pollution plume due to high traffic levels (LA County Public Health), and that affects smaller cities and natural areas. There is evidence of Los Angeles pollution can reach as far as 210 kilometers away in Joshua Tree (NPCA Report, 2019), but patterns along that path are unclear. Important pollutants include nitrogen oxides (NO_2 and NO, collectively NO_X) and ammonia (NH_3) in the air, along with nitrate (NO_3) and ammonium (NH_4) in throughfall, or canopy runoff, and in the soil. Inputs of

NO_X come largely from anthropogenic sources like tailpipe emissions but tools that reduce NO_X emissions can increased NH_3 emissions (Suarez-Bertoa et al. 2014, Xu et al. 2018). NH_3, or other reduced nitrogen compounds, make up increasingly large portions of total deposition, up to 60% of inorganic nitrogen, but is underestimated when measuring on-road emissions (Li et al. 2016, Fenn et al. 2018a, Walker et al. 2019). Understanding ecosystem response to nitrogen deposition can help to model nitrogen cycling and predict biosphere response to global change (de Vries et al. 2014).

Past research informs our study sites, deposition gradient, and characteristics of desert shrub canopy and soil. Previous work identified desert sites with annual deposition from 5 to 30 kg N/ha in two separate years, which showed decreasing deposition further from urban sources (Allen et al. 2009). This research helped to identify a deposition gradient in Southern California from city to desert. The desert where the sites are located is characterized by shrubs, primarily creosote (*Larrea tridentata*), interspersed with open interspace. Shrub canopy in deserts create islands of fertility, where nutrients and soil moisture are high under the canopy compared to interspace (Schlesinger et al. 1996). Islands of fertility have higher net N mineralization and nitrification rates spatially, but have little temporally variation (Schade and Hobbie 2005). Nitrogen deposition can also be important for increased growth, and therefore survival, of plant species (Horn et al. 2018). The amount of nitrogen that reaches the soil after passing through the canopy, and throughfall, or the amount of precipitation that reaches the soil after having passed through the canopy, is a useful measure of nitrogen inputs to the soil. Canopy roughness or canopy uptake can trap some nitrogen in the canopy, but the amount is variable

(Bortolazzi et al. 2021). There is evidence in a semiarid ecosystem that a substantial portion of nitrate in soils is from the atmosphere, so input to the soil is important in spite of the portion captured by the canopy (Michalski et al. 2004). Once nitrogen is deposited from the air and canopy, the soil biogeochemical processes become important. Soils across this gradient are exposed to over 16 kg N ha^{-1} yr^{-1} near Los Angeles—with localized studies measuring up to 29 kg N ha^{-1} yr^{-1} (Sickman et al. 2019)—and as low as 3 kg N ha^{-1} yr^{-1} further inland (Schwede and Lear 2014; National Atmospheric Deposition Program 2022). In dry weather nitrogen will be deposited to dry soils while microbes are dormant, and nitrogen appears to only be limiting when drought stress is relieved (Ladwig et al. 2012). Nitrogen built up in soil can then be emitted with rewetting, and soil emissions of NO and N_2O in deserts is a potential pathway for ecosystem N loss and may affect air quality (Eberwein et al. 2020, Krichels et al. 2022). Characteristics of the air, canopy, and soil nitrogen processes are important to understand in order to determine patterns downwind from urban areas.

Seasonal differences, particularly between the dry and rainy seasons in the desert, likely also effect patterns of air, canopy, and soil nitrogen. Deserts in the American southwest are characterized by wet winters which leads to vegetation greening, and isolated summer rain with moisture limited to the upper soil layers (Scott et al. 2000, Notaro et al. 2010). This pattern is consistent in the Southern California Mojave Desert with the majority of rain in the winter/spring, with isolated monsoons (CSU Desert Studies Center). Local precipitation has high variability, which may not be captured by long-term averages (Petrie et al. 2014). Nitrogen pollutants, and therefore inputs to the desert ecosystem, also vary seasonally. A pilot NH_X monitoring network showed atmospheric NH_3 tends to peak in late spring to summer (Chen et al. 2014), while NO_X concentrations tend to peak in winter months (Roberts-Semple et al. 2012).

The desert system and unique urban sprawl in Southern California is ideal to understand teleconnections. California and the Mediterranean Basin are among the areas most threatened by nitrogen deposition (Ochoa-Hueso et al. 2011). Deserts cover 25% of global land surface, and aridification is increasing worldwide, highlighting the importance of understanding effects on desert ecosystems (Ezcurra et al. 2006). Southern California desert ecosystems are also facing land use change from urbanization. Urbanization has increased significantly more within Riverside, CA than in the Coachella Valley, representing "leapfrog" development which will likely affect teleconnections (Chen et al. 2010).

This study asks how multiple nitrogen pollutants vary across a deposition gradient and how those pollutant concentrations vary over time. Along a deposition gradient, we measure NO_X and NH_3 in the atmosphere and NO_3 and NH_4 from the canopy and soil. We ask how these compounds vary horizontally across a gradient, and vertically at individual sites. We also identify temporal patterns in air, canopy, and soil. We link desert sites through ecosystem processes involving nitrogen, serving as a case study of urban land teleconnections.

Methods

Southern California produces high concentrations of atmospheric nitrogen, which travels to natural desert areas. Sites were organized along a deposition gradient (Allen et al. 2009) from Cabazon, California to the eastern edge of Joshua Tree National Park.

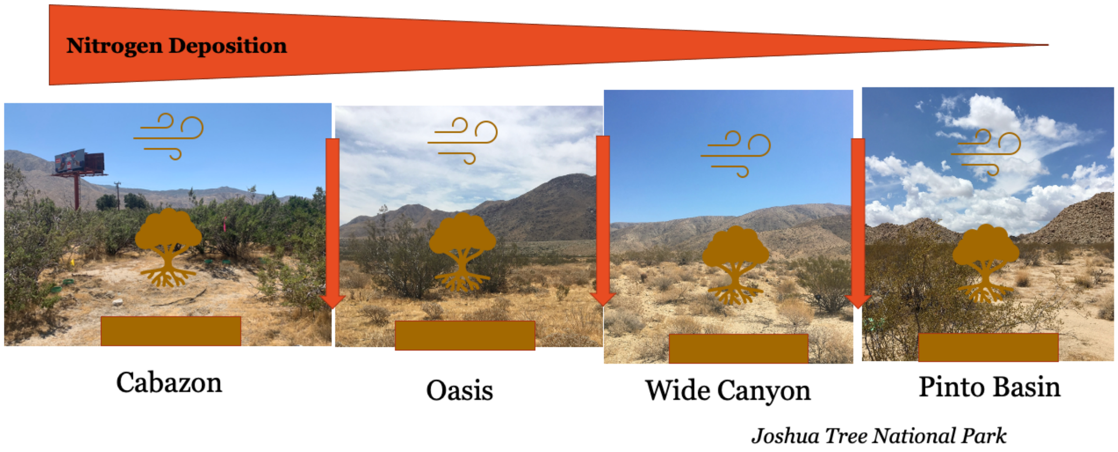

Figure 2.1: Conceptual diagram showing deposition gradient used to measure teleconnections and effects at site level.

Sites are referred to as Cabazon, Oasis de los Osos (hereafter Oasis), Wide Canyon, and Pinto Basin. Cabazon is protected land directly adjacent to Interstate 10. Oasis is a UC Natural reserve site located near Snow Creek Village, CA. The site is near the freeway but undeveloped. Wide Canyon is located on the western edge of Joshua Tree National Park close to Sky Valley, CA, a rural area. Pinto Basin is located in the eastern side of Joshua Tree National Park, within park boundaries and therefore undeveloped. Wide Canyon and Pinto Basin have been previously studied in the context of nitrogen deposition (Bell et al. 2014).

To measure atmospheric nitrogen of NO_X, NH_3, and NO_2, we used Ogawa passive samplers (Fenn et al. 2018b) deployed biweekly to monthly at each site. These observations provide an integrated concentration amount for each sampling period. Each sampler contained two Ogawa filters for each gas, and totals were averaged. Samplers were mounted on wooden poles under weather shelters approximately two meters high. Each sampler contained two Ogawa filters for each gas, and totals were averaged. We collected data from Ogawa filters from June 2018 – November 2020. Ogawa samplers were processed at the US Forest Service Southwest Research Station, where values from filters were converted to concentration values in parts per million (ppm).

To measure nitrogen captured in the canopy, we measured throughfall NO3 and NH4 using ion exchange resin collectors (IERs) placed under creosote (*Larrea tridentata*) canopy. Samplers were exposed for 6-month periods from June- November 2018- 2020 and were attached to funnels to better collect throughfall from the shrubs. Funnels were open full time and therefore collected dry deposition along with some leaf litter. IER columns were processed at the US Forest Service Southwest Research Station using their designed method (Fenn et al. 2018b).

To measure soil NO3 and NH4, we collected soil monthly at each site. At each site, we collected five soil samples under shrub canopy and five soil samples in the interspace. We extracted soils (5 grams) in 2 M KCl solution; soil solutions were shaken for one hour, filtered (Whatman 42 filter paper, 2.5 micrometer pore size), and frozen until analysis. Extracts were analyzed at the Environmental Sciences Research Laboratory at the University of California, Riverside (https://envisci.ucr.edu/research/

environmental-sciences-research-laboratory-esrl). We used one-way ANOVAs to determine statistical significance of nitrogen concentrations across sites and dates for air, canopy. and soil.

Results

Spatial Patterns

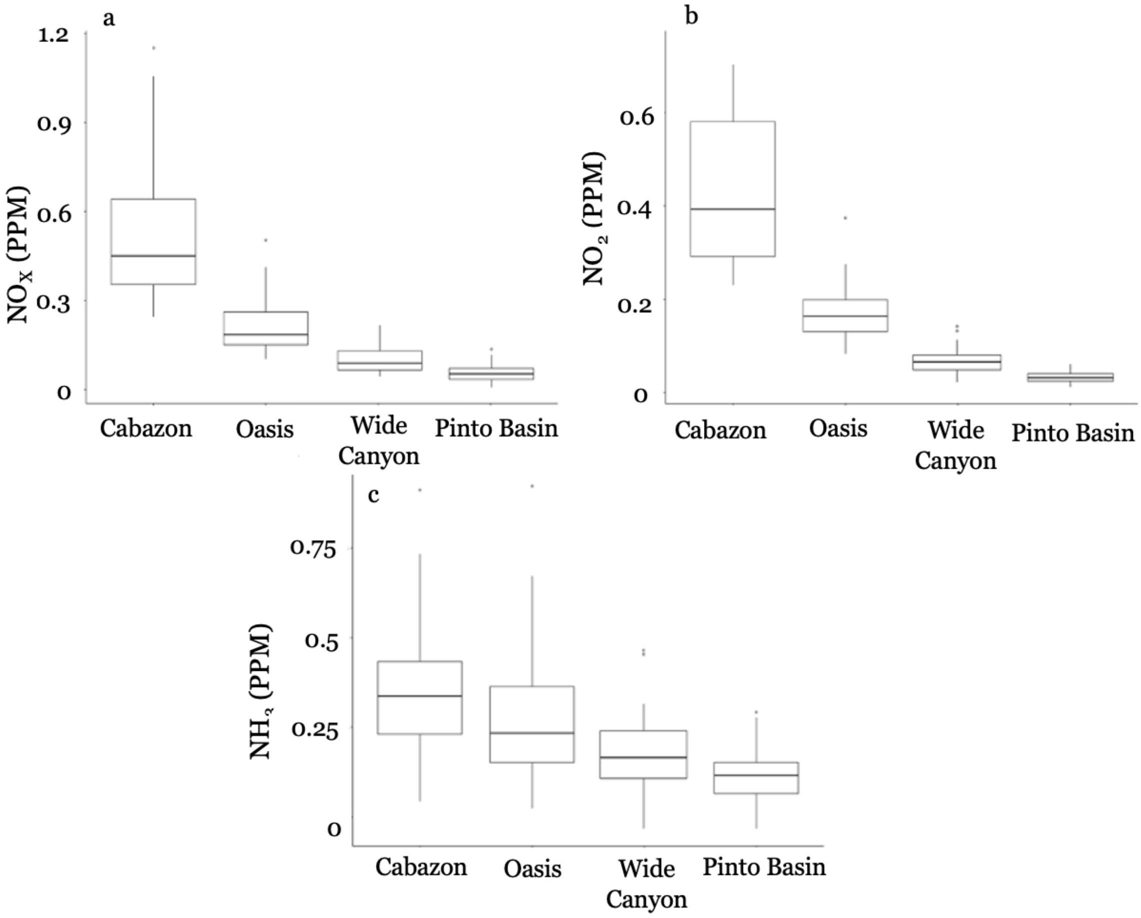

Figure 2.2: Atmospheric nitrogen concentrations (a. NO_X, b. NO_2, c. NH_3) at each site in gradient.

Atmospheric concentration data supported the deposition gradient, with concentrations decreasing from Cabazon to Pinto Basin across the entire sampling period, as shown in Figure 2. A one-way ANOVA showed atmospheric nitrogen concentrations differ by site overall, with decreased atmospheric concentration with increased distance from urban areas. We found maximum NO_X, NO_2, and NH_3 concentrations of 1.2 ppm, 0.736 ppm, and 0.92 ppm, respectively, all observed at Cabazon, and minimum NO_X, NO_2, and NH_3 concentrations of 0.04 ppm, 0.02 ppm, and 0.03 ppm. All four sites are significantly different for both NO_X and NO_2 (NO_X: F (4,155) = 105.2, $p < 0.0001$; NO_2: F(4,156)= 174.2, $p < 0.001$). For NH_3, Cabazon and Oasis were significantly different from Wide Canyon and Oasis (F (4,157) = 14.7, $p < 0.0001$). The confirmation of the deposition gradient in the air helps provide context for canopy and soil patterns, but the patterns vary between nitrogen compounds.

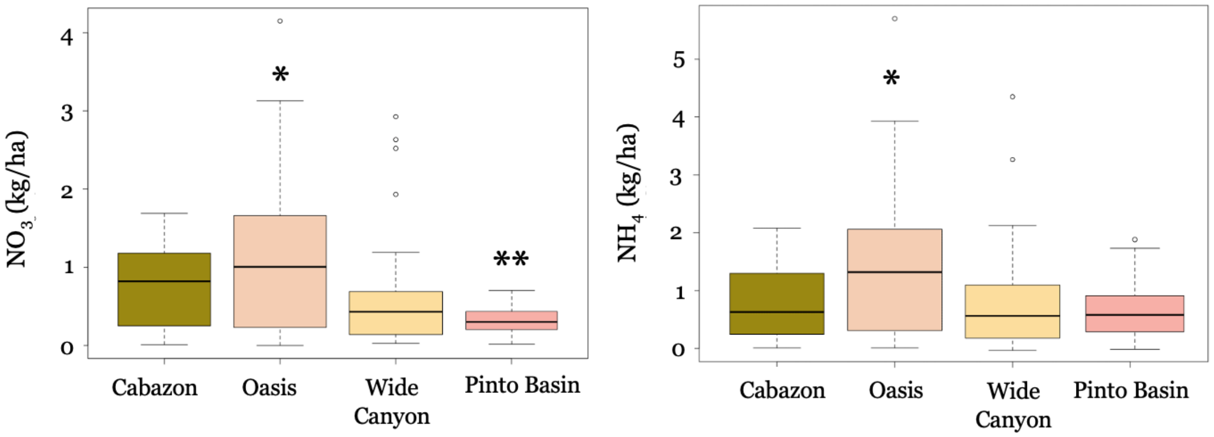

Figure 2.3: Throughfall concentration of NO_3 (left) and NH_4 (right) at each site in gradient, significance denoted with asterisk.

In canopy and soil, we see a departure from the air patterns and a disruption in the gradient. Figure 3 shows that canopy throughfall does not directly follow the deposition gradient. For NO_3, site is a significant factor ($p < 0.001$). Oasis is significantly different from Wide Canyon and Pinto Basin ($p < 0.001$ for both pairs in a Tukey post hoc test). Pinto Basin is significantly different from Cabazon and Oasis ($p < 0.001$ for both pairs. Endpoints of the gradient are therefore more important for NO_3. Unlike the atmospheric pattern, Oasis is higher in throughfall than Cabazon. Though the difference is not significant, it is a positive trend ($p < 0.1$). Site was also a significant factor for throughfall NH_4 ($p < 0.001$). Oasis was also highest throughfall for NH_4 and significantly different, but other site differences were not significant. Throughfall, to show nitrogen captured in the shrub canopy, shows that the deposition gradient differs in the canopy compared to the air.

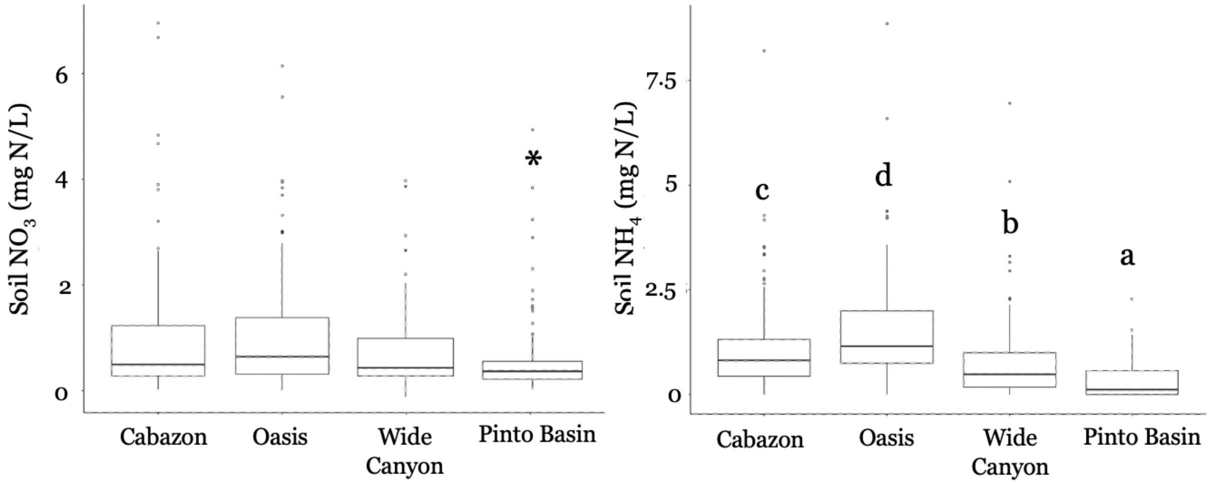

Figure 4: Soil NO_3 (left) and NH_4 (right) at each site in the gradient, significance denoted with asterisk and letters.

Soil NO_3 and NH_4 showed a pattern similar to throughfall, shown in Figure 4. Oasis on average had higher values than Cabazon, though this was only significantly different for NH_4. Site was a significant factor for soil NO_3 ($p < 0.001$), though only Pinto Basin was significantly different from Cabazon and Oasis according to a Tukey post-hoc ($p < 0.01$, $p < 0.001$). Site was also a significant factor for soil NH_4 ($p < 0.0001$), and all site pairs were significantly different according to a Tukey post-hoc test, with the greatest difference between Oasis and Pinto Basin ($p < 0.0001$) and the smallest difference between Oasis and Wide Canyon ($p < 0.05$). Despite similar spatial patterns, canopy throughfall does not predict soil nitrogen. We did not find any significant pattern when plotting soil NO_3 against throughfall NO_3 or soil NH_4 against throughfall NH_4.

Seasonal Patterns

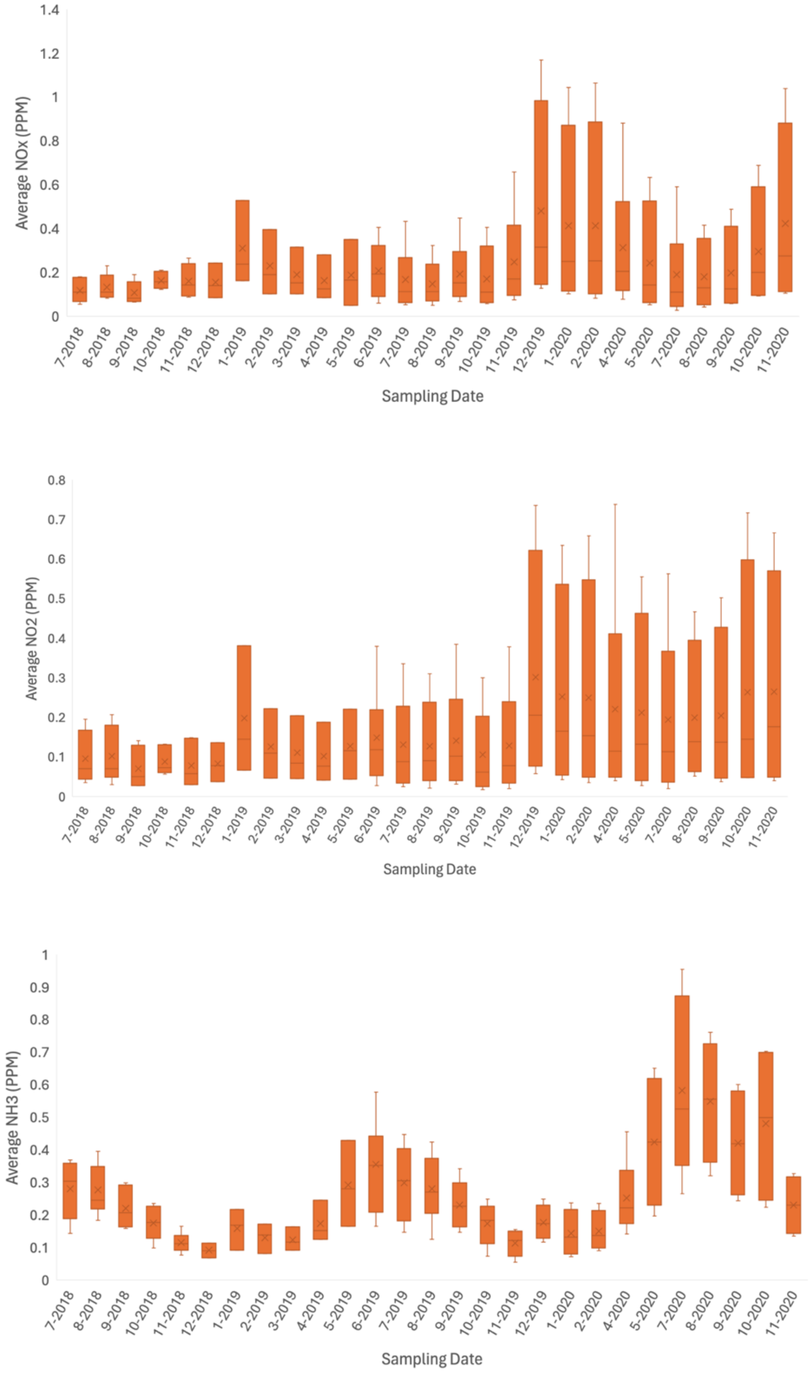

Figure 2.5: Atmospheric concentrations of NO_X, NO_2, and NH_3 by month at all sites.

Over the sampling period, NO_X and NO_2 had similar seasonal patterns while NH_3 differed (Figure 7). NO_X and NO_2 peaked in the winter during winter months, particularly in January 2019 and 2020, but date was not a significant factor for NO_X ($p< 0.1$) or for NO_2 ($p> 0.1$). Both NO_X and NO_2 had a wide range of variation, especially after December 2019; the coefficient of variation for the entire sampling period for NO_X is 0.96, and for NO_2 is 1.05. NH_3 peaked during the summer months, specifically in June of 2019 and July of 2020 and date was a significant factor ($p < 0.0001$). Specifically, July and August of 2020 stood out as significantly different in the post-hoc Tukey test.

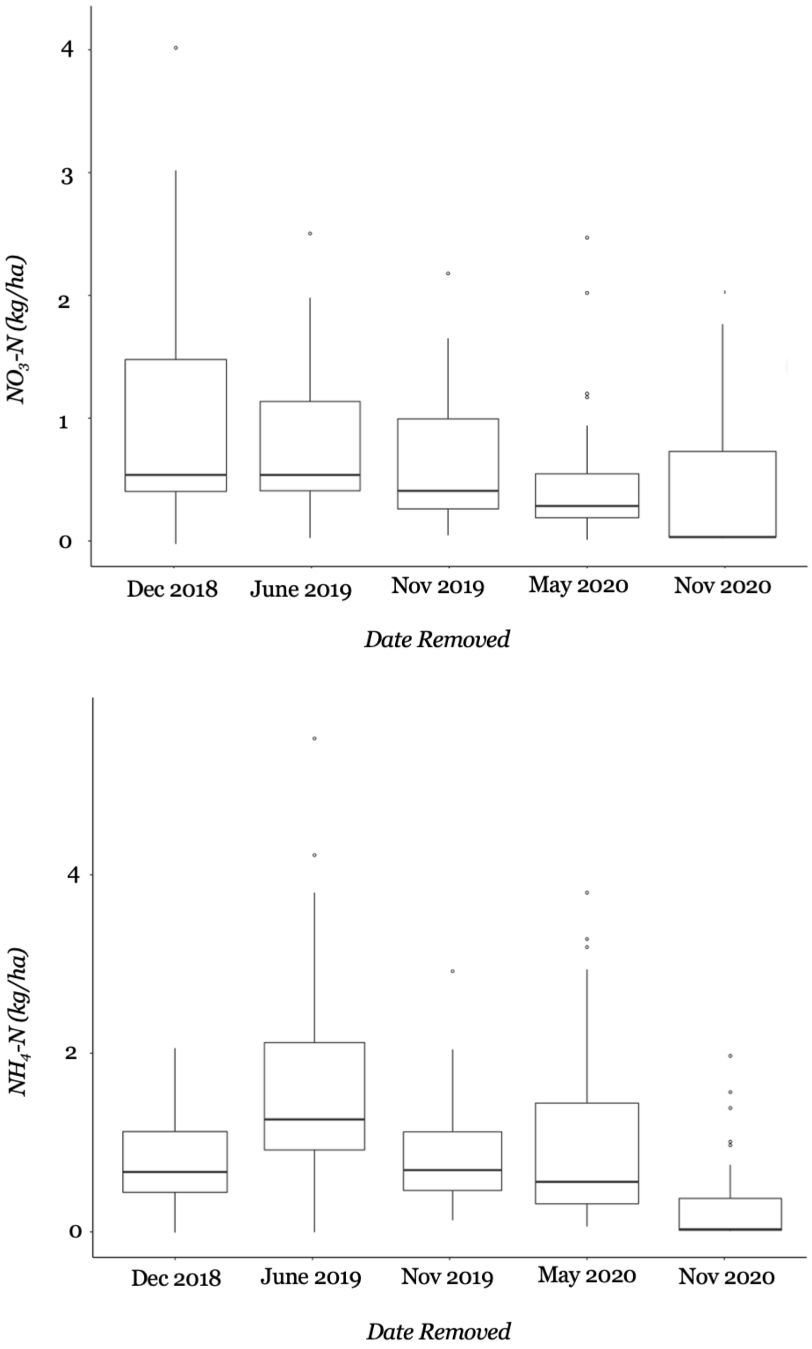

Figure 2.6: Throughfall NO_3 and NH_4 by month. Months on x-axis refer to the end of the sampling period (i.e. June 2019 refers to samplers exposed from December 2018 to June 2019).

Canopy throughfall NO_3 is higher from June - December, while NH_4 is from December – June (Figure 8). This pattern is significant for the summer-winter of 2018 for NO_3 ($p < 0.01$), and the winter-summer of 2018-2018 for NH_4 ($p < 0.01$). For both NO_3 and NH_4, the sampling period from May – November 2020 has significantly lower values according to post-hoc Tukey tests ($p < 0.05$ for pairs including the final sampling period),

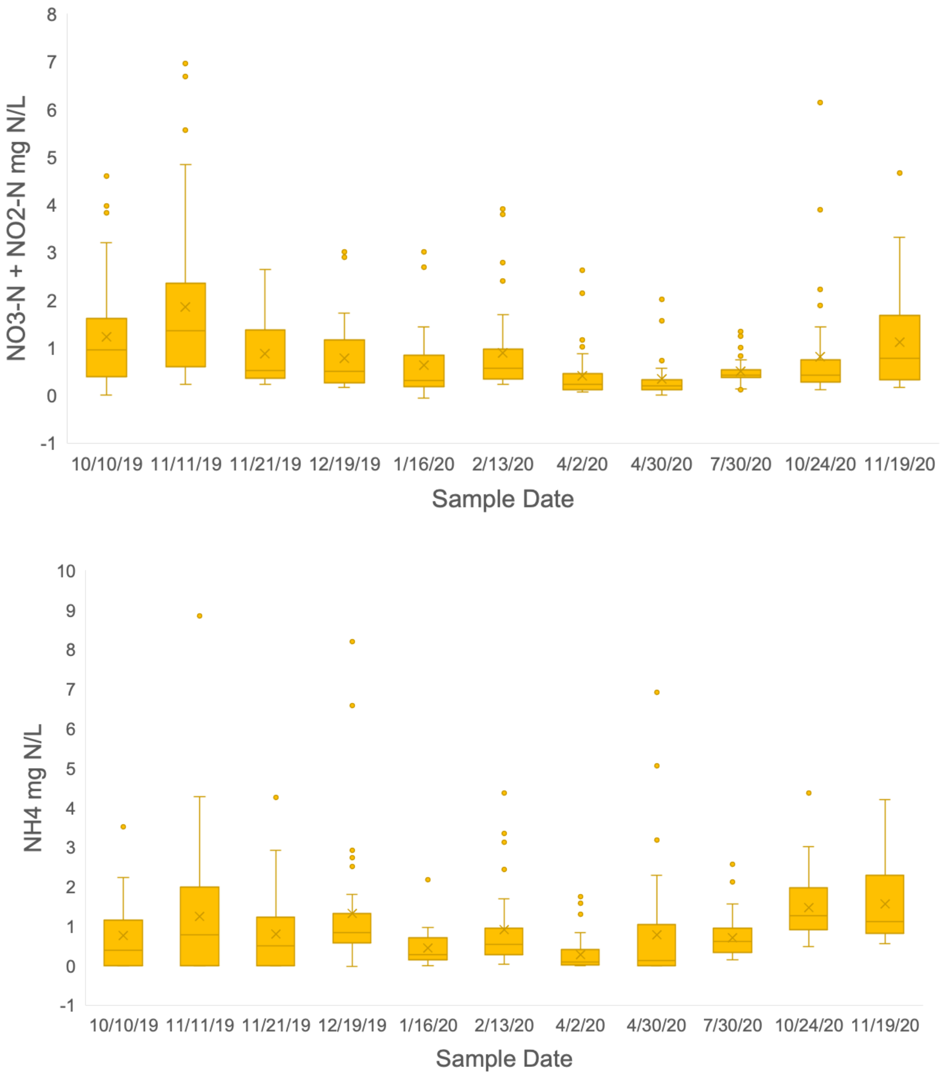

Figure 2.7: Soil NO_3 and NH_4 by date of sample. Extractions were completed the same day the samples were taken.

Soil NO_3 and soil NH_4 have similar seasonal patterns (Figure 9). Soil NO_3 peaks in October and November of 2019 and November of 2020, with a peak value of 6.9. Soil NH_4 also peaks in November of 2019 and 2020, with a peak value of 8.9. Both soil NO_3 and soil NH_4 are at the lowest in April 2020, with minimum values of 0. In a one-way ANOVA, date was a significant factor for NO_3 ($p < 0.0001$). NO_3 winter values from October 2019 and November 2019 and 2020, were significantly higher than other dates and April 2020 was significantly lower than other dates in a post-hoc Tukey test. Date was also a significant factor in an ANOVA for NH_4 ($p < 0.0001$). Similar to NO3, November 2019 and 2020, along with October 2020 were significantly higher than other dates, and April 2020 was significantly lower, according to a post-hoc Tukey test.

Discussion

This work is a case study of teleconnections, highlighting the horizontal path nitrogen follows as it travels, and the vertical path of deposition at a site. Our results show processes in the air, canopy, and soil vary along the deposition gradient, with canopy and soil pattern diverging from those in the air. Ecosystem processes therefore differ from place-based hypotheses, where the gradient would be maintained in canopy and soil patterns. Seasonally NO_X and NH_3 have an inverse relationship, while NO_3 and NH_4 follow similar patterns. Spatial and temporal patterns of ecosystem processes help to understand teleconnections and the effects of long-range pollution on multiple parts of natural ecosystems.

The deposition gradient is supported for all measured types of atmospheric nitrogen. The gradient used was built on past work which included Wide Canyon and Pinto Basin (Allen et al. 2009), and our results support reduced atmospheric concentrations with distance from urbanization. Using observed nitrogen deposition gradients allows for better understanding and measurement of ecosystem processes that can be affecting the biosphere (Bebber 2021). We observed interesting patterns, particularly the difference between NO_X, NO_2, and NH_3. The pattern of atmospheric NH3 differs in that it is not as clear of a gradient. This pattern could be due to increased particle capture by shrubs because of higher deposition velocity of NH_3 (Hanson and Lindberg 1991). Differences between NO_X and NH_3 could also be a result of changes in atmospheric input by catalytic converters, which could be connected to car age or make near the sites (Suarez-Bertoa et al. 2014).

Throughfall patterns measuring nitrogen trapped in the canopy show an interruption in the deposition gradient. The difference from the gradient could be explained by ecosystem processes that differ once nitrogen is deposited. Oasis showed the highest throughfall values, which could be due to canopy characteristics or weather patterns at the sites. Shrub sizes were not consistent at all sites on the gradient, and shrubs with larger canopy may capture more nitrogen leading to increased throughfall measurements. Increased capture of nitrogen pollutants has been correlated with variables like leaf size, leaf complexity, and plant arrangement (Hagler et al. 2012, Barwise and Kumar 2020). Throughfall measurements also rely on precipitation events, when the IERs capture nitrogen. Three of the four sites are within the Coachella Valley, while

Cabazon is located outside of the valley just beyond the mountain pass. Cabazon has more frequent rainfall compared to the other sites (Unpublished Data) which could affect throughfall input, though it is unclear if that would affect average nitrogen values.

Soil processes mirror throughfall patterns between sites, but NO_3 and NH_4 patterns differ. The differences from the atmospheric gradient may be supported by past studies which have observed non-linear relationships between soil nitrogen concentrations and distance from urban core, which was mainly explained by site age (Du et al. 2022); this study shows lower concentrations midway from the urban core and increased concentrations closest and farthest from the core. Our results show a different pattern, but this highlights differences between expected or observed atmospheric patterns and soil patterns. Another study found higher soil NO2 concentration in suburban soils compared to urban soils (Wang et al. 2017). Peaks of soil NO_3 and NH_4 at Oasis rather than the site with highest atmospheric concentration, Cabazon, could be due to differences in understory; Oasis has more invasive grass in the understory while Oasis has more native species. Increased nitrogen deposition has been connected to reduced native forb richness and increased cover of nonnatives, which may be the case at Oasis (Valliere et al. 2020). Cabazon may have higher atmospheric concentration and perhaps deposition, but tribal land management may be protecting native forb diversity at this site (Schmidt and Peterson 2009). It is also important to note whether throughfall nitrogen measurement can predict soil nitrogen, and we did not find evidence of a relationship in this work. This highlights the need to understand air, canopy, and soil pollution as different processes within an ecosystem.

Seasonal differences among pollutants highlight changes in air quality in dry versus rainy seasons. We observed an inverse relationship between atmospheric concentrations of NO_X and NH_3, where NO_X peaks in winter and NH_3 peaks in summer. The opposite seasonal pattern between NO_X and NH_3 is supported by past research in Riverside County (Piper et. al, in prep). However, NO_X and NO_2 are not significantly affected by date as a factor, but that may be due to the higher amounts of variation we observed compared to NH_3. NO_X often varies with anthropogenic patterns (Roberts-Semple et al. 2012), so that variation may be affected by variation in traffic patterns over time. Soil NO_3 and NH_4 peak in the fall ton winter, which is usually when the first rainfall of the wet season occurs at these sites. The most predictable regional rain in the Mojave Desert falls between late September and early December, which starts the growing season (Beatley, 1974). Soil microbes are often dormant during dry periods, and deposited nitrogen builds up over time (Schimel 2018). It appears that after rainfall at these cites, nitrogen cycling becomes more active and soluble nitrogen increases. Rainfall is also important when considering throughfall since the majority of nitrogen collected by IERs comes during precipitation events. We observed significantly lower throughfall NO_3 and NH_4 from May to November 2020, and significantly lower soil NO_3 and NH_4 in April 2020. These drops in nitrogen input may be connected to reduced nitrogen emissions as a result of COVID-19 lockdowns (Berman and Ebisu 2020, Zhang et al. 2021). Though we did not observe significant changes to atmospheric concentrations at our sites during those time periods, average NH_3 concentrations were more variable after April 2020 and average NO_X and NO_2 concentrations were more variable throughout

2020. Increased variability may highlight a need to further investigate spatio-temporal patterns on atmospheric reactive nitrogen concentrations.

This study shows how multiple nitrogen pollutants vary across a deposition gradient and how those pollutant concentrations vary over time. This study further highlights urban teleconnections and effects of pollution. Teleconnections are important to consider with increasing urbanization and ensuing land change, which is led by and affects human health and socio-ecological systems. Atmospheric nitrogen pollution can lead to adverse health effect for humans (Festy 2013), and nitrogen pollution in soil can affect soil eutrophication or can affect the system via losses via leaching or soil emissions (Aber et al. 1998, Beier et al. 2008). Human-led alteration of the global nitrogen cycle has affected atmospheric composition, with negative effects on the climate and ecosystem services (Erisman et al. 2011). Parsing direct effects of urban pollution on a system from indirect effects, like those from deposited nitrogen once it reaches the canopy or soil, could be important for understanding pollution effects on urban and rural residents. Pollution mitigation strategies for rural areas, indirectly affected by urban pollution may be different than within cities. Ecological issues originating in cities travel beyond city limits, and sustainable processes and policies should be developed with both urban and non-urban areas in mind (Seitzinger et al. 2012). Environmental impacts differ in newly developed areas of cities compared to older areas, with adverse impacts mainly in newer areas (Zhou et al. 2022). As urbanization continues, effects on rural areas must be considered to support healthy, sustainable ecosystems, as well as how rural areas may change. As cities continue to expand, we must consider how mega cities, or mega regions form, encompassing existing and transitioning urban areas (Zhou et al. 2022); the Los Angeles megacity is home to 18 million people (US Census) and continues to expand. Understanding the continuum from urban to rural, and the changes along that continuum, will help protect ecosystems from negative pollution effects within and beyond urban areas.

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Chapter 3: A Resilient, Wicked Problem in the Salton Sea Socio-Ecological System

Abstract

The Salton Sea is a looming catastrophe with many groups vying for alternate solutions. The community surrounding the Salton Sea and government agencies work to support and improve the environment, but groups operate independently, and goals are disparate. There is a substantial network of different agencies with different jurisdictions and responsibilities in a system that continues to degrade. The Salton Sea serves as a case study of socio-ecological system resilience in the context of wicked problems. Through review of existing policy and interviews with key stakeholders, we address a central science policy question of prioritization and compromise among stakeholders in a socio-ecological system facing a wicked problem. Priorities vary and goals are not aligned between the community and decision-makers, particularly those at the state level. The system is degraded but highly resilient, complicating restoration. Implementing the socio-ecological future the community wants must include collaboration, increased communication and education, and an overall focus on the human element at the sea. Co-created solutions to wicked problems the Salton Sea may be the key to escaping a resilience trap.

Introduction

The Salton Sea is a looming catastrophe with many groups vying for alternate solutions. The sea serves as a valuable case study of socioecological system resilience. The community surrounding the Salton Sea and government agencies work to support and improve the environment, but groups operate independently. Separations among stakeholders leads to limited information flows to the community and differences in decision-making goals. Decisions at the state level have contributed to ecosystem decline (Lynch and McNeece 2020). The ecosystem continues to degrade, with decreasing water level, increasing salinity, and wildlife habitat loss. The costs of wetland loss, particulate matter pollution, and other negative effects are estimated to range from $500 million to $1 billion in 2019 USD (Ayres et al. 2022). However, the degraded system is resilient and therefore resistant to change. The sea faces environmental policy problems, and understanding the key problems and needs is key for determining solutions.

The Salton Sea has degraded over time, with the most change in the last 50 years. The sea formed when an agricultural leak flooded a dried prehistoric lakebed and became a recreational oasis for fishing and boating in the Southern California desert in the 1950s and 1960s. As inflows decreased due to conservation measures and water transfers from agricultural use, the lake levels dropped and exposed the playa, or lakebed. Over 50 years, salinity increased, fish and bird die offs were reported and recreation dropped when shoreline resorts flooded, and communities were advised against fishing. Groundwater in the basin is now shallow and the quality varies widely (Tompson 2016). In 2000, Congress and the Bureau of Reclamation release plans for Salton Sea restoration

(SSA). From 2000 to today, stakeholders have continued to work on projects surrounding the sea. There are over 30,000 residents living in the six census tracts directly adjacent to the Salton Sea across Imperial and Riverside counites, all of which are identified as disadvantaged by the Climate and Economic Justice Screening Tool (CJEST). These census tracts are majority low income; the population surrounding the sea also faces other indicators of vulnerability including legacy pollution, housing insecurity, and health risks (CJEST). However, other communities near the sea include wealthy areas, and that wealth disparity is important when considering the difference in access to basic needs and amenities in areas close to the sea. The Salton Sea is also on the edge of the greater Los Angeles area, which is home to 18 million people (US Census), and brings millions of visitors to the region. Degradation of the sea's ecosystem is the worst in its history, affecting millions of Californians.

There is a substantial network of different agencies and groups with varying jurisdictions and resources aimed at addressing environmental policy problems at the Salton Sea (Figure 1). This large network contributes to complexity in parsing problems and solutions in the region. Key stakeholder groups vary in both their capacity to affect the system and vulnerability to dynamics.

Figure 3.1: Conceptual diagram showing diversity of stakeholder groups surrounding the Salton Sea.

When considering the broad goal of "saving the sea", or at least reducing the environmental risks associated with the sea, there are multiple priorities put forward by policymakers, researchers, and community groups. Major priorities include health, conservation, economic opportunity, and basic needs access. Health risks are largely related to exposed playa, or lakebed, as the sea level lowers due to evaporation (Jones and Fleck 2020). Dust from areas surrounding the sea has been linked to lung inflammation (Johnston et al. 2019, Biddle et al. 2021, 2023), leading to respiratory issues for both residents and visitors. Asthma rates near the sea are disproportionately high, with approximately 15% of residents within Imperial county experiencing asthma symptoms (Aguilera, 2019). Pediatric risk is also high, with the rate of emergency room visits and hospitalizations of asthma-related complications double the state average (Farzan et al. 2019). Data is often limited to support public health issues in areas with minority populations, and past interviews have provided evidence for exposure to dust and chemicals with potential public health effects (Cheney et al. 2023). Adverse effects from the sea affect wildlife as well as humans. The sea is home to wildlife and endangered species facing conservation concerns. Native, endangered fish populations are depleted due to increased salinity, and the ecosystem becomes increasingly inhospitable as only euryhaline tilapia and the desert pupfish remain to sustain the bird population (CDFW). This area is also a part of the Pacific Flyway, serving as a stopover for endangered and protected migrating birds for 30-50% of some species' North American populations and providing productive nesting areas (Lyons et al. 2018); Audubon California). The sea is a landmark for tourism in terms of ecology. The past as a recreational tourist destination, and struggle to build new opportunities, present an economic challenge. Lithium mining near the sea provides hope for job creation, though there are environmental concerns (Salton Sea Task Force). While lithium would be mined in the sea, there are also concerns that longer term jobs, such as infrastructure for energy storage or manufacturing including lithium batteries, will be focused away from the sea; there is evidence in manufacturing that job benefits are disconnected or inaccessible to those with lower education, leading to higher rates of unemployment and lower wages (Charles et al. 2018). Underserved groups living near the sea face an overall unsafe environment, which includes limited access to basic needs. Urban infrastructure surrounding the region degraded with the sea. This includes paved roads, internet access, and amenities, all of which have not been built near the sea as the ecosystem degrades (Advisors 2023). The area surrounding the sea is a food and healthcare desert, and the community has been under resourced for decades, all of which increase health burdens on these underserved populations (Bullard 1993, Cook et al. 2021). These multiple priorities, concerns, and challenges further complicate planning and solution creation surrounding the sea.

Potential solutions to address issues at the Salton Sea range from specific to broad and differ in feasibility. The Ten-Year Plan, led by the Salton Sea Management Program (SSMP), is the top priority for implementation on the state level, and is focused specifically on dust mitigation and habitat restoration. The state also solicited water import proposals in 2021, which most often suggest a transfer of water from the Sea of Cortez. Water import from the Sea of Cortez would require an international water agreement, along with extensive infrastructure, which reduces feasibility. Proponents argue increasing water flows would solve multiple problems simultaneously, while ending or delaying water transfers will decrease bird and fish populations (Kjelland and Swannack 2018). The SSMP also released a long-range plan public draft for comment in 2022. The long-range plan includes concepts both with and without water importation and evaluations of multiple environmental variables, along with thirteen potential restoration concepts with expected benefits and costs. The plan also includes evaluation on analysis on greenhouse gases, air quality, and salinity, along with identified areas of uncertainty. Proposed solutions at the Salton Sea can be improved by focus on defining problems and needs within the ecosystem.

Addressing problems and identifying solutions for the range of stakeholders surrounding the sea can be strengthened by established community engagement strategies. The community is the primary stakeholder of local ecology; major environmental movements in the 1960s led to the current definition of community engagement, where community members contribute ideas to be included in policy development through open forums for advocacy (DWAF, 2005). Framing the research process within the community context improves application of scientific research (Adams et al. 2014). There tends to be a gap in perception between community members and practitioners (Swapan 2014), and it is important to work with the community to co-create programs and reduce that gap. Community engagement is diverse, and what constitutes successful community engagement can vary by project and should be viewed beyond failure versus success (Boland and Zhu 2012). In the area surrounding the Salton Sea, work continues to bring the community into government projects, like environmental monitoring. One bill, AB 617, was written and implemented to address air pollution impacts and environmental justice by requiring local air pollution reduction (SCAQMD). The program includes a community plan process and community air monitoring and is built to be unique to each community's needs. Understanding existing support from the federal and state government for community benefits helps to understand the foundation of community needs.

The Salton Sea is a resilient ecosystem trapped in a degrading state and can be described within the framework of wicked problems. Resilience theory provides insights into complex systems like the Salton Sea, where the system is impervious to change. A common definition of resilience is the capacity of a system to return to a stable state following a disruption (Gunderson 2000, Lake 2013). While resiliency is regarded as positive, a system that is not flexible to change can be a danger if in a degraded state. The Salton Sea's complex socio-ecological system is facing multiple interconnected hazards which makes it hyper-resilient. With unpredictable or unexpected dynamics, poor management can have effects on resilience (Cumming and Peterson 2017). Government policy has both negative and positive impacts on resilience, and depends on context (Quandt 2023), so resilience is a complex factor necessary to understand. With high resilience in a degraded state along with many interconnected stakeholders vying for different solutions, the Salton Sea fits within the framework of wicked problems. The term "wicked problem" is used to describe problems which cannot be definitively described and cannot have objective solutions (Rittel and Webber 1973). Wicked problems have been organized in the context of ecology around ideas of multilevel communities and collaboration, important to resources and adaption of ecological systems (Trickett 2019). The wicked problem framework also fits complex environmental health problems like air pollution, because these problems within communities are often linked to others and stakeholders may have conflicting interpretations of the problem or potential solutions (Kreuter et al. 2004). Community ecology and wicked problem research has been centered on improved community capacity, with partnerships between communities and academia on a local scale (Caron and Serrell 2009). In the 50 years since Rittel and Webber introduced this concept, others have even described “super wicked problems”, characterized by features described as: time is running out, those who “cause” the problem seek the solution, the central authority to address the problem is weak or has limited capacity, and irrational discounting pushes responses into the future (Levin et al. 2012). Super wicked problems have also been attached to urban renewal and associated regulatory frameworks, multitude of stakeholders, and property fragmentation (Lami 2019), which bears similarities to restoration efforts around the Salton Sea. Wicked problem research is dispersed across disciplines, applications in sustainability and climate change have increased in the past decade (Lönngren and van Poeck 2021), and there is substantial room for wicked problems to be better applied to sustainability research as a theoretical concept (Lönngren and van Poeck 2021).

Here we evaluate pathways of change around the Salton Sea in the context of resilience and wicked problems. In addressing this challenge, we ask: how do socio-ecological futures vary across stakeholder groups and how do these futures differ from those at the policy and research level? We evaluate these questions through stakeholder interviews aimed to understand problems and needs surrounding the sea. We use these interviews to identify pathways for the future of the Salton Sea that improves the well-being of local communities.

Methods

To better understand community needs, we conducted interviews with five people working on a variety of projects around the Salton Sea. Interviews aimed to understand similarities and differences in the community about current policy, research science, and visions for the community. Interviewees were contacted via email and electronically consented. Interviews were conducted with stakeholders and community leaders during the summer of 2021. University of California Riverside Institutional Research Board (IRB) Protocols determined risks of participating in this project were minimal and methods were approved (Supplemental Documentation). Interviews were recorded and transcribed, and once transcribed the recordings were deleted.

Interviewee responses were anonymized and aggregated. Using a semi-structured format, questions focused on interviewee background, understanding of community needs and interests, and visions for the future of the sea and surrounding communities (Appendix A).

To analyze results from interviews, we used a thematic analysis and coding approach (Braun and Clarke 2006, Byrne 2022). We coded responses as positive, negative, or neutral, and assigned codes for topics such as health issues, basic needs issues, water import, wildlife concerns, and others. We further focused themes based on interviewee experiences, problem and solution identification, and goals or socioecological futures for the sea. We used these tools to create a thematic map and determine recommendations.

Results

Interviewees represent a range of stakeholder groups in the community surrounding the Salton Sea. Interviewees have 41 years combined doing work related to the Salton Sea, and several were engaged with the sea for decades through their career and volunteer work. All interviewees live in the Coachella Valley or Imperial Valley. Multiple have led programs in the area that include education, community engagement, community organizing, or monitoring. Themes, subthemes, and connections identified through interviews are mapped in Figure 2. Though interviewees are experts in the Salton Sea, but even as leaders feel the complexity makes it difficult to understand all existing issues surrounding the sea. Informing the community and providing tools for them was a consistent goal across interviews. Community members also fear their social, economic, and political capital is not enough to hold the attention of decision-makers' attention, making issues difficult to overcome. Interviewees felt that overarching goals and state objectives have been consistent over time while personnel and stakeholders changed. Interviews highlighted specific concerns within the community which should be considered when addressing wicked problems in a complex adaptive system, but overall community leaders remain optimistic about the future of the sea.

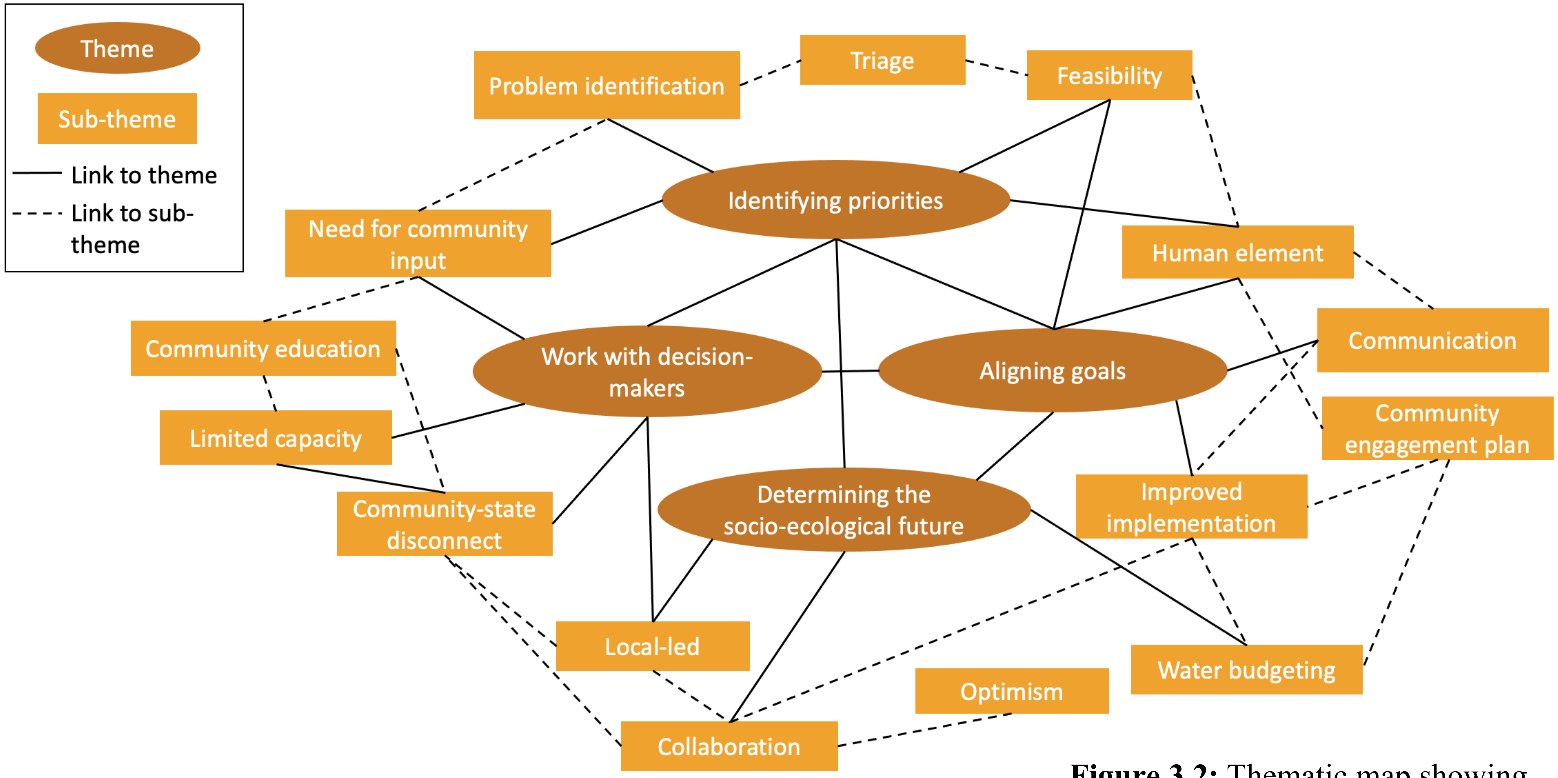


Figure 3.2: Thematic map showing themes, subthemes, and connections shared in interviews.

Identifying priorities

Interviewees provided important understanding of current priorities and identification of problem where work should focus. Community health is related to environmental justice concerns. Communities should have a healthy livelihood that is all encompassing: "people deserve to live in a dignified way, even near an ecological crisis." Stakeholders highlight a need to understand communities on a discrete level, as different areas will need different solutions. Further, work by the state has focused shoreline inward, with monitoring, research, and mitigation work within the bounds of the sea. Community leaders focus shoreline outward, with community needs as their main priority.

To the community, the sea feels trapped in a degrading state which needs major changes, and the human element is largely missing from plans. Community members feel that the status quo has not been planning for future generations the way healthy ecosystems do, and advocate for a change in approach. One example is the expectations work at the sea, where the community was promised restoration. However, what the community has seen so far is mitigation that is behind schedule.

Interviewees also shared a desire for focus on realistic project planning, over ambitious projects that they continue to see stall. Feasibility is important to the community, after feeling discouraged by the lack of progress. This informs how most interviewees viewed water import proposals, as a hopeful but unlikely solution. An interviewee who advocated for water import argue that most issues at the sea are symptoms caused by lack of water, and addressing the cause will be best to solve problems. Those who question the feasibility of water import proposals remain concerned about ecosystem health, arguing that it is a "moral responsibility" to keep as much alive as possible in the region. The environment around the sea is strange, but communities agree humans made it that way and should work to improve it as stewards of the region.

The key issue identified in interviews is that core problem is not well identified, "triaged", which contributes to the focus on mitigation of issues over long-term solutions. With contrasting visions between the community and decision-makers, it is difficult to envision the destination. Community leaders want to help build a healthy ecosystem, but identifying the problems and needs explicitly is a task no one has taken on. Problem identification is complicated by limited access to data for community members. The community sees large amounts of data collected with limited applications or access to data. Data access is particularly important for local non-profits, who apply for funding where applications require or are strengthened by peer-reviewed data that they do not have to capacity to collect. Gaps in communication between the state, decision-makers, and community members also adds difficulty to problem identification and solution design.

Working with decision-makers

Decision-makers for the sea at the state and federal level have been involved for decades, but their work for and with the community has changed over time. Interviewees agreed that in the last 5-10 years, there have been significant improvements in state efforts surrounding the sea.

Community leaders feel a responsibility to make the sea a healthy, sustainable place for their community. As a result, aligning with the state priorities and activities is seen as productive. While interviewees criticize the state plans for not being comprehensive, the state plan is considered the most feasible and therefore worth supporting. A strong plan for the area would address big issues like climate change through a multi-benefit approach.

Communities can be disconnected from work led by decisions-makers, which mean community needs can go unaddressed. Communities declined in sympathy with the decline of the sea, but locals feel that the human element is underrepresented in ongoing work and solution creation. Local groups' limited capacity makes it difficult for them to follow all policy changes and updates. The potential for lithium mining, for example, came as a shock to many community members who had not been involved in early discussions. Increased opportunities for communities to be involved in state agency or committee meetings would be of particular interest.

Project funding also contributes to the disconnect between communities and state decision-makers. Large amounts of state and federal money are awarded to consulting firms or project managers based outside of the local area. Community interviewees argue that when the state invests in environmental projects, they should benefit the ecology as well as the people. Communities would ideally like for the state to provide resources and funding within the local community. Community groups align with the state overall, but share the major reason is that agency ideas are not consistently grounded with the processes of implementation.

Issues and concerns risen by community interviews are exemplified in opinions on the ten-year plan led by the state and the Salton Sea Management Program. The ten-year plan is the clearest example of the perceived triage approach by the state. The community perceives this plan as “an act of contrition” by the state when they recognized work had been delayed. The delay of work in the past also contributes to the view that the state is and will continue to struggle to meet a goal that cannot be achieved in the time frame. The general frustration is that the plan overall does not address the human element: as the sea declined, property values fell, and communities became more disadvantaged. Community members fear that the ten-year plan does not address this and lacks goals focused on restoring what communities lost at the sea, such as recreation, infrastructure, and health and safety. Communities want to be engaged in planning moving forward, to identify and quantify resources and needs. Still, the community aligns with the ten-year plan and activities. Though there are concerns it is not comprehensive, it is a good start, and what they currently have to work with.

Opinions on the state remain overall positive, but concerns are focused on building on the existing foundation and adding more action to the work. Interviewees had few complaints or weaknesses to raise, beyond the concern that the state does not understand the full picture seen by locals. Being based in Sacramento, over 800 kilometers from the Salton Sea, can make decision-making based on local needs difficult. Research and seed funding often does not reach the local community; locals see pilot projects led by outside consulting firms stall or fail, and want opportunities provided instead to their community-based organizations. Interviewees feel the state will be "largely ineffective" unless they can use local expertise to educate community members and inform solutions. Local non-profits also struggle to apply for federal funding or other large grants, since they often require peer-reviewed data that they do not have access to or is shared sparingly. Scientific research is valued by locals at the sea, but there have been decades of studies and locals see limited outcomes on the ground. Lack of data access for the community, along with perceived insufficient engagement, leads to misinformation at the community level and creates false expectations. Without addressing those expectations with education or data, the overall positive view of the state may become negative.

Decision-makers hold a view of the Salton Sea as toxic and unsafe, while many who live there see beauty and have a love for the land. Interviewees feel action at the sea will be connected to appreciation for the ecosystem: "People will not care for something they do not know how to love first." Balancing that support for the ecosystem with the knowledge that it is in crisis is key for community members who have felt limited respect. It is important to remember that this community is disenfranchised and has fair reasons for distrust in government, but their understanding of the sea is unmatched.

Aligning goals

Addressing issues at the sea requires an understanding of the totality of problems and alignment of goals. Habitat restoration and dust mitigation are necessary goals to address but represent a subset of community concerns. Interviewees argue for the need to determine factors contributing to health and build plans around human health goals. "We need to [define] the boogeyman, rather than just saying it is the sea." Balance between social, economic, and environmental goals is important. Environmental goals are addressed in the ten-year plan, but social and economic goals like job creation, infrastructure improvements, and basic needs access, are important to local communities. Community leaders fear that misaligned goals, along with the slow pace of government work, will contribute to community discouragement.

Stakeholders maintain that communication to, and support for, the general public is lacking. Community interviewees believe there is a need for a community engagement plan, which would bring residents' needs and interests to the forefront of the work at the sea. It would envision the sea, if supported well, as a vibrant gathering place for both residents and wildlife. Without a community engagement plan, these stakeholders believe the state plan is missing major goals. The community knows there is support for the sea, but progress is not tangible. As one interviewee said, "The state has a 10-year plan to reduce dust and build habitat around the Salton Sea, and more than $365 million in funding has been approved. However, work at the Sea has been stalled and the region has been ignored far too long."

Project goals would benefit from an increased focus on implementation improvements, with long-term planning with operation and maintenance funding included. Concerns of course remain, as funding is hard to secure in the amounts many want. "If we struggle for funding now, how can we [secure funding] intergeneration projects?" On the state level, implementation is complicated due to work with multiple landowners. State work aims to improve efficiency in permitting and implementation, but state leaders agree there is room for improvement. Implemented and built projects need to be able to be maintained; a few past wetland projects near the sea were built, but non-functioning within two years. Operation and maintenance planning and funding is necessary. “It is a moral responsibility to protect the ecosystem, but there is also a moral responsibility to do things for the community.” The community and decision-makers agree on many needs, and collaborative work to align goals can improve the ability to address community concerns.

Determining the socio-ecological future

Interviewees were optimistic about socio-ecological futures surrounding the sea, but shared insight on how to reach their optimistic visions. Community leaders acknowledge the large number of stakeholders involved and the range of interests, but are most concerned with decision-makers, who responsible for work at the sea, rarely visiting the sea. Decisions appear to be made without key information, while community leaders know what they need but lack funding or state support. Interviewees also highlighted the need for feasible projects, particularly related to water budgets. A clear, realistic water budget does not exist: “What can we do with the water we will have, not the water we want to have?” Adding water is generally considered idealistic, and most interviewees were adamant that water will continue to be limited and we must be sustainable with the current water. In addition, better directives for research, focused on solutions over understanding, are important to community leaders. Long-term monitoring and data collection is perceived by the community as more than sufficient data collection when the community is ready to design and implement projects.

The vision for the future of the sea is hopeful: “it’s got good bones.” Improving education, access to resources, and a diversified economy would make the Salton Sea a healthy place to live. Projects being implemented should reflect community input while addressing state priorities, allowing the community to have input on their future while the state advances important legislation. Community interviewees acknowledge it is unlikely the future of the sea will fit what every person is looking for, particularly as water becomes scarce. To build on those good bones, collaborative work is the ideal strategy. “We need to make sure no one works in silos.”

Discussion

Based on the interview findings and historical and resilience research, the Salton Sea is likely in a rigidity trap. A system in a rigidity trap has high capital, high connectivity, and high resilience, meaning substantial changes to the system are rare. Resilience can be positive or negative (Barrett et al. 2021); in a beneficial stable state resilience is a positive, but the Salton Sea is trapped in a stable state while degradation continues. As the ecosystem continues to decline, negative effects continue and are resilient. Resilience traps have also been defined in governance as a danger of adopting short-term strategies or expanding existing strategies, which can slow progress by continuing work that has not been effective (Curșeu and Schruijer 2017, Kythreotis and Bristow 2017). Interviewees shared similar concerns about the state of work at the state level. The Salton Sea faces multiple challenges as a complex adaptive system. Resilient socio-ecological systems can handle negative environmental challenges without regime shifts (Li et al. 2014), but this can also mean that a resilient degraded system can receive changes without a regime shift occurring. Evolving beyond a degrading stable state requires extensive effort, and identifying potential solutions is key in understanding the future of the sea.

Collaboration with decision makers

Research on the history of and stakeholders in the sea, along with interviews, highlight conditions which keep the system in a resilience trap, including limited collaboration. Past community research in the sea highlights community concerns focused on water consumption, public health, and local employment, while topics like lithium mining have been more important to those outside of the community (Slattery et al. 2023). Community concerns therefore have been separated from decision-makers actions, and this could be due to limited capacity, insufficient communication, or complexity of the system. One criticism of resilience literature posits that it has been unsuccessful in capturing the complexity of governance processes at play in addition to ecosystem processes (Biesbroek et al. 2017). Power, agency, and inequality are important for the Salton Sea community, but are not well-represented in academic resilience work (Cretney 2014), and could be supplemented by work with local and state level stakeholders. Government leadership and goals are not well understood by many in the community, which gives the community little power to collaborate for substantial change. Governance challenges, including who governs and who is prioritized, are linked to sustainability, and the political drivers of socio-ecological systems must not be ignored (Smith and Stirling 2010). Interviewees understood the state faces challenges, but the missing link is that the community members at the sea do not feel prioritized. Another study found local interviewees shared a “systemic incapacity” on the part of the state (Buck 2020). While we did not find that in our interviews, with positive reactions to recent work at the state, community members still see the effects of blind spots for decision-makers. Community opinion that the current state plan fails to address key obstacles, like the human element, is a common problem supported in policy literature (Hughes 2020). Power in the form of social change is linked to environmental change in socio-ecological systems (Cote and Nightingale 2012), so environmental change at the sea could improve community power to collaborate with decision-makers. Stakeholder diversity improves decision quality when decision-makers acknowledge and work with differences among stakeholders (Curșeu and Schruijer 2017). Participatory and shared social responsibility models have been shown to be effective avenues to improve corporate support of communities, and may be able to apply to governmental decision-makers (Gold et al. 2018). Collaboration by decision-makers with a broad cross-section of community members and leaders local to the sea has strong potential to address this wicked problem.

Aligning goals through a resilience, wicked problems framework

The term “wicked problem” succinctly describes the sea, its community, and its government, and can inform improved goals and implementation. Stakeholders on different levels want different outcomes. The difficulty in defining solutions is linked to the issue of defining the problems (Levin et al. 2012), as highlighted in the interviews. Community members shared an interest in focusing on feasible, local solutions, rather than ambitious efforts which have stalled. An example problem which is defined, is a lack of water; more water flow to the sea would solve health, conservation, and some economic issues, but, to the community, does not appear feasible. While water import would solve problems, community members overall feel a focus on these proposals ignores feasible proposals, though there is certainly some optimistic community support for water import. Socio-ecological resilience has been connected to planning relatively recently, and studies argue for increased attention to ecological theory in planning (Wilkinson 2012). Planning for an ecologically resilient area must include problem identification to support realistic, community-led solutions.

Determining problems and solutions surrounding the Salton Sea falls at the nexus of wicked problems and resilience. In discussions with stakeholders, different groups of problems will be addressed. By not defining problems, no solutions are closed off, but without planned goals it is hard to reach any solution. This is not to say potential solutions need to be a small list of options; multiple pathways can be pursued at once and multiple management schemes can and should be cultivated. Naming problems and solutions and pursuing multiple approaches can support building a holistic approach, moving beyond mitigation, to address the wicked problem. Sustainability and resilience are linked but can be considered distinct for project design and implementation. Implementing sustainability is built on the combination of environmental, social, and economic concerns, while implementing resilience tends to focus on the ability to absorb impacts, recover, and adapt; both are linked explicitly to providing benefits to people in these ecosystems (Marchese et al. 2018). There are multiple elements to address holistically; flexibility allows movement beyond mitigation alone. Tension between problems and solutions should be managed to address the range of concerns from the community and decision-makers to escape a resilience trap.

Wicked problems, like the Salton Sea, require work and acknowledgment of complexity to reach solutions. The complex disconnect between community and government interests is a common environmental policy challenge. The Salton Sea faces this challenge primarily with local communities and state governments, but issues and stakeholders range from individuals like landowners to bi-national groups evaluating water import. In determining solutions to wicked problems, there is a need to navigate socio-ecological futures we have not seen before. People often aim to solve problems by addressing liner cause and effect relationships, but is a simplification when causality and solutions can more accurately be mapped as webs (Steinhall et al. 2023). While social and governance changes are uncertain, these is a need to plan for grounded future scenarios. A resilience trap constitutes a wicked problem (Figure 3) which requires a holistic approach that is able to address complexity.

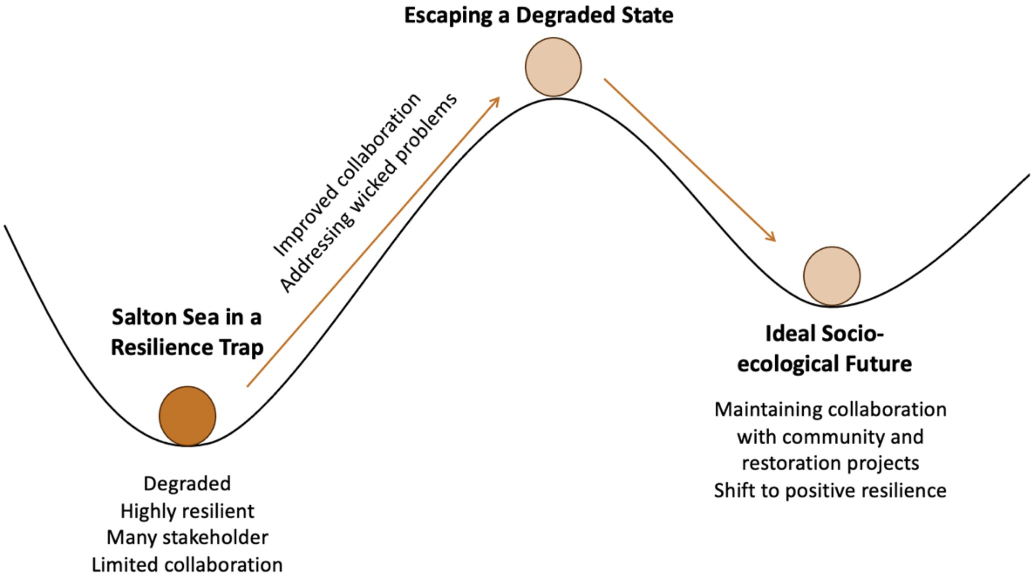
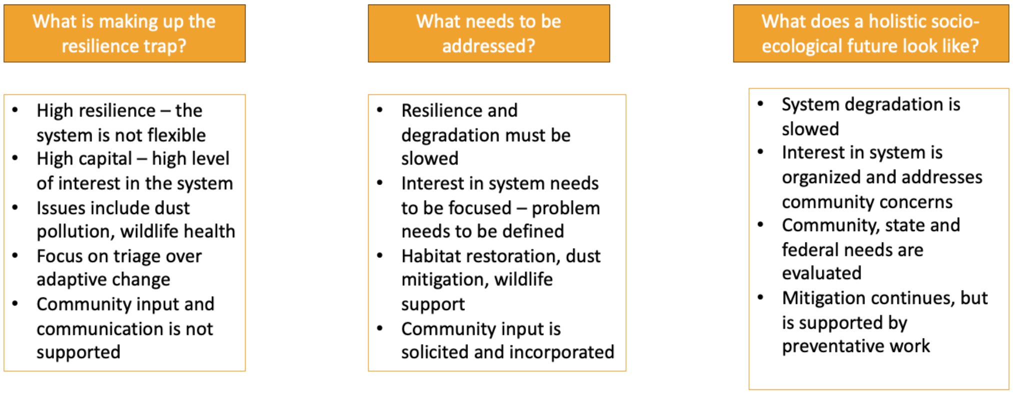


Figure 3.3: Conceptual diagram of a resilience trap affecting the Salton Sea and how to shift out of the trap, to a new regime.

Recommendations for an ideal socio-ecological future

In ideal socio-ecological future for the sea will need to be accomplished with a holistic approach. The Salton Sea presents a particular challenge, when considering research that shows ecological degradation issues have been difficult to address explicitly, and actions to achieve sustainability tend to focus on resilience (Domptail et al. 2013). New approaches for the sea need to reduce resilience for this negative state, while supporting resilience for a future ecological state. A meta-coupling framework is one conceptual base to holistically approach human-nature interactions, since the framework focuses on tradeoffs, spatio-temporal dynamics, and understanding of networks (Liu 2023). Figure 4 present a framework to understand and address the resilience trap holistically. A holistic approach could further include expanded data access. Communities struggle to access up to date data for their area, and partnerships with universities or central data repositories would help to bridge gaps identified by the community. Cross-sector partnerships, including sustainable business practices and their impact on both resilience of organizations and socio-ecological resilience, can be important to address concerns on complex systems (Dentoni et al. 2021). A holistic approach provides economic benefits as well: costs of inaction are greater than the costs of action, and action in one area may not offset inaction in others (Cohen 2014). For a plan to be truly holistic, we must also consider community input as shared in interviews.

Interview findings were used to determine recommendations for future projects and planning by community, state, and federal leaders. Research-policy gaps have been observed in other resilience studies, with findings that suggest translating research findings into tools for local communities could help bridge that gap (Talubo et al. 2022). Spotlight projects focused on restoration would act as a morale boost: the community members need to see results of their advocacy. Though areas around the sea are rural, all existing projects take place far from residential areas, so the average resident sees little evidence of state progress and has little knowledge about current projects. Completed planning projects as well, specifically a water budget, would be useful tools for community leaders and stakeholders to plan for future work. Community interviewees were also specifically interested in grant programs for local project funding, as they are the experts in their lived experience, needs, and priorities. Building these recommendations into a holistic state-level plan improves community morale and support for the state and decision-makers, crucial to a healthy socio-ecological future.



What is making up the resilience trap?

- High resilience – the system is not flexible
- High capital – high level of interest in the system
- Issues include dust pollution, wildlife health
- Focus on triage over adaptive change
- Community input and communication is not supported

What needs to be addressed?

- Resilience and degradation must be slowed
- Interest in system needs to be focused – problem needs to be defined
- Habitat restoration, dust mitigation, wildlife support
- Community input is solicited and incorporated

What does a holistic socio-ecological future look like?

- System degradation is slowed
- Interest in system is organized and addresses community concerns
- Community, state and federal needs are evaluated
- Mitigation continues, but is supported by preventative work

Figure 3.4: Framework to understand and address a resilience trap at the Salton Sea and a potential future.

Conclusions

Interviewees have a unique perspective, defining problems as the community experiences them, and suggesting solutions that the community would support. The state has heard a number of these concerns over the years and does work to address them. The current focus is building structure to streamline processes for project implementation. The state also knows the complexity of the process is hard to see from outside. The state owns less than 1% of the land at the sea, so every project must start with getting land and water access before permits. The state also recognizes the pace has been slower than many want. The optimism remains that work will only improve as projects continue to move through the pipeline. Community input is included within project planning at the state level, and building in that feedback is a major goal. Community members also advocate for a focus on feasibility when prioritizing projects. While there is community support for conservation projects, acute pressures that may be quicker to address are higher priority within the community. However long-term commitment and support, including operations and maintenance funding and programs, are also important to convey care for the prosperity of the community. Ensuring community members stay engaged will only improve state projects.

The community does not feel that they live in a sustainable place and are constantly reminded it is toxic, and that is disheartening. It is important to remember that this community is disenfranchised and has fair reasons for distrust, but their understanding of the sea is unmatched. With government work already slow-paced, community leaders fear community members will get discouraged. Support for improved amenities and recreation may improve wide perception of the sea, shifting away from the ideas that it is simply a toxic area. Improved infrastructure, public art, and other services can improve perception and show support for the community. Policy makers should consider a net-benefits approach, to evaluate returns on public spending and can add transparency to the decision-making process (Schwabe et al. 2008). Engaging with the community by focusing on providing support or benefits improves work surrounding the sea and improves well-being.

A vision for the future of the Salton Sea looks different to individuals, but understanding of the complexity of the system and resilience theory provides guidance to bring about ideal socio-ecological futures. All interviewees agree that progress has greatly improved, but still reflect on times their community felt under supported. Optimism surrounding what the sea should be supported with communication, holistic solution planning approaches, and long-term support. As one interviewee said, “there is no silver bullet for the Salton Sea”. Wicked problems require wicked solution, where the need to reframe resilience is needed to escape a resilience trap and support a healthy, community-driven, socio-ecological future.

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Appendix A

Background

What does your current position include? How long have you been working in this capacity?

How long have you been engaged with Salton Sea?

Why were you originally drawn to working in the Salton Sea? What has kept you there?

Current Activities with Salton Sea

What work does your group focus on in the Salton Sea? What are the top "needs" at the Salton Sea? What are your top priorities? Why?

Do you ever work with the state or federal policymakers?

Government Connection to Community

Do you think your group's goals align with the state? Why or why not?

Do you think the state is transparent enough?

What is the state's biggest challenge?

What is their biggest weakness?

Do they have strengths you see?

What would be your top choice for the state money?

How do you see community and constituents' reactions to the states' work?

Science Needs?

How could academic research contribute to addressing needs? Do you think it is tuned in to current work at the Sea? Why or why not?

- What information would you be most interested in if available?

Conclusions

Who else should I talk to in order to get other views?

Do you have questions for me? Or anything you want me to ensure I share with the state?

In your perfect world, what will the Salton Sea become in 10 years? What is your personal vision for the Salton Sea? This does not have to reflect your organization.

Conclusion

Complex socio-ecological systems and understanding processes on local scales guided this body of work. Urban systems are heterogeneous with varying tree canopy, pollution distribution, and human-nature interactions. Cities and socio-ecological systems can vary by orders of magnitude in population and area, so ability to understand patterns across scales is important (Uchida et al. 2021). Spatial scale affects ecological and social patterns. Integration of human drivers and feedbacks will improve conservation of ecosystems, because cities are fundamentally driven by human activities (Des Roches et al. 2021). Understanding both ecological processes and the key roles humans play are crucial for socio-ecological systems. Urban complexity can be considered a given, and trans-disciplinary approaches are important to address that complexity (McPhearson et al. 2016). Observing scales within and beyond urban areas, along with local patterns near a degraded system, provides insight into complex socio-ecological systems and their patterns and processes.

Urban nitrogen has both local and far-reaching effects which are important for scientific and human impacts. Atmospheric concentration of nitrogen pollutants within a city are important to human exposure and health, and this work highlights the importance of local variation. Riverside acts as a case study city, with both local and regional pollutant effects. Despite pollutant impacts from the Los Angeles megacity, local pollution patterns emerged. Cities are often responsible for their own pollution reduction, and understanding of local patterns can better equip city leaders (Miller & Michalak, 2016). Traffic is a clear predictor of atmospheric concentration, but pollutant input trapped by tree canopy did not appear to improve air quality. Future research could focus on parsing inputs via deposition from atmospheric concentration or pollutant exposure. Atmospheric concentrations can affect health (Jonson et al. 2017), so improved knowledge of hotspots of concentration could focus mitigation near health concerns.

We also identified differences between NO_X and NH_3, highlighting complexity of pollutant patterns. Anthropogenic NO_X is well documented with traffic amounts (Roberts-Semple et al. 2012), while NH_3 is underestimated in urban areas (Fenn et al. 2018). Strategies to reduce NO_X are common, with many cities seeing reduction in the last 20 years. Catalytic converters reduce NO_X output from vehicles but produce NH_3. There may therefore be a tradeoff between these pollutants, evidenced by opposite patterns seasonally, with winter NO_X peaks and summer NH_3 peaks. Local measurements of multiple pollutants would help to further identify differences in pollution patterns, which could be used for targeted pollution reduction.

Urban nitrogen pollutants travel beyond city limits, and teleconnections help to describe effects on ecosystems based on ecological processes. Nitrogen travels horizontally across the landscape along a deposition gradient and vertically at sites from the air to canopy to soil. Atmospheric nitrogen followed that horizontal pattern, with decreased nitrogen with increased distance from urbanization, but canopy and soil patterns diverged. Nitrogen peaked for both soil and canopy in the second highest atmospheric concentration site, showing that there is a disconnect between atmospheric concentration and ecosystem inputs. This could be due to canopy characteristics (Barwise and Kumar 2020), rain (Unpublished data), site age (Du et al. 2022) or some other difference, but highlights the need to understand processes both along a regional gradient patterns and within local sites. Seasonal differences in the air mirrors what we observed within the city of Riverside providing further evidence for the tradeoff between pollutants. As urbanization continues, we must consider the growth of megacities (Zhou et al. 2022), where far-reaching effects combine with local ecological processes.

The compounded effects of far-reaching urban patterns and local processes is further complicated by a degraded ecosystem in a resilience trap. Resilience can be positive or negative, and substantial work is necessary to shift a system out of negative resilience (Barrett et al. 2021). The Salton Sea also faces environmental justice issues, through systemic racism that affect access to healthy nature (Schell et al. 2020). A holistic approach, which includes resilience, justice, and collaboration among stakeholders can be productive for socio-ecological systems. Trans-disciplinary research is necessary to disentangle ecological, social, and political drivers around the Salton Sea. This work must center community experts to improve solution identification, and participatory models have been shown to be successful (Gold et al. 2018). Urban health indicators as a framework have the most impact when embedded in local institutions and well-resources over time, with trust and collaboration as support (Pineo et al. 2020). A concern risen in other studies is a struggle for attention. As a rural area housing underserved people, advocates find that community needs can be ignored in favor of priorities based on more urban areas (Cantor 2021). The Salton Sea is a complex system facing a wicked problem, but community interviews identified goals and potential tools to address concerns.

Ecosystems will likely only become more complex. As urbanization increases, trans-disciplinary models will likely continue to be productive across scales. Peri-urban areas dominated by industry will grow fastest (Salvati and Serra 2016), so areas like those along our deposition gradient and those surrounding the Salton Sea are likely to see major urbanization changes. Connectivity and heterogeneity are major drivers of urban change, and the complex socio-ecological systems we explored had high levels of both connectivity and heterogeneity (Alberti et al. 2020). These connections will only become more complex with added urban change. Future research on local scale, either within cities, across landscapes, or near degraded systems, will improve understanding of socio-ecological systems, processes, and effects on urban residents and the hinterlands.

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