Water Resources and Phosphorus

LRES Capstone, Fall 2023
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Introduction to Capstone Paper

Santo Mallon

Welcome reader to the capstone conglomeration of the Montana State University LRES Autumn 2023 class. The following is a collection of papers and reports from a total 12 people, generally divided into 3 groups, and myself squeezed into the many middles and enveloping the periphery. The content of this great report will be explained in a moment, but let us first start with a paragraph on the formatting, so if you don't care, you can just skip to the next paragraph, easy peasy.

There are a total of 8 different papers, merged into 3 (consisting of 1 paper of 1 part, 1 paper of 4 parts, and 1 paper of 3 parts) broader papers. In between these papers are brief intermissions providing context and connections. References and further reading, for those curious, will be combined at the end of the paper for all sections. Several parts of this paper include endnotes, ranging from fun topics we don't have enough time to talk about, added detail and stories that we find worthwhile but are unable to fit in, or stuff like bonus math, definitions, and context. These endnotes will be formatted as: [1] and can be found similarly at the bottom of each major section.

The sections of this paper begin firstly with a paper on water, with a specific focus on the Gallatin Valley of Montana. The topics included in this water paper range from scarcity issues to the engineering of our occasional excess stormwater, as well as some of the pollutants that end up in our waters, including new revelations such as those regarding PFAS, and finally ends with a discussion on the water access laws of Montana and what we can do to keep our waterways clean.

The second part of this paper shifts gears, moving from water to something important not just in our waters, but to all life. Phosphorus. While it may seem somewhat disconnected from the water topic of earlier, it was actually Phosphorus that began the whole process of this paper, which the Water paper then evolved to their own marvelous ends. Going back to where it all began, we talk about not just Phosphorus in general, but take a deep and pointed dive into the role of Phosphorus in farmland, the way it cycles, how it gets added, used, and what happens when we end up with too much and where that ‘too much’ goes.

The final part of this great endeavor keeps the focus on Phosphorus, but rather than looking at a strictly Environmental or Agricultural Science viewpoint, shifts to one more understanding of the humanities and the stories that make Phosphorus ultimately important to us, the humans. These include, but are not limited to, some fun stories about The Land Down Under, and how the first Euro-Australians had particular trouble adapting to the harsh realities of a Phosphorus-poor landscape, a discussion on where the Phosphorus that was brought to Australia came from and the paradoxically atrocious effects for the people who live in those places, and finally a conversation in how we can close some of our Phosphorus losses and what that means for the sustainability of our futures.

While long, varied, and occasionally confusing (usually my fault), we hope you enjoy the many perspectives presented in this paper. This is the culmination of, depending on your interpretation, anywhere between a combined 4, 48, or 864+ months of work and dedication to understanding the world around us and learning how to communicate those revelations to a populace far beyond what we ourselves are familiar with.

Thank you for reading, and enjoy.

Navigating the Flow of Bozeman Water Resources

Jeremy Emmer, Jonathan Landin, Emily Carey, Kacie Donaldson, and Audrey Reynolds

> “We never know the worth of water till the well is dry” -Thomas Fuller

Introduction

Water and its abundance serve as a crucial factor for biological sustenance. This document commences by providing an extensive examination of the water resources within Bozeman, Montana. It underscores the significance of adopting sustainable practices in water utilization and management, considering the existing water supply and the expanding population in the vicinity. Furthermore, it delves into the existing measures as well as prospective solutions for addressing these challenges.

Part of what “fills” the well of water resources is stormwater, which arises through increased populations as mentioned previously. This section emphasizes the importance of properly managing stormwater by the city for the purposes of maintaining both its stormwater pollution permit as well as the health and well-being of residents. The end of this section explores future options that the city can start to use, or increase their utilization of, to further reduce the impacts of stormwater on local waterways.

Abundance of water resources is meaningless without a thorough analysis of its quality. This section develops an understanding of sediments in waterways and how the resulting turbidity impacts local waterways. Following, is a section on nutrient enrichment which further explores some of the consequences of stormwater as well as . After this point, while still focusing on Bozeman, the paper shifts to a broader perspective to analyze microplastics and PFAS in both the general sense as well as how it affects local waterways.

Streams and rivers have served a multitude of purposes from the beginning of time, starting with providing water and fish for communities, to becoming a place for people to recreate. The paper concludes with Montana stream access laws, which brings in people from all over the world to indulge in streams and rivers in a variety of ways. With an influx of people using Montana waters, there becomes an increase of pollution. This section brings an understanding to the complex language of the constitution and case law into an environmental and recreational light. Also, it shows how human influence contributes to water quality and quantity.

Water Quantity in Gallatin Valley

Jeremy Emmer

Introduction

Water in the western US is the most vital resource and its abundance is necessary for all forms of life. In the arid landscapes of the Western United States, where vast expanses of deserts, rugged mountains, and sprawling cities coexist, the intricate dance between water supply and demand has never been more critical. Bozeman, Montana has no exemption from this; with depleting yearly snowpacks and increased population growth, Bozeman is predicted to have a gap in water supply and demand in its near future.

Bozeman is classified as a semi-arid region and is located in a closed basin in south-western Montana. Bozeman has three major water sources: Hyalite Reservoir, Sourdough Creek, and Lyman Spring. Hyalite Reservoir and Sourdough Creek are sourced from snowpack in the Gallatin Range and account for roughly 80% of Bozeman’s drinking water. Lyman Spring is a groundwater source and accounts for the last 20% (Ahlstrom 2023). Although Lyman is classified as a groundwater source, it is essentially also a snowpack driven system, where all the water has infiltrated through the Bridgers from the previous year's snowpack.

Gallatin Valley has a total population of 124,857 as of 2022, and is one of the most rapidly growing counties in the U.S. (*U.S. Census Bureau 2022).* Climate change is inducing elevated average temperatures within this region, resulting in an increased influx of atmospheric moisture in the form of rain, consequently diminishing snowpacks and depleting reserves. This combination of factors has led experts to question when Bozeman’s water supply is going to run out. An estimate in 2013 stated there would be a gap in supply and demand sometime in the next 50 years. More recent estimates have given Bozeman 4-10 years to change the way we use water, estimating that we could run into major issues as soon as 2027 if we don’t reduce our water consumption (Ahlstrom 2023).

This section embarks on a comprehensive exploration of the underlying factors contributing to water scarcity in the Gallatin Valley. It commences by analyzing the overarching water consumption patterns within the region. Secondly, it delves into the distinctive attributes of Bozeman's geographical context and its impact on the water scarcity dilemma. Lastly, this study examines innovative and sustainable solutions aimed at addressing this pressing issue.

Water Usage

Bozeman is becoming an increasingly popular destination to live due to its pristine surrounding landscape, access to outdoor recreation, and community safeness. According to city engineer Brian Heaston, the city's population has more than doubled between 1980 and 2020, but overall water use by the city was actually slightly lower last year than it was 40 years ago. The per capita daily water use in 1980 was 291 gallons. It was 114 gallons in 2022 (Shelly 2021). This significant reduction in per capita water use over the last four decades is a beacon of hope for current residents in the region.

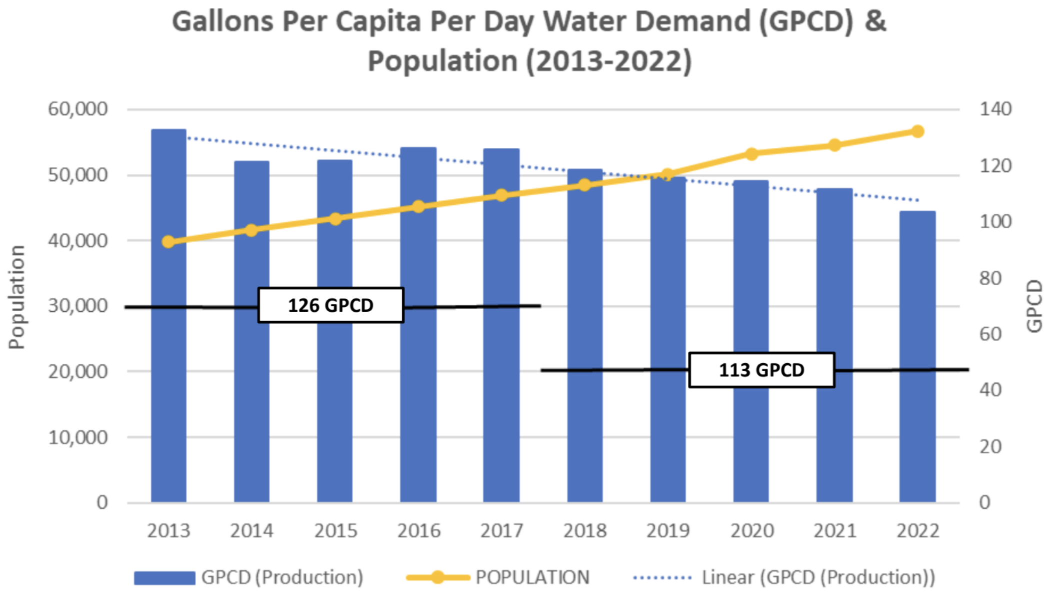

Figure 1: Per Capita Water Use and Population Growth in Bozeman Montana from 2013-2022

Figure 1 shows average daily water demand represented by the blue bars, and population growth represented by the yellow line, from 2013-2022. This graphic provides similar insight as Heaston, that although the population is growing, per capita water use is actually decreasing (Figure 1, Ahlstrom 2023). If residents of Bozeman can maintain or enhance this trend in the coming years, it signifies a positive step towards long-term water resource sustainability and responsible population growth management in the area.

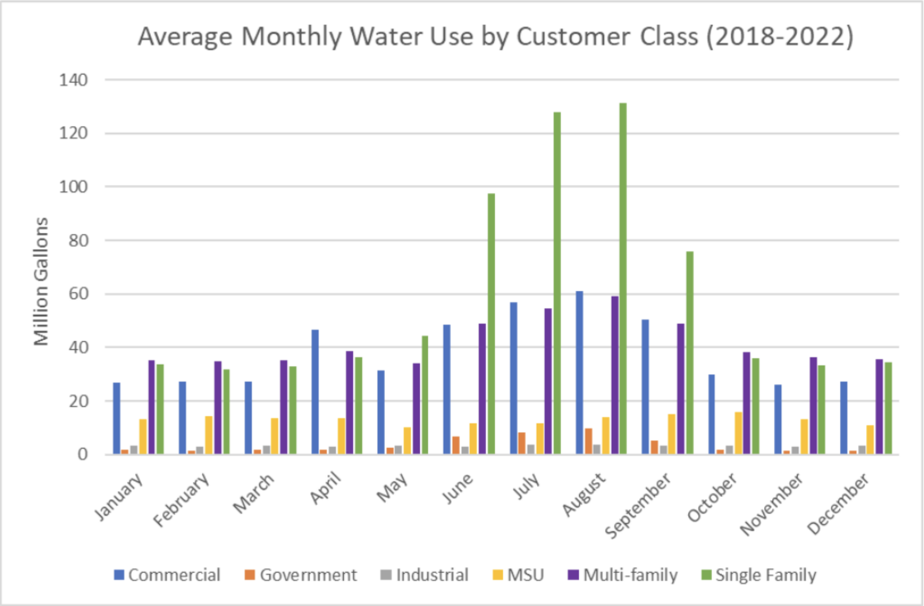

Figure 2: Seasonal Water Usage in Bozeman, Montana from 2018-2022

To better understand how city residents are using water, we can look at data that examines how much water was used per month by different customer classes from 2018-2022 (Figure 2, Ahlstrom 2023). Water use skyrockets throughout the summer relative to other times of the year. It is also important to note that the largest spike in water use is single family residential homes which is directly correlated to irrigation of personal lawns. Bozeman's City Manager Jeff Mihelich stated that during a normal summer, 50% of the city's potable water is used for lawn irrigation (Shelly 2021). This represents a particularly imprudent and inefficient allocation of our most precious resources. Efforts to promote water conservation and responsible lawn care practices are crucial to ensure a sustainable and environmentally responsible future for our community.

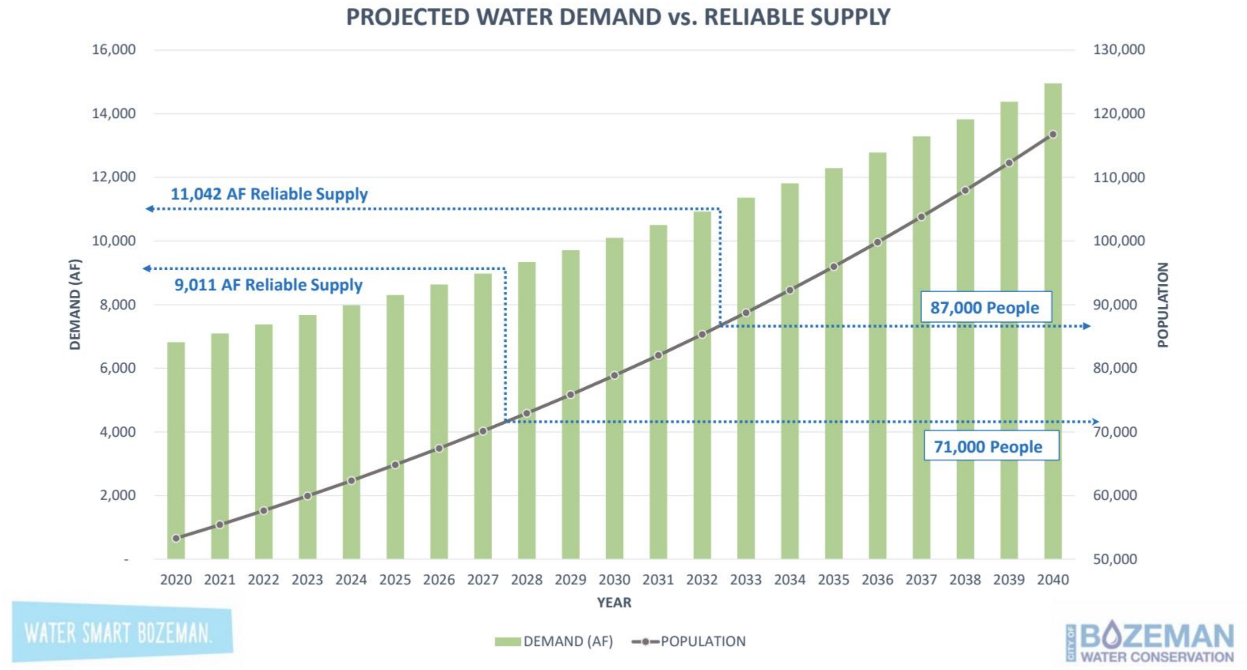

Figure 3: Projected Population Growth and Water Demand for Bozeman, Montana from 2020-2040

To understand the demands of our growing population on future water supply, we can consider projections of population growth and water availability (Figure 3, Ahlstrom 2023). The dark line represents Bozeman's population growth (4.3%) from 2020 to 2040 and the green bars represent overall water use by the city. The water supply is calculated at two different climate scenarios: given the current climate, weather patterns, and historical hydrological cycle, Bozeman has a current reliable supply of 11,042 acre-feet of water. The second scenario adds in a "Climate Change Level 2" where future drought drops our reliable supply to 9,011 acre-feet, with 25% precipitation and 75% temperature. For scenario one, Bozeman's population will reach a point where it exceeds its current reliable supply around the year of 2031. For scenario two with depleted environmental conditions, Bozeman could run into supply and demand issues as soon as the year 2027. This model has sparked headlines and scared local residents with the looming idea of a water supply doomsday. It has led to large conservation efforts that hope to preserve Bozeman's future.

Bozeman's Geographical Location

Bozeman has a unique location within the local watershed that separates it from most other major cities and regions of population growth in the west. Where most towns and cities are built next to large rivers or downstream from major reservoirs filled by massive rivers, Bozeman sits dangerously close to the top of its watershed. The definition of a closed basin is when all available water has been allocated to various uses (Svendsen 2005). For Bozeman this is the case, and efforts are placed on increasing the productivity or value of every drop of water.

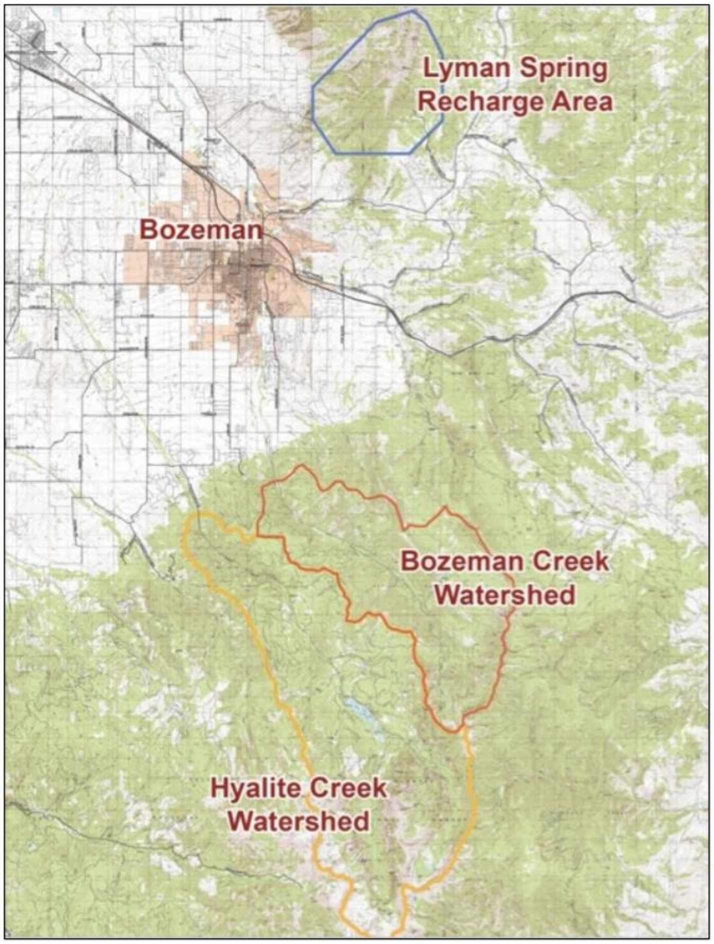

Figure 4: The Three Separate Watersheds for Bozeman, Montana

This unique location increases the difficulty of finding solutions to the supply and demand issue. The city has discussed bringing in water that originates outside of the valley but it is unrealistic and extremely expensive. In order for Bozeman to bring in water from Canyon Ferry Lake, for example, the water would need to be pumped up over the Horseshoe Hills, and typically efficient water transport relies on harnessing gravity rather than opposing it. There are also legal issues involved with obtaining water from outside Bozeman’s watershed. The water rights law in Montana states “If the owner of a water right wishes to change the point of diversion, place of use, purpose (beneficial use), or place of storage (including adding storage), they must apply for and be granted a change authorization (“change in use”) through the

Montana Department of Natural Resources and Conservation” (Sigler 2017). Modifying water rights is a complex and lengthy procedure, rendering the task of making changes particularly challenging. More straightforward solutions are available within the valley and will be elaborated upon in the following section.

Solutions

Each and every individual residing in this valley has the potential to exert an influence, whether substantial or minor, on the water conservation problem. Modest personal initiatives of water use reductions across extensive populations and extended time frames is one of our best hopes. As the city of Bozeman affirms, "Straightforward solutions can yield a significant cumulative effect" (City of Bozeman 2023). Furthermore, it is imperative to underscore that the preservation of water within the watershed carries a significantly more cost-effective proposition compared to the importation of water from external sources (Ahlstrom 2023).

Based on the data the biggest “waste” of water that occurs in Bozeman is watering lawns and gardens. As mentioned earlier, in the summer months, 50% of the city’s drinking water is used to maintain residential short-cut non-native turf. The city has made several attempts to mitigate this situation but it's far from enough. They have created a drought plan with four stages, the amount of water they are attempting to save, and different actions that need to take place for that to occur. In the dry summer of 2021 Bozeman declared a stage two drought, where the following lawn watering rules were applied: Single residential properties with odd-numbered addresses: Saturday, Wednesday single residential properties with even-numbered addresses: Sunday, Thursday. All others (multi-unit, HOAs, commercial, industrial, government): Tuesday, Friday. No watering between the time of 10am-6pm. Although this system dropped water use by 20%, it’s ridiculously organized and impossible to enforce. Future reform of this regulation is crucial for improved applicability and enforcement, even though sufficient data to do so is not currently available.

The city has also been attempting to pay residents and business owners to upgrade to high efficiency sprinkler nozzles, smart controllers, rain sensors, drip irrigation and even drought tolerant plants (City of Bozeman 2023). They have revised their landscape standards so that new residential projects are allowed 35% turfgrass for single family homes and 20% for commercial

(City of Bozeman 2023). The remaining majority of the landscape must be equipped with drought tolerant landscaping.

The city is also offering a variety of free products that help conserve water on the personal scale. They offer mulch to put at the base of trees to hold more moisture in, shower heads that release 1.5 gallons of water per minute as opposed to the average of 2.5, and faucet aerators and spray valves that reduce water use from an average of 2.2 gallons per minute, down to 0.5-1.0 gallons per minute (City of Bozeman 2023).

With Bozeman being one of the most rapidly developing areas in the country, water conservation specialists are troubled with how to regulate new development (*U.S. Census Bureau 2022)*. The new 2023 water conservation plan highlights a 1:1 strategy, where new developments must offset their required demand by efficiency. For every acre foot of water used by the new development, they must offset an acre foot of water by different water efficiency strategies. This could be projects that reduce on-site demand as well as investing and participating in retrofitting offsite existing projects. This plan is scheduled to go into effect in 2033 and could yield massive water saving initiatives from groups that previously would have not participated.

In confronting water scarcity, Bozeman is part of a global narrative. Diverse civilizations have faced and triumphed over comparable challenges, revealing a collective ability to navigate and overcome issues of water scarcity. One case study that could be useful for Bozeman to consider is from Cape Town, South Africa, which has a similar climate to Bozeman, most of its precipitation comes in the winter and there are generally dry summers. Cape Town has a much larger population than Bozeman, growing at a steady rate of 2.57% (Kerri et al. 2017).

Cape Town faced a major water crisis in 2017 where the city was only 90 days from turning off the taps. Through various conservation efforts they were able to avoid this crisis and refill most of the nearby dams from 37% (last 10% is unusable) to 80% capacity (Kerri et al. 2017). Drawing inspiration from Cape Town's approach, we can enhance the effectiveness of Bozeman's water conservation initiatives. Cape Town implemented water saving competitions between households, which shows that there's power in tapping into people's competitive spirits. This community-driven approach could be a smart move for Bozeman. The idea of imposing fines for excessive water use, something Cape Town did successfully, can help encourage people in Bozeman to follow the rules more closely. We could also borrow from Cape Town's playbook by banning water usage for non-essential purposes – like irrigation, in order to preserve

Bozeman's water supply (Kerri et al. 2017). This could potentially be the best solution to this problem in Bozeman where we use an outrageous amount of water for lawn irrigation. By adopting some of these lessons from Cape Town, Bozeman can create a more comprehensive water conservation plan, tailored to its own unique needs, and help ensure a more sustainable future.

Conclusion

In conclusion, the issue of water scarcity in the Gallatin Valley, particularly in Bozeman, Montana, is a pressing concern exacerbated by a combination of factors such as population growth, changing climate patterns, and inefficient water use. Despite the city's population doubling over the past four decades, there has been a commendable reduction in per capita water consumption, offering hope for sustainable practices. However, the excessive use of water for lawn irrigation during the summer months remains a significant challenge. Efforts to promote water conservation, responsible lawn care practices, and sustainable solutions are essential to address this issue.

The looming 2027-2031 deadline, when population growth is predicted to surpass the current reliable water supply, underscores the urgency of the situation. The existing drought plans and water-saving measures have made some progress, but more radical actions may be necessary to ensure the sustainable use of this vital resource. Each resident's contribution, no matter how modest, can collectively make a significant impact in preserving Bozeman's water resources for future generations. As the community unites to tackle this challenge, innovative and sustainable solutions will play a pivotal role in securing a water-secure future for the Gallatin Valley.

Stormwater

Jonathan Landin

Introduction

Stormwater is the water from rainfall, snow, or other inputs flowing across land or an impervious surface where it is not able to be absorbed into the ground. This runoff collects leaf litter and decaying organic material, in addition to human-made pollutants such as fertilizers or trash, carrying them toward drainages. Roadside drainages then lead into underground pipes, in the case of urban areas, which transport the polluted water into local or regional waterways without any processing or treatment. It is this lack of treatment for stormwater that can lead to impairment or destruction of local or regional waterways.

Natural pollutants such as leaf litter or grass clippings can significantly impair the water quality of stormwater. This impairment arises from two critical issues associated with organic materials in water, oxygen depletion and release of phosphorus and nitrogen. Oxygen depletion results because the microorganisms that break down the material rely on aerobic processes which consume oxygen. Phosphorus or nitrogen release is also a secondary consequence of decomposition, when the nutrients bound within the material are released in a bioavailable form.

Human-made pollutants include common household items such as fertilizer which is applied to flower beds or entire lawns to maintain the health and well-being of the vegetation by supplying critical nutrients such as nitrogen and phosphorus, both of which are critical for terrestrial and aquatic life. However, in both systems too much of any nutrient is detrimental to the system, the critical difference though is the quantity.[1]

With the aforementioned considerations in mind, nutrient enrichment and other contaminants entering drinking water supplies is becoming increasingly concerning. With increased dependence on plastic products and synthetic nutrient applications to maintain current standards of living in addition to urban aesthetics, considerations of stormwater must be addressed. Given the pace of population growth and development in Gallatin County, how can current and future technologies be used to decrease the environmental impact of urban stormwater runoff? Additionally, how can these new innovations and methods be applied to cities such as Bozeman?

Background

Stormwater has been a problem for humans for as long as cities or permanent settlements have been around. Constant occupation of one place for the purpose of habitation results in soil compaction, which decreases the ability of the soil to quickly capture and retain moisture. This problem arises because compaction decreases the spacing between soil pores which limits the ability of water to penetrate and percolate through the soil profile, thus allowing for overland transport of the water. With the creation of permanent settlements, permanent infrastructure became a necessity, which worsened the problem of stormwater management. This was due to the use of impervious materials, such as rocks, which were excellent for easing the movement of humans, but made it increasingly difficult for water to penetrate the soil without overland travel.

The creation of permanent infrastructure necessitated the creation of stormwater management. It became a necessity to divert the overland travel of water before it reached major population centers. This can be seen in depictions of ancient Roman road designs with the road having a gradual arch to it, thus diverting the water into the sides of the road, which could then feed into drainage ditches (Davies 1998). Arching of roads, or “outsloping”, is a construction industry standard practice to this day. Outsloping of roads, trails, or other surfaces, allows for the rapid drainage of stormwater away from the surface and into new areas to either capture that water, like the side of the road, or move it to an alternate location (drainages, diversion ditches, culverts, etc.).

Modern adaptations of this design have divided roads into individual segments. Each of these segments consists of one or multiple storm drainages which collect overland flow from a predetermined area outlined in the road design prior to construction, after which they will be placed underground. During a storm event, these individual segments capture the majority of the flow and funnel it into a singular pipe, after which it eventually leads into a main discharge pipe, which increases the efficiency of stormwater removal from undesirable areas.

After enough water has accumulated on an impervious surface, and after flowing through underground pipes, it can wind up at one of three possible facilities prior to being discharged into a waterway. The primary location, as well as the oldest, is a wastewater treatment facility where it is processed with sewage prior to being discharged back into the waterway. This method is not commonly seen in western states like Montana where stormwater is treated as a separate entity, and not mixed with sewage.

Another possible destination would be a stormwater retention facility, which will completely stop the travel of stormwater and hold it in place until it either infiltrates through the soil or is evaporated. The final destination where stormwater could go is a detention facility. In contrast to a retention facility, a detention facility will only hold the water for a limited time and discharge it at a controlled rate. The latter two destinations are limited within the context of Bozeman, but there have been additional pushes to increase the number of detention and retention facilities.

There is an additional fate to befall stormwater within the urban context, which is the discharge of it directly into public waterways with no treatment. This no treatment route is, unfortunately, the most common pathway by which stormwater is discharged in Bozeman ("MuniCode Library," n.d.). Untreated water is allowed to be discharged through an MS4 permit in Montana, which outlines the requirements that a city or large development must adhere to allow for legal discharge of stormwater (Montana Department of Environmental Quality 2016). These MS4 permits require an annual review so that adjustments can be made accordingly in conjunction with good engineering, hydrologic, and pollution control practices. MS4 permits strictly apply to residential and commercial areas, but are invalid for industrial and construction areas (The National Association of Clean Water Agencies 2018).

MS4 permits require permittees to develop and maintain a Stormwater Management Plan (SWMP), which includes best management practices (BMPs), control techniques, systems, designs, good standard engineering practices, and such other provisions necessary to reduce the discharge of pollutants from the permit. The permittee shall effectively manage a storm water program inclusive of the six minimum control measures: public education and outreach; public involvement and participation; illicit discharge detection & elimination; construction site stormwater management; post-construction site stormwater management in new and redevelopment; and pollution prevention/good housekeeping for permittee operations.

While MS4 permits provide a legal framework for untreated stormwater discharge, annual reviews can leave stormwater departments in cities like Bozeman in limbo when it comes to pursuing new innovations and methods. Additionally, annual reviews can make it difficult to secure funding for new ideas due to the fact that they might not be considered a universal best management practice (BMP), which is required for the MS4 permit to not be revoked.

Current Methods

Bozeman, as well as other cities, have implemented new solutions for stormwater management within the urban setting. While the aforementioned detention and retention facilities have helped to stem the issue of pollution from stormwater, they do not help the city in retaining its MS4 permit. To this end, the city has installed hydrodynamic separators (HDS's), dry wells, and rain gardens, which have shown promise in retaining the city's MS4 permit.

HDS's are an excellent tool for the separation of solids such as sediment or trash, or liquids like oil. HDS's are installed beneath manhole covers where they intercept stormwater from underground pipes and give it a chance to slow down. This is done by taking advantage of gravity to either swirl water through a spiral track, or by forcing the water through baffles (StormTrap, 2022). With this method, solids and liquids are allowed to fall to the bottom or the top of the separator. Once separated, the HDS acts as a storage unit for the water contaminants, retaining them until they can be removed via a vacuum truck. Most of these units in Bozeman are installed along Main St. and Rouse Ave.[2]

Dry wells are another tool used by the city of Bozeman which allow stormwater to translocate deep underground where it can undergo the natural filtration process through percolation. Generally, most of these dry wells are 3 feet wide at the surface and anywhere from 30 – 70 feet deep and are hidden in plain sight along Main St. and the Montana State University campus. Many of these wells have a tree or shrub in the middle of the well surface to hide the opening and have a metal grate around the base to allow water to easily enter the well. The sides of these wells are lined with perforated casings which can be filled with crushed rock or left empty.

Modern dry wells also include a pretreatment surface in the lining or surrounding the well which serves to bind up oil or other stormwater contaminants before entering the soil. This addition is included because soil can effectively bind natural pollutants (nitrogen, phosphorus, etc.), but frequently struggles to bind hydrocarbons, which are non-polar. Soil can act as a natural filter for pollutants before the water enters the aquifer (Edwards et al. 2019). This tool is extremely situational based on the height of the water table; if the water table is too high, the chance of groundwater contamination exponentially increases. So, while this method works well in more arid environments, like Bozeman or the western United States, it would be impractical in areas with greater annual precipitation.

Bozeman also utilizes rain gardens, which are like a roadside drainage, but more aesthetically pleasing. Rain gardens are created by depressing part of a landscape such that stormwater from surrounding surfaces is funneled into it. The depression can then be planted with native grasses, shrubs, and flowers which act as a sponge to soak up water as it infiltrates and percolates through the area (U.S. EPA 2023). This tool acts in a similar way to the dry wells mentioned previously but relies solely on vegetation and soil properties to act as a filter for the water before it eventually reenters the water table.

With proper plants, a rain garden is able to absorb 30% more water and 80 – 90% of nutrient inputs compared to a regular lawn or garden (The Groundwater Foundation 2022). This increase in water and nutrient absorption is achieved through removing/altering the soil composition in the desired depression. Adding or replacing the existing soil with sand allows for water to be translocated downward at a much more rapid rate compared to previously. Sand, while being much larger in terms of size than the other components of soil (silt and clay), has the lowest specific surface area because of the lack of pores on the surface of each grain. Decreasing the available pore space means that water has less of a chance to bind to the individual grains, allowing for it to be pulled down by gravity far more quickly than it would be in a clay or silt dominated soil.

While sand is a critical component for a rain garden, it does very little to hold the water in place long enough for it to drain properly, nor does it make the establishment of plants a simple matter. For these reasons compost, or some other form of organic matter, is added to the upper level of the soil. In regards to drainage, organic matter (OM) is far worse than sand due to its high specific surface area (SSA) of 560 – 800 m^2/g (Chiou et al. 1990) for liquid absorption in OM (compared to 5.6 – 85 m^2/g for clays[3] (Macht et al. 2011). However, this poor drainage means that stormwater is held in place for an extended period of time. Retention of stormwater by using a component with poor drainage prevents water from continuing overland travel and also ensures that water remains in the soil long enough for vegetation to make use of it. Additionally, most plants grow poorly in just sand due to large pore spaces on individual grains, which struggle to bind up the necessary nutrients for plant growth.

Compost is also added for the opposite effect that sand has. Organic matter (OM), such as compost, has the highest specific surface area among the components of soil. With a specific surface area (SSA) of 560 – 800 m^2/g (Chiou et al. 1990) for liquid absorption in OM (compared to 5.6 – 85 m^2/g for clays (Macht et al. 2011) it can quickly bind up stormwater and prevent it from continuing overland travel. Once the storm event has ceased this water can then be either evaporated or translocated through the sand and into the soil by gravity.

This combination of OM and sand allows for the retention and translocation of water at a quicker rate than in traditional gardens. Rain gardens are dry within 48 hours of the end of a storm while regular gardens can take anywhere from 48 hours to a week to dry post-storm due to the lack of sand for easy drainage. Additionally, this solution is cheap enough for regular homeowners to easily implement. The cost associated with building a rain garden ranges from (\$3 - \$5 per ft^2) for a DIY project or (\$10 - \$15 per ft^2) if done by a contractor (Prince George's County Department of the Environment 2022).

Future Methods

The future of stormwater management will be contingent on decreasing the number of impervious surfaces present in the urban setting and increasing the retention time before the water is discharged. Pervious pavement, bioswales, and green roofs could be excellent technologies for the city of Bozeman to incorporate into future development moving forward. Additionally, cheap methods such as rain gardens could be incorporated into residential rebate programs to help decrease the burden of city stormwater utilities and infrastructure.

First among these potential future methods is pervious pavement/concrete, which is meant to provide the same support as regular pavement while being permeable to stormwater and allowing it to infiltrate into the underlying soil. This is achieved through adding coarser bedding material as depth increases below the pavers which can then feed into an underdrain if needed, or directly into the soil below. This material reduces the dependency on outsloping for walkways, allowing for a better walking surface for foot traffic. Additionally, pervious pavement reduces the burden placed on urban stormwater infrastructure by allowing for the stormwater to continue its original path. By preventing stormwater from being impeded, this method also has the potential to reduce the number of pollutants accumulating in the stormwater due to the decrease, or elimination of, overland travel.

Pervious pavement does come with some inherent flaws which make it unappealing for the city to adopt into future management plans. The primary one being that the lifespan of the material is not long enough to justify its use. Normal concrete has an average lifespan of 30 – 100 years before it requires replacement or significant maintenance, but pervious concrete/pavement tends to only last up to 40 years. Material cost is another consideration, as regular concrete is usually cheaper at $110 - $165 per cubic yard (excluding labor). Pervious concrete tends to cost $200 - $270 per cubic yard (excluding labor). These two factors in conjunction likely deter Gallatin County from making the switch for large scale projects such as new residential neighborhoods or commercial areas. However, this also presents an opportunity for the county to shift to a smaller scale for implementation.

Should the county want to adopt pervious pavement, it could implement a rebate program for homeowners. Rebates could be based on how much money is saved on a per person basis in terms of managing and maintaining current stormwater systems for the county or individual cities. This could then be paid to the homeowner in exchange for replacing their impervious outdoor surfaces, like driveways, with permeable materials. By using this method, the homeowner isn't fully responsible for the cost of installing a more expensive system, the county fulfills part of its MS4 permit requirement, and drinking water is cleaner for residents. From the program, the county could also gather data to determine if it is cheaper in the long run to utilize these pervious systems because of the reduced burden on public infrastructure.

The second potential future method is bioswales, which act in a nearly identical way to rain gardens but are meant to support a significantly larger area. Bioswales usually take the form of a vegetated strip between large impervious surfaces such as between roadways and sidewalks, or in between parking rows in a parking lot. These bioswales are placed on a shallow slope (<5%) in the low point of the desired area to capture and filter water in the same way a rain garden would. Unlike its smaller counterpart though, bioswales can often be combined with other BMPs such as check dams or even weirs on steep slopes (>4%). All of these BMPs working in conjunction with one another forms a "treatment train", which is considered to be the most effective method of stormwater management (U.S. EPA 1999).

Gallatin County, and the city of Bozeman in particular, already utilize swales, including bioswales, for managing stormwater in the city. But, beyond the stormwater angle there are a multitude of reasons for the city to invest more heavily into the implementation of this tool. Due to the natural approach of swales, this tool can enhance urban biodiversity and provide habitat for native insects and plants while simultaneously improving the aesthetic and recreational value of urban areas. Incorporating green infrastructure such as this, urban areas can create visually appealing landscapes which serve to promote the well-being of residents. The synergistic interplay between these positive factors would allow the city of Bozeman to better align itself in creating sustainable urban development with ecologically resilient and ecologically balanced urban areas.

Despite these positive factors, there are challenges associated with increasing the use and prevalence of bioswales and other swales in Bozeman. Maintenance requirements during the establishment phase of plants can be demanding on city resources, especially if being installed in high use areas. Bioswales are also only as effective as the soil they sit upon, meaning that significant resources may need to be allocated to ascertain where bioswales can even be considered, disregarding if it is useful in that area. This means that urban centers, like Bozeman, must carefully evaluate site-specific conditions while simultaneously investing in proper design, construction, and maintenance to maximize benefits.

Green roofs, also known as living roofs or eco-roofs, are another innovative approach to stormwater management in urban areas. These systems involve the cultivation of vegetation on building rooftops, providing a range of environmental benefits, including stormwater control. Green roofs operate by absorbing and retaining rainwater through the plants and the growing medium, reducing the volume of stormwater runoff. This retention and delayed release of water aims to help alleviate the burden on stormwater infrastructure and help prevent issues such as flash flooding and erosion. The vegetation on green roofs also assists in the natural filtration and purification of rainwater, reducing the load of pollutants that might otherwise need to be treated.

One significant advantage of green roofs is their ability to improve energy efficiency in buildings. The layer of vegetation acts as insulation, reducing heat absorption and energy consumption for cooling in the summer and providing additional thermal insulation in the winter (Minnesota Pollution Control Agency 2022). This dual functionality contributes to the mitigation of urban heat island effects and can lead to energy savings for building owners.

However, the adoption of green roofs comes with certain considerations. The initial cost of installation is higher compared to traditional roofing systems, and not all buildings are structurally suitable for the added weight of a green roof (Minnesota Pollution Control Agency

2022). Additionally, the success of a green roof depends on factors such as climate, plant selection, and maintenance practices. Without proper care, green roofs can become a breeding ground for pests or invasive plant species, potentially compromising their ecological benefits. However, it is estimated that the average annual cost of upkeep is significantly cheaper over the lifespan of the green roof compared to a conventional roof (Porsche, U. and M. Kohler 2003).

Green roofs offer a multifaceted solution to stormwater management by combining environmental benefits with energy efficiency. While their initial costs and maintenance requirements may pose challenges, the long-term advantages in terms of reduced stormwater runoff, improved water quality, and energy efficiency make green roofs a compelling option for sustainable urban development. However, the city must work in collaboration with scientists and homeowners to find a blend of plants that work well to manage stormwater without being an eyesore or money pit for the homeowner (Miller et al. 2010).

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[1] Terrestrial systems generally tend to have higher nutrient requirements than aquatic systems. For an example of this with Scots-pines, N fertilizer would have to be applied at a rate of 250-1000 kg N/ha (~223 lbs N/ac) for the tree to begin showing signs of N poisoning (Jokela et al., 1995). With phosphorus though, a gardener could use 20 lbs of 13-13-13 fertilizer (13% N - 13% P - 13% potassium) to cover a 1000 square foot plot, which would translate to 2.53 lbs of phosphate (or 110 lbs/ac). Of this, 43.6% (1.1 lbs) would be taken up by common garden vegetables like tomatoes or peas, but only 27.3% (0.7 lbs) would actually be used, leaving 72.7% (1.8 lbs) of the P to build up in the soil (Alabama Cooperative Extension System, 2023).

Aquatic systems are significantly more sensitive to nutrient inputs than terrestrial systems. Animals in the water start to become poisoned by N, depending on the ionization state of ammonia, around 0.05 mg/L - 2.0 mg/L. This toxicity arises due to nitrogen bonding with the hemoglobin in the bloodstream, which prevents it from being able to adequately transport oxygen within the body, which ultimately results in death from hypoxia. However, aquatic plants are not as sensitive to fluctuations in nitrogen content. This is due to P being a more limiting factor in aquatic systems in comparison to nitrogen, while the reverse is true on land. Phosphorus generally maintains low background levels in freshwater systems (<0.05 mg/L), placing an upper limit on how much plants can grow (Spring Harbor Environmental Magnet Middle School & Kotoski 1997). When this level is exceeded as a consequence of nutrient inputs, the limitation on plant growth is raised substantially because the plants can uptake more N before P levels are depleted in the system. This results in the toxic algal or cyanobacteria blooms, depleting oxygen, thus killing most, if not all, life in the affected area.

[2] GIS web viewer for Bozeman infrastructure. Feel free to explore to gain a better understanding of where various structures, drainages, or other structures are within the city limits. https://gisweb.bozeman.net/Html5Viewer/?viewer=infrastructure

[3] This depends on the type of clay in question (Осипов 1975). Clays that are 1:1, like kaolinite, are held together very tightly by hydrogen bonds, decreasing the SSA. 2:1 clays, like vermiculite, are weakly held together by colloidal forces which allow the clay to swell when it gets wet. This swelling increases the SSA of the clay while it is wet, and then decreases it when it dries. This results in soil heaving which can uplift sidewalk pavers or other solid surfaces.

Water Quality in Gallatin County

Kacie Donaldson and Emily Carey

Introduction

Rapid urbanization within Gallatin County poses threats to freshwater ecosystems through increased pollutants and degradation of water quality. Urbanization directly increases surface runoff by increasing impervious landscapes, altering natural hydrology, channel morphology, sediment transport, stream temperature, and delivery of pollutants. Pollutants reported in Gallatin County include, but are not limited to organic pollutants, heavy metals, microplastics and PFAS, often traced to industrial waste, agricultural practices, and wastewater treatment.

Sediments

As urbanization continues to reshape the landscapes within Gallatin County, the influences on sediment dynamics and water quality within freshwater ecosystems becomes more of a prevalent question. Total suspended solids (TSS) refer to waterborne particles exceeding two microns and are commonly used as an indicator of water health (Water Science School 2018). These particles, suspended in the water column, may include soil debris, decaying organic matter and particles discharged from wastewater. TSS occur in the environment naturally through erosion or runoff, but their concentration is exacerbated by anthropogenic factors, most notably urbanization. As discussed before, urban expanse heightens sediment in water by increasing impervious surfaces leading to lower infiltration rates in soils and reduced vegetation cover (Kjelland et al. 2015). Due to human impact, increased pollutants, excess nutrients and unnatural particles, such as microplastics, can end up in aquatic systems, causing a decrease in water quality, increase in eutrophication, and aquatic organismal loss. As urbanization spreads and vegetation cover declines, surface runoff is intensified, which causes rain, often carrying various pollutants and sediments, to quickly move over the landscape and into nearby bodies of water (Kjelland et al. 2015). In Gallatin County, where sedimentation is not a major issue but urbanization is rampant, concerns regarding the effects of excess sediment on water quality must be acknowledged to mitigate future issues that may arise.

Turbidity

High amounts of suspended sediments can cause water to lose transparency. The resulting cloudiness in the water is referred to as turbidity which can negatively affect water quality. Turbidity measures the scattered light caused by suspended particles in water and is commonly recorded in Nephelometric Turbidity Units (NTUs; Chamberlain & Ioannou 2019). In Bozeman, sediments in the water are not a major issue due to water treatment plants filtering out the sediments from the drinking water (Bozeman Water Treatment Plant 2022). The issues with suspended sediment and turbidity have been more prevalent in the surrounding areas of Bozeman, such as the West Fork of the Gallatin River and its tributaries up near Big Sky, Montana (Gallatin River Task Force 2021). Some of the streams in the Upper Gallatin watershed and the West Fork of the Gallatin watershed are impaired, thus, not meeting the state quality standards for sediment (Figure 7 & 8). The streams have sediment pollution largely caused by the topography of the landscape where landslides and large amounts of sediment runoff were likely to occur. Along with natural impacts on sediments, anthropogenic factors such as urbanization appeared to impact the sediment loads due to many of the sampling sites being along major roads (Figure 5 & 6). Some of the sites along the road ways such as West Fork and South Fork of the Gallatin along with the Taylor Fork showed a major spike in turbidity during spring runoff which was most likely due to both geography and the increased runoff from impervious surfaces

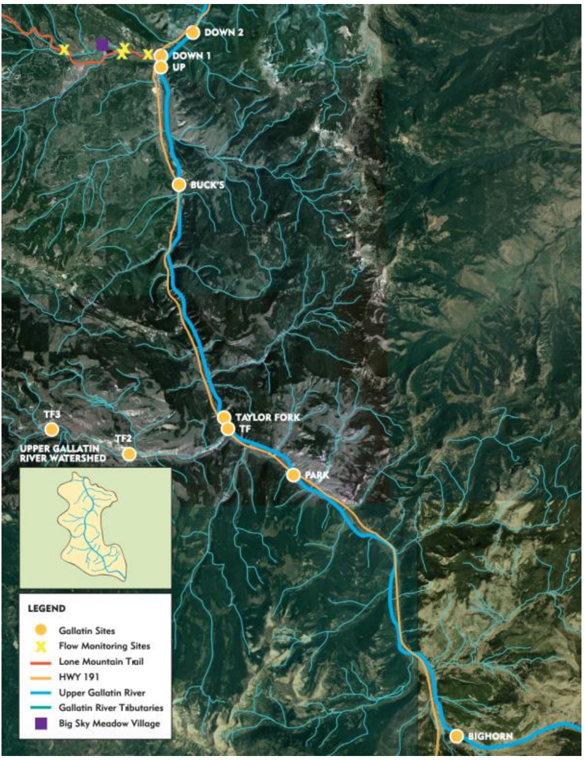


Figure 5: Eight sites on the mainstem Upper Gallatin River and three sites on the Taylor Fork that were monitored in 2018 to look at water quality (Gardner & Bednarski 2018).

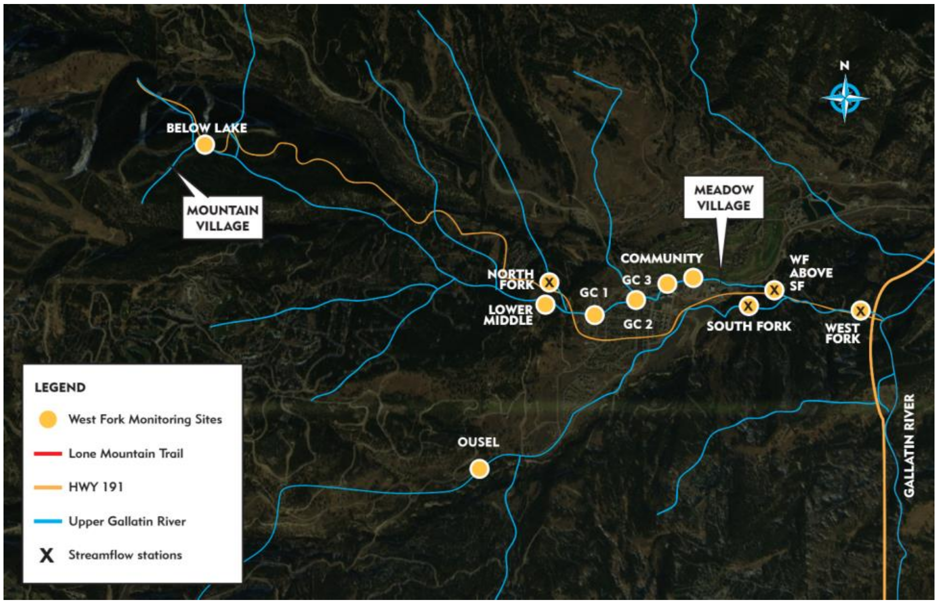


Figure 6. Eleven sites on the West Fork watershed that were monitored in 2018 to examine water quality. The yellow circles were monitored four times a year and the yellow circles with black X’s were continuous monitoring stations*(Gardner & Bednarski 2018).*

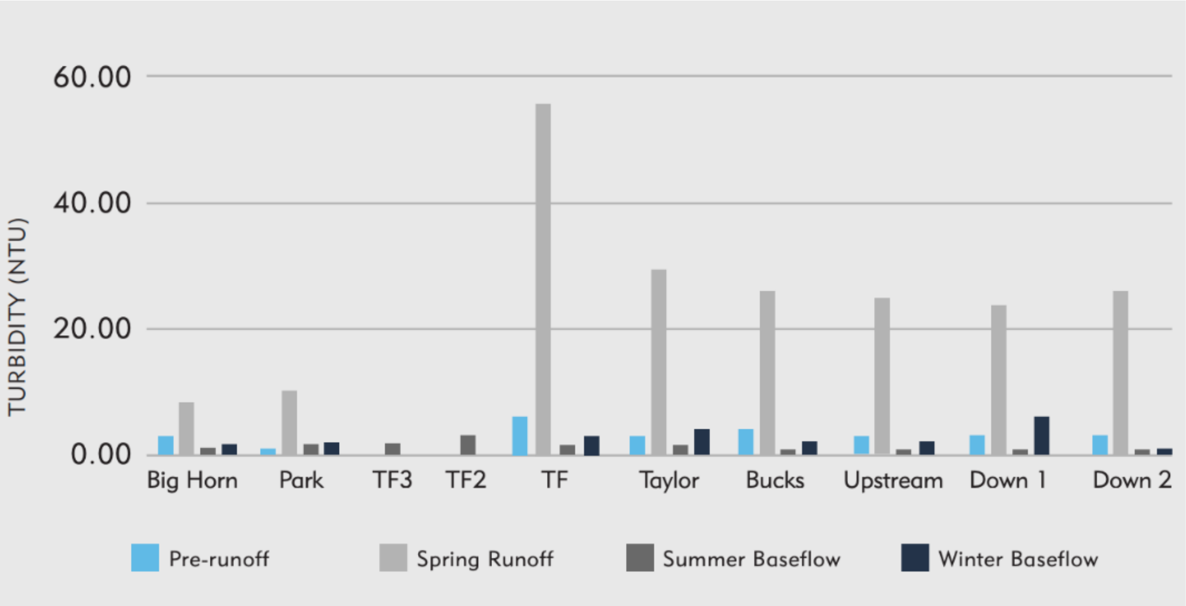


Figure 7. Turbidity values during pre-runoff, spring runoff, summer baseflow, and winter baseflow in 2018 in the Upper Gallatin Watersheds. Turbidity is a measure of water clarity, and naturally varies throughout the year with highest values during spring runoff. (Gardner & Bednarski 2018).

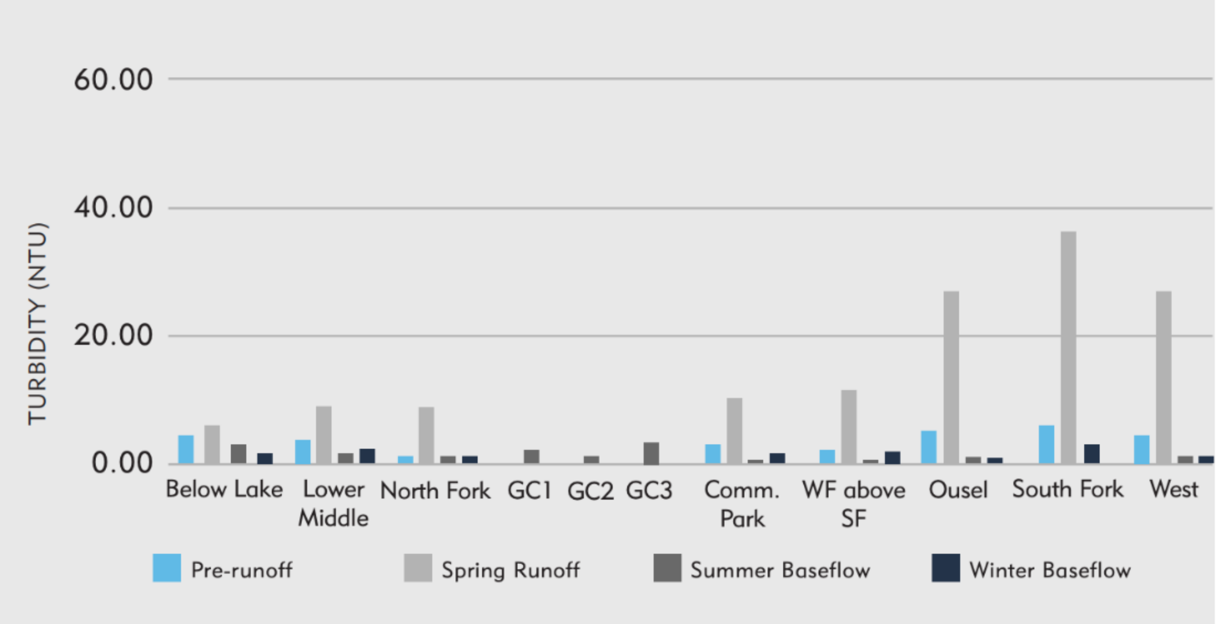


Figure 8. Turbidity values during pre-runoff, spring runoff, summer baseflow, and winter baseflow in 2018 in the West Fork of the Gallatin Watersheds. Turbidity is a measure of water clarity, and naturally varies throughout the year with highest values during spring runoff (Gardner and Bednarski 2018).

Larger surface runoff can overwhelm aquatic systems with excessive concentrations of sediment causing a loss of transparency in water (MacKenzie et al. 2022). Elevated turbidity levels can obstruct the penetration of sunlight into the water, preventing aquatic plants from photosynthesizing and stunting plant growth (NRCS 2012). Aquatic plants are essential for providing oxygen and natural sediment traps for aquatic organisms' habitat. When the cloudiness in the water is very intense, plants may die off, decreasing the amount of dissolved oxygen in the water. This is more prevalent in areas with slower moving water where water flow is not bringing in much oxygen and can result in high depletions of dissolved oxygen where organisms have to either adapt to the poor conditions or relocate. In some severe cases, dissolved oxygen concentrations can be so low that dead zones occur where no aquatic life can exist. Also, the reduction of light can impact the ability for aquatic species to see, causing alternative feeding patterns. Many species of fish also rely on vision to catch prey, so high turbidity can increase the time to locate food and can decrease the organism's reactivity and foraging abilities (Higham et al. 2015).

Moreover, inflated turbidity levels can directly affect the health of aquatic organisms. Fish and other organisms can ingest the suspended sediments which can lead to injuries to their gills and feeding challenges (Gallatin River Task Force 2021). Due to the variation in feeding patterns and complications with direct ingestion, reduced growth rate and increased loss of weight have been observed with long-term exposure to suspended sediments (Lowe et al. 2015).

Nutrient Enrichment

Algae, an organic suspended solid, is an important indicator of nutrient enrichment in freshwater ecosystems. Nutrient enrichment is caused from an excess in nutrients in a water body, typically nitrogen (N) and phosphorus (P). Both nitrogen and phosphorus are essential elements for plants, however excess leads to degradation of soil health and water quality, seen in eutrophication of water bodies. Excess fertilizer or pesticide application, animal manure, runoff, septic systems, and fossil fuel combustion are among the primary sources of nutrient pollution (Frei et al. 2021). Eutrophication of water bodies can exacerbate the effects of climate change in a positive feedback loop by increasing greenhouse gas emissions by, for example, shifting vegetation dominated by macrophytes to algae and ultimately increasing methane emissions (Beaulieu 2019). Alterations in precipitation patterns and temperature increases predicted as a result of climate change will increase nutrient loading and promote the growth of harmful algal blooms (Rodgers 2021). From the 2017 Montana Climate Assessment, it is expected to see more precipitation in winter months, less in summer, and warmer overall temperatures (Whitlock et al. 2017), putting the Gallatin County at a heightened risk to nutrient pollution.

Stormwater data collected from the City of Bozeman in 2017 showed that four of the eight tested sites showed significantly high levels of N and P. Measurements for nitrogen and phosphorus were reported in mg/L and compared to permit benchmarks, likely set by the EPA standards. According to the Gallatin Watershed Council, 15 streams in the Lower Gallatin Watershed did not meet state water quality standards in a 2019/2020 surface water monitoring report (GWC 2020). In 2022, the Montana Department of Environmental Quality proposed to list a section of the Gallatin River as impaired due to harmful algal blooms as a result of nutrient pollution (DEQ 2022). Nutrient enrichment is a threat to freshwater ecosystems throughout Gallatin Country. While certain contributing factors, such as fertilizer application rates may be decreasing with changes in land use and urbanization, new threats arise from increases in impervious surfaces and infrastructure.

Many sources of nutrient enrichment come from nonpoint sources which lack government regulation. The Clean Water Act addresses point source pollution, which has significantly reduced across the US. However, regulation of nonpoint sources is crucial to mitigating this problem, including fertilizer, animal waste, atmospheric deposition- often from vehicle exhaust or coal and oil-burning power plant emissions (Manuel 2014). Many contributing factors of nutrient enrichment can be mitigated with outreach and education. Using the correct amount of fertilizer and pesticide application rates will reduce the amount of nutrients left unused by crops and plants. Keeping livestock further from streams reduces the nutrients that infiltrate from manure. On a larger scale, transitioning to cleaner energy sources and safer practices, this problem can be mitigated.

Microplastics

Microplastics are small plastic particles, less than 5mm, that can come from fragments of large pieces of plastic or microbeads and from industries that manufacture plastics (Isaac and Kandasubramanian 2021). These particles can be found in everyday products including toothpaste, sunscreen and aluminum cans, along with a number of foods and water sources. In recent years, major concerns have been centered around the ingestion of microplastics by humans and aquatic organisms due to the potential risk of toxins and bioaccumulation.

The two main categories of microplastics are primary and secondary (Lee et al. 2023). Primary microplastics are deliberately manufactured into small particles that are used in cosmetics, detergents and industrial products, whereas secondary microplastics are typically larger pieces of plastic that break down into smaller fragments over time. Both of these microparticles have low biodegradation meaning they will stay in the environment for long amounts of time (Lee et al. 2023). Runoff from urban areas, industrial processes, wastewater discharge and large plastic debris are major sources of primary and secondary microplastics in water. In cities similar to Bozeman, outdoor recreation activities such as hiking, biking, fishing and boating introduce microplastics from fishing lines, nets, and deteriorating equipment. Rain can wash these particles into water bodies, transporting them downstream, where they can be found in the sediment, water column and the riverbanks in both urban and remote locations (Barrows et al. 2018).

In Montana, studies have been done sampling surface water to examine the presence of microplastics. In Flathead Lake, microplastics were detected with highest concentrations near the most populated areas around the lake (Xiong et al. 2022). Similarly, microplastics have been detected throughout the mainstream and tributaries of the Gallatin River that are frequented by outdoor enthusiasts. The presence of the particles in the more remote tributaries of the Gallatin suggests that the microplastics have been primarily caused by outdoor recreation (Barrows et al. 2018).

In Bozeman, stormwater runoff can largely contribute to impairment in the city's creeks causing debris, namely microplastics, to readily enter the water systems (Oliver 2022). In these urban areas, tire wear from vehicles is a major microplastic contributor, and can easily be transported to waterways via stormwater runoff. Consequently, as populations and developments in Gallatin Valley continue to expand, concerns about microplastics are increasing. Population size has been linked to increased microplastics in water systems due to consistent trends of more plastic waste and secondary plastic breakdown where populations are larger (Chen et al. 2022).

The proliferation of microplastics in the last several decades has raised concerns about their effect on humans. Research has detected microplastics in various foods, such as table salt and rice, along with raw water sources and treated drinking water, including tap and bottled water (Koelmans et al. 2019). Moreover, microplastics have been detected in human bodies including, but not limited to, the bloodstream, lungs and the placenta (Lee et al. 2023; Ragusa et al. 2021). The widespread presence has created concerns for human health related to bioaccumulation and potential toxicity from the microplastics. Additionally, microplastics can sorb heavy metals and, when consumed, can be extremely toxic to some organisms due to the accumulation of contaminants (Munier & Bendell 2018). Most plastics have additives such as plasticizers, flame retardants, UV stabilizers and dyes that are used to create color, transparency, and resistance to degradation (Campanale et al. 2020). These additives are harmful to human systems and some are linked some to cancer or disruptions to the endocrine system. Although the studies on the effects of microplastics on human health are limited, there is rising concern for the impact on human digestive and immune systems, inflammation response, and newborns (Lee et al. 2023). Ongoing research needs to be a high priority to uncover all of the damage microplastics have on human health.

Recreational activities, like fishing, are a major part of the culture that draws people to Bozeman, so keeping the water clean is imperative to the permanent community, tourism and overall ecological health of the natural environment. Unfortunately, microplastics have a far-reaching effect, and aquatic health has also been heavily impacted. The microplastics that are washed into waterways can be harmful to aquatic organisms both indirectly and directly via ingestion and respiration (Miller 2020). Due to the small size of the particles, a variety of aquatic organisms from zooplankton to large fish, ingest these particles which can lead to impairments in feeding, gills, reproduction and growth (Isaac & Kandasubramanian 2021).

Furthermore, microplastics may be able to make it through the aquatic food web and be transferred through organisms, causing bioaccumulation and biomagnification (Miller 2022). Bioaccumulation refers to gradual accumulation of microplastics and toxins over time within organisms due to repetitive uptake, while biomagnification is the movement of toxins or microplastics transferred from organisms via the food web resulting in an increased concentration of contaminants in higher trophic levels. Studies have shown that microplastics can bioaccumulate in both producers and consumers, further research needs to be done to confirm whether or not biomagnification can occur across aquatic food webs in the wild (Miller 2022).

PFAS

Per- and polyfluoroalkyl substances, denoted as PFAS, are a group of synthetic organofluorine chemical compounds used to make fluoropolymer coatings, found in clothing, furniture, food packaging, cosmetic products, fire-fighting response and training, non-stick cooking surfaces, and adhesives. PFAS, commonly referred to as forever chemicals, encompass over 4,000 highly fluorinated man-made substances, composed of fluorine atoms attached to an alkyl chain.

These chemicals are extremely resistant to degradation in natural environments, have bioaccumulation properties, and are toxic to fish, wildlife, and humans. Bioaccumulative chemicals build up in human bodies and wildlife when they are absorbed and not secreted. PFAS are unique because they bind to proteins in blood in the human body, while most bioaccumulative chemicals build up in fatty tissues (Lewis 2022). Long chain PFAS can accumulate in the blood, liver, kidney, and bones, while short chain PFAS have been shown to accumulate in the lungs, kidneys, and brain (Lewis 2022). Similarly, studies have shown that PFAS accumulates in the fatty tissues of fish, which becomes a human and wildlife health issue because most cannot be eliminated with cooking (George 2023). The mobility of PFAS allows them to move through soils and contaminate ground water and drinking water because of their high water solubility and tendency to not bind to other materials. Short chain PFAS can migrate from soils to plants, and concentrate in edible parts of fruits and vegetables. The EPA explains that human studies have found associations between PFOA and or PFOS, exposure and effects on the immune system, cardiovascular system, human development, and cancer (EPA 2021). PFOS, perfluorooctane sulfonate, and PFOA, perfluorooctanoic acid, are the two most studied forms of PFAS (EPA 2017).

In 2021, the Montana Department of Environmental Quality published a PFAS monitoring report focused on urban and industrialized landscapes in Bozeman, Helena, Billings, and Great Falls, testing for 28 PFAS based on current analytical capabilities. Overall findings from this report showed that 58% of the sites tested had detections of one or more PFAS compounds. It was determined that multiple PFAS were present at moderate levels in at-risk sites, varying in magnitude depending on site location. Eight sites were analyzed in Bozeman, four of which showed non-detect values for the 28 PFAS. The highest concentrations of PFAS were in the East Gallatin River, one mile downstream of Springhill Road bridge (12.83 ppt), and the Mandeville Creek at Bozeman High School (26.4 ppt). Results indicate that PFAS are likely entering surface waters from wastewater treatment plants, industrial facilities, military installations, airports and urban runoff.

The Montana DEQ released a PFAS action plan in 2020, aiming to address and quantify PFAS contamination as well as mitigation strategies. The five objectives outlined in the action plan include: to identify and inventory known and potential PFAS sources and sites, to provide public outreach and education, to protect drinking sources and ecology, to identify resources and funding and determine legislative restrictions, and to identify disposal options and reduce use of products that contain PFAS (Montana DEQ 2020).

The chemical nature of PFAS poses significant threats to freshwater ecosystems throughout Gallatin County. A study on PFAS in freshwater ecosystems found that some PFAS can partition to sediments and may act as a sink to serve as secondary sources for biotic exposure. This is especially prevalent when disturbed through dredging, storm events, bioturbation, or any developments (Lewis 2022). According to the EPA, there are currently three known techniques to effectively remove PFAS from drinking water and wastewater, including granular activated carbon, ion exchange resins, and high-pressure membrane systems, but any of these techniques entail costly solutions (EPA 2020).

The drastic effects of PFAS have been demonstrated on the environment, wildlife, and humans, yet all of the papers read about PFAS stress the need for further research. Considering the rapid urbanization occurring throughout Gallatin County, PFAS pose a dangerous potential to the quality of our freshwater ecosystems.

Stream Access and Montana Recreation

Audrey Reynolds

Modern Montana is known for its big skies and environmental freedoms, but before environmental laws were put into place, the perception of Montana was much different. Viewed previously for its mass amounts of gold, silver, and gems, it was a mining hotspot in which people were willing to brave the cold to have acres of property and hopefully enough materials to make immense amounts of money, with little or no regard to the effects of the environment. In 1972, Montana turned over a new leaf and a new constitution was put into place by the vote of the people. A shift had occurred: Montana was now focusing more on the environment instead of the intensive mining that had taken place for decades. Though mining is still a part of the economic culture of Montana (and the remnants of mining pollution is still stuck in our environmental systems), we are in a new era where recreational tourism is bringing in a lot of people, which in turn is bringing in a lot of money. The human race is willing to spend immense amounts of money to enjoy the rivers and mountains, and that’s something that is very important to Montana’s government. The main inflow of recreational money comes from boating and fishing, which is not just due to the beautiful streams and rivers, but also to the freedoms in public stream access laws. These laws protect both the common citizen and the intense fisherman when they are participating in almost any activity they enjoy within any stream and river in Montana. These laws differ from almost every other state in the country, and help to make Montana stay unique. Even so, are there downsides to allowing the public to access any waterway they want? Is the promise of positive financial gain and a good reputation just too good for the Montana government to pass up? Or should public citizens really have the right to access streams and rivers in any capacity that they please?

The Montana Constitution is a lengthy piece of writing that outlines all the laws in Montana. Diving into this, the laws for recreating in streams and rivers are tucked into Title 23, Chapter 2, Part 3. An easier read is the simplified version of the stream access laws within a brochure curated by Montana Fish, Wildlife, and Parks. As stated in 23-2-302§1, MCA in the constitution, “Except as provided in subsections (2) through (5), all surface waters that are capable of recreational use may be so used by the public without regard to the ownership of the land underlying the waters.” Without reading all the subsections, the Montana Fish, Wildlife, and Parks brochure incorporates them into a more condensed definition: “All surface waters capable of recreational use may be so used by the public up to the ordinary high-water mark without regard to the ownership of the land underlying the waters. The limit on water-related pleasure activities is the water resource itself. The laws do not apply to recreational use of lakes.”

What is an ordinary high water mark? The Montana Constitution definition in 23-2-301§9, MCA is “ the line that water impresses on land by covering it for sufficient periods to cause physical characteristics that distinguish the area below the line from the area above it. Characteristics of the area below the line include, when appropriate, but are not limited to deprivation of the soil of substantially all terrestrial vegetation and destruction of its agricultural vegetative value. A flood plain adjacent to surface waters is not considered to lie within the surface waters' high-water marks.” This concept is one of the reasons that public citizens get confused and sometimes even arrested on private property. The high water mark changes from year to year and from river to river. It highly varies between times of year as well. When there is very low water flow from run off and lack of precipitation, then the water will be much lower than the high water mark, giving a person more access to the land above a stream or river on private property.

As stated above, the only restrictions to what an individual can do in a stream or river in Montana is purely dependent on whether or not the water permits it. The definition for recreational use in the Montana Constitution is “with respect to surface waters: fishing, hunting, swimming, floating in small craft or other flotation devices, boating in motorized craft unless otherwise prohibited or regulated by law, or craft propelled by oar or paddle, other water-related pleasure activities, and related unavoidable or incidental uses (MCA 23-2-301§10).” This is a broad, almost vague, definition of recreational use. It can be interpreted in many ways, but allows almost infinite use of streams and rivers, which is why Montana is a fishing site mecca.

Other states have very different laws. Even states that are bordering Montana or are known for recreational activities, such as Colorado and Utah, have nowhere near the same amounts of public freedoms for their streams and rivers. There are a few main differing points between the other states and Montana, one of them being the streambed itself. Public citizens in Montana are able to access not just the streams and rivers, but also the riverbeds underneath.

They are able to anchor their boat, walk through the water, or anything else that is not damaging to the landowner's property. Utah law states that "a person may not access or use a public water on private property for recreational purposes if the private property is property to which access is restricted, unless public recreational access is established under Section 73-29-203" (73-29-201). As one continues to read the rest of the Public Waters Access Act within House Bill 141 for Utah, it simply relays the fact that someone can only float on water unless of an emergency. A person on the river cannot stop on a landowner's personal property due to the fact that the riverbed is still private. Colorado laws are very similar to this.

In 1979, a few fishermen were heading downstream on the Colorado River when they decided to take a detour through a tributary river. This tributary flowed through a private property, in which multiple people, including the landowner, told the fisherman that they were not allowed to float through the privately owned ranch. The fishermen decided to go anyway in their raft, which was the right size for the river and had leg holes in the bottom to steer away from any objects in their way or the shore. The landowner pressed charges and the case went to trial. The court ruled that the men were in the wrong and were convicted of third-degree criminal trespassing. One of the main points for this case was a property law that became codified into statue 41-1-107, C.R.S. 1973, which states: "The ownership of space above the lands and waters of this state is declared to be vested in the several owners of the surface beneath, subject to the right of flight of aircraft." This would mean that rivers and streams on private property were completely owned by the private landowner. They own not just the water, but the rocks at the bottom and the sky above. This constricts a lot of land from being enjoyed by the public, and gives more power to the landowners. This is vastly different to Montana, which allows all parts of a stream and river to be used by the general public and visitors. Figure 9 shows some similarities and differences between Utah, Colorado, and Montana.

	Public Recreation Rights	Public Easement On Private Streambeds	Public Portage	Easement Across Private Property
Colorado	Flotation Only	No	No	No

Wyoming	Flotation Only	No	Yes	Depends
Montana	Virtually Unlimited	Yes	Yes	County Roads

Figure 9: A table of different aspects of stream access laws in Colorado, Wyoming, and Montana based on different cases and constitutions.

The draw of people to Montana is the quiet wilderness and plethora of activities that can be enjoyed outside. One of the reasons that stream access laws are important is because of the freedom of recreation. Activities such as boating and fishing are very popular in the United States, and with Montana having such a lack of restrictions for rivers and streams, people from all over the country venture to this state for the opportunity to spend their time, and money, as they please. Fishermen are the main demographic for Montana stream public access law appreciation. Just with a simple online search of fishing opinions, my computer was flooded with rants about the stream access laws in other states. Out-of-state individuals who are willing to spend whole paychecks for a new fishing pole or even a boat to cruise on the river are now willing to spend that money in Montana. They know they have the most rights in Montana than any other state, even in the western part of the United States.

The economics of recreation are massively important to Montana. For starters, Montana has the second highest recreational revenue for global domestic product (GDP) within the United States, with Hawaii taking the number one spot. Activities such as hunting, skiing, and motorcycling bring in more money in Montana than the national average (Figure 10). The last reported accruement of income from the Montana Department of Labor and Industry showed that recreation brought in \$2.5 billion of annual gross domestic product for 2021, with a large portion of that coming from boating and fishing. A total of \$163 million was brought in from boating and fishing, with part of that being from boat sales and from guided tours on Montana streams and rivers.

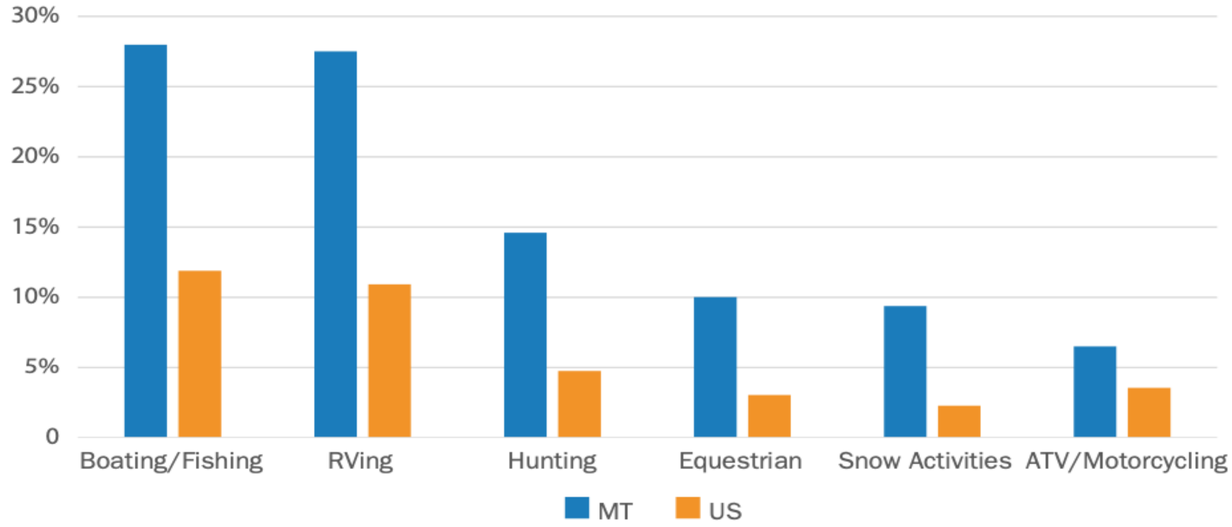


Figure 10: A graph from a brochure based on the total recreational GDP from the Montana Department of Labor and Industry written by Logan Hendrix. The graph shows a comparison between the percent of recreational income from the United States and Montana based on activity type.

Part of this money comes from people who are coming from out of state. People not just from the United States, but from all over the world venture to Montana to see the national parks, snowy hills, and the beautiful big sky. They also come to partake in recreational activities that only can be done so freely in Montana. As people come to this state, they usually don't understand, or particularly care, that even though there is virtually anything you can do in Montana's streams and rivers, that doesn't mean you should.

There are over 300 fishing sites that have public access in Montana and though the stream access laws allow almost unlimited recreational use of these river sites, that doesn't mean there are unlimited ways that an individual can fish. Fishing has changed since the beginning of the United States. Fishing was once for food and sustenance, providing meals for families and communities. Though this was beneficial at first, excessive fishing started to deplete all fish populations, especially trout. The fish did not have a chance to repopulate, and the economics of selling or trading fish also started to deplete as well. Fishery managers started to realize that if they put regulations onto the amounts of fish, and the weights of the fish caught, then they could have more fish for the next year and the year after that (Clark et al. 1981). Then as time went on, fishing became more recreational. Fishing started to become a leisure activity, then eventually it became a competitive sport. This would mean that the dynamic of fisheries would start to change as well. Having complete fishing freedom in streams and rivers came at a cost. Laws were starting to be put into place in every state across the nation in the late 1800s that would only allow a certain amount of fish that could be kept and under a certain weight (Rahel 2015).

Montana Fish, Wildlife, and Parks currently release a yearly brochure of regulations for each river and stream in Montana, lakes and ponds have different fishing regulations, and these regulations for fishing in streams and rivers vary from the amount of each species one can catch to the months that a fishing site is open. Regulations for river closure are a vital part of Montana state laws as well. “Waters operated as fish hatcheries and rearing ponds by FWP and the U.S. Fish & Wildlife Service shall be closed to fishing at all times. Waters in which FWP operates fish traps and other structures are closed to fishing as posted. Certain water-supply lakes, streams, and hazardous areas are also closed as posted (Montana FWP 2023).” There are also fishermen and fishing companies that understand the freedoms they have and want to honor them by creating their own code of morals to allow everyone to use the beauty that is stream access laws for all kinds of fishing. For an example of morals, Montana Angling Co. has a list of viewpoints on their website that represents their ethical code for their guides and anglers. This list includes catch and release, following all game laws, and no use of lead. One of their ethical codes is to not target spawning fish. They state: “Anglers need to avoid targeting actively spawning fish and redds” because they are the “future of wild trout fisheries. The rivers and streams of Montana depend on healthy reproductive rates to maintain the quality of our fisheries (Montana Angling Co. 2020).” This is an important part of education not just for anglers, but also someone who may not have the prior knowledge of fish populations and fisheries. Using and sharing an ethical code as not just a company but also as an individual could be a very advantageous way of spreading beneficial information from person to person.

Both examples of a more government based approach to regulations and also an individual’s morals show that conserving fish populations and ecosystems is more important than an individual’s rights to stream access. To allow someone to fish in public streams and rivers there needs to actually be sufficient amounts of healthy fish to catch. When people interrupt the spawning fish or fisheries in general at river sites, there is a risk for negative impacts in more ways than one.

Pollution is increasing in every part of the world. You see growths of green algae in lakes and trash piles brought from stormwater sitting on the side of the street. A lot of pollution currently being found in water sources is derived from microplastics, which are pieces of plastic that are smaller than five millimeters. Plastics and microplastics found in the environment can come from a variety of sources (Liu et al. 2000). Some primary sources where microplastics are found are artificial turf, sewage systems, paint, personal care products, and even tires. The secondary sources of microplastics stem from bigger pieces of plastic that have not been properly disposed of. This form of pollution stems directly from humans. In the grander scale of water, fishing nets and ropes are used when fishing in large bodies of water, and those being left behind contribute to a lot of waste.

Coming back down to the local scale of water pollution, fishing paraphernalia is still a large part of water pollution in Montana. With the popularity of fishing, there comes quite the foot traffic in popular fishing sites, and an increase of trash left behind. One study conducted by Environment Montana Research and Policy Center found that microplastic pollution including bags, water bottles, and fishing line were found in 66% of the fifty popular fishing sites analyzed in Montana. Of the sites where microplastic pollution was found, 42% of them had fishing lines present (2019). Microplastics heavily affect the fish that inhabit Montana’s public streams in rivers. As stated above, microplastics can absorb heavy metals and then can be ingested by zooplankton, fish, and other organisms that live in any bodies of water. Keeping the fish population healthy is important not just for the economic benefits of recreational fishing, but for the ecosystem as well. An unwell ecosystem hurts plants, animals, and even people.

In conclusion, Montana is unique in a multitude of ways. There is so much freedom to recreate in this state, but understanding how you can recreate, without damaging the natural habitat, is severely important for ecosystems and organisms within an environment. Though stream access laws state that the recreation of an individual in a stream and river is virtually unlimited, other government regulations protect the fish and the environment first. That doesn’t stop anglers or others from spending their money to fish and boat on public access sites. Through all laws and regulations, humans are still a direct source of water pollution, usually putting plastics into popular fishing and recreation sites. The public shouldn’t have rights to do whatever they please in streams and rivers. Regulations are needed to keep Montana waters clean and fish populations intact. In the end, education is the most important tool for understanding water in Montana. Water is so abundant in life for organisms and memories for people. From someone’s first fish they’ve ever caught to just playing in a stream, water provides not just the necessary fuel for life, but a fuel for living life. Making sure that people understand the proper ways to recreate and protect the environment is key to keeping Montana’s streams and rivers free.

From Water to Phosphorus: A Brief Interlude

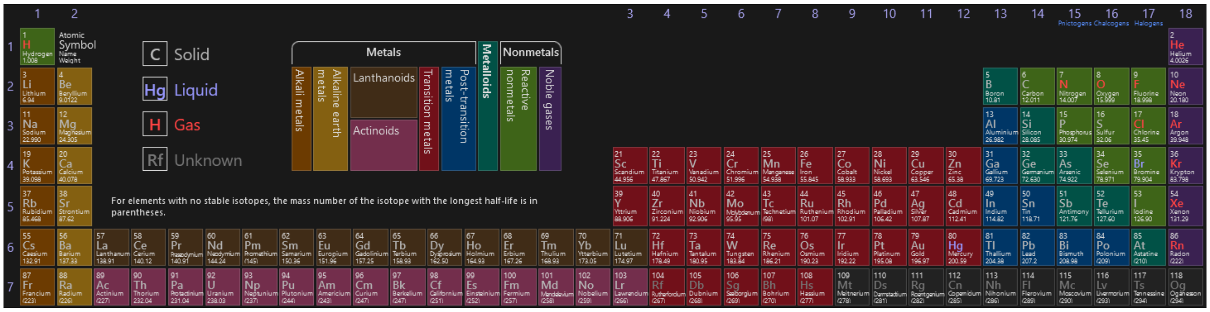
Santo Mallon

The one thing everybody has in common is water. H_2O, DiHydrogen Monoxide, is one of the most basic and important molecules, and generally, topic, in not just science but the universe in general. Whole worlds are made up of water (or rather, different forms of ice) (Quick 2020).The water is where life began, and even still makes up the majority of the mass in most life (Mitchel 1945, Watson 1980). Wars have been fought over access to water, some of our greatest discoveries and most important mysteries have been based in water. NASA even believes it will be water that brings us to the Moon and beyond, as with enough electricity we can split the water-ice on the Moon into Oxygen to breathe and Hydrogen to burn for rocket fuel and more electricity (NASA).

On Earth however, water is even more precious. A vital resource that makes up ~70% of our surface (USGS). And I don't know about you, but personally I don't often find myself delving too deep into the Earth trying to find more... there is more down there, it’s just not very useful to us unless you are a geologist. No, instead we are stuck with what we have on the surface, which in fairness, is still a lot. Even once you google “how much water is there” and click the first (hopefully USGS) link that pops up and you learn that only 0.001% (you can add or remove a 0 or two, doesn’t make a difference) of all our water is freshwater in rivers and lakes, that’s still A LOT of water, not to mention that ALL that salt water will eventually evaporate, rain down, become life, return to the streams, and get salty again as it arrives in the ocean. Part of a natural cycle, one all life on Earth is ultimately bound by. A cycle itself bound by a plethora of other cycles and if I remember there will be an endnote here mostly made up of “things you should google for fun” [4]. Basically, all these cycles have a lot to do with each other, no one exists in a vacuum, though some are a bit more independent than others, and some are certainly a lot more interesting than others. But it’s not like the idea of “some things are cool and some aren’t” is new to anyone, after all, none of the authors of this paper chose to be environmental scientists because we thought that “plants are boring”. If anything, the opposite is true, we are here because the Environmental Sciences embodies many of our favorite things.

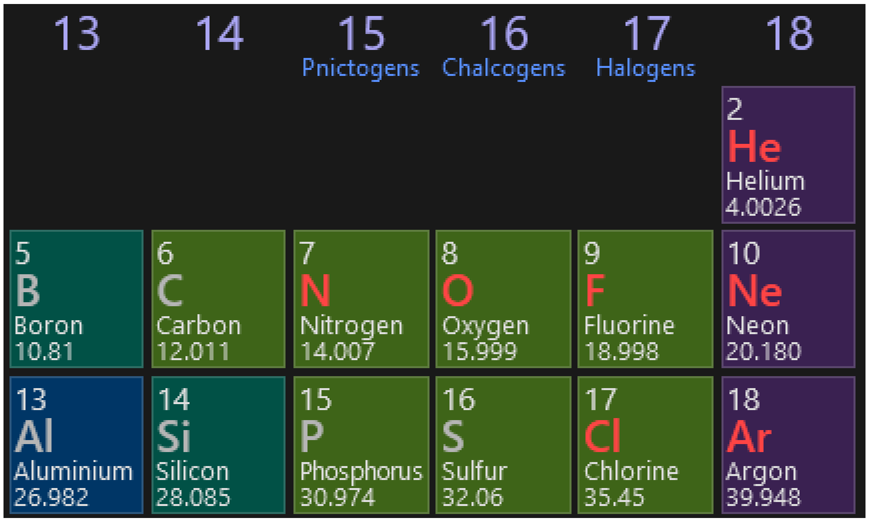
If you’ve ever spent 10 minutes with an 8-year-old kid, you’ve probably been asked about your favorite Dinosaur. Brontosaurus is my answer. “Why” you ask? Thunder-Lizard! You might not have a favorite Dinosaur, although I would hope to be wrong, but you probably have lots of other favorite things. Favorite cookie, drink, flag, color, favorite kid. All reasonable things to have favorites of, right? But what about your favorite element? Most people who aren't either nerdy 8-year-olds or scientists don't really think about “The Elements” in an abstract way often. But I do, and when you ask me my favorite element, Boron, naturally, is the answer. I could go on for ages about the spectacle that is Boron. An element most people have probably never heard of, or consider ‘boring’ simply based on the similarity between the two words. But let me talk about some of the marvels of Boron, about how the modern kitchen & science are built on its use in heat-resistant glass [5], how Boron-Nitride is basically a better version of diamond [6], the fact that fireworks are green because of it, how the Borax in your washroom that gave us Death Valley National Park is the same stuff you used to make Flubber in 3rd grade, and of course, the fact that a lack of Boron is the most common micronutrient deficiency in plants. Now that you’ve let me stand on my 20 Mule Team soapbox [7], let me elaborate on that last point, and a broader idea in general. Why should we even care about the “elements” and especially, any individual element? And what can those elements teach us about our place in the universe?

Probably unsurprisingly, the answer to that is basically everything. Boron, as cool as it is however, does not have as many pressing questions to ask nor vital answers as some of its nearest neighbors on the Periodic Table. If we go but one to the right we meet our good friend Carbon. Carbon is the vast majority of life, or at least it would be if we ignored water (Freitas 1998). Nearly every single molecule in our body consists of several Carbon bonded together in what chemists pretend are long squiggly lines(a footnote about Lewis dot structures, just so that “squiggly lines" makes sense, ‘cause, it's really a visual thing). The same amazing properties that let Carbon take the form of diamonds and graphite also allow us to create fat, muscle, DNA, and so much more. It's this amazing bonding ability that leads Carbon to create complex combinations with Oxygen, Nitrogen, Hydrogen, Sulphur, Calcium, Phosphorus. As we move further to the right, we increase in the violent reactivity of the elements, and yet they remain vital for life. Nitrogen, with its unique attributes forms another backbone of life. Most molecules necessary to life work, ultimately, because of Nitrogen in what we call ‘Amino Acids’. Next to Nitrogen is an element that needs no introduction, Oxygen. Including water, Oxygen is by mass the majority of the human body, and most all living things. Oxygen is 30% of all the mass of the Earth, second only to Iron (at barely more, 32%). Whether you're eating a salad or a hamburger, on a hike in the woods or looking at rocks, the majority of what you're touching is, almost always, Oxygen. Aluminum makes our soda cans and airplanes. Silicon (with Oxygen) is the backbone of most rocks. Sulphur displeases us and warns us of dangers, be them in food or the air around us. And Chlorine is one of our most useful tools for cleaning the world around us, from our countertops to pools, and even some more nefarious uses (NLM).



For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

Figure 1. A “wide” view of a Periodic Table. Usually the Lanthanides and Actinides (Brown and wine-red) are below to save space, rather than this more accurate depiction. Most of our story is in the upper right. The S block consists of the far left (and Helium), the P block consists of the Blue-Cyan-Green and Purple guys, D is the Red and F is the Brown and win-red (see footnote 6.1).



13	14	15 Pnictogens	16 Chalcogens	17 Halogens	18
					2 He Helium 4.0026
5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
13 Al Aluminium 26.982	14 Si Silicon 28.085	15 P Phosphorus 30.974	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.948

Figure 1.1 A more zoomed in view of the rather small area of the Periodic Table we actually care about. The number in the top left of each cell is the “Atomic Number” or another way, how many protons it has. The Number in the bottom left of each cell is the “Atomic Mass” of the element in units Im pretending not to care about. The blueish purple numbers at the top are the column they appear in, and are important for a long winded conversation found in footnote [9.1]. No, I do not know how to pronounce Pnictogens.

But there is one more important element that most people tend to forget about, if most people even know about it. A name we hear less, not because it's so drastically uncommon or useless, but simply because it's less glamorous. One beneath Nitrogen is an element that shares many of the same attributes, but generally more extreme. A greater ability to form bonds but with the same patterns, larger, more violent, and harder to spell. Phosphorous. Deoxyribonucleic acid, DNA, the basic code for all life [8] only works because the active groups are held together by Phosphorus. Phosphorus plays a lot more roles than just keeping the code of life together. ATP, the basic energy source for functionally all life is also based in Phosphorus, quite literally that's what the P means [9]. There are other uses in life for Phosphorus, many, but it's these two, ATP and DNA that make it so necessary. If we do some simple math and assume the average human is ~50% water (more realistic than the 75% we were all told in 3rd grade) then Phosphorus makes up roughly 2% of our dry body mass. That is to say, 2% of the 50% that isn't water. Maybe that's not very impressive to you, but considering that makes it the 6th most abundant, both by mass and number of atoms, I'd say that's pretty impressive. If I got at least 6th place in most competitions I competed in I'd probably be doing something much more fun with my life than writing a paper for Capstone. And that's really just a tiny bit about Phosphorus in Humans, there's plenty more that could, and will, be talked about later by other authors, but for now let's worry about Phosphorus on a grander scale.

To start the Phosphorus cycle I'm gonna lean into the major I should have gone down, and start with what might seem a bit odd of a springboard; Geology. Phosphorus can be found in a plethora of minerals, almost always as the negatively charged molecule [10] Phosphate $(PO_4)^-$ [11]. Many minerals contain Phosphate, but very few different families of minerals contain an appreciable amount of it, and the vast majority of minerals that do are often considered 'Apatites' or at least, Apatite adjacent (Mindat). Just as Similar to how rats and mice are very similar, but still different, yet if we need to talk about them together it's easy, we just call them rodents. This is the same with minerals, nearly all minerals with an important amount of Phosphate can be called some version of Apatite [12]. Now that I've made lots of mineralogists upset [13], it's time to actually introduce the Apatites. Important for us are three varieties that will come up again later: Hydroxyl-, Fluor- (pronounced Floor) and Chlorapatite, the difference between them being whether they have a Hydroxyl ion $(OH)^-$, a Fluorine ion F^-, or a Chlorine ion Cl^-. You've maybe even heard the word Hydroxyapatite before, likely in a dentist's office, and if you see where I'm going with this, yes, your teeth and bones are both mostly made of Hydroxyapatite, and the reason we brush our teeth with Fluoride is to replace the OH with an F, making our teeth stronger (NLM). When I was a young Geology student in Mineralogy class, I was told that if I remember nothing else, it should be that fun fact, and now I pass it on to you. So what do our teeth have to do with rocks? Well, a lot actually, but we'll focus less on the teeth part, and more on the microorganisms part, which yes, still aren't rocks... yet. Phosphorus-rich microorganisms in the ocean die one way or another, maybe they get eaten by a shrimp, which then poops them out, or gets eaten by a fish and so on, until eventually, somehow the Phosphorus rich organism somehow finds its way to the seafloor, where it stays for millions of years. Generally this is happening pretty close to shore, not nearly as much in the open ocean. After millions of years and lots of changes to the planet, namely from our beloved plate tectonics, the Phosphorus that's been deposited on the floor gets smooshed together, and often reacts with ground water to form Phosphate and eventually forms one of the three varieties mentioned above–Fluorapatite from hydrothermal vents, the other two more directly from the organisms themselves. Another few million years may go by and the tiny amounts of Apatite get concentrated in a few bands, some only a few cubic centimeters, some much more massive. These are rarely gem quality apatites; those come from Metamorphic rocks and are even rarer, but they are very important for other reasons [14]. Sometimes these Phosphorus-rich rocks eventually find their way out of the sea and onto land, and once on land can be eroded away, thus the Phosphates flow into the streams and rivers, the sediment they are a part of getting deposited across the landscape by floods, picked up by plants, eaten by animals, pooped out, taken back up by plants, so on so forth and thus it may get carried from a pile of rocks in Morocco [14] to a Zebras carcass in Kenya. Eventually it might return to the sea, to a little plankton, and thus the cycle, ultimately bound by the slow march of geology, continues anew.

At some point, or even a couple different points in this cycle, we humans mine the Phosphorus in one of two forms, either as the masses of Apatite from the Sedimentary rocks, or sometimes so much poop gets massed in one spot that they quite literally create guano deposits, usually in tropical and subtropical islands without substantial rain (Akiboh). We already know how important and how limiting Phosphorus can be, so when our gardens are looking a bit short on that oh so vital element, why not go straight to the largest reservoirs of it? That same Phosphorus that once went from plankton to fish to birds to poop, now gets put into bags of fertilizer and shipped all over the world, often at great detriment to where it came from. After all, ripping up the ground and shipping it across the world doesn't sound too good no matter where in the world it was ripped up from. Nonetheless, this process of exporting Phosphorus feeds huge swaths of the world. And if whatever is grown off that fertilizer ends up getting exported too, there goes that Phosphorus, continuously traveling around the world, getting caught in a plethora of tiny loops and cycles, many of which are quite bad.

But let’s go back to water for a moment. Phosphorus as a tiny little speck of fertilizer is, for simplicity, a tiny rock. Rocks are famous for doing something called weathering, and even if that fertilizer is in the soil, soils love to do something we call eroding. Weathering and eroding are... not very different, for us here at least. Either way, Phosphorus doesn’t usually have too much trouble making its way to the sea or a lake or wherever (USGS). Large wet events, say a massive storm, can help this process along by adding lots of runoff to pick up lots of this Phosphorus rich dirt. Then, once in the body of water, a shortage of water might help increase the concentration of Phosphorus, since water can escape in one way Phosphorus can’t, evaporation. More Phosphorus in an area means more growth and now if the conditions are right, we have just created a massive algae bloom and, here's a $5 word, caused what we call ‘eutrophication’(USGS).

Ever heard of a red tide? Or the Gulf of Mexico Dead Zone? Or seen photos of goopy green Lake Erie, or even a local smelly nasty pond near where you live that didn't used to be so gross when you were a kid? All of that is some sort of Eutrophication event. Occasionally natural, and not always caused by Phosphorus, sometimes other nutrients are the limiting factor, often if it’s not Phosphorus, it's probably the lighter brother, Nitrogen, which is also applied readily as a fertilizer on farms (USGS). See how it’s all connected?

Ok, time to stop burying the lede. The next segment of this paper is about those Phosphorus additions and usage on a farm and shows us how tracking that Phosphorus and drawing conclusions is not always so easy with something as sneaky as soils, as well as the implications that Phosphorus has, both on the farm, and once its lost.

Phosphorus in Montana: Analysis of Phosphorus Accumulation in an Agroecosystem

Jack Allen, Richard Baumgarten, Jack Swanson

Introduction

Phosphorus is an extremely important resource to all living organisms. This essential nutrient is required by all known forms of life, meeting the common need between all organisms to form the phosphodiester backbone of DNA. The leading human use for P is in fertilizer, linking this nutrient to global food security. Unlike other main fertilizer components, nitrogen, P does not involve the atmosphere in its biogeochemical cycle. To meet these fertilizer needs, phosphate rock is extracted from the earth by large scale mining operations. P reserves are not unlimited and predicted peak extraction will be reached in 2033 (Cordell et al. 2009). Unlike renewable energy generation and the Haber process for nitrogen fixation, P has no viable alternative. This extraction has the potential to bring major geopolitical issues in the future, because of the disproportionate concentration of P reserves located in Morocco (Elser et al. 2011, Vaccari et al. 2009). Food is essential for all human life, making P fertilizer directly linked to survival.

The impending shortages and necessity of P for food production, highlight the importance of understanding the P balance on agricultural lands. To assess whether P concentrations are accumulating or decreasing in soil from fertilizer additions, requires a holistic approach, which relies on both biogeochemistry knowledge, and informed management practices. The benefits of creating a P budget, whether it be for profitable crop production or to decrease P pollution into waterways, requires the attention of new minds. Due to concerns for future food security, now more so than ever, it's important to analyze how the possible accumulation or loss of P can provide helpful insights. Leading to the sustainable management for agroecosystems. By looking at data to address P inputs and outputs on a single farm, we can mathematically create a budget. If the change in P is positive, it will indicate that P has been accumulating in the system. Between the essential nature of P to all life and peak P extraction quickly approaching, it is imperative for farmers to manage their phosphorus in all aspects.

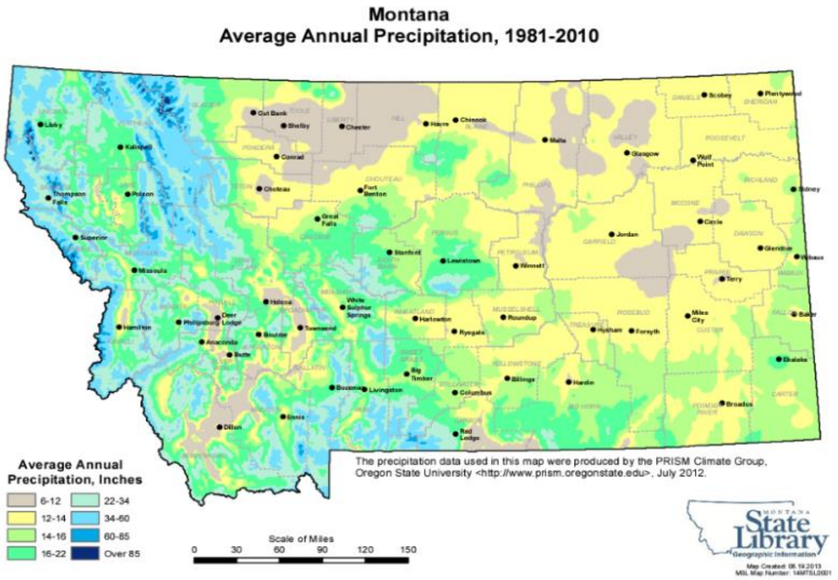
Understanding biogeochemistry is essential to learn from this P issue. Due to the lack of an atmospheric phase, the phosphorus cycle is less complex when compared to nitrogen and carbon in terms of movement. P resides in soil, stored as both organic and inorganic compounds. P generally has low mobility in soil, moving by diffusion of soluble P compounds through soil or by deposition of dust and erosion of soil particles (Metson et al. 2012).

Non-anthropogenic sources of P come from a few main processes, like the dissolution of apatite (phosphate rock) caused by mechanical weathering and mineralization of organic P from decomposition of organic matter. Anthropogenic P comes mainly from the physical mining of apatite and is turned into fertilizer that is applied to the soil as P pentoxide (P2O5). Historically, many organic sources like bones and guano were used to fertilize agricultural fields (Egan et al. 2023). The soils in northern Montana mountains surrounding and in Glacier National Park are associated with calcareous parent material (Bamberg et al. 1968). The relevance of calcareous soils could contribute to P accumulation through sorption and precipitation. In calcareous soils, the Olsen P test is used to quantitatively characterize phosphorus. The chemical absorption of P to metal ions present in the soil is one factor that dictates P movement and availability (Elser et al. 2020). Creating a P budget will enable these processes to be addressed through calculations.

To understand this P balance, a family-owned farm in northern Montana agreed to provide data. The farm, located in Toole County, is situated just south of the Canadian border and east of the town of Sunburst (Figures 1 and 2). Toole county receives between 6 to 20 inches of precipitation per year with southern Toole County receiving significantly less rain than

Figure 1: Location of Nagy Farm in Toole County

Figure 2: Location of Toole County in Montana



The precipitation data used in this map were produced by the PRISM Climate Group, Oregon State University <http://www.prism.oregonstate.edu>, July 2012.

Figure 3: Average Annual Precipitation in Montana

northern Toole County (Figure 3). The large difference in precipitation causes a variety of different agricultural practices to be used between northern and southern Toole.

The Nagy farm is roughly 7,000 acres and grows barley, though many different crops are rotated with barley. The crops grown throughout the provided data include barley, lentils, chickpeas, canola, and spring wheat. No fields are left fallow and are continuously cropped. Continuous cropping and reduced till have been used steadily over the past 15 years and have a great impact on organic matter incorporation into the soil. According to Don Nagy, the historical owner and operator of the farm, continuous cropping and reduced till account for the majority of decreased soil loss due to wind erosion, and increased organic matter incorporation into the soil. In fact, the wind in Toole County is so powerful, that the Glacier Wind Farm, constructed and operated by NaturEner USA in 2009, became Montana’s largest wind energy project at the time, with 100 of the 140 towers located within Toole County (About Toole County, toolecountymt.gov). Seeing how most soil P is unavailable to plants, and is chemically bound to soil surfaces, wind erosion may have driven a large loss of P until continuous cropping and reduced till were in effect.

As soil organic matter increases from continuous cropping and reduced till, so does plant available soil P. This increase mainly occurs through mineralization or by competition with phosphates adsorbed to soil surfaces. Organic matter competes with phosphates by producing protons associated with organic acids that change the pH environment thereby reducing P retention in the soil. This is the same mechanism by which plant symbiosis with arbuscular mycorrhizal fungi is used to increase P uptake (Klugh and Cumming 2007, Klugh-Stewart and Cumming 2009).

Another benefit to these practices is the reduction of saline seep on the land. Saline seep occurs when water percolates through the soil dissolving and picking up salts along the way. If this water then resurfaces at a lower point in the watershed it can leave behind salt on the soil surface. This salt is identified as saline seep and can greatly reduce soil fertility. These salts originate from the lithology in Toole County which mainly consists of marine deposits rich in salts. Continuous cropping is a particularly effective method by which to reduce saline seeps. By having more living plants in the soil year-round, less water percolates below the root zone thereby decreasing saline seep.

Soils in Toole County are generally silty clay loams with 2% organic matter (Toole County NRCS 2019). Soils at the Nagy farm fit this classification and feature calcareous Bk horizons (NRCS Web Soil Survey). These Bk horizons indicate the buildup of carbonates which originate from the calcium-carbonate-rich marine deposits. In calcareous soils, P retention and immobilization take place due to aforesaid precipitation and adsorption with carbonates in the Bk horizons. While these soils may be prone to saline seep and are highly erodible due to wind, management practice by the Nagy farm overcomes these problems. Understanding how P is accumulating or diminishing within this system will provide useful insights into phosphorus cycling and its movement in the soil.

Methods

To evaluate the accumulation or loss of P on the Nagy Farm, finding the overall delta P per year is needed. Don Nagy's personal records contained fertilizer rates, crop yields, as well as soil samples. By subtracting the amount of P the crops stored in the yields from the P added by fertilizer, delta P can be calculated. The soil tests are conducted by AGVISE Laboratories through the collection of multiple soil cores per field. The cores are collected to a depth of 24 inches and then averaged so that each nutrient has one value for each tract. These soil tests are used to evaluate soil nutrients, one of the nutrients being P through an Olsen P test which shows the plant available P present in the soil. Comparing Olsen P and delta P year over year allows for the observation of the relationship between available P and delta P in the soil. P_2O_5 is used in our calculations because it is the form of P found in fertilizers and crops. Due to inconsistent testing of the soils, Olsen P is unavailable across all five years for certain tracts, therefore, only tracts with three or more soil samples over the five years were used. Once the calculations were completed, Excel was used to visualize the relationship between Olsen P and delta P (ppm).

<u>Calculations:</u>

Calculating the weight of P_2O_5 added from fertilizer per acre was completed by multiplying the ratio of P_2O_5 by the weight of fertilizer added (Eq. 1).

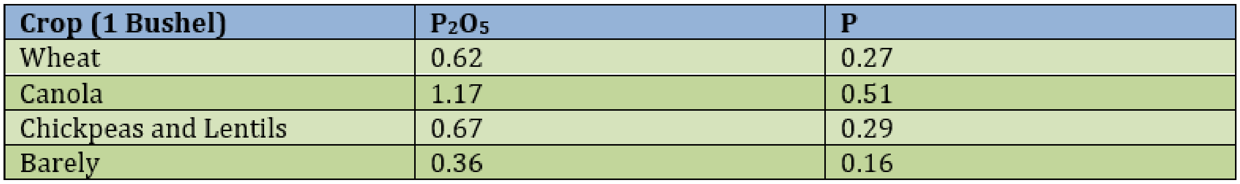
Fertilizer Ratio * Weight of Fertilizer (lbs) = P_2O_5 applied (lbs).

Once the weight of P_2O_5 was calculated it was multiplied by the percent mass of P in P_2O_5 (0.4364 %) to find the weight of P applied per acre (Eq. 2).

P_2O_5 applied (lbs) * Percent P in P_2O_5 (0.44) = P added (lbs)

The weight of P applied per acre could then be converted to parts per million (ppm) through a conversion factor of 0.5. The same process was applied to calculate weight of P removed by plant uptake; the yield per crop was multiplied by the crop's percent P_2O_5 and subsequently by percent phosphorus (Eq. 3). Crop percent P_2O_5 can be seen in Table 1.

Table 1: Values of P available in one bushel of each crop in the form of phosphorus pentoxide and in phosphorus.



Crop (1 Bushel)	P_2O_5	P
Wheat	0.62	0.27
Canola	1.17	0.51
Chickpeas and Lentils	0.67	0.29
Barely	0.36	0.16

Total bushels per acre * Percent P in each bushel = P removed (lbs)

Finally, the change in phosphorus was calculated by subtracting phosphorus outputs from inputs, then multiplying by 0.5 to get ppm (Eq. 4).

P added - P removed = ΔP * 0.5 = ΔP ppm

Results

Over the 5 year time frame 69.7 tons of P were added while 90.5 tons of P were removed across the 7000 acre farm. This is equal to 21.94 pounds per acre were added while 28.50 pounds per acre were removed across the farm, which is a loss of 6.56 pounds an acre for the five years or a removal of 1.31 pounds an acre each year.

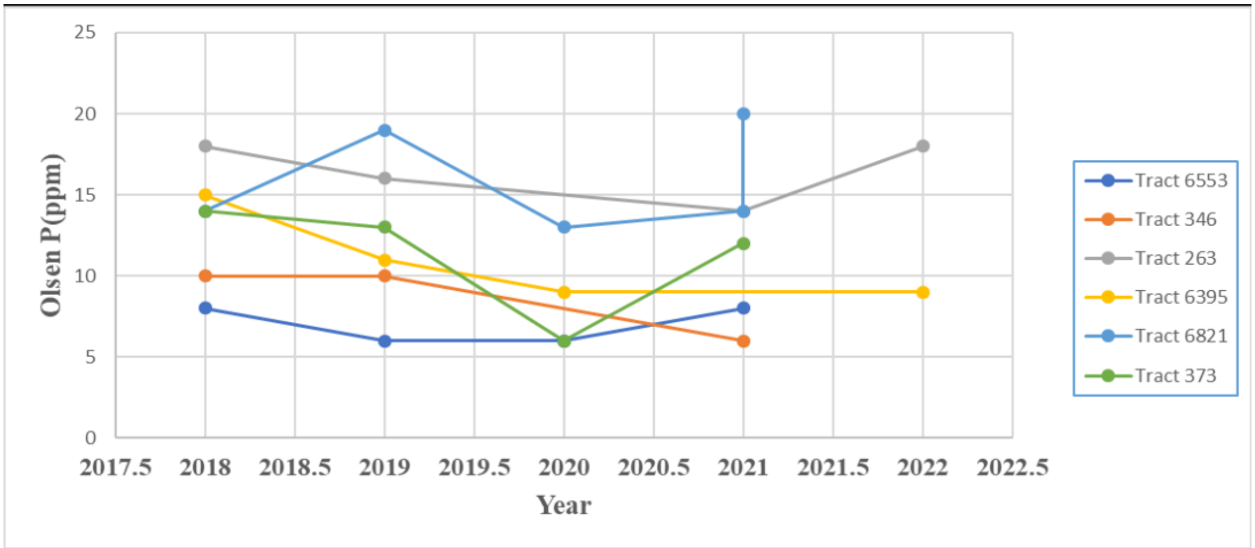


Figure 4: Change in Olsen P per year over 5 years

Figure 4 shows Olsen P (y-axis) over the 5 years (x-axis) separated by tract. For the majority of tracts, Olsen P did not change greatly when looking over all years. Tracts 6395 and 346 were the only tracts which experienced a noticeable decrease in Olsen P. Although the majority of tracts showed no increase or decrease over 5 years, there is noticeable change between years. For example, Olsen P in tract 6821 between 2019 and 2020 dropped more than 5 ppm. Tract 6821 also has two data points for the year 2022 due to there having been two separate soil tests for that tract. The heterogeneous nature of soils shows the difficulty of accurately finding the nutrient levels in tracts of this scale.

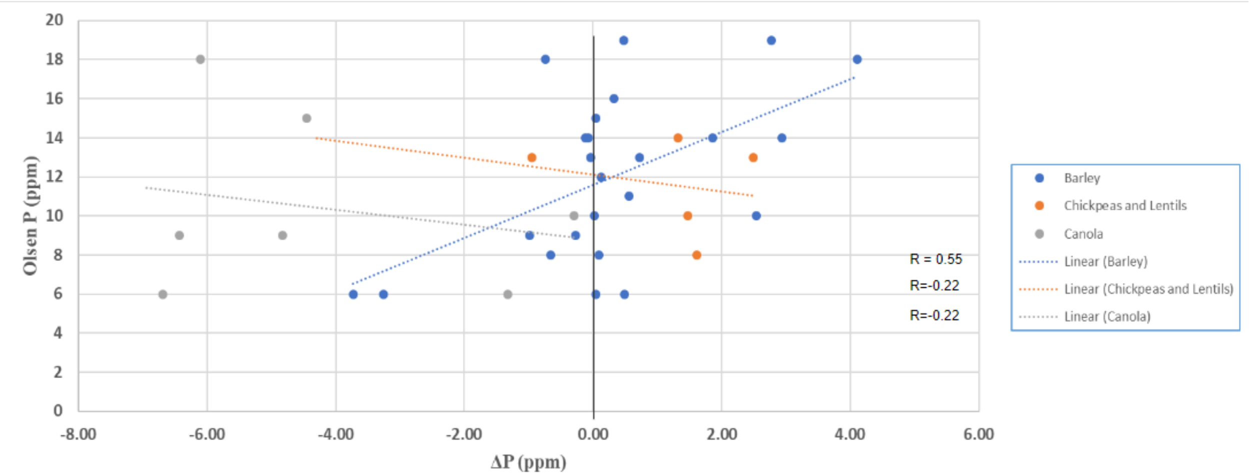


Figure 5: Overall change in Phosphorus vs Olsen P for all tracks and crops.

Figure 5 depicts the relationship between Olsen P and ΔP by crop where the x-axis represents change in P in ppm and the y-axis is Olsen P in ppm. Olsen P represents available P in the soil which is only a fraction of the total soil P. For chickpeas, lentils, and canola available P increases when you remove more than is applied. The trend is opposite for barley. Barley's trendline shows a positive slope, indicating that as change in P becomes positive, the plant available P increases as well. The R value for Barley is 0.55 which indicates that there is a strong positive correlation between change in P and Olsen P, whereas the canola, chickpeas, and lentils all share the same R value of -0.22. An R value of -0.22 shows poor negative correlation between change in P and Olsen P. The fact that Olsen P is lower when harvests are large, is supported by similar findings across Montana soils, with 20 years of fertilization and cropping data (Jones et al. 2002)

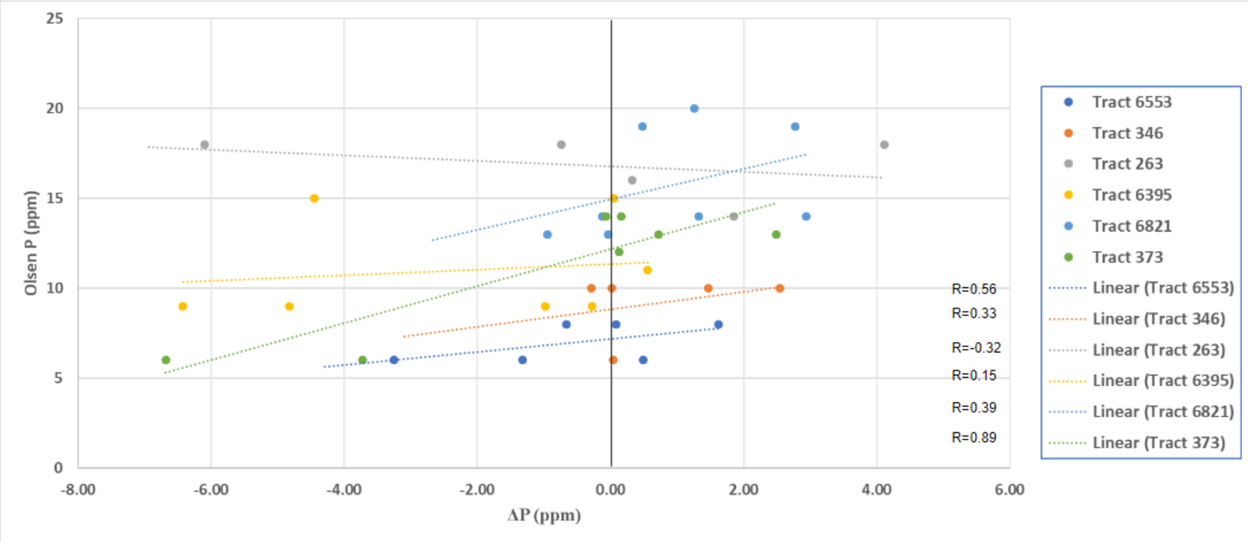


Figure 6: Overall Change in Phosphorus vs Olsen P by Tract

Figure 6 is another iteration of the figure 3 but is separated by tract. All tracts, except for tract 263, demonstrate a positive relationship between Olsen P and delta P. Tract 373 shows the strongest correlation with an R value of 0.89 and the tract with the weakest correlation is tract 6395 with a R value of 0.15. This shows that for some tracts a change in P affects Olsen P while for others the change in P has little effect on Olsen P. The rest of the tracts vary between R values of 0.56 and 0.32 that show moderately strong to moderately weak correlations. Tract 263 is the only tract with a negative correlation.

Discussion

Now let's discuss the exciting possibilities of what is happening to the P in this budget. The data collected from Don's farm was used for comparison of phosphorus inputs and outputs, to plant available P. Based on Figure 2, P is not accumulating in the soil due to fertilizer additions, meaning on average fields are losing phosphorus. Reduced till and continuous cropping practices are not adding the extra phosphorus observed in the budget but could be involved. These practices have the ability to contribute to the remobilization of built-up P that was chemically tied up in the soil. In terms of sustainable farming in an agroecosystem and the world's P extraction, this is beneficial.

In Montana, although soils are highly erodible soils and are calcareous in nature, they are generally not P deficient, but the P is not plant available. P already present in the soil, will slowly sorb to bicarbonate, chlorine, ammonium, and goethite by ion exchange which can decrease available P (Delgado et al. 2000). The reincorporation and buildup of organic matter through reduced till and continuous cropping can produce acids that aid in the desorption of phosphates from calcium carbonate (HCO_3). The same organic matter also competes with sorbed phosphorus, decreasing phosphorus retention to soil surfaces. Releasing P bound to the soil makes it available for uptake by plants or microbes.

Biogeochemistry combined with the calculated change in P, lead to the prediction that P already present in the soil is being accessed and alleviating the difference between inputs and outputs. The fluctuations observed in Olsen P, but overall minimal net change support the fact that plant available P is not changing due to the change in P. In addition to P fertilizer, nitrogen is also being applied on the farm. A result of nitrogen fertilization in agriculture is soil acidification. Due to the calcareous aspect and basic pH, the soils present in this region of Montana, calcium bound P becomes more available as the pH approaches neutral. Another reason for the increase in plant available P is the crop rotation between barley, canola, and chickpeas/lentils. The roots of these legumes could have the ability to release anions, acids and enzymes like ATPase and acid phosphatase that are capable of chemically interacting in the rhizosphere of soil to free up plant unavailable P (Vance et al. 2003).

The ability to draw conclusions from this study on P present in the soil was limited by the data and testing. The soil tests only consisted of one soil test per field, introducing possible room for inaccuracy. To improve the study for the future, soil test quantity per field should increase to accurately characterize the soil. This is especially important when looking at such a large scale and heterogeneous area. Information obtained from the soil tests posed limitations in terms of understanding total P in the soil as Olsen P was the only test obtained. Therefore, our ability to analyze the fate of soil P was limited to characterizing what is happening to the plant available P. Looking to the future of both P and agriculture practices on the Nagy farm, there is one major concern. P mining is only feasible for so long, eventually the P present in the soil will be depleted. In response, fertilizer additions must increase to make ends meet. This problem will only be exacerbated by population growth stressing food security.

Conclusion

The goal of this study was to gain a deeper understanding of phosphorus in the environment. This was achieved by analyzing the inputs and outputs of P in a northern Montana agroecosystem. As fertilizer is applied and crops are harvested, P pools in the soil fluctuate. These fluctuations show that plant available P remain the same over time while other forms of P in the ground are slowly shrinking to compensate for that which is removed through the crops. Overall, educated agricultural practices over the past 15 years have likely limited the waste of phosphorus on this northern Montana farm. Informed agricultural practices are beneficial for resource pollution and pollution reduction.

From Toole County to The World

Santo Mallon

There’s lots of places around the world that are short on Phosphorus, but there's one place in particular that is famous for its lack of Phosphorus, just in a more abstract way. The harsh and difficult reality created by a lack of Phosphorus is not unique in the Sunburnt Land, where every animal seems to want to kill you, and the most famous export is a man named Steve Irwin. I am of course talking about The Land Down Under, otherwise known as Australia. And the stories this ancient continent can teach us about Phosphorus, its limitations, and how it impacts the people who live on its soil are important to our broader understanding of what it means to be sustainable, and how we might be able to solve some of our biggest challenges, not just with Phosphorus, but other pollutants, and even some humanitarian problems as well.

Phosphorus: The Broken Loop

Bryce Pease, Sophia Moreno, Rebecca Pyles

Introduction

Globally available phosphorus resources are being exhausted rapidly while simultaneously, excess phosphorus is causing eutrophication of freshwater bodies across every continent. Mined phosphorus fertilizers underpin food security and are heavily relied upon to support the burgeoning human population. Preceding contemporary methods for phosphate rock extraction is a long history of humanity seizing every last substantial source of natural phosphorus, from bones to bird guano, and finally to the current source: phosphate rock deposits.

Plants, People, and Phosphorus:
What We Can Learn from Australia's *Banksia*

Bryce Pease

Australian Beginnings

With the American Declaration of Independence in 1776, England had a problem; after years of shipping convicts–mostly small debtors and petty thieves–to the American colonies to relieve English prisons, there was now no colony to take them (Gonner 1888). And prisons were filling up, fast. The English decided to start a new colony for their convicts on the newly claimed southeastern coast of Australia. In 1788, a fleet of ten English ships arrived at Botany Bay in New South Wales carrying 850 convicts and the soldiers to guard them. The land they encountered beyond the blue water and beaches was a mixture of open forest and woody scrubland marked by a blisteringly hot climate and inhabited by unfamiliar plants. After months of disease, death, and food rationing on their ships, the land was not what they had expected from prior reports.

Ten years before, Captain James Cook had led the first European exploratory voyage along the Australian coast. The *Endeavor*'s crew spent eight days in the fall of 1770 exploring Botany Bay, gathering supplies, and unsuccessfully trying to make contact with the people living there. The ship's naturalist, Daniel Solander, and fellow naturalist and benefactor, Joseph Banks, collected and described 132 new plant species which led to Cook naming the area Botany Bay (Cook 1893, Benson and Eldershaw 2007). Cook made multiple trips inland with Solander, Banks, and others, where he described a flat, barren landscape broken only by bogs and marshes where streams ran down to the bay. The soil was a light white sand supporting bunchgrasses, shrubs, eucalyptus, palms, and mangroves (Cook 1893). Cook also noted "in many places a deep black soil" in meadows which he thought were capable of agriculture (Cook 1893). A few years after the *Endeavor*'s return to England, Joseph Banks was called to Parliament to speak on Botany Bay's fitness for colonization. Banks successfully advocated for Botany Bay as the site for the new penal colony over west Africa, describing a favorable soil and climate "where a colony would readily become self-supporting" (Gonner 1888).

However, when the English colonists arrived in the bay in 1788, they found the area inhospitable. One of the Englishmen on board remarked, "The fine meadows talked of in Captain

Cook's voyage I could never see, though I took some pains to find them out" (King 1982, as cited in Benson and Eldershaw 2007). Banks likely over-exaggerated the fertility of the land at Botany Bay, which both he and Cook described in their journals as sandy, in his eagerness to establish it as a colony site (Benson and Eldershaw 2007). Most of the dark, fertile soil Cook found on the *Endeavor* trip was in deep marshes and draining them for agriculture would have taken too much time and labor (Benson and Eldershaw 2007). The English decided instead to sail north to Port Jackson Bay, where Sydney is today, and began clearing trees and rocks for planting wheat, oats, potatoes, cabbages, turnips, and other European staples (Newling 2021).

What followed there were years of famine called "the hungry years" as the colonists struggled to adapt to a new land with old agricultural techniques and with a labor force of convicts and soldiers poorly prepared–and motivated–to be farmers (Davey et al. 1945). Seeds that hadn't rotted on the voyage did so in the ground (Newling 2021). The weather oscillated between extreme rain and drought (Damodaran et al. 2018). The convicts were "pale with disease and wasted with famine" (Tench 1795) and, as unwilling settlers, viewed farm work more as a punishment than as an opportunity to build a new life (Davey et al. 1945). A food supply ship from England sinking while en route to the colony further reduced settlers' weekly rations (Newling 2021).

In addition to the main government farm, all colonists were encouraged to establish personal gardens to help feed themselves. However, as one of the colonists complained, "nothing seems to flourish vigorously long… [crops] shoot up suddenly after being put in the Ground, look green & luxuriant for a little Time, blossom early, fructify slowly & weakly, and ripen before they come to their proper Size. Indeed, many of the Plants wither long ere they arrive at these Periods of Growth" (Newling 2021). Many resorted to sneaking into gardens and fields at night to steal food (Tench 1795). The poor crop growth was blamed on the infertile soil, and the government farm was abandoned for the more successful and further-inland Rose Hill Farm just two years after landfall (Newling 2021).

The Australian soils the colonists were trying to cultivate were incredibly nutrient-poor, and low in one nutrient in particular: phosphorus (Viscarra Rossel and Bui 2016). Phosphorus is one of the two most important plant nutrients, the other being nitrogen. In natural ecosystems it originates from one source: the chemical weathering of rocks. Rocks close to the surface break down and release phosphorus slowly over time, and when phosphorus is washed into streams and eventually the ocean by rain, it can only be replaced by more chemical weathering of rocks, or by small amounts of phosphorus blown into the area as dust (Vitousek et al. 2010). As soils age without renewal, phosphorus is inevitably depleted from the exposed rock surfaces and the nutrient becomes increasingly scarce (Vitousek et al. 2010). Australia has the oldest soil of any continent, and therefore some of the most phosphorus-poor on the planet. Unlike other continents that formed at the same time, little of the Australian crust that split off of the supercontinent Gondwana 100 million years ago has been disturbed by volcanic activity, formation of mountain ranges, or glacial scraping of soil to expose new rock, providing few new sources of phosphorus (Huston et al. 2012). Only the southeast coast of Australia where the settlers landed has young mountains, a history of glaciation, and some of the most fertile land on the continent (Colhoun & Barrows 2011, Viscarra Rossel and Bui 2016).

Indeed, the settlers soon found their feet and produced some of their first successful crops at Rose Hill Farm in 1791 (Newling 2021). Still, the years of starvation became ingrained in the Australian ethos. One historian concluded that the first five years of famine the settlers faced on their new continent led to an attitude of viewing the land as an enemy which had to be subdued, “from whom a living must be wrung with sweat and tears” (Davey et al. 1945). Moving into the 1800s, Australians found that they continued to need supplements not of food, but of fertilizer, to survive.

Phosphorus Adaptations

As the Australian colonizers struggled to grow European crops on their new continent, they had a lot to learn from the original colonizers of the land–not just from the Aboriginal people of Australia who arrived 50,000 years prior and whom the colonizers scorned “as people who ‘barely existed’ on [the] hostile soil,” but from the native plants that had adapted to phosphorus-poor soils over hundreds of millions of years (Davey et al. 1945). In fact, the infertile and sandy scrubland that the English had left behind at Botany Bay was dominated by Banksia trees belonging to one of the most phosphorus-adapted plant families in the world.

The plant family Proteaceae is distributed throughout the southern hemisphere but most abundantly in Australia and southern Africa (“Proteaceae” 2020). The family is named after the Greek god Proteus, who could shift form, appropriate for the incredibly diverse shrubs, trees, and forbs that span 80 genera and almost 2,000 species (“Proteaceae” 2020). The Banksia trees of

Botany Bay are one of the most emblematic members of Proteaceae in Australia. They have thick, waxy, evergreen "sclerophyll" leaves, and their vivid, yellow-to-orange, tubular flowers are distinctive for being densely packed in large compound cones, similar to the sunflowers or coneflowers of North America.

Proteaceae members can thrive with phosphorus levels ten times lower than optimal, such a small amount that other plants go into phosphorus starvation (Lambers et al. 2015). Banksia are so well-adapted to this nutritional deficit that they have lost the ability to slow or regulate their phosphorus uptake. Even small amounts of added phosphorus in fertilizer can be deadly, with phosphorus building up in leaf cells in such high concentrations that it acts as a toxin [17] (Hawkins et al. 2008). On the other hand, Banksia are extremely efficient with the limited phosphorus they *do* have. Members of Proteaceae like Banksia and harsh hakea (*Hakea prostrata)* have the lowest recorded leaf concentrations of phosphorus in the world (Lambers et al. 2015). Within plants, phosphorus is used primarily in ATP molecules that help cells generate energy, phospholipids that make up cell membranes, and rRNA in ribosomes that build the proteins needed for new stems and leaves (Veneklaas et al. 2012). There isn't one adaptation that allows these plants to succeed so spectacularly, but instead an entire physiology and physiognomy built to efficiently extract phosphorus, to carefully reuse what they have, and to reduce what they need in the first place.

First, Banksia have to extract phosphorus from the soil, not all of which is plant available. Specialized proteoid roots help. Proteoid roots look like shaggy, overgrown pipe cleaners, with thousands of tiny rootlets and root hairs clustered around the roots to form a thick fuzz. Unlike nitrogen, which is very mobile and travels to roots, phosphorus stays in place; most phosphorus in soil is tightly chemically bound, or "sorbed," to the soil's smallest clay and silt particles–up to 50% of the phosphorus farmers apply to their fields is locked up this way (Hasan et al. 2016). The rootlets act to physically seek out phosphorus in the smallest cracks between soil particles and to release phosphorus from soil surfaces by exuding concentrated bursts of chemicals called carboxylates and phosphatases (Lambers et al. 2015). All plant roots release exudates, but the increased surface area of the Proteoid root hairs and the concentrated burst of chemicals in a small area make them much more effective at phosphorus uptake (Dinkelaker et al. 1995).

rRNA makes up 30% of the phosphorus in plant leaves. There is both cytosolic rRNA, found free-floating in plant cells which help the plant grow, and plastid rRNA, found in chloroplasts which give plants their green color and help them photosynthesize (Lambers et al. 2015). Normally, when plants experience phosphorus starvation, they will strip phosphorus from mature leaves to maintain high levels of rRNA in new leaves, killing the old leaves in the process (Lambers et al. 2015). Instead, Banksia uses an adaptation known as delayed greening. Banksia leaves grow red instead of green, normally a sign of phosphorus starvation, because they don't invest any phosphorus in creating chloroplasts until the leaf is mature. As the leaves reach maturity, the plant pulls the phosphorus from cytosolic rRNA and puts it into building chloroplasts. The leaf turns green and starts producing food for the plant. The plant reduces how much phosphorus it needs at any point by splitting its use of phosphorus temporally. Even during "delayed greening" Banksia has low levels of cytosolic rRNA compared to other plants, constraining how fast the leaf can grow. In the long run, delayed photosynthesis and slowed growth aren't detrimental to Banksia because it allows them to create a niche in low-phosphorus conditions where other plants can't survive.

Other than delayed greening, there is in general much less protein–which requires phosphorus–in Banksia leaves (Lambers et al. 2015). Banksia replaces the phosphorus-rich phospholipids making up its cell membranes with similar compounds made with sulfur and sugar, called sulpholipids and galactolipids (Lambers et al. 2015). Their leaves live for much longer, reducing the amount of phosphorus needed to grow new leaves and the loss of phosphorus when leaves die (Lambers et al. 2015).

A lot of internal phosphorus efficiency can be attributed to the increased mobility of phosphorus within Banksia. Harsh hakea (*Hakea prostrata)*, a relative of Banksia, can recycle 90% of the phosphorus from their dying leaves with the help of phosphorus transporters (Lambers et al. 2015). Phosphorus transporters are proteins embedded in cell membranes that help move phosphorus in and out of the cell (Schroeder et al. 2013). Banksia have more phosphorus transporters, creating a transportation system that allows the plant to move phosphorus where it's most needed very quickly (Schroeder et al. 2013). Banksia also keep cell membranes functioning for longer than other plants as leaves die, giving more time for transporter proteins to pull phosphorus and other nutrients out of cells for reuse (Lambers et al. 2015).

These are maybe half of Banksia's low-phosphorus adaptations. Many of them are normally stress responses to phosphorus starvation, just turned into life-long adaptations that allow the plant to prepare for, rather than react to, adversity. Each adaptation required complex genetic mutations of normal plant processes as Australia’s soils aged and lost their original phosphorus over millions of years; Banksia and Australia evolved together. Banksia species replace phosphorus with other elements, work hard to prevent losing phosphorus they have, and carefully ration it over time. While some of the strategies Banksia use are found in other plant species, no other plant family approaches their extreme specialization. For example, proteoid roots which were once thought to occur only in Proteaceae have been found in the pea, birch, she-oak, oleaster, and fig families (Skene 2002). Eucalyptus trees, another emblematic Australian plant, transport phosphorus within their trunks and leaves and replace phosphorus in cell membranes similarly to Banskia (Silva et al. 2022) [16].

While Australian plants worked to efficiently extract, retain, and recycle the phosphorus already available to them, Australian settlers in the 1800s turned primarily to Banksia’s strategy of extraction – but through slash, burn, deplete, and abandon agriculture rather than proteoid roots. A ‘frontier farming mentality’ prevailed among farmers. The Australian government was selling land at the frontier at such low prices that it was cheaper for farmers to work their land until its soil was exhausted–then abandon it for new, unbroken sod a few miles inland (Byerlee 2021). Fertilizing and preserving soil was an unutilized practice, partly because fertilizers were so much more expensive than land. Between 1860 and 1880, planted wheat acreage increased from 274,000 to two million acres, and farmers pushed into the drier and less fertile land found in the center of the continent (Smith 1988). Simultaneously, from 1850 to 1880, wheat production in Australia dropped from 1.1 to 0.4 tons per hectare on average (Byerlee 2021).

The Australian government, concerned about the declining quality of wheat yields, hired Englishman John Custance to start the country’s first agricultural college. He would be fired five years into his tenure after a misunderstanding with the Secretary of the Australian Lands Department, but before then he would revolutionize Australian farming as its first advocate for phosphorus fertilizer (Adelaide Special Collections [ASC] n.d.; Smith 1988). An English agricultural scientist and professor who had taught in both England and Tokyo, John Custance worked tirelessly in service of farmers and his students (ASC n.d.). In the four years before Roseworthy Agricultural College accepted its first students in 1885, John Custance set up rigorous crop breeding and fertilizing experiments on depleted, 25-year-old farmland purchased for the college’s experimental farm. He cultivated 180 wheat varieties from around the world with 157 different fertilizer treatments (ASC n.d.), including combinations of salt, gypsum, ashes, lime, manure, Peruvian guano, bone dust, and superphosphate, an “artificial” fertilizer produced from phosphorus-rich rock mined from islands in the Indian Ocean (Smith 1988). Custance found that out of all the fertilizers he tried, superphosphate improved yields the most significantly; he subsequently became Australia’s “superphosphate evangelist” spreading the word of superphosphate to Australia’s farming communities (Smith 1988).

While superphosphate had existed for 40 years before Custance started his experiments, the low cost of buying new lands and the “firmly held belief” that unused soils were better than fertilized ones meant that farmers had been reluctant to adopt fertilizers (Henzell 2007). Even with farmers’ initial reticence, the advocacy of Custance, his contemporaries, and a burgeoning phosphorus industry made Australia a quick and early adopter of superphosphate. Traveling salesmen representing phosphorus companies would demonstrate the effects of “Super” on farmers’ fields for no charge if their yields did not double (Byerlee 2021). In 1910, superphosphate was applied to 80% of farmed acreage in Australia, up from 27% just twelve years earlier (Byerlee 2021). While superphosphate had been applied to fields in Kansas in the United States at the time, it would not become widely used until the 1940s (Byerlee 2021). Prior to World War I, Australia used more phosphorus fertilizer than any other land-abundant country (Byerlee 2021).

While the immediate phosphorus problem had been solved by superphosphates, later advances in “ley” cropping strategies helped retain nutrients in topsoil (Smith 1988). Ley farming uses nitrogen-fixing clover as a cover crop to let soil nutrients recover between years of producing wheat, instead of letting soils “fallow,” or remain bare (Smith 1988). Soil acidification from fertilizer use and resulting metal toxicity became a major problem in the 1900s. Lime, powdered limestone rock, is commonly spread on fields to correct soil acidity. As the soil’s pH (a measure of acidity) is restored with the application of lime, metals are locked back up to soil particles and are no longer toxic to plants. One Australian government researcher in 1988 predicted that if the cost of lime could be lowered and supplies distributed, “the last great problem of sustainable agriculture would start to be overcome” (Smith 1988). Ever since the settlement of New South Wales by the English convicts, Australian farmers have sought for a “permanent agriculture” where farming is perpetually sustainable without reliance on English supply ships or, later, food imports.

However, Australian agriculture still relies on phosphate rock imported from finite, and dwindling, global supplies. Dana Cordell, an Australian graduate student from the University of Sydney, was the first to call the alarm on rapidly dwindling phosphorus resources (Elser and Haygarth 2021). Realizing that there was no information available on global phosphorus reserves, she started her graduate degree to address her curiosity. What she found was that we are rapidly approaching the point of "peak phosphorus," estimated by Cordell to be before 2035, at which our demand for phosphorus will exceed our supply in minable phosphorus reserves (Cordell 2009). In 2008, phosphate prices spiked more than 800% globally due to the recession, Chinese export taxes on phosphate rock, and shifts towards eating more meat and growing corn for biofuel which increased both crop production and fertilizer demands (Brownlie et al. 2023). The combination of Dana and other scientists' scholarship and the 2008 phosphate price spikes woke the world to our phosphorus vulnerability (Elser and Haygarth 2021). In 2021, phosphate prices spiked again, this time affected by COVID shutdowns in China and extreme weather events in the US which halted mining, soaring energy prices increasing transportation and production costs, rising fertilizer demand due to US grain subsidies and agricultural growth in South Asia and Latin America, and international trade sanctions from the Russian invasion of Ukraine (Brownlie et al. 2023). What was an unknown and invisible problem less than 20 years ago is now gaining traction, with people attempting to find solutions and raise awareness from many angles. One of those angles is working towards using less phosphorus fertilizers by improving the phosphorus efficiency of our crops.

Lessons for the Future

True sustainable agriculture balances the phosphorus applied on fields with the phosphorus removed in harvested crops and washed away by rain. In some parts of human history, phosphorus sustainability was achieved through the careful collection of human sewage and animal manure to be spread on fields, recapturing the phosphorus lost when crops were harvested for food. Nothing was wasted. It was a system similar to Banksia's, with intricate cultural and agricultural practices in place to retain phosphorus and reduce what was needed. Today, rising fertilizer costs, limited phosphate rock reserves, and the role of fertilizer runoff in creating algal blooms in our waterways make it more important than ever to find solutions for permanent agriculture. In our modern world, maybe what we need is to learn how to be more like Banksia.

Today, researchers are learning how they can improve the phosphorus efficiency of crops using some of Banksia's strategies. Phosphorus use efficiency (PUE) is a combination of a plant's ability to 1) uptake phosphorus in the soil and 2) efficiently use it in their leaves, stems, and roots (Rose et al. 2012, Hasan et al. 2016). Another way to improve PUE is looking at how much phosphorus is invested by plants into growing fruits, grains, and vegetables versus growing their stems and roots, which aren't harvested. If plants use a lot of phosphorus to grow the parts of plants we use as food, phosphorus is lost when we transport food to our grocery stores (Veneklaas et al. 2012). Separating PUE conceptually into phosphorus uptake, use, and removal during harvest helps us understand the impacts on farmers' fields and decide the best ways to breed new crops. For example, increasing phosphorus *uptake* may improve crop growth temporarily, but it will also remove phosphorus more quickly and make farmers need to apply more fertilizer (Veneklaas et al. 2012, Rose and Wissuwa 2012). Instead, we should focus on creating new crops that use less phosphorus by using it more efficiently (Neto et al. 2016).

Banksia is evolutionarily adapted to thriving with low amounts of phosphorus through evolutionary trial and error spread over millions of years. It's going to take some work to move our modern crops to the same point through *human* trial and error so we can use less phosphorus fertilizer in agriculture. Unfortunately, there is a genetic "glass ceiling" that stops us from improving crops to the level of Banksia because we can't select for plant genes that aren't there–or just locked away–without genetic modification, a controversial practice. But, fortunately, we have Banksia as a model for study, helping us find genes and traits that might otherwise have been unknown as possibilities. We can learn similarly from crop varieties that have already-existing PUE adaptations. Researchers have already started looking for these well-adapted crops and have found high-PUE varieties of coffee (Neto et al. 2016), potatoes (Chea et al. 2021), and wheat (Osbourne and Rengel 2002). Most of our crops are also annuals that farmers have to replant every year, and researchers are working on engineering perennial versions of crops that can retain phosphorus from year to year (Crews and Brookes 2014). Crops that stay alive throughout the year can hold soil in place with their roots, preventing soil erosion and fertilizer runoff that create phosphorus pollution in our streams (Crews and Brookes 2014). They also rely more on slow-releasing phosphorus bound up in decaying organic matter, so require less fertilizer (Crews and Brookes 2014).

An even more promising approach, because it is one immediately within our grasp, is using other plants and microorganisms to help crops access phosphorus. Covering crop seeds before planting with spores of mycorrhizae, specialized fungi that attach to plant roots, can help increase phosphorus uptake (Hasan et al. 2016). Most plants can form symbioses with these mycorrhizae, which give plants nutrients in exchange for energy. Mycorrhizae acquire phosphorus for plants similarly to how Banksia trees do with their proteoid roots–by exuding chemicals that convert phosphorus to usable forms (Hasan et al. 2016). Similarly, some members of the pea family, like white lupin, have proteoid-like roots. Planting white lupin along with other crop species allows the white lupin to free up nutrients in the soil that the other crop can use (Hasan et al. 2016).

We might not *want* our crops to be as efficient as Banksia. Another problem researchers are running into is the usefulness of low-phosphorus traits outside of low-phosphorus ecosystems like Australia. Plants have different strategies for growth, often dictated by the resources available to them. Plants like Banksia grow slowly, deliberately. Every molecule of phosphorus–or nitrogen, carbon, potassium, or water–is used as efficiently as possible to increase survival. On the other end of the spectrum, where resources are available in excess, plants grow wildly. If they don't, other plants will beat them to resources and crowd them out, leading to stunted growth or death. Think of annual plants that only live for one growing season–there isn't as much incentive in using phosphorus carefully as in growing quickly and releasing seeds before winter cold kills the plant. Plants make trade-offs with the resources they have, investing in traits that help them survive. Banksia survive in Australia by growing slowly and living in areas that other plants can't, and so isn't suited for the rapid growth needed for agriculture. Not all Banksia traits will be useful to us as we transition to phosphorus-sustainable crops. But there's still a lot we can learn, and not just in improving our crops.

Fundamentally, human societies and plants like Banksia all operate under the same basic rules of economics, and ecologists study these trade-offs using human economic tools like cost-benefit analyses and phosphorus budgets (Lerdau et al. 2023). With delayed greening, rapid growth is too phosphorus-expensive to be a viable strategy. With proteoid roots, Banksia invest large amounts of carbon to produce the chemicals that they need to release bound-up phosphorus in the soil. Similarly, humans have been faced with trade-offs and decisions on how to feed themselves and survive economically. Australians did not have the energy or resources needed to transfer from a system of treating land as disposable and later, relying on imported superphosphates to maintain agriculture. Our human society has shifted into an era of rapid growth facilitated by phosphorus and reliance on the food security it provides. Already, increasing fertilizer prices have made it so farmers in poorer countries can't afford fertilizers for their crops and increasingly face food insecurity (Brownlie et al. 2023). Our challenge is to find ways to return towards sustainable growth and phosphorus cycles before we hit peak phosphorus.

Conclusion

We have broken a phosphorus cycle that has existed for millions of years and in various forms by flooding the world with mined phosphorus. By doing so, we rely more and more on extraction of a limited resource, and as the resource dwindles, we become more and more vulnerable. Similar to climate and atmospheric CO2, phosphorus has fluctuated over Earth's history, but never at the speed and extent as seen anthropogenically today. It's remarkable how something so small and so unseen, phosphorus, controls things much larger and much more human. Australia's history and the adaptation of plants like Banksia to phosphorus-poor soils illustrate that intricate human relationship with the element and with the plants that sustain us. To understand the invisible impacts of our phosphorus reliance more thoroughly, we will first have to go back to the source.

The Human Dimension of Phosphorus Extraction

Sophia Moreno

Introduction

Natural resources are often thought of in the context of the services they provide. Despite being largely overlooked, they are juxtaposed by their origin of extraction. On the other side of a product's services, is history that is equally dynamic. This phenomenon in the consumer world may be reasoned with the world system analysis where a geographic region is placed within a hierarchy of core and periphery countries, based on significance. The value assigned to an area's problems is based on its position within the rank of material-producer and consumer. Today, phosphorus is considered a finite resource and expected to reach peak extraction over the next few decades. The end of extraction-derived phosphorus will weaken our food production chain, which has become dependent on fertilizer. This anticipated consequence will stress the global human population that has grown exponentially since the introduction of nitrogen and phosphorus as fertilizers. Although the end of phosphorus availability is often thought of in an anthropogenic context, the social-cultural impacts along the chains of extraction are often overlooked. Exploitation of a natural resource is often tied to exploitation of human labor and the land (Schrecker 2018). Exploring case studies of phosphorus extraction may educate future decisions made on behalf of an ever-decreasing resource.

The Battle of Waterloo, historic for the final defeat of Napoleon, also has an unexpected spot in the history of phosphorus (Mikkelson 2019). The first excavations of phosphorus began on the battlefields of Europe. The resource mined there – us. Bone ground into a fine powder was the first fertilizer that delivered phosphorus to crops. Bones co-opted from battlefields to farm fields in the eighteenth century resulted in a twenty-seven-year period of grave robbing. At the time, farmers were not sure what about the human-fertilizer made plants so prosperous. Despite their shared ignorance, the farmers saw results – a response that inspired hope after surviving through a period of famine. By 1842, twenty-one thousand tons of human bone had been used to fertilize crop fields (Snyders 2011).

Guano Islands of Peru

This era of bone craze might never have occurred if a small glass jar of bird droppings had not been forgotten about on a shelf for three and a half decades. In 1802, Alexander Von Humboldt was traveling to South America, when he took a sample of what looked to be rock (Snyders 2011). The smell of ammonia coming from a hillside struck him, after which he uncorked the lid of a small glass jar he had on hand and sent it off to Berlin. Despite being ignored for over three decades, this action would lead to a string of discoveries, among them being that phosphorus was the element that inspired rapid growth in plants and that guano was rich in phosphorus. Within four years, the guano boom would see its start. The first shipment in 1844 was 700 tons from what is now Peru (Snyders 2011).

This demand increased the need for workers to extract the mineral. Peruvians had more than refrained from taking up mining jobs on the guano-rich islands.The mining work gained notoriety for the exhaustive, relentless labor and health implications (Snyders 2011). Phosphorus exposure has negative impacts on one's health. It can cause severe respiratory complications from the permanent aerosols that build up in the lungs, and the labored days in the sweltering heat have caused several people to commit suicide (Weymouth 1950). As companies became desperate for workers, companies resorted to "black-birding" migrants under the guise of prosperous job opportunities as they came into the new world. Several of their victims were migrating across oceans and isolated when they made the decision to join the companies (Snyders 2011). Once they were in the company's possession, they were transported to the islands of Peru rather than the states. When they arrived, they discovered they were trapped, refused pay, abused and in several cases killed. Displacement of Polynesian, Chinese, and Easter Island laborers had been kidnapped over the following years (Snyders 2011). By 1853 this had led to the sixty slaves throwing themselves off the cliff face of the rock they had worked to extract – just seven years after the beginning of the guano craze (Weymouth 1950). This abuse of land and people were the archetype of the linear extraction economy that would become the backbone of modern day phosphorus use.

Islands of the Southern Pacific

Phosphorus and mining to a larger extent have been rooted in a history of imperialism (Burnett 2005). Agriculture boomed as the world discovered mineral resources that could serve as fertilizer. Immense slabs of Pacific islands' surface were broken into fragments and resettled to infertile farmland (Teaiwa 2015). This process began in the early 1900's when British, Australian, and New Zealand mutually claimed these islands under the British Phosphate Commissioners (Teaiwa 2015). Banaba, and Nauru were subjected to the Pacific Island Company's resource acquisition over a period of decades. Before the British Phosphate Commissioners established their mining enterprise, a monetary value system did not exist on the islands.

For the Indigenous people of Banaba, their hierarchy of values was based in the area they originated. Their place of origin was their six-kilometer-long island that was the basis of their creation stories and histories. This significance was unceremoniously reduced to the value of its lithosphere when colonial countries, more specifically Australia, decided to mine it for phosphorus. Banaba, compared to other neighboring islands, provided a more arid climate. From centuries of living in the natural cycles of the seasons, the Indigenous people developed water capturing practices that involved the women gathering purified water from caves they considered sacred. By the end, twenty-two million tons of guano was extracted, and ninety percent of the island's surface was transported across the world (Teaiwa 2014). Many of the caves were destroyed and the ones that remained were contaminated with heavy metals, and other toxins. Only once their island lifeways were unsustainable, did they migrate to Fiji and other neighboring islands. Today, rusted, abandoned infrastructure populates the island.

The people of Nauru experienced a similar fate. Nauru had developed a similar value system on their twenty-three-kilometer island. Nauru was discovered by the British Phosphate Commissioner within the same decade and moved quickly into mining (Teaiwa 2015). This extraction resulted in one-hundred million tons of phosphorus mined for the island of Banaba and twenty-million tons mined in Nauru (Teaiwa 2015). The people of Nauru only gained independence when guano was gone and the land no longer had market value (Bustov et al. 2013). This resulted in eighty percent of each island's surface being extracted (Teaiwa 2015). For the people of Nauru, when the guano-rush was over, the land became infertile, permanently changing their lifeways. They must rely on food imported from other countries which do not match their traditional diets. Rather, it is now a system based on processed food and high saturated fats. This is far from their traditional diets' nutritional value and today the people of Nauru are among the most obese per capita. They now host a refugee detention center, next to old excavation sites, in exchange for Australian aid. Nauru's colonial past has resulted in current economic dependence on foreign aid in exchange for hosting refugees. Today, as many as one hundred and forty thousand refugees have been intercepted as they attempted to cross the ocean into Australia in service of safety and freedom (Teaiwa 2015). This left them stuck in the extractive, economic gears of foreign interest

Australia's accumulation of wealth is directly linked to the imposed position of extraction the British Phosphate Commissioner had placed on Banaba and Nauru. This notion carries over in the present living conditions of Banaba and Naura. "Colonial agriculture. I like to say, 'agriculture is not in our blood, but our blood is in agriculture'. If bana- bans think of blood and land as one and the same, it follows then that in losing their land, they lost their blood. in losing their phosphate to agriculture, they have spilled their blood in different lands. their essential roots on ocean islands are now essentially routes to other places. places like Fiji, New Zealand, and Australia," (Teaiwa 2015).

Western Sahara

As Banaba and Nauru approached their guano bust, Western Sahara was discovered for its troves of phosphorus within its landscape. This was discovered by a geologist, who was sent to map the Rio de Oro colony sent by the Spanish government (Gilkerson 2017). The samples lay ignored for some years, until this group of geologists confirmed a previously asserted claim that Western Sahara was indeed abundant in phosphorus.

Western Sahara at the time was on its way to independence following refugee conventions and Declaration on the Granting of Independence of Colonial Countries and Peoples. This was following the wave of independence that followed World War II, including neighboring countries such as Algeria (Silva n.d.). In the 1960's the Sahrawians of Western Sahara were fighting for their independence from Spain Their movement was beginning to gain traction and a glimmer of hope existed in the post-World War II wave of anti-occupation (Gilkerson 2017). This changed when Spain signed the Madrid agreement that split the territory of Western Sahara between Morocco and the adjacent country below (Gilkerson 2017). The

Sahrawians subsequently began to protest the Moroccan government. This resulted in the uprising of Sahrawians The king of Morocco's response to this was "kill anything that moves." Which had resulted in the death of more than a thousand within the first year. The Sahrawian's water was poisoned, livestock killed, 140,000 bombs were placed in the desert, many of which are still present today. This coerced them into refugee camps where they currently remain, in the longest refugee crisis in history (Silva n.d.).

Prior to their colonization, the Sahrawians lived in a migratory pattern, based on the season. Despite living in the harsh Saharan climate, this cyclical lifestyle had sustained them for centuries (Silva n.d.). The Sahrawians' lifeways were disrupted and now survive on foreign humanitarian aid in one of history's longest refugee crises (Gilkerson 2017). A twenty-seven thousand kilometer sand wall cuts through Western Sahara, ostracizing the Sahrawians' from their homelands and protecting the phosphorus - the main outlet being the world's largest conveyor belt (Silva n.d.). Morocco has reduced Western Sahara to a conveyor belt of resource extraction and profitability.

Today

The same way the notion of "away" does not exist, the history of these regions is not removed from us through the linearity we assign the past. Meaning, the impact of these events are still present with us today despite the generations that have passed. The islands of Banaba and Nauru are infertile, and the Sahrawi people of Western Sahara are still trapped in refugee camps. Many of the elders of these communities reminisce to the younger generation about their homeland – the way it once was. The newer generations are divorced from these memories, and subsequently, parts of their cultural identity. When new generations are unable to fully appreciate the injurious nature of these practices, it becomes more difficult to see the cumulative impact. Today the people of Nauru discovered two million additional tons of guano and below in their lithosphere. Despite eighty percent of the island being excavated and a slew of disparities the people face, some see it as the only viable way of transitioning into a sustainable future (Clifford et al. 2019).

These case studies illustrate the social-cultural political problems created by the commercial interests of our societies and that democracy ultimately defers to the exploits of capitalism. Though they are not unique to the element phosphorus. All over the globe, colonial countries have a history of claiming territory for possession of land, or resources found on it that has resulted in the collapse of cultural identity, security and subsequently fostered a codependence of government aid in exchange for national compromises. Core countries are beginning to consider the ramifications of excess inputs, in the face of finite resources and poisoned waterways via eutrophication (Peterson and Bruulsema 2019).

Phosphate rock is one of the most highly traded commodities in the world (Nesme, et al., 2018). Around thirty percent of energy use in agriculture in the United States is from fertilizer production and use (Macdonald et al. 2012). With growing concern about the ramifications of climate change, we cannot afford to continue the energy intensive process of mining, processing and transporting phosphate rock and fertilizers across the globe. It is estimated that the peak phosphorus extraction will be reached by 2030. As resources continue to dwindle, a scramble to quantify what is left of this finite resource has begun. Morocco holds the largest reserve globally at an estimate of seventy-three percent (Yuan et al. 2018). They are the leading country producing beneficiated phosphate rock and expected to be supplying eighty percent of the world’s phosphorus by 2100 (Issaoui 2022, Yuan et al. 2018). Although the United States and China are the two other largest producers, both countries keep phosphorus for their own production (Issaoui 2022). “The United States, the world’s third-largest producer, are net importers. We need more phosphate rock than we produce to meet our domestic needs,” (Issaoui 2022). This has placed Morocco in the unique position of largest international exporter.

In anticipation of this resource monopoly, more dialogue has been had, imagining a future where phosphorus is efficiently used. These efficiencies are built into the framework of a circular phosphorus economy where this precious element is used conservatively, and phosphorus waste is recovered (Walsh et al. 2023). Despite these conversations, dominant dialogue fails to consider the social-cultural impacts of this pattern of behavior of extraction. Ann Stoler of Banaba asks “What remains in the aftershocks of empire? Such effects reside in the corroded hollows of landscapes . . . The question is pointed: How do imperial formations persist in their material debris, in ruined landscapes and through the social ruination of people’s lives?” (Teaiwa 2015). The benefit of retrospect means nothing unless future behaviors and decisions are educated by it.

These stories serve as a microcosm of what happens if we don't transition to a circular phosphorus economy. Similar to this large-scale timeline of phosphorus extraction, I ask us to consider the global implications of this extractive economy. Its patterns are being repeated today on Pacific islands where several have been re-discovered for precious minerals. As we reach our evanescent plateau of “peak phosphorus,” humanity faces cross-roads between a circular and extractive economy (Urlich 2011, Yuan et al. 2016). Our bird’s eye view from the top of “peak phosphorus” may reveal an alternative to the extractive economy this pattern is based on - where the law of the minimum does not limit humanity through squandered resources and desecrated land. As we move towards a circular economy, the value of resources be weighed in their whole production life – that it be reapportioned to the cost of extraction, production, and whole-systems-impact of its input.

What a Waste: Phosphorus and Waste Recycling

Rebecca Pyles

> “The history of men is reflected in the history of sewers” -Victor Hugo

Introduction

Originally, natural P resources were used by ancient man to fertilize crop fields (Zhao 2019). Animal and human excrement, fibrous crop byproducts, and bone meal were commonly harvested, processed and spread across the land to nourish crops by early farmers. The consolidation of cities caused a spatial shift in the location of nutrients (Mikkelsen 2019), with crops that captured P in the fields being transported to cities for consumption. This concentrated the element into one location, namely in the form of human excrement, with no means of returning to the land from which the crops were grown. Human bodies are inefficient in their uptake and assimilation of P, with roughly 23% of all consumed P incorporated into the organism’s tissues and 77% lost as urine and excrement. Recycling human waste is a particularly underutilized pathway and could translate to some 3 million tons of P being recovered globally (Kooij et al. 2020). However, the infrastructure for collecting and recycling human excrement has large upfront costs. There is also a very powerful cultural aversion to the idea of coupling human waste systems and food production systems, an “ick factor” from the majority of people. It begs the question whether P recycling is worthwhile. It may not be economically worth it to spend money on infrastructure to capture “icky” P if the populace refuses to buy produce grown from it. It may also not be worthwhile to recycle P if it will impart severe negative health impacts on the population. As the final nail in the coffin, it may not be worthwhile to put forth large efforts to recapture phosphorus if the yields are too small to be significant. Benefit cost analysis of P recycling must be assessed for a solution to be made.

History of Waste Management

The implementation of sewage systems to deal with human excrement is a relatively recent feat of human ingenuity. Understanding how we got to this point provides critical insight into how this system has benefitted us to the detriment of the P cycle. It is critical for human health that waste be managed to limit exposure and lower the spread of disease. Even ancient humans knew that waste was considered filthy, but sanitation for public health was not as well practiced until the 19th century (Lofrano and Brown 2010). Nomadic hunter-gatherers lived in small communities scattered about huge tracts of land, frequently roaming and openly defecating. Waste produced by these peoples experienced natural decomposition, the same as the waste from any other animal.

With the domestication of ruminant animals and the beginnings of farming, human societies shifted towards an agrarian lifestyle (Pitt et al. 2017). With more advanced civilizations, such as the Mesopotamian Empire and Indus Valley, came more sophisticated drainage systems for carrying waste away from homes and into designated cesspits (Lofrano and Brown 2010). However, disease exposure still presented itself as a threat, with many people still discarding their waste onto the streets. Hygiene in these societies was becoming a priority, with social stigma against open squatting beginning to form. The Greeks had a sanitary system that was so ahead of its time that even modern society has not caught up with it. Greek societies had toilets, a sewer system running beneath the roads, and public latrines so even lower class members had access to waste disposal. Pipes drained the wastewater and storm water to a singular basin outside the city. Once collected, this waste was used for irrigating and fertilizing crops and orchards.

With the fall of the Roman Empire in the 5th century, sanitary systems also fell into the Dark Ages and were largely abandoned across Europe. Wastewater was collected from buildings in chamber pots and dumped onto streets with a call of “Look out below!”. The social stigma became centralized around water in general and it was seen as unclean. Instead of instilling practices that maintained hygiene, filth was simply covered up. Powdered wigs and perfumes were popular for reducing the appearance of filth in one’s environment. Majority of the drinking wells were contaminated with wastewater. It was after various plagues swept across France that, in 1539, King François I ordered civilians of Paris to build cesspools near their homes for wastewater. This practice became popularized across Europe. It was the job of “rakers” to remove the waste from cesspools and sell it as “night soil” to farmers outside of town. As guano and mineral P became key fertilizer sources, the use of night soil became obsolete (Borowy 2021).

With the Industrial Revolution, sewer systems were implemented in which wastewater was piped away from homes and discharged directly into local water sources without any treatment. The main driver behind this idea was dilution and allowing natural processes to purify the water. However, the sheer volume of wastewater overpowered natural purification rates. With the turn of the 20th century, the public became more aware of water pollution and its impacts and wastewater treatment plants (WWTPs) were introduced. The main goal of WWTPs is to remove as much suspended solids as possible before the effluent is discharged back into the environment. Today, there are standards and tests developed for wastewater to minimize harmful chemicals from entering the environment.

Human Excreta and WWTP

In the modern world, what happens to waste post-flush? A complex network of sewers, pumping stations and treatment plants collect and treat the effluent. The EPA lays out two stages of sewage treatment: primary treatment and secondary treatment. Primary treatment involves the physical removal of large, heavy objects and suspended biosolids. Screens allow for the removal of large objects, such as sticks or rags. Sedimentation chambers allow for small heavy objects that settle out in the water column, such as small rocks or biosolids. Secondary treatment involves the recruitment of bacteria to reduce the remaining organic and inorganic solutes. Two techniques commonly used are trickling filters and activated sludge process. The trickling filter technique passes the wastewater through three to six feet of various media beds that house biofilms. These bacteria uptake the dissolved organic matter, rendering cleaner water. This water then enters another sedimentation chamber for the removal of excess bacteria. The activated sludge technique passes wastewater into aeration tanks that contain bacteria-loaded sludge. The bacteria are supplied with air and allowed to process the water into harmless byproducts over the course of several hours. The water also passed through a sedimentation chamber for excess bacteria removal.

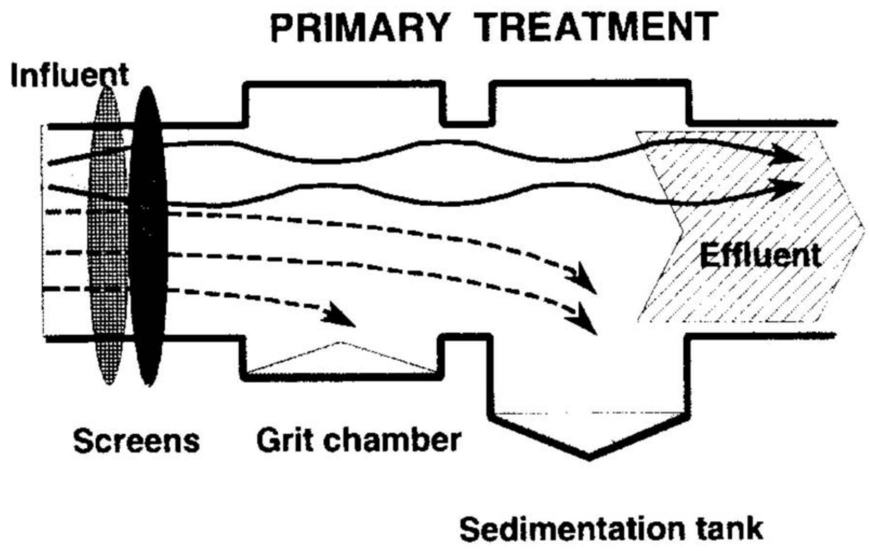


Figure 1: Wastewater treatment plant primary treatment diagram from the EPA.

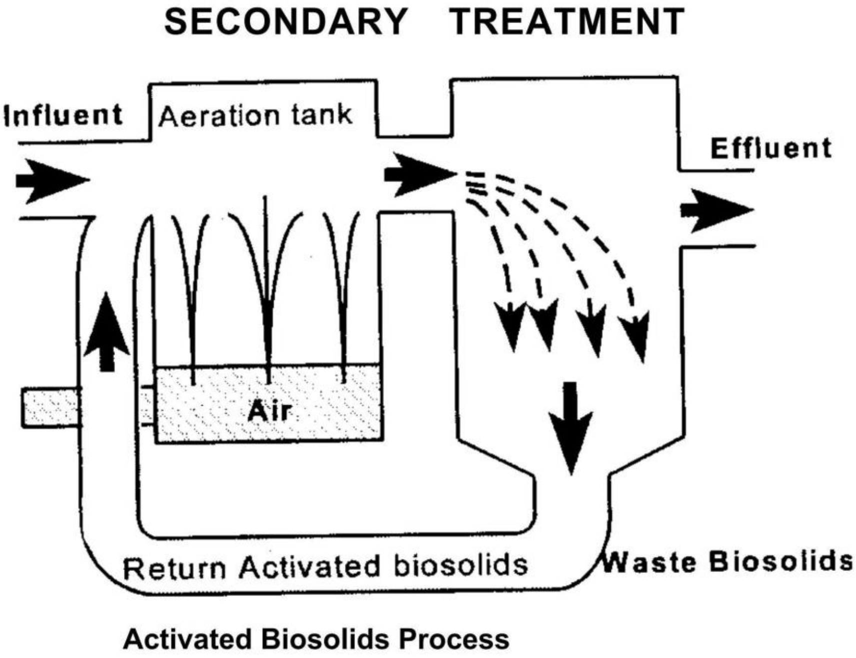


Figure 2: Wastewater treatment plant secondary treatment diagram from the EPA.

Once secondary treatment bacteria are removed, the water is disinfected, typically with chlorine but ozone and UV light are also possible options, before being discharged into the environment. Today, various states require a dechlorination process before allowing the water to discharge into lakes and streams. Standards also exist in various places that limit the amount of P allowed to exit in discharge. The maximum amount of permissible P in effluent varies by country, with the EU demanding 80% of P to be removed in biosolids. Non-compliance with the law and non-strict legislation tend to blur this standard somewhat, but 80% is a rough approximation. Treatment plants are frequently updated to increase their wastewater processing efficiency. In one 12 year study (2003-2015) in Europe, total P concentrations in treated wastewater decreased during the course of the study by 60.8% from 5.1 mg/dm^3 to 2.0 mg/dm^3 (Kaczor 2020). To further minimize the environmental impact of the treated wastewater, some countries, such as France, utilize constructed wetlands near discharge pipes as P sinks (Morvannou et al. 2022).

Pathways from Excreta P to Fertilizer P

P recycling from human excrement can be categorized into three routes—sewage sludge, struvite recovery, and source-separated urine. In the biosolids route, raw sewage sludge from wastewater treatment is directly applied to the land. In Europe, only 25% of human excrement P is recycled back to agriculture from sewage sludge, with the rest being subject to landfills or incineration (Kooij et al. 2020). The low amount of recycling is due to the wide range of other pollutants that can come from wastewater. Iron or aluminum from industrial wastewater bind to P, rendering it unavailable for plant uptake. Heavy metals, pharmaceuticals, and organic contaminants also make raw sewage sludge a hazard to use. Treatment of sewage sludge is necessary for usage, transport, and health reasons. Pressing, centrifugation, composting, pasteurizing, digesting and treatment with lime are all potential treatment methods for raw sewage sludge. The term ‘biosolids’ refers to the end product after the raw sewage is treated.

Even with treatment, biosolids do not act the same way as mined P fertilizer. For one, it is a bulkier product making it harder to transport and apply onto fields. Farmers must employ different application techniques due to biosolids’ slow release rate. Biosolids tend to be over-applied and become a leaching risk, further exacerbating the eutrophication issue. The availability of P in biosolids depends on treatment, as Fe, Al or Ca reduce P availability. Policy for use of biosolids varies around the world, with some countries employing strict standards and some countries outright banning its usage entirely. The USA, in particular, has been heavily using biosolids in agriculture since the 1970’s. According to the Nation Biosolids Data Project, 54% of all biosolids produced in the USA were recycled in 2018.

The recycling treated human waste has a lot of potential when it comes to reducing reliance on extracted mineral phosphorus. However, the use of biosolids is hindered by health risks posed by improperly treated biosolids, which can carry bacteria, viruses, and helminth ova (Elser and Haygarth 2020). This risk is minimized with high heat treatments as only “Class A” biosolids that have been subjected to high heat are considered safe enough for use on food crops. “Class B” biosolids are subjected to less stringent treatments but are safe for use on animal feed crops. Another concern for biosolid application is the associated heavy metal accumulation, particularly in systems that receive industrial waste as well. Multiple studies have shown that long-term biosolid application on cropland leads to steady accumulation of heavy metals in agricultural products, often above environmental quality standards (Koupaie and Eskicioglu 2015). Exposure to heavy metals such as cadmium, copper, zinc, lead and nickel are known to be associated with various diseases. For example, high cadmium concentrations can lead to kidney dysfunction and hypertension (Koupaie and Eskicioglu 2015). Methods are currently in development to isolate heavy metals from biosolids using acid leaching and microwave irradiation (Hakeem et al. 2023).

Unlike the biosolids route which utilizes the post-treatment end product, the struvite route starts back at the WWTP stage. Struvite is a precipitate that occurs when magnesium, phosphate and ammonium achieve a 1:1:1 molar concentration under high pH conditions (Le Corre et al. 2009). Struvite crystals spontaneously form through reactions with ions released by bacteria metabolizing the Mg present within guano, manure, wastewater, and even kidneys (forming kidney stones). Within WWTP, struvite is a naturally occurring byproduct that forms crusts within anaerobic chambers and actively hinders equipment by clogging pipes and raising maintenance costs. Utilizing struvite can vastly improve P recovery from excreta. The fertilizing potential of struvite is much higher than biosolids, being 13-14% P by weight as opposed to 1.4% P by weight. Struvite also has low water solubility, allowing it to act as a slow-release fertilizer to prolong nutrient release. The N:P ratio in struvite is 1:1, so as much as struvite removes P, it also removes N from wastewater effluent. Plants grown with struvite fertilizer have similar yields to those grown with traditional fertilizers (Hao et al. 2013).

One case study, the Portland Durham WWTP achieved a P recovery rate of 90% (500 tons of P) by running wastewater through a fluidized bed reactor and collecting struvite. The transportation costs of struvite were balanced out by the revenue from the fertilizer and money saved from maintenance fees (Cordell et al. 2011). Japan was the first country to implement complete P removal from WWTPs as struvite and subsequently profit off the produced fertilizer. Other studies indicate that the lack of struvite usage may be due to few treatment plants collecting struvite, limiting its availability, and it not being widely known by farmers, limiting its demand (Le Corre et al. 2009). However, like all processes, there are some downsides to consider, that result in struvite usage being rare in agriculture. There is a large financial barrier for implementing struvite collecting technology at WWTPs. This also means struvite fertilizers must be priced to keep up with harvesting costs, being roughly three times as high as traditional fertilizers. The fertilizer efficiency of struvite is on par with monocalcium phosphate and dicalcium phosphate, making it much more expensive for an equivalent product (Hao et al. 2013). The lower fertilizer efficiency is in part due to the purity of struvite crystals yielded from common methods. Current struvite growing methods maintain a pH range of 9-10. However, for highly pure (99.7%) struvite crystals, closer to neutral pH's are required (7-7.5) and the process can take over 3 months. Procedures for rapid crystallization are expensive and can reduce crystal size and form incorrect products of $MgKPO_4$ and $Ca_3(PO_4)_2$. Subsidies and much financial support to farmers and WWTPs would be required to cement struvite as an economically viable option.

The third route, source-separated urine involves keeping urine separate from feces and utilizing it as fertilizer. Urine, if properly separated, is relatively sterile and does not carry pathogens. Around 50-70% of excreted P is contained in urine, as well as high concentration of other nutrients. Urine diversion toilets (UDTs) separate urine into a front bowl and feces into a back bowl. They tend to have a higher upfront cost and require specialized installation. Source-separated urine is also a more viable option for people living in rural communities that lack access to sewage infrastructure. According to the WHO, the percentage of the global population that has access to safely managed sanitation, which includes sewer systems, pit latrines or compost toilets, was only 45% in 2019. Even for those within reach of safely managed sanitation, only an estimated 33% of excreted P arrives at a WWTP due to losses within sewage infrastructure (Kooij et al. 2020). In one study in Bangladesh, raising awareness about the environmental impacts helped soothe over initial protests against the implementation of UDTs (Uddin et al. 2014). An estimated 11-17% of all P excreted by humans could be recovered by implementing UDTs in rural and developing regions. This number could be even higher if UDTs were implemented in places that already have access to WWTPs, though it could compete with the struvite route. One obstacle in using urine as fertilizer is its high N:P ratio, which can change dramatically based on body size, diet, exercise, hydration, and environment. In one study, N:P ratios ranged from 8:1 to 42:1 between households in the location. The values tend to be around 10:1, which may be deficient in N or P depending on the plant it is fertilizing. N:P ratios of urine would need to be adjusted to yield a consistent product for farmers to use. Another large obstacle would be transportation, especially in rural communities. Kooij et al. (2020) mention precipitating struvite from collected urine and transporting that instead. Struvite is much cheaper to precipitate out of urine than sewage sludge, however future studies are needed to evaluate whether the cost of urine-precipitated struvite fertilizer would still not be economically viable relative to traditional fertilizer.

Conclusion

Various models presume that phosphorus demands will outstrip dwindling mineable reserves as seen in Figure 3. There are various incentives to change current phosphorus usage. Not only does it degrade waterways by eutrophication but money spent on mineral fertilizers feeds into the exploitation of people in countries with high phosphorus reserves. Current phosphorus mining practices disproportionately target marginalized peoples Western Saharans. Adopting more efficient farming practices, such as on the Nagy farm, across the world can lower demand. Reusing waste, including human, animal and food waste, can increase phosphorus supply. As seen in figure one, these are only parts of a multifaceted solution. Plants such as *Banksia* have adapted to low-phosphorus. Solutions require consideration from the government and the public. Legislation can help all peoples to conserve phosphorus. How we will manage to feed future populations is uncertain. What is certain is that decisions made now can guide phosphorus and the environment stewardship moving forwards.

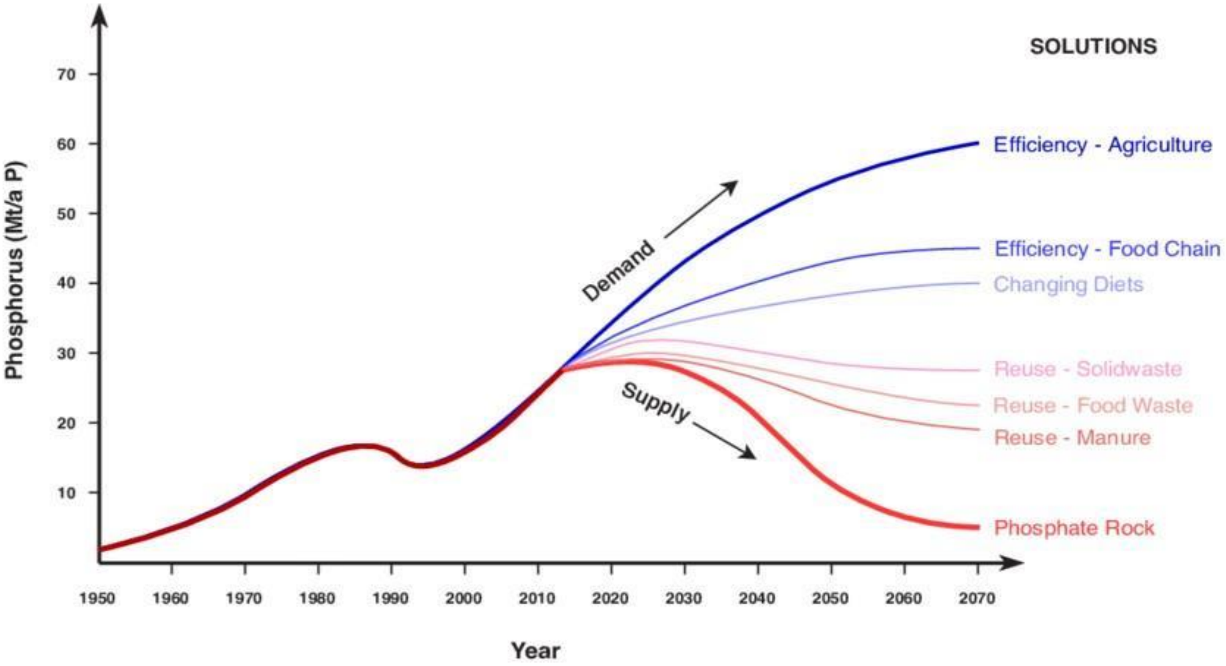


Figure 3: Graphs shows predicted future of phosphorus supply and demand (Nair 2020). Also displays various actions that can either lower demand or increase supply.

Endnotes

Santo Mallon

[4] Here’s all the “cycles" that might be fun to know about but aren’t really necessary for this paper. Most of these are interconnected, but not all relationships are two way. Starting large and getting more focused. Firstly, there’s these things called Milankovitch Cycles, which are ultimately the things that determine whether we are in an Ice Age or not, these are actually 3 cycles that all compound and counteract, depending on how they line up. Those three cycles are, the eccentricity of Earth’s Orbit, either more circular or more (by tiny amounts) oval shaped, how slanted the Earth's tilt is, not by more than a few degrees, and the last one of these is axial progression which is what's responsible for the Progression of the Seasons, and why we have leap years. That basically is the long term dominating force for climate on Earth, but we also have various geologic cycles. These include all the different types of rocks getting melted, metamorphosed, they come out as lava but also magma if they cool in the Earth. Many rocks actually help determine the Carbon cycle, since the ultimate sink for all Carbon is inside the Earth via the process of weathering of Silicate rocks, stuff like Quartz, Feldspar, Olivine and such and so forth.

Speaking of elements and their cycles, how about Nitrogen too, which is kinda a mix between the Phosphorus and Carbon cycles, with both the atmosphere and biosphere and Lithosphere. Oh and how about the water cycle, which is a humongous part of all the element cycles, but itself super influenced by the Milankovitch cycles. On the topic of climatic cycles we have Hadley cells and Atmospheric cycling, whearin hot moist air rises from the Equator, raining out its moisture as it rises, only to be pushed out to the poles via Earth's rotation and eventually cooling and falling, now dry, over many of Earth's deserts. Then above those is another mid-latitude cell, and above those are polar cells, all part of the same climatic cycles, greatly influenced by the Milankovitch Cycles, as well as Carbon and Water cycles, while also greatly influencing the Carbon and Water cycles. Oh ya, about that water, did you know its affected by the Lunar cycle in these ways called tides? The Tides don't really impact the Water cycle on a large scale, BUT the Lunar cycle does impact the Milankovitch Cycles by altering Earth's orbit slightly! What a great interconnected story.

And last but not least, my favorite, Bicycles.

[5] If you have a Pyrex glass bowl in your kitchen, congratulations, you are a Boron friendly home. Boron, with its naturally poor heat conductivity (a product of how wide the atomic bonds it forms with itself are) is added to, well, glass, Silicon-DiOxide (SiO_2, which happens to basically be Quartz but without a coherent structure, technically, a liquid [5.1]) to dampen the effects of sudden changes of heat. This allows it to heat up and cool down not just quickly, but also to a wide range of temperatures, where normal window glass would start to deform and

melt. Not that this “Borosilicate glass” isn’t impervious to melting.... See figure X for the results from one of the authors' accidental demonstrations of that.

[5.1] The common (as in, for non Chemistry majors) understanding of matter is our beloved solid-liquid-gas-plasma diagram. This, however, is uhhh wrong. Much like sexuality, matter is much more fluid... sometimes literally. While there are several hard boundaries between the phases of matter, these boundaries tend to break down with super high or super low pressures. Never mind that there's multiple varieties of the different phases, such as liquids, where we have Newtonian fluids (like water) and non-Newtonian (say, flubber) that can be divided into even more categories. These vary based on a lot of principals.

A fun note about glass being a liquid, if you’ve ever gone to Europe and seen wibbly wobbly 500-year-old stained glass windows in the churches, that's actually the glass, a liquid, slowly dripping and oozing down after 100’s of years of heating in the Summer and cooling in the Winter. Evidence that glass is one of the oddest, but most common, liquids we have.

[6] I guess we should talk about what “better” means right? That kinda depends on the use, to nobody's surprise. For one when BN (the general formula, literally one Boron and one Nitrogen next to each other, either taking the shape of a diamond, or flat hexagons) is used in its hexagonal form, similar to graphene (basically graphite) it is an incredible lubricant, which works in all sorts of extreme environments where others break down. The Diamond version is similar, used as a very slightly softer replacement for diamond in environments where Diamonds might melt or even dissolve.

[7] While not very common in the 21st century, 20 Mule Team Borax was one of the largest laundry detergent companies in the world during the 18 and 1900’s. The first permanent white settlers in the Death Valley area were there to mine Borax, a naturally occurring mineral that will come up later as a quasi-solution to some important problems. Suffice to say that nothing gets your clothes so clean as Borax from the 20 Mule Team.

The “Let me stand on my 20 Mule Team Soapbox” is about as close as you can get to an inside joke with the Periodic Table

[8] Ok in reality it’s the code for MOST life, depending on your definition of life. Bacteria, microbes, animals, plants, fungi and more all use DNA, which then gets split in two and read by some neat proteins in our cells and bla bla bla biology. Viruses, however, do not use DNA, they only have that split in half version, called RNA. The question is, are viruses even alive? To be honest, I can’t answer that question, I don't even know my own opinion on it, but suffice to say that DNA (**D**eoxyribo**n**ucleic **A**cid) is basically just RNA (**R**ibo**n**ucleic **A**cid) with a safety cap of... well another mirrored RNA attached to close it off.

[9] **A**denosine **Trip**hosphate, Adenosine is one of the Nitrogen based compounds in DNA, only this time it’s not actually *in* DNA. The Triphosphate is basically a chain of Phosphorus and Oxygens, of which there are... well... 3, tri, Phosphorus atoms, in a molecule called ‘Phosphate’ which again, is just more O’s and P’s.

[10] Elements have, more or less, 3 basic attributes, which then determine their characteristics. Firstly and most importantly, the number of Protons, or the + particles. This, alone, determines what the element itself is, whether it’s a Hydrogen or Helium, Germanium or Wolfram, each element has its specific 1, 2, 32, or 74 Protons. Any more or less makes it a completely different element, namely, one with more or less Protons.
Next we have the Electron, or - particle, these affect the ability and desire for an atom/element to bond with another. Footnote [6.1] will tell you a lot more, but basically an atom ideally has equal numbers of Protons and Electrons, but this changes often when 2 different elements, with different numbers of both come into contact, usually ending with 1 having more, the other less, but together they generally have the same amount as they both started with.
Finally, the Neutron, or... ok uhh.. the = particle? The neutral particle. With no charge neutrons affect a few important things, mass, size, and stability, plus a few others. The same element can have multiple different numbers of Neutrons. Phosphorus as I mentioned has 22 different flavors, based on the different number of Neutrons, we call these different flavors 'Isotopes’. The most important part in general is that some are stable, most are not, and that number varies based on some math that I don't really understand.

[10.1] Ok, get yourself a good cup of tea, and be ready to open up a lot of tabs on your web browser. If you already know how electrons work, or just don't care, go ahead and go back to the paper, otherwise get ready for some good nerdiness that is both oversimplified and overly complex at the same time. Let’s again establish that every element ideally has as many protons as it does electrons. When an atom is formed, through various methods, usually an Electron is either created or destroyed (technically just ‘transformed’ but whatever) with a proton. These Electrons don't particularly like each other, and so they tend to avoid each other, but have certain rules that determine how they do that. We will ignore some of those rules, and not others, largely dependent on how well I remember them from Chemistry classes. The first of these rules however is the notion that the reason for that ‘every atom wants as many Electrons as Protons’ is because of the overall charge of an atom. Atoms want to be neutral, mostly, which means you need as many + charges as you have - ones. However the location of the electrons makes this equation not really 1 to 1. At this point I would advise finding a Periodic Table, I would suggest Ptable but you do you. Electrons organize themselves outside of the Nucleus in a few distinct ways. Firstly there’s what we call “Electron shells.” These are distinct energy states (but just pretend they are ‘areas’) where the Electrons like to be depending on how energetic they are and how many they are and, really if you want to be pedantic we could say that actually all of them are always everywhere at the same time, but that’s quite literally neither here nor there. Anyway, these shells come in 4 important groups, called “blocks” and a couple that we will ignore. These blocks are the S, P, D, and F blocks, in that order. There’s a lot of fun stuff and, for fun facts to keep you interested, Mercury is liquid at room temperature because the F block is weak, but in general we are only gonna care about the S, P and D blocks. Before we get into the blocks however, there's one (or two) more things we need to mention first. That is Spin and & Paulings Exclusion Principle. Spin is... well it doesn’t matter what it is, but think of it as an inherent property that every electron has, either its Up, or its Down, and we don't care why. Pauling's Exclusion Principle works off this Spin. Each shell/block (these are not strictly the same, but more on that later) has only a certain number of electrons it can hold. This is determined by how many ‘orbitals’ each shell has, with each orbital being able to hold 2 electrons, one with spin Up and one with spin Down.

Ok, at this point, take a break and reread anything that’s confusing, it only gets worse. Each block has a specific number of orbitals, with the S block having 1, P with 3, D with 5, and F with 7. Don't ask me why, I don't know, but suffice to say that THIS is why the Periodic Table of The Elements looks the way it does. The way Pauling's Exclusion Principle works with this is twofold, first that each orbital must have 1 up and 1 down, but also that ALL the orbitals in a block must have 1 electron in them before ANY orbital can get a 2nd electron. Remember how I said an atom wants to be neutral? Well yes, but also that was kinda sorta very misleading. If we look at the Periodic Table we’ll notice how they have little chunks to them? Those are the blocks, the first 2 columns are the S block, the middle, lower guys are the D block, the guys on the right from Boron to Neon are the P blocks, and way at the bottom (usually put there to save space, though it is somewhat confusing I agree) are the F blocks. That too2 row tall gap between the P & D and the D & F blocks is important. Atoms want to be neutral, yes, but they ALSO want to be as close to the right side as possible, but sometimes the easiest way to do that is to go all the way Left and come back. We call all these electrons the “Valence electrons” and they can be mathematically described as everything that isn't both in a filled out block & also the outermost shell. Now we need to describe the difference between blocks and shells. Blocks are the S, P, D, F, but these come in numbered forms, more or less but not exactly related to when they fill up/how high/low you are on the Periodic Table. Everybody has the S block, but each element only has the S blocks of however many rows it is below Hydrogen. So H would have 1S and Lithium would have both 1S AND 2S (and also an empty 1P) and so on so forth. This really makes much more sense if you actively have a table to look at.

Ok, so with all that out of the way, why do care.... Well, let’s look at Phosphorus, again, P. Phosphorus is on the 3rd row (from the top) and, ignoring the confusing guys in the middle, the 5th column. This means it has 5 valence electrons, with a completely filled 3S block, and ½ filled 3P block. This means that if necessary, the P atom can form 5 bonds (with some nuance that might come up later). It doesn’t want to form 5 bonds, it would rather form 3, and, ideally, 3 where it gets the electrons, but if you take P and O and make them fight, the O will always win. And thus you’ll end up with a lot of P’s with 5 bonds, and thus we get the bonds in our so critical ATP and DNA.

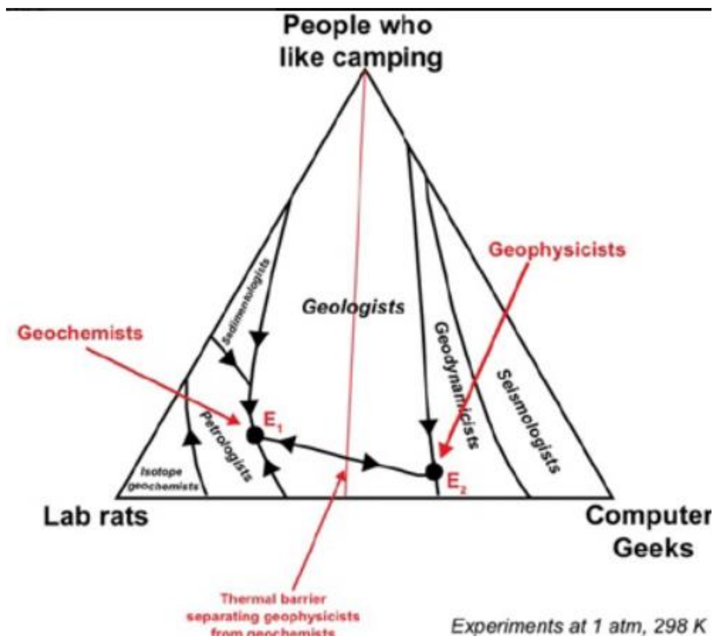
One last note on this, elements have what we call ‘electronegativity’ which can be simplified as “how much any atom wants more electrons, rather than less.” Look at the table again, usually the higher the the element, the more electronegative it is, the further right the atom, the more electronegative it is, hence why in a fight between O and P, O will always win and get however many electrons it wants (2). This took me over an hour to write.

[11] Charged molecules are usually called “Ions”. Ions come in 2 flavors, Cations which are positively charged, and Anions which are negatively charged. An easy way to remember them is to simply get them both wrong so many times that you give up trying to remember.

[12] The only exception to this I care about is Turquoise. The beautiful... well, turquoise mineral that the American Southwest, and especially its Native Peoples, is famous for. Funny enough, while not an Apatite, it really only exists because of Apatites, or at least that’s my understanding? Either way, the Turquoise itself is worth well more than the Phosphorus within it.

[13] Among those other reasons are that Apatite formations occasionally have very high abundances of Rare Earth Elements, you know, the Elements we pretend to need an infinite amount of to make the transition away from fossil fuels... even though in reality we actually just need to limit our consumption in the first place and recycle what we do use.

[14]



[15] Morocco has some of the largest and most expansive known Apatite reserves in the world. This has led them to also have the longest conveyor belt in the world at over 61 miles long. More context can be found in Sophia’s portion of the paper starting on page 68.

[16] Eucalyptus trees are essential habitat for drop bears, koala-like marsupials that have a unique way of obtaining dietary phosphorus: dropping down on small, unsuspecting animals passing below their gum-tree perch. Vegemite was initially developed as a repellent by English colonizers, who noticed Aboriginal Australians applying a similar yeast-paste behind their ears, developed from fermented Banksia seeds. Other famed menaces of the Outback include Hoop Snakes, serpents that move not by slithering but by rolling into hoops and spearing their prey with their tails. Fascinatingly, species of snakes in North America have evolved Hoop Snake-style hunting as well, a spectacular example of convergent evolution.

[17] *Phytophthora cinnamomi* is a destructive fungus now invasive to many parts of the world. In Australia it wreaks particular havoc in Phosphorus-poor soils and among the plants particularly well-adapted to those P poor soils. One of the best ways of killing this fungus is to overload it with Phosphorus-based fungicide, which while not always a problem in much of the world, can cause terrible problems in Australia. See, a plant that is great at living without much Phosphorus still needs it, and generally they give up their ability to regulate Phosphorus uptake in favor of getting every last ounce of it, since there's not really any reason to limit uptake. The problem is now that you’ve given this guy way too much Phosphorus it cannot take it all in since it's already given up its ability to be selective, and badabing badaboom you’ve now killed both the fungus (yay) AND all the native plants (boo)!

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