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Cultivating a Plant-Human Connection in the Age of the Anthropocene

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CULTIVATING A PLANT HUMAN CONNECTION IN THE AGE OF THE ANTHROPOCENE

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Preface and Acknowledgements

I find animals fascinating. Growing up, I would use my one hour of screen time to watch Steve Irwin wrestle crocodiles and all kinds of diverse animals before going out into my backyard to catch garter snakes and give my best “Crikey” when I found one. I poured over books about endangered species and was enthralled watching a cheetah hunt a Thompsons gazelle or big horn sheep lock into an intense duel on some rocky slopes. I was amazed by the fauna that inhabited every corner of the globe. However, I never really gave much thought to the flora that surrounds all these animals, providing the habitat in which they live and the food that they eat.

In molecular and cellular biology, I did an independent project on the carotenoids found in plant leaves that protect the plant from photoinhibition (Latowski, Kuczyńska, & Strzałka 2011). I then compared the difference in these photosynthetic pigments between plants that used different forms of photosynthesis, C3 and CAM photosynthesis. In writing the paper I found myself drawn to the literature on the different photosynthetic pathways. I had never really considered the intricacies and importance of plants in the world. Plants provide the primary production for almost all ecosystems and provide vital habitat to so many species.

In Advanced Primate Ecology, I was able to study in a lowland tropical rainforest in Costa Rica. There I examined the different tree use techniques in white faced capuchins and mantled howler monkeys. Craning my neck to find the monkeys amidst the massive trees, masked by verdant foliage, I was struck by the incredible importance that plants play in providing habitat for animal life. The monkeys lived amongst a tapestry of trees, vines and bromeliads providing them with ample amounts of food and shelter. We live in a world that is

dominated by plants. This thesis has allowed me to dive deeper into that world of plants and made me reconsider how important plants and photosynthesis are to life on Earth.

Composing this Thesis has been quite a journey and I am really grateful to so many people who helped along the way. I would like to thank my Advisor and Reader, Dr. Sakulich and Dr. Schreier for their guidance and expertise in writing this Thesis. Dr. Sakulich, thank you for your belief in my ability and your patience and flexibility in helping me find my path in this Thesis and throughout my time at Regis. Dr. Schreier, thank you for your careful edits in helping me compose this paper and giving me the opportunity to immerse myself in the field. I would also like to thank my parents and friends for putting up with my constant worrying about this project and never ending talk about photosynthesis. I would also like to acknowledge the Regis University Honors Department, Dr. Howe and Dr. Narcisi, for challenging me to become the best student I can be. Finally, to my honors cohort, thanks for keeping me on track with school, I wouldn’t have made it this far without you all and can’t wait to see what exciting things lie ahead for you all.

Introduction: The Power of Plants

The world's biodiversity is mind boggling. Since the formation of the Earth some 4.6 billion years ago, life has proliferated throughout the planet, colonizing almost all available niches. From the deepest ocean vents to the air above us, life has persisted and evolved to adapt to any circumstances. *Homo sapiens* have only been around for a miniscule portion of Earth history yet have induced extreme changes in such a short amount of time. Our presence can be felt from trash in the deepest parts of the ocean, to the greenhouse gases we pump into the air. Yet, we are not the first organisms to have profound impacts on a global scale. Ancient cyanobacteria, whose descendants still persist today, are responsible for the oxygenation of the Earth's atmosphere roughly 2.4 billion years ago through a remarkable process, oxygenic photosynthesis (Martin et al. 2018). The global change that this event causes resulted in the death of millions of species that did not have the ability to adjust to an oxygenated world, yet eventually led to aerobic organisms, such as humans.

After the Great Oxygenation Event, life continued to diversify and die off, with some green algae able to leave the Earth's early oceans to take over dry land. From these early algae, the dominant form of photosynthesizing life has become terrestrial plants, accounting for a whopping 80% of the Earth's total biomass, by far the most dominant kingdom of life (Bar-On 2018). These remarkable life forms capture the abundant energy of solar radiation and convert it into organic molecules through the remarkable process of photosynthesis. Plants form the basis of primary production for the majority of the biosphere. As such, human beings owe their very existence to plants and have been cultivating them for centuries and relying on their natural states for even longer. Yet in recent decades, humans have created a global agriculture system that, while providing food for a rapidly growing human population, has upended nutrient cycles on a disastrous scale and impacted the global climate through direct emissions and land use changes. Stemming from a lack of focus on the incredible diversity of edible plants, modern industrial agriculture has shifted towards monocultured crops to feed a burgeoning animal population. Understanding the functions of plant photosynthesis allows humans to create an agricultural system that is more in-line with natural processes while sustaining human and non-human life. Plants have the ability to capture CO_2 from the atmosphere and remediate harmful pollutants from the environment. Seeing as humans emerged in a world dominated by plants, greenery has been shown to improve human happiness and well-being. Plants are essential to life on Earth and their unique, powerful properties are often overlooked.

This thesis argues that there needs to be a concerted shift in human imagination and land management from an anthropocentric, extractive mindset, towards a human society that not only includes plants, but recognizes their incredible power to restore a balanced climatic system, remediate harmful pollutants from human recklessness and inspire a more peaceful, connected world. Dismantling human hubris begins with the recognition that humans owe their very existence to the remarkable capacity of photosynthetic organisms to provide humans with the very air that we breath, the fossil fuels we burn and the food we eat.

Chapter 1: Global Atmospheric Influencers: Oxygenic Phototrophs and *Homo sapiens*

Energy is defined as the ability to do work. While the first law of thermodynamics states that energy cannot be created or destroyed, it can only change form (Energy 2017) . As the world begins to see a change in climate driven by anthropogenic forces, it is fascinating to consider that ancient photosynthesizing organisms harnessed so much of the energy that is now being released into the atmosphere through the burning of fossil fuels. These ancient plants captured the energy of the sun into organic molecules through a remarkable process called photosynthesis and in doing so, provided an ancient form of stored energy that modern humans have exploited to build a complex, energy rich civilization. Unfortunately, the massive release of energy into the atmosphere from stored sources in the geosphere has upended the composition of the Earth's atmosphere, trapping more solar radiation inside the Earth and thus heating the planet (Berner 2003). Humans have taken the gift of stored energy left over by photosynthesizing organisms to create a world that is increasingly dominated by humans, leaving both human and non-human life vulnerable to changes. However, this is not the first time that the Earth has experienced dramatic shifts in atmospheric composition from biologic origins.

Organisms have an impact on the environment around them as they struggle to survive and pass on their genes. Some biologic alterations to the environment are more consequential than others. Perhaps the most striking atmospheric change induced by organic life is the Great Oxygenation Event that occurred roughly 2.4 billion years ago. This compositional change in Earth's atmosphere is thought to be one of the most important events in Earth history as oxygen is an essential component of complex life (Martin et al. 2018). It occurred through the advent of the most momentous biologic process on Earth, oxygenic photosynthesis. This process fundamentally changed the composition of the atmosphere to include oxygen. It is remarkable to imagine tiny cyanobacteria influencing geologic processes on a global scale. Yet, as Louis Pasteur, the great 19th century microbiologist put it, "The role of the infinitely small in nature is infinitely great" (Louis Pasteur Quotes, n.d.). Thus, examining the geologic and evolutionary history of photosynthesis is essential to understanding the present conditions on Earth. Looking to past global changes can give insights into the current age of human domination and provide context to the rapid rate at which humans have initiated global changes.

From The Soup to The Salad: A Brief Review of the Evolution of Oxygenic Photosynthesis

Photosynthesis has a long, complex evolutionary history that has major implications for life on Earth. It is hard to imagine the planet 3.8 billion years ago, as it was radically different from the world in which we currently exist. Looking back at both the geologic history and phylogenetic trees can provide insights into the origins of photosynthesis in living organisms. The conditions that gave rise to life and photosynthesis are important to understanding the current forms of photosynthesis employed by extant taxa. The oxidation of water is of major consequence for the evolution of life and occurred through one special molecule that split oxygen from water. The proliferation of oxygen in the atmosphere is thought to have been generated by cyanobacteria oxidizing H2O, inadvertently producing O2 as a biproduct through a special molecule called photosystem II. This molecule is the only known place in nature where oxygen is oxidized and this process, called oxygenic photosynthesis began to pump oxygen into the atmosphere starting around 2.4 billion years ago. This marked the beginning of a process called the Great Oxygenation Event, which eventually went on to kill the majority of life on Earth but led to the development of aerobic life (Fisher, Hemp & Valentine 2016). However, photosynthetic primary production is believed to have emerged 3.4 billion years ago (Martin et al. 2016). Thus, life on Earth and phototrophy emerged in an anoxic environment. This also implicates biologic phototrophy as the mechanism for increased oxygenation in the Earth, allowing for a major diversification of life.

Looking at the geologic record for evidence of early life gives some sort of time frame for when the first organisms appeared and provides context for emergence of the first phototrophs. Evidence from the 3.8 billion year old Isua Greenstone Belt in Greenland is thought to indicate the presence of early life through banded iron formations and graphite containing the organic carbon 13 isotope (Tashiro et al. 2017, Olsen 2006). Olsen, reviewing the literature in 2006, found the organic carbon 13 percentages to be within the range for possible H_2 driven photosynthesis. A decade later Tashiro et al. 2017 found enough evidence to support the claim that organic life was responsible for the rock formations. However, these data are inconclusive and a more easily agreed upon sign of early life comes from the microfossils found in the 3.4 billion year old Strelly Pool Formation in Australia (Betts et al. 2018; Sugitani et al. 2015; Olsen 2006). These microfossils show a non-random pattern of carbon isotopic heterogeneity that cannot be explained through abiotic phenomena. The lenticular flanged microfossils held their structural, morphological integrity and cahin-like attachments under acid extraction (Sugitani et al. 2015). This provides a definitive place to root biologic origin and used by Betts et al. as the place to root their molecular timescale analysis of early life evolution.

Regardless of the exact date of the earliest records of life, before photosynthesis, the only significant source of electrons to power primary production was from H_2 produced in geothermal vents. This process, called serpentinization, oxidizes Fe_{2+} minerals in the crust to produce H_2 that is released in the discharge of the hydrothermal vents into the water surrounding the vents (Martin et al. 2018). The serpentine reaction can be simplified to $3FeO + H_2O \rightarrow H_2 + Fe_3O_4$ (Sleep, Bird and Pope 2011). This H_2 can then be used by early organisms to reduce CO_2. Thus, the earliest lifeforms prior to the advent of photosynthesis were likely restricted to areas where serpentinization was occurring. These early organisms were reliant on the Earth's geochemical interactions to survive. It is thought that these early organisms may be similar to extant acetogens that employ the Wood-Ljungdal reductive pathway to produce acetate (Ragsdale & Pierce 2008).

With this pathway, these organisms are able to create a source of organic carbon and was likely the first form of metabolism around the hydrothermal vents.

These same hydrothermal vents are thought to be the initial environment for photoautotrophs to capture light in a reaction center. (Martin et al. 2018). The lower intensity light from the hydrothermal vents would reduce the risk of photooxidation (photoinhibition) that results from the intense oxidizing power of chlorophyl induced by intense UV light that would be irradiating the early Earth in the photic zone of the ocean. Without atmospheric ozone providing protection from strong UV radiation, it would have been challenging for early phototrophs to deal with UV intensity (Wellman & Strother 2015). Additionally, the concentration of life around hydrothermal vents would suggest that phototrophic metabolism would originate in this environment (Martin et al. 2018). Regardless of the exact origin of the first photoautotrophs, anaerobic photosynthesis was the only way forward for phototrophs, until the all-important Great Oxygenation event 2.4 Billion years ago. The leap between anaerobic photosynthesis and aerobic photosynthesis was of critical importance for the development of not only aerobic life, but more broadly the global Earth system.

Through looking at past climatic conditions and conserved phototrophic lineages, we can infer the original electron donor, although there is still much debate. It is unlikely that H_2 was used by the original phototroph because chemolithotrophy was already a finely tuned processes and the investment in a reaction center and chlorophyl would not be beneficial towards the end goal of carbon fixation. H_2S is likely the first electron donor as it has a low redox potential (-270mV) and was abundant in early oceans (Martin et al. 2018; Olsen 2006). Indeed, many extant cyanobacteria lineages have anaerobic sulfide generated photosynthesis conserved. The inclusion of H_2S in metabolism freed life from the constraints of the low light intensity hydrothermal vents. A cyanobacteria cultured from a sulfide spring was found to utilize both aerobic and anerobic photosynthesis. The cyanobacteria could switch from aerobic to anerobic photosynthesis seamlessly, induced by changing levels of sulfur in the environment. The late protozoic ocean was likely euxinic, meaning there is no oxygen but large amounts of H_2S, thus showing the importance of sulfide in the evolution of photosynthesis (Klatt et al. 2015). In this oxygen deprived world, utilizing both aerobic and anerobic respiration likely fueled primary production and conferred advantages to organisms that could utilize both pathways. The ability to switch rapidly between metabolisms would be essential to early photosynthetic organisms ability to survive a changing Earth.

The colonization of land by the plant kingdom was a remarkable event in evolutionary history that resulted in major physiologic changes to the early cells that emerged from the water. Land plants account for the basis of almost all primary growth in terrestrial ecosystems. They are a monophyletic lineage that can trace its origin to a group of green algae that underwent physiologic changes to reproduce in full contact with the atmosphere around 470 million years ago during the Silurian Period. Likely not the first organisms to transition out of the water onto the land, nor the last, these early green algae are without a doubt the most important land colonizers as this lineage as gone on to cultivate the conditions that we currently find ourselves in (Delwiche & Cooper 2015). Of the three bacterial lineages with plastids the glaucophytes, red algae and green algae, green algae is the group from which land plants emerged. The extant lineage of green algae that are most closely related to land plants are the charophytes (Delwiche & Cooper 2015; Welwich & Strother 2015). Thus, modern land plants share similar morphologic characteristics to charophytes including the primary plastids that contain both chlorophyl a and b.

With the emergence of land plants, the colonization of terrestrial environments was possible. From this small group of single celled organisms, incredible diversity has emerged.

While there is some discussion of unresolved plant taxonomy, the Plant Kingdom is generally broken into 12 phyla under two broad categories, the vascular and nonvascular plants. The nonvascular plants consist of 3 phyla, Hepaticophyta (liverworts), Bryophyta (mosses), and Anthocerophyta (horn worts). The vascular plants are broken into two broad categories, seed containing and seedless plants. The seedless plant phyla include Pterophyta (ferns), Psilophyta (whisk ferns), Lycophyta (club mosses), and Arthrophyta (horsetails). These plants reproduce through spores and are the ancestral predecessors to the seed bearing plants. The seed bearing plants are further broken down into two categories, gymnosperms and angiosperms. The gymnosperm phyla are (Gnetophyta, Cycadophyta, Ginkgophyta, Coniferophyta), and the angiosperm phyla is (Anthophyta) (Hader 2018). This final group, the angiosperms, have grown to become the dominant autotrophs for land ecosystems.

The angiosperms, or flowering plants, are the most abundant and diverse group of land plants. They form the major source of primary production for almost all terrestrial systems. Of the calculated 550 gigatons of carbon biomass distributed through the four kingdoms of life, plants make up 450 gigatons of the biomass on Earth (Bar-On et al. 2018). The angiosperms have become incredibly prominent and human life would not be possible without them. It can be easy to forget the importance of microscopic life when standing under the shade of a massive oak or eating a juicy apple. Yet, it is essential that future research focuses on the origins of photosynthesis in early organisms, especially further inquiry into phototrophic microbial forms of life. This provides insight into the earliest forms of metabolism and allows a richer understanding of extant plant physiology. Additionally, understanding the evolutionary history of plants can whittle away at the anthropocentric mindset that modern human society has propagated.

The Great Oxygenation Event

The current atmospheric concentration of O_2 is about 21% (Fisher, Hemp, Valentine 2016), making it the second most abundant gas after nitrogen in Earth's atmosphere. Yet for much of Earth's history, oxygen was not present in more than trace amounts. Sedimentary rocks deposited before 2.4 billion years are rich in minerals, like pyrite (FeS_2) and siderite ($FeCO_3$), that are quickly oxidized and destroyed in the presence of even trace amounts of oxygen. Thus, large quantities of oxygen were not present before 2.4 billion years ago (Fisher, Hemp and Valentine 2016). However, there is sufficient evidence to conclude that there was small amounts of oxygen in the atmosphere as much as 300 million years before the Great Oxygenation Event in quantities higher than the expected rate of oxygen formation from geologic processes. Thus, oxygenic photosynthesis may have an earlier inception than initially thought. With aerobic photosynthesis pumping oxygen into the atmosphere for 300 million before large scale climatic changes are seen, the importance of oxygenic photosynthesis as the only substantial method of creating oxygen in the atmosphere is clear as well as the large timescale that is needed for global effects to take place (Crowe et al. 2013). Thus, the Great Oxygenation Event is not a discrete event, but a continual process that involved many millions of years of oxygen accumulation. First, the oxygen was absorbed into the Earth's oceans before they became oversaturated, and the oxygen began entering the atmosphere (Fisher, Hemp and Valentine 2016). Yet, basically all of Earth's oxygen is from the splitting apart of the water molecule and the release of O_2 as a biproduct from organic, life processes. Incredibly, thought there is great diversity in oxygenic phototrophs, there is only enzyme that is known to split apart water, photosystem II. This remarkable protein has been conserved in all oxygenic phototrophs and is responsible for essentially all oxygen on Earth (Lubitz, Chrysina & Cox 2019). Photosystem II is conserved throughout all aerobic photosynthesizing species, making it one of the most common and essential molecules to life on Earth (Lubitz, Chrysina & Cox).

The first organisms to experience the increase of atmospheric O2 were likely unequipped to handle this new molecule. *Oxyphotobacteria* is the lineage of cyanobacteria that are thought to have the earliest ancestors of oxygenic photosynthesis and created novel ways to deal with reactive oxygen species (Fisher, Hemp & Valentine 2016). Reactive oxygen species are molecules such as peroxides, superoxide and singlet oxygen that can cause oxidative stress in cellular functioning and likely caused the extinction of many organisms that were not able to cope with these reactive molecules. Modern photosynthetic organisms have developed many enzymes to get rid of these problematic molecules through many years of evolution (Fisher, Hemp & Valentine 2016). However, the changes induced by the sudden appearance of oxygen resulted in the disappearance of many organisms that could not adapt to this new environmental reality. Figure 1 from Lubitz, Chrysina & Cox 2019 shows some of the milestones in the evolutionary history of oxygenic photosynthesis. It emphasizes the immense time scale over which life evolved and diversified.

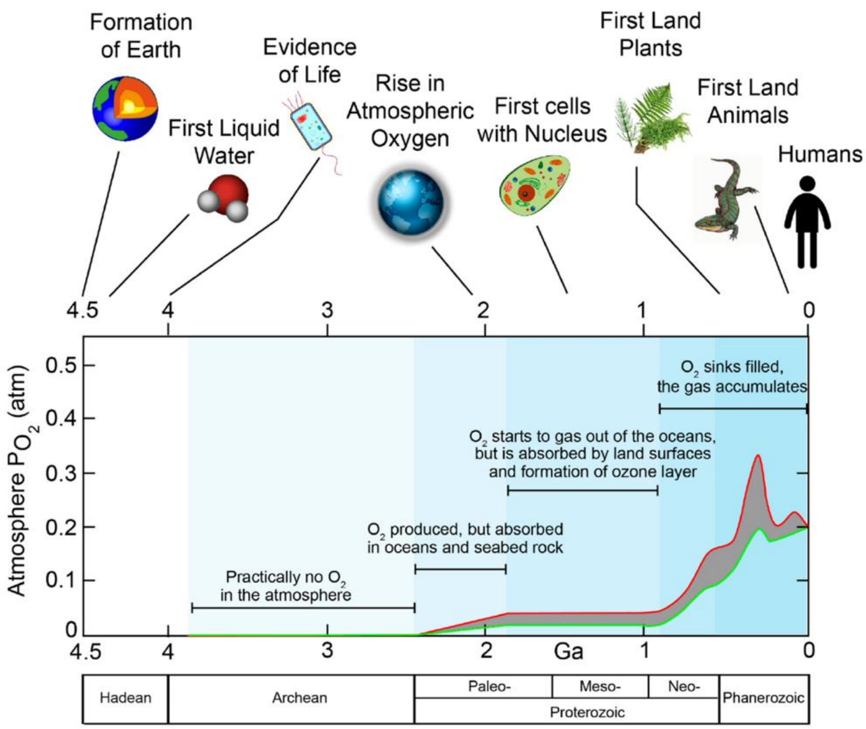

Fig. 1 Oxygen build-up in the Earth's atmosphere on a time scale of billions of years (Ga) and some major events in the development of our planet. The red and green curves denote an upper and lower estimate of the oxygen in the atmosphere. Oxygenic photosynthesis started about ≈ 3.5 Ga ago (Planavsky et al. 2014), the release of O_2 in the atmosphere ≈ 2.4 Ga ago (Bekker et al. 2004). The present level of O_2 is ≈ 21% (Holland 2006)

This massive change in atmospheric composition allowed for the proliferation of animals life and ultimately humans.

Scrutinizing the ways that ancient photosynthetic organisms have influenced global geologic processes provides context to the current changes that the Earth is undergoing, catalyzed by the actions of humans. If microscopic cyanobacteria were able to cause the extinction of thousands of species of organisms and fundamentally alter the course of life history, imagine the kinds of lasting changes that humans are imposing upon the planet with our newly synthesized materials and alterations in land use. Waters et al. (2016) noted that the amount of novel anthropogenic materials such as ceramics, concrete and new organic polymers, is the greatest expansion of new materials on Earth since the Great Oxygenation Event 2400 billion years ago. While changes to atmospheric oxygen have ultimately resulted in human life, they were catastrophic for organisms that were not adapted to an oxygenated world. Yet, this change occurred over a span of some 600 million years and still caused mass extinction (Crowe et al. 2013). In contrast, the changes that humans have begun to induce on the planet have taken a matter of decades, with some potentially devastating consequences for both human and non-human life. The rate at which humans have been able to alter global geochemical processes stands in sharp contrast to the vast majority of Earth's changes throughout geologic time. The scale and rate of human disturbance has led some geologists to declare a new geologic epoch, the Anthropocene.

Plants and Anthropogenic Climate Change

Earth's climate is once again changing. The year 2019 was 0.98 degrees C warmer than the long-term average ("Climate Change" 2019). The last 19 of the 20 warmest years on record have happened since 2001. The extent of Artic Sea ice in September is decreasing 12% every decade ("Climate Change" 2019). The signs of a changing climate are myriad and troubling for both human and non-human life. This anthropogenic induced climate change is indeed the result of human activity, primarily through alterations to the carbon cycle through the burning of fossil fuels. Interestingly, these fossil fuels are composed of ancient marine algae. The ancient algae harnessed the energy of the sun through photosynthesis to produce organic carbon. When the algae died, they dropped to the bottom of the ocean and were crushed through under extreme weight and pressure to become the fossil fuels, namely oil and natural gas, which humans are now extracting and burning (Berner 2003; Chapman 2013). This has led to unprecedented, rapid warming of Earth's climatic system as massive quantities of CO_2 are released into the atmosphere. It is remarkable to consider that ancient plants are the basis for this change in atmospheric composition. Human activity has become so influential and consequential that we have altered geochemical processes on such a scale that a new geologic epoch has been formally proposed by geologists.

The Holocene was ratified as the current geologic epoch in by the International Geologic Congress in 1885. This epoch describes the interglacial period of the past roughly 12-10 thousand years (Steffen, Crutzen, & McNeill 2007). However, in the past two decades, geologists have proposed a new formal geologic epoch, the Anthropocene. This is a hotly debated topic as it has profound implications for the future of human endeavors. Waters et al. (2016) found that the physical markers of the proposed Anthropocene are enough to conclude that the Anthropocene could be formalized as its own geologic epoch. Among the stratigraphic markers included in the analysis was the extreme increase in atmospheric concentration of CO_2 compared with past atmospheric conditions preserved in Antarctic ice cores. From this historic geologic marker, an incredible increase in CO_2 concentrations have been recorded. Since 1850 CO_2 concentrations have risen 120ppm with the rate increasing to roughly 2ppm per year for the past 50 years. Additionally, the methane concentrations during the Holocene ranged from 590 - 760 parts per billion. In 2004 it was an astounding 1700ppb (Waters et al. 2016). These remarkable changes can be attributed to the rampant burning of fossil fuels by humans in the past century and a half. However, the changes to atmospheric greenhouse gas concentrations are just one of the extraordinary changes that humans have wreaked on the Earth. Though humans have altered the global carbon budget, we share this planet with special neighbors that are able to harness the power of the sun to capture some of this carbon. Human beings need to recognize that power plants burning fossilized plants created this mess and conversely, the photosynthetic power of plants can help humans return the globe to a more balanced world; one where the dominant force on Earth is not *Homo sapiens* but organisms that harness the power of the sun.

Just like the ancient photosynthesizing algae that compose fossil fuels, modern plants capture carbon from the air to build their organic molecules through photosynthesis. Thus, one of the simplest and effective ways to capture atmospheric CO_2 is through plants, as discussed later in this paper in further detail. Seeing that plants are the primary production for most ecosystems, when land is left to natural processes, plants take back over, capturing and sequestering carbon. Protecting natural ecosystems in their wild state is essential to reducing the amount of CO2 in the atmosphere. However, humans still need to provide food and shelter to an ever growing human population. Thus, deciphering a balance between meeting human needs while maintaining a planetary system that can support vast quantities of human and non-human life is essential in the coming decades. Through studying plants and their remarkable physical properties, human beings can hope to reverse some of the incredible changes that have been wreaked on the globe and led to the Anthropocene.

Chapter 2: Plant Based Energy: Examining a Plant Powered Life

Food has always been at the center of human civilizations. From the hominid hunter gatherers to the complex farming civilizations along river valleys, the means of food production dictate the foundations of a human society. In modern times, thanks to the Green Revolution following World War II, food production has skyrocketed to provide for an exploding population. This revolution involved the intensification of agriculture to produce higher yields through synthetic fertilizers, mechanization and genetically modified crops. While these technologic advances have led to a reduction in global hunger and allowed for the human population to continually increase, there have been some troubling repercussions that need to be addressed if humans hope to create a world that allows for human and non-human life to flourish.

Among the challenges presented by modern intensive agriculture, is the increasingly apparent greenhouse gas emissions associated with food production, which accounts for close to 30% of the world's greenhouse gas emissions (Clark et al. 2020). The lack of food for 800 million people who go to bed hungry each night and the dearth of nutrition in the processed food we do consume, with one in two Americans suffering from pre-diabetes or type two diabetes, leaves much to be desired from our current means of food production (Hyman 2019). Additionally, the excessive use of nitrogen based fertilizers that are applied in copious amounts to produce monocultured crops have disrupted the natural rhythms of aquatic nutrient cycles, resulting in ecological chaos (Soumare 2020). Through the continued monoculture of row crops grown intensively under repeated tillage and pesticide application, soil degradation has accelerated, as plants are unable to retain soil year round and replenish vital nutrients.

The massive amounts of CO2 in the atmosphere, the degradation of topsoil, nutritious food and eutrophied aquatic systems are problems that all arise from a lack of connection with food production in industrialized nations and a focus on quantity over quality. However, Dr. Mark Hyman points out in his most recent book, *Food Fix,* that there is a better way forward and plants can help in the fight against climate change and lack of nutrition. As he puts it, "We have the technology, it's low cost, it's available globally, and it has been proven and tested (for billions of years). It's called photosynthesis" (Hyman 2019 p. 285). Dr. Hyman lays out many of the issues with the global food system and promotes a growing movement for producing food that focuses on a regenerative means of production that take into account the natural nutrient cycles of the land to grow healthy, abundant food. Grounded with in-depth knowledge of plant physiology and ecosystem dynamics, humans have the capability of creating a regenerative method of producing food; a system built upon the foundation of terrestrial ecosystems, plants. Thus, understanding the remarkable process of photosynthesis that plants utilize to grow is essential to creating a food system that embraces plants.

Plant Photosynthetic Pathways: Harnessing the Power of the Sun

Almost all the energy in the food we eat is initially generated by a fusion reaction within our Solar System's Sun. The energy is released through photons of light that radiate across time and space before some reach Earth's atmosphere. Some of this light is first captured by a protein complex called photosystem II, initiating the first of the two photosynthetic processes, called the light dependent cycle. The second part of the cycle is known as the light independent processes or the Calvin-Benson-Basham cycle. The goal of photosynthesis is to produce glucose and other carbon molecules to be used in the physiology of the cell with the basic equation being $6CO_2$ + $6H_20$ + light = $C_6H_{12}O_6$ + $6O_2$ (Winter 2019). There have been three recorded methods of achieving this common metabolic goal in plant physiology named C3, C4 and CAM photosynthesis, with many unique plants that display intermediaries of these varieties (Winter 2019). These three photosynthetic pathways are remarkably similar, and all share the light dependent cycle as it is one of the fundamental processes that allows life to proliferate on this planet.

The light dependent cycle is used to gather the energy from the sun in the form of solar radiation. This energy is then stored with the addition of a phosphate group to adenine diphosphate, ADP, creating Adenine Triphosphate, ATP, and the addition of a hydrogen atom to NADP+, creating NAPDH. This is accomplished through the generation of a chemiosmotic gradient within the thylakoid membrane (Keiler, Mackerness, Holmes 2003; Kothe et al. 2013). However, to capture the energy, life has created a fascinating method of harnessing energy, while inadvertently cultivating the conditions for other lifeforms to evolve with the splitting of H_2O and the production of O_2. Roughly 3 billion years ago, cyanobacteria utilized a light driven enzyme (photosystem II) to split apart the water molecule into molecular oxygen and hydrogen powering the reduction of CO_2 into organic carbon molecules. Though oxygenic photosynthetic organisms are extremely diverse, they all share the same cellular machinery to split apart water, inadvertently providing oxygen for aerobes to breath (Lubitz, Chrysina & Cox 2019).

Photosystem II, or Ps2, is a remarkable complex of proteins that first captures an electron from solar radiation in the light harvesting complex composed of chlorophyl and carotenoid pigments, though there is much diversity in this area among species. Incredibly, Ps2 oxidizes oxygen, splitting apart the two hydrogen atoms from the lone oxygen atom. This is the only known biologic reaction where oxygen is oxidized (Lubitz, Chrysina & Cox 2019). The freed electrons are then excited by the incoming energy of the sun captured in light harvesting complexes. The electron is then transported down a series of protein complexes in the thylakoid membrane. This creates a chemiosmotic potential of H+ ions in the thylakoid. These H+ ions then diffuse out of the thylakoid through ATP synthase and NADP+ reductase, creating ATP and NADPH to be used to produce sugars. These two molecules are then used as the energy source for the Calvin-Benson-Basham Cycle, which produces the saccharides needed for life processes to occur (Kothe et al. 2010; Winter 2019). It is in the beginning of the second step that the changes in metabolic pathways bifurcates in known plant species. Three categories of photosynthesis are generally described, C3, C4 and CAM photosynthesis.

C3 Photosynthesis

Accounting for roughly 85% of described plant species, C3 photosynthesis is the most common variety of photosynthetic pathways (Sage 2014). It gets its name from the first stable carbon molecule synthesized, Phosphoglycerate, is a three-carbon molecule. These carbon atoms will then go through additional intermediates to be eventually synthesized into Glyceraldehyde 3 phosphate, G3P. This can then be used to synthesize any carbon-based sugar needed by the plant. This is the most common way for plants to perform photosynthesis. However, to decarboxylate the carbon, the enzyme Ribulose 1, 5 biphosphate carboxylase/oxygenase or Rubisco for short, can not only react with CO_2, it can also react with O_2. Rubisco, which is responsible for the carbon capture to begin the Calvin Cycle in every plant cell, becomes inefficient when too much O_2 is present, resulting in a process called photorespiration. This is where the CAM and C4 metabolic pathways are thought to be selected to reduce photorespiration and make the plants more efficient (Sage 2011).

Photorespiration is an evolutionary accident that occurs when the enzyme in plants that first fixes the carbon from the CO_2 molecule, Rubisco or Ribulose 1, 5 biphosphate carboxylase/oxygenase, mistakenly fixes oxygen onto the Ribulose Biphosphate molecule, creating a two carbon molecule, Phosphoglycolate (2PG) instead of Phosphoglycerate (G3P). This is likely due to photosynthesis first developing in an anoxic world. All oxygenic photosynthetic organisms have developed a photorespiratory pathway to get rid of the toxic products of photorespiration and reduce carbon loss (Dellero et al. 2016). Essentially 2PG goes through intermediaries to reach the final goal of G3P to be assimilated into the Calvin Cycle. The most consequential of these intermediaries is glycine, which must be decarboxylated through the Glycine Decarboxylation Complex to produce serine. This is then synthesized into glycerate, which is finally utilized to produce the G3P product. Clearly, this oxygenase activity by Rubisco utilizes a significant amount of energy to reach the starting point for the carboxylase products. This enzyme is so bad at its job, that in C3 plants, half of all Rubisco activity is oxygenase activity, resulting in costly photorespiration for the plant (Ulf-Ingo, Westhoff & Dario 2016). In fact, Rubisco is such an inefficient enzyme and plants have to produce such vast quantities of it, that it is the most abundant soluble protein on Earth (Edwards, Franceschi, & Voznesenskaya, 2004). However, some plants have developed specialized ways to reduce photorespiration through anatomic and biochemical adaptations.

C4 Photosynthesis: Fixing Photorespiration

Avoiding photorespiration is so advantageous to plants, that C4 photosynthesis has evolved at least 65 times independently, making it one of the most convergent evolutionary pathways ever discovered (Sage, Khoshravesh, & Sage, 2016). To date, 7500 species of C4 plants have been identified (Sage 2011). Intriguingly, only angiosperms have been found to perform C4 photosynthesis, with the majority of these lineages being found in three higher plant families, the grass family (*Poaceae)*, the sedge family (*Cyperaceae)* and the rush family *(Chenopodiaceae)* (Sage 2011; Edwards, Franceschi & Voznesenskaya 2004). Rubisco oxygenase activity is more active at higher temperatures, likely why the majority of C4 plants are found in arid environments, where selection for carbon fixation without the threat of photorespiration is thought to be most beneficial. Even though C4 plant species account for roughly 3% of known angiosperms, C4 plants are estimated to produce between 20-30% of terrestrial productivity. This is due to their predominance in grasses found in the expansive tropical and subtropical grasslands (Edwards, Franceschi & Voznesenskaya 2004). Additionally, C4 crop plants include maize and sugarcane, which are staple crops in many countries.

C4 photosynthesis is characterized by spatially separating the fixation of CO_2 by Phosphenol Pyruvate Carboxylase (PEPC), into a four carbon molecule and the subsequent transfer of this four carbon molecule to be decarboxylated and concentrated around Rubisco. This spatial compartmentalization is highlighted by dimorphic chloroplasts, wherein pyruvate pi dikinase (PPDK), which creates PEPC, is contained in one chloroplast type and Rubisco in another (Edwards, Franceschi & Voznesenskaya 2004). The classic C4 photosynthesis is characterized by Kranz anatomy, which consists of two different cell layers, the mesophyll cells and bundle sheath cells, coordinating the initial fixation of CO_2 with PEP carboxylase in the cytosol of the mesophyll cells and the successive transport of CO_2 to the bundle sheath cells for decarboxylation and utilization in the chloroplasts containing Rubisco. Kranz bundle sheath cells surround the vascular bundle and typically have more numerous chloroplasts, thick cell walls to reduce CO_2 leakage and are more tightly packed, reducing the intercellular space to facilitate diffusion of CO_2 between the cells. In these bundle sheath cells; Rubisco utilizes the now decarboxylated carbon and begins the Calvin Cycle unhindered by the costly O_2 molecule and photorespiration.

There are three kinds of biochemical Kranz type C4 photosynthesis based on the decarboxylase enzyme used in the bundle sheath cells (Edwards, Franceschi & Voznesenskaya 2004). These are NADP malic enzyme (NADP-ME), NAD malic enzyme (NAD-ME) and PEP carboxykinase (PEP-KE). In all three types, the mesophyll cells contain the initial carbon fixing PEPC in the cytosol, while the decarboxylases and Rubisco are centered in the bundle sheath cell chloroplasts. The chloroplasts in each cell type not only differ in quantities of enzymes contained within, but also the quantities of grana and thylakoids, thus being referred to as dimorphic. However, not all C4 plants have definitive Kranz anatomy such as the aquatic plant *Hydrilla verticillate* and *Borszczowia aralocaspica* that achieve C4 photosynthesis within a single cell (Pederson 2020; Voznesenskaya et al. 2001). Additionally, there are some plants that display C3-C4 intermediaries within their anatomical structures and biochemical pathways (Sage, Khoshravesh, & Sage, 2014).

In photorespiration one of the main intermediaries between the initial oxygenase activity of Rubisco creating 2 PG and the final product of G3P is glycine. To decarboxylate this molecule, the glycine decarboxylase enzyme, GDC, is one of the most costly enzymes to build as it requires four subunits. In C3 plants, this occurs in the mitochondria of the mesophyll cells. However, some plants that utilize predominately C3 photosynthesis, in that they fix carbon with Rubisco, have developed a glycine shuttle that moves the glycine to the adjacent bundle sheath cells to be decarboxylated with the GDC, producing serine. The serine is then sent back to the original mesophyll cell, where it is utilized by mesophyll chloroplasts to produce G3P and continue the regular Calvin Cycle (Sage, Khoshravesh, & Sage, 2014; Schlüter & Weber 2016). Intermediates that utilize a glycine shuttle to activate the bundle sheath cells in photosynthetic processes are becoming more widely discovered and are viewed as evolutionary intermediaries between C3 and C4 photosynthesis.

Incredibly, some plants have been found to perform C4 photosynthesis within single cells. This challenges the long held idea that Kranz anatomy, with dual cell processes, as the only method to perform C4 photosynthesis. One such plant is *Suaeda aralocaspica*, which is able to complete single cell C4 photosynthesis through dimorphic chloroplasts which compartmentalize the cell into two distinct categories, the carbon fixation portion and the decarboxylation portion. Near the distal end are the chloroplasts containing PPDK to create PEPC and in the proximal end, farther away from the air diffusing in is the Rubisco containing chloroplasts (Koteyva et al. 2016). With the finding that single cells can find perform C4 photosynthesis, many additional species will likely be uncovered that perform C4 photosynthesis or some version of C3-C4 intermediaries. This has great consequence for work looking to make important C3 crops, such as wheat and rice, more efficient and drought tolerant. Identifying ways to create transgenic crops that utilize C4 photosynthesis to reduce photorespiration is a growing field of research and could be a viable way to increase crop yields (Schuler et al. 2016). The final known version of photosynthesis has already created an ingenious way of preventing water loss and photorespiration through temporally spacing its carbon fixation.

CAM Photosynthesis

The third described metabolic pathway is called Crassulaceae Acid Metabolism. This is because it was first described in the Crassulaceae Family and uses malic acid as an intermediate for carbon storage. The main component of CAM is the temporal spacing of photosynthetic activity throughout a 24 hour period. This method fixes CO2 through the stomata at night into malic acid utilizing Phosphenol Pyruvate as the carbon acceptor and Phosphenol Pyruvate Carboxylase (PEPC) as the carbon fixing enzyme, similar to C4 photosynthesis except during dark hours. Unlike C4 though, the malate is then stored in the mesophyll cell vacuole overnight until it is transported out in the morning to be decarboxylated and refixed by Rubisco when the sunlight returns. The returning radiation stimulates the cycle and with the stomata tightly closed, the cell begins the process of utilizing the available CO_2 with Rubisco and initiating the Calvin Cycle (Barrow and Cockburn 1981). This process is categorized into a roughly four periods throughout the day, as shown in Figure 2. From Black and Osmond 2003.

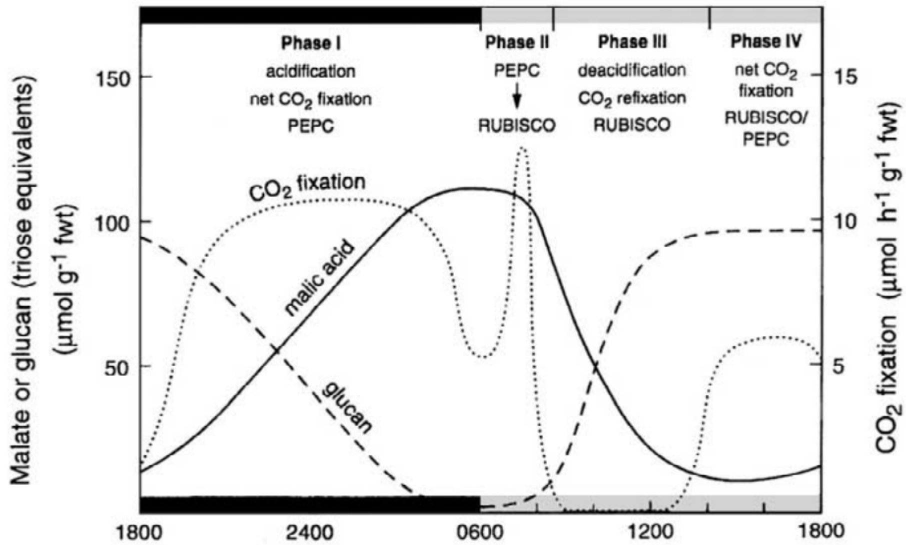

Figure 4. Typical daily patterns of CO_2 fixation and the reciprocal malic acid and glucan (carbohydrates) levels in a CAM plant given good cultural care, in full sunlight, with a 10 to 15 °C difference in the day vs. night temperature. To help understand CAM photosynthesis, the day is divided into four phases (Osmond 1976) with the main carboxylation and acid decarboxylation times noted. The exceptionally high internal CO_2 levels, 0.2 to 2.5%, noted by Cockurn et al. in 1979 occur in Phase III when the stomata are tightly closed. Note the closely coupled, but reciprocal, glucan (carbohydrate) and malic acid curves each day. PEPC – PEPCase.

Temporally spacing out the carbon fixation not only allows the Calvin Cycle to produce carbon-based sugars without the threat of photorespiration reducing the efficiency of the process but most importantly, opening the stomata during the nighttime hours reduces the amount of water loss. CAM plants can be so efficient at utilizing water that Charles Darwin once hung a cut succulent, *Echeveria stolonefira,* upside down and observed the roots begin to grow down and branches grow up. This member of the Crassulaceae family was able to persist without any external water, as CAM is so efficient at preserving water (Black and Osmond 2003). Spacing out the temporal and spatial fixing of CO2 indicates the evolutionary advantage of reducing photorespiration and retaining water (Winter 2019; Brautigan et al. 2017). Conserving water is essential for all plants, especially in arid environments and has led many species to develop methods to fluctuate between C3 photosynthesis and the water conserving CAM photosynthesis. There is increasing research on the amount of plant species that utilize this remarkable form of metabolism and the different forms that this water saving technique can appear, even some that can shift from C3-CAM and back again.

Increasing amounts of research have unearthed the intricacies and plasticity within the phenomena known as Crassulaceae Acid Metabolism. Characterized by the 24 hour photosynthetic cycle, there has been a remarkable number of species, from diverse plant families, that utilize CAM. CAM has been found in 33 families of terrestrial and aquatic plants, comprising roughly 15,000-20,000 species (Black and Osmond 2003). However, this number is constantly increasing as the physiologic mechanisms of CAM are continually teased out. One of the most incredible findings is that CAM can be induced under stress in certain plants. Increasingly, evidence has pointed to numerous categories of CAM.

The most straightforward version of CAM is the constitutive or obligate CAM plants, such as *Sedum lanceolatum* (Gou et al. 2017). These plants are characterized by photosynthetic tissues that consistently mature to utilize a 24 hour photosynthetic cycle wherein the plant fixes all or almost all of its CO2 at night from phosphoenolpyruvate into malate by the enzyme phosphoenolpyruvate carboxylase (PEPC). The CO_2 is then decarboxylated in the cytosol and utilized by RUBISCO in the Calvin cycle (Winter 2019). These plants always utilize this pathway in mature photosynthetic tissue. Typically, constitutive CAM plants live in arid conditions and rely heavily on the sequestration of water to survive.

Facultative CAM is when plants that typically utilize C3 photosynthesis are induced to switch to CAM through some kind of environmental stressor. This was first uncovered in the succulent, *Mesembryanthemum crystallinum,* when it was found to switch to a nightly CO_2 fixation cycle when watered with high salinity H_20. Incredulous, the scientific community concluded that this was part of a natural ontological switch. Yet, under successive experiments, *Mesembryanthemum crystallinum* was found to complete its whole life cycle using C3 photosynthesis when grown under ideal conditions (Winter 2019). Originally from the Sinai desert, this succulent has been introduced across the world and now grows in the wild throughout North America, Europe and Africa. The ability to switch photosynthetic pathways may have contributed to its widespread success as its incredible plasticity in photosynthesis enables it to adapt to different environmental stressors, while maximizing metabolic output.

Some of the most surprising species that have been found to utilize CAM come from the tropics, as CAM is thought to be most beneficial in arid conditions. One intriguing group of plants that displays large plasticity in photosynthetic pathway is the *Clausia* genus. It contains 300-370 species which have species that utilize constitutive CAM, facultative CAM and purely C3 plants (Winter & Holtum 2014). One species of note, *Clausia pratensis,* is a woody shrub that displays the only documented complete transition from CAM to C3 and back during the life cycle of a single leaf (Winter and Holtum 2014). This incredibly plasticity in metabolism is remarkable and has positive implications for utilizing these hardy plants to reduce soil erosion in places that have both a dry and wet season.

Focusing on Plant Based Agriculture

There is a major problem with modern industrial agriculture, humans have forgotten the power of plants. The incredible process of photosynthesis is able to harness the energy of the sun to create food for people to eat. Plants utilizing this process form the basis of primary production for so many ecosystems and has led to a remarkable diversity of plants. Yet only 12 plant species are responsible for 75% of the food humans eat, with 60% of that being made up of the big three, corn, wheat and rice. Additionally, close to 1/3 of the crops humans produce are processed to make animal feed to satiate the burgeoning animal population which is growing to keep up with the human population's appetite for meat (Hyman 2019). The lack of diversity in crop production is driven by mass production to create staple food that can be refined rapidly and cheaply into processed food, much of it to be fed to animals. Reminding ourselves of the diversity of plants and working towards cultivating more varieties can lead to a more healthy and wholistic agricultural system.

Humans are heterochemotrophs, meaning they must break down organic molecules through cellular respiration to produce energy containing molecules, like ATP and NADH to power cellular processes. Since humans have to eat food containing organic molecules to power our cells, they rely on plants to harness the sun's energy to first make organic carbon through photosynthesis. Yet so much of this energy is inefficiently directed towards livestock, rather than humans. The emphasis on meat consumption rather than primarily plant based diets has led to some of the more disastrous changes imposed on the Earth by human forces.

Humans and livestock have truly taken over the world. The wild mammalian biomass has decreased by a factor of 6 from pre-human times, while the total mammalian biomass has increased fourfold from 0.04 GT C to 0.17 GT C (Bar-On 2018). Humans have removed the large mammals from ecosystems the world over and replaced them with large quantities of animals for human consumption. The removal of large mammals from some ecosystems can have deleterious effects on the rhythms of that environment. Take the American Great Plains for example, where millions of bison once roamed across a never ending sea of grasses and wildflowers (Hyman p. 286). Indigenous peoples utilized all parts of the bison to provide food, make shelter from its hide and fashion tools from its bones. In Lakota spirituality, humans are descended from bison and thus treated with reverence and a sense of brotherhood. With the arrival of American pioneers and their misconstrued notion of a manifest destiny, the bison were identified as the life support to the peoples the American Government and systematically removed. Hunters were hired to exterminate the massive ungulates, expunging them in obscene quantities to a few remaining bison hiding in the remote mountains of Yellowstone, leaving the Indigenous peoples of the plains little choice but to surrender to the U.S. government and move onto reservations. These massive ungulates acted as a keystone species on the plains ecosystem. Their hooves churned up the soil aerating it and their dung served to move nutrients across vast areas. Their selective grazing left grass root systems largely intact, while shearing the nutrient rich blades, promoting grass regeneration from intact roots and in turn capturing and storing large amounts of carbon (Hyman, p.286). In the past century, humans have replaced these great herds with even greater quantities of ungulates, cows, though in contained feeding operations that can contain thousands of cows in a few acres. In fact, 97% of native grassland in North America has been lost since European colonization (“North American Bird” 2011), replaced by monocultured row crops. Instead of large mammals churning up soil and grazing grasses across vast swathes of land, many of these animals are trapped within a few acres.

Confined Animal Feeding Operations, CAFOs, are factories for mass producing animals in an efficient and cost effective method. Characterized by unsanitary conditions meant to produce massive quantities of animals for rapid human consumption, CAFO numbers have exploded in recent decades. In 2019, U.S. Confined Animals Feeding Operations produced 8.7 billion animals to be slaughtered (Gilbert 2020). Remarkably, these vast complexes of animals have become so large, and the human influence so great, that humans and domesticated mammals account for 96% of land mammalian biomass. Human biomass accounts for 0.06 GT C while mammalian agriculture, predominately cattle and pigs, is 0.1 GT C. The wild mammalian biomass accounts for only 0.007 GT C. (Bar-on 2018). While biomass is directly proportional to the size of animals being measured, and humans and cows are heavy animals, the incredible scale of animal agriculture is evident. As median wealth has risen across the world, an increase in animal agricultural efficiency has corresponded with an increase in meat consumption across the globe. In China, meat production rose 250% from 1986 to 2012 (Gilbert 2020). The appetite for meat is likely to continue to increase as more world economies become developed. However, production of large amounts of animals naturally requires vast amounts of plants to be produced at cheap prices to fatten up the animals for slaughter.

To feed the vast quantities of cattle confined in these farms, massive amounts of feed must be generated. To ensure a competitive price for the cattle, feed must be inexpensive and easy to process. Thus, vast monocultures of corn and soy are becoming ubiquitous across the globe with the seeds being controlled by a handful of companies. In the U.S. 36% of the corn grown is fed directly to animals in feedlots (Gilbert 2020). In 2018, Monsanto’s seeds accounted for 90% of U.S. corn, 91% of cotton and 94% of soybeans grown (Hyman 2019 p. 267). This seed monopoly held by Monsanto, which recently merged with Bayer, rakes in massive revenues from not only seeds but also the associated fertilizers and pesticides that these seeds are genetically modified to respond to. Thus, Monsanto has both a lateral monopoly in the market but also a vertical monopoly, controlling means of production along all steps of the supply chain. Since 1/3 of the crops go straight to producing animals, big seed companies like Monsanto have a vested interest in continuing the mass production of animals in CAFOS, perpetuating a vicious cycle of overproduction that has deleterious impacts on global and local systems.

This continued planting of commodity crops is tied directly to legislation that perpetuates the cycle. Every five years, the United States Congress passes what is known as the Farm Bill. This omnibus spending bill incorporates everything from conservation initiatives to food assistance programs, making it one of the most influential pieces of legislation that the Federal Government enacts ("What is the Farm Bill" 2019). It is first drafted in the Senate and House Committees on Agriculture before being debated on the floor of the Congress and eventually signed into law by the President. The current bill, titled The Agricultural Improvement Act of 2018, was signed into law by President Trump in December of 2018 and expires in 2023, when a new bill will be drafted ("What is the Farm Bill" 2019). One of the largest problems with the Farm Bill is the vast subsidies for certain commodity crops. While subsidizing the food system is certainly necessary in that the typical market forces of supply and demand do not apply to food (i.e., shortage of food means hungry people), only a few kinds of commodity crops are subsidized, leading to those crops being overproduced. Of course, farmers should have crop insurance to protect them and their families from a failed crop, especially due to weather events. However, farmers get trapped into a cycle of repeating the same commodity crops as "specialty crops," such as nuts, fruit and vegetables are not covered under the federal farm crop insurance (Barth 2019). This omission of healthy, nutrient dense foods ensnares the American agricultural system into producing vast amounts of the same monocultured crops that can be easily processed.

When monocultured row crops, such as corn and soy are planted year after year, they degrade the soil of the vital minerals that enrich plant growth like nitrogen and phosphorous. In order to replace the disappearing nutrients, vast quantities of relatively cheap fertilizers can be applied to continue production. These fertilizers are created through a process known as the Haber-Bosch process (Gilbert et al. 2014). This remarkable feat of capturing atmospheric nitrogen has been one of the most consequential acts of all time and a major reason why the Earth is able to support such a robust population of humans through increasing crop yields (Christopher 2017). However, the advent and subsequent overuse of nitrogen based fertilizers has upended the natural nitrogen cycle and is causing many problems with nutrient loading in aquatic ecosystems.

Eutrophication: Upending the Balance of Nutrient Cycles

The Haber-Bosch process was a created by two German scientists in 1913, just before the beginning of WW I. This remarkable feat of chemical engineering captures atmospheric nitrogen and converts it into ammonia with the equation $N2 + 3H2 \rightarrow 2NH3$ (Gilbert et al. 2014). Ammonia is essential for plant growth and is thus a major component of fertilizers. However, ammonia is also a major component of many types of explosive and incendiary devices. During the two world wars, ammonia was produced on massive scales to create weapons of war that resulted in the death of millions of people. When the wars finally ended, the Green Revolution was catalyzed by the large production capabilities of ammonia factories. With these facilities pumping out new and improved pesticides and fertilizers, crop production soared. The amount of nitrogen based fertilizers have increased from 10 megatons in 1950 to 170 megatons in 2013 (Gilbert et al. 2013). However, only 50% of the nitrogen fertilizer is actually taken up by the plants when applied on fields due to denitrification, NH3 volitization, leaching and runoff (Gilbert et al. 2013). When these excess nutrients flow into the rivers and streams, the change in nutrient concentrations can create complex problems for aquatic ecosystems.

Eutrophication occurs when an overabundance of nutrients builds up in a system. These compounds, namely nitrogen and phosphorous, are usually limiting nutrients to algal growth in these waterways. Nitrogen is typically limiting in marine systems while phosphorous is usually the limiter in freshwater systems (Gilbert et al. 2014). When increased quantities of limiting nutrients are no longer constraining algal growth, harmful algal blooms can occur in which an overabundance of photosynthesizing cells can choke the system. Some of the algal species are not toxic on their own, while some forms of cyanobacteria can be extremely harmful to humans (Gilbert et al. 2014). As the vast quantities of algae die, their carbon is utilized by detritivore bacteria that eat the dead organic material. Many of the bacteria species respire and utilize all of the available oxygen in the water leading to anoxic conditions. Furthermore, many aquatic plants are not able to survive as the surface dwelling algae have blocked out all the sunlight needed for photosynthesis, so no fresh oxygen can be produced, leading to a dead zone where no or little aerobic life can persist. These tragic dead zones can be observed on massive scales at the mouth of large rivers. Marine dead zones are increasing across the globe, especially in areas that use large amounts of fertilizer in crop production (Lin et al. 2020). Creating ways to measure eutrophication levels is of tantamount importance towards incentivizing the reduction of fertilizer runoff.

One way to measure the eutrophication level is to assess the chlorophyl content in the water, as this is indicative of the photosynthesizing cells, be they cyanobacteria, dinoflagellates or algae, that proliferate when released from nutrient constraints. Categorized into five groups based on the concentration of chlorophyl ranging from 0mg/L to the highest at over 25mg/L, this is the most direct way to measure the intensity of algal blooms (Lin et al. 2020). The chlorophyl content is taken with other measurements like dissolved oxygen and nutrient levels to determine the severity and likelihood of harmful algal blooms. The problem of eutrophication and harmful algal blooms highlights the urgent need for humans to reconsider the methods in which they produce food. Incentivizing and prioritizing finding a balance with natural nutrient cycling to ensure a healthy and productive human society and natural systems is essential to continue human flourishing. One way to combat the excessive use of pesticides is to take a new approach to crop production that views farms as interconnected systems of living things interacting with each other, much like how one would view a naturally occurring ecosystem. At the center of this farm ecosystem is the incredible complexity of plants.

Regenerative Agriculture: A Wholistic Approach

The regenerative agriculture movement focuses on managing farm outputs as part of a comprehensive system. Regenerative Agriculture has become a buzzword over the past several years and utilized by many to incorporate numerous diverse agricultural practices. However, one of the major components of this movement is promoting healthy soil, which is composed of millions of microbes and heavily influences the quality of plant production (Christopher 2017). One of the keys points made by many regenerative agriculture proponents is the ability of healthy soil to draw down CO_2 from the atmosphere, helping to mitigate climate change. Creating healthy soil can be achieved through managing farms as interconnected systems, rather than simply blank slates on which to construct CAFOs or plant rows of monoculture crops. This regenerative agriculture movement has the capacity to regenerate soil, increase biodiversity and complement natural nutrient cycles, rather than disrupt them. Yet, the question remains, can these practices be scaled up to feed a human population of 7.8 billion?

One of the biggest benefits with regenerative agriculture is the focus on encouraging natural sources of nutrients for plants to utilize. In contrast to inputting large amounts of nitrogen based fertilizers, regenerative agriculture focuses on capturing nitrogen through naturally occurring nitrogen fixing bacteria that live symbiotically in the root structures of many plant species, like legumes. The nitrogen fixing prokaryotes form a symbiosis in the root nodules of their host plants where the plant provides 12 g of glucose to the associated bacteria for 1 gram of biologically usable nitrogen in the form of ammonium (Soumare et al. 2020). Introducing legume cover crops such as alfalfa and lupin are ways to increase soil nitrogen availability without the need for synthetic fertilizers. Thus, focusing on plant mediated methods of enhancing production is essential to creating a more regenerative agriculture system and reducing overuse of fertilizer. However, many ranchers suggest that animals should be integral players in a holistically managed farm as they are a consequential part of many ecosystems and can help the growth of plants through disturbance and nutrient cycling.

Grass raised beef is a controversial, complex topic. While CAFOS are unequivocally bad for environmental health globally and locally, could a reduction of meat consumption coupled with sustainably raised beef be a part of the solution to creating a more wholistic agricultural system? Dr. Hyman lays out the case for grass fed beef in the final chapter of his book, *Food Fix*, citing the benefits of multipaddock grazing simulating the movements of large herds across grasslands, much like the aforementioned bison of the Great Plains. The shearing of the grass blade, leaving the root balls intact stimulated regrowth in the plant and more carbon sequestered in the roots. One study conducted on White Oak Farms in Georgia found a net carbon sequestration from land grazed by holistically managed cattle herds through all steps of production (Hyman, 2019 p. 319).

Throughout the book Hyman promotes the benefits of grass-fed beef for prompting carbon sequestration. While I agree that the studies cited show the benefit of grazing animals to the health and carbon sequestration potential of some ecosystems, the scale at which this labor intensive process would need to be applied makes me skeptical of the possibility that this sort of wholistic grazing can be implemented broadly enough to maintain current meat consumption while reducing emissions. However, encouraging people to minimize meat consumption and look for equitably sourced food is beneficial towards reducing climate emissions. Yet, grass raised beef cannot compete on a global scale with CAFO raised meat.

A recent study from the World Resource Institute found that many areas of regenerative agriculture can produce large benefits for reducing agricultural Green House Gas emissions. Yet, the authors were skeptical of the ability of regenerative agriculture to be scaled up effectively enough to make a significant impact on agricultural emissions (Ranganathan et al. 2020). For example, the use of cover crops in 85% of agricultural land could sequester 18% of total agricultural emissions in the U.S. Unfortunately, cover crops are presently used in only 4% of U.S. cropland (Ranganathan, Waite, Searchinger & Zionts 2020). However, if legislation was passed to incentivize farmers to try and adopt regenerative practices to access federal subsidies, there could be a significant improvement in the adoption of more environmentally friendly practices. Finding ways to combine practical policy with good science will define the future of agriculture in the U.S.

Photosynthesizing organisms have tremendous power to impact the systems in which they exist. From sequestering carbon in soil, providing healthy food to humans or exploding algal numbers wreaking havoc on ecosystem dynamics, the power of harnessing the suns energy is of major consequence for the global system. Finding a balance with natural nutrient cycles to reduce the overproduction of harmful photosynthetic organisms while maximizing output of crop plants to fulfill human needs is essential towards creating a more wholistic, regenerative system of food production. Understanding the unique properties within each plant is imperative in creating a more equitable world. Whether it is the unique photosynthetic mechanisms housed in a plant mesophyll cell or the symbiotic relationship with fungi in a plants root system, researching the complexities of plants should be a key in producing an agricultural system that not only provides food for to support human life, but also allows for the sustained vitality of wild spaces and organisms.

Chapter 3: Recognizing and Utilizing the Virtues of Plants to Better Human Life

Terrestrial Forests As Carbon Sinks

Trees are some of the most successful land plants, with large swathes of land dominated by these incredible pioneers. Forests have provided human beings with lumber, food and aesthetic value for generations. Consequentially, they sequester vast quantities of the greenhouse gas carbon dioxide through photosynthesis, reducing the amount of human expelled CO_2 and thus keeping the climate in check. All told, terrestrial forests sequester 2.4 +- 0.4 petagrams annually with the current total carbon stock in forests at 861 petagrams. Interestingly, this carbon is not only stored in the biomass but spread out between multiple components of the forest ecosystem with 44% stored in the soil to 1m, 42% in living biomass, 8% in deadwood and 5% in the litter (Pan et al. 2011). With less than half of total forest carbon being conserved in living biomass, these data accentuate the need to protect intact forest systems to sequester the most carbon. When forests are lost, it is not only the large carbon based trees that are removed as a carbon sink but also the soil, deadwood and leaf litter that are no longer sequestering carbon. Especially when these forests remnants are then burned to clear the land, carbon emissions skyrocket as the carbon in the trees is released into the atmosphere. Based on the unique properties of individual forests, carbon storage percentages differ among global forest types. Of the three broad forest types, tropical forests store 471 PgC, boreal forests store 272 PgC and temperate forests hold 119 PgC. Interestingly, tropical forests store 55% of their carbon in living biomass while boreal forests hold only 20% in biomass and 60% in the soil (Pan et al. 2011). This is due to the favorable growing conditions in tropical forests where any available carbon is recycled through decomposers and utilized immediately by surrounding plants. When this forest is chopped down to make room for agriculture, the soil is nutrient poor and massive amounts of carbon are released into the atmosphere. Additionally, these now barren lands that used to hold such high densities of plant life are extremely vulnerable to soil erosion. With a decrease in soil quality, producing crops requires vast amounts of fertilizers (Pan et al. 2011). Unfortunately, the global loss of forests shows few signs of abating.

Deforestation to make room for agriculture, namely ranching and crop production, have decimated forests in recent decades. In the Brazilian Amazon, a total of 169,126 km^2 of forest was cut down between 2001-2010. This deforestation accounted for roughly 4195 Tg C of aboveground biomass lost, which produced 1530 Tg of carbon released into the atmosphere (Numata et al. 2011). The disappearance of this incredible carbon sink is extremely consequential for global and local carbon capture. As tropical forests have poor soils but high biomass, protecting standing tropical rainforest is imperative to conserving the most carbon possible through natural processes. Yet, the insatiable desire for humans to eat meat is the major driver of deforestation in the Brazilian Amazon as more and more forest is turned into pastures for cattle (Numata et al. 2011). The destruction of forest for beef is a remarkably inefficient process for optimizing land use productivity in areas where tropical rainforests naturally occur, especially in capturing and sequestering carbon. However, finding solutions that work with natural systems can be a challenge as humans need to produce food and money to survive. Finding ways to protect forest systems while providing for human flourishing is of tantamount importance in the coming decades. However, a few recent global initiatives have been picking up steam to combat deforestation.

Though deforestation has been an issue for decades, a new campaign has shed fresh light on the subject and gained much popularity in the media. The Trillion Trees campaign is a collaboration between some heavy hitters in the conservation world, Birdlife International, The Wildlife Conservation Society and The World Wildlife Fund, to “connect funders with forest conservation ventures and inspire the world to protect and restore 1 trillion trees by 2050” (The Vision). This project has gained steam as prominent youtubers, like the well known Mr. Beast got in on the action launching campaigns of their own with the Arbor Day foundation to plant 20 million trees (Calma 2021). Even former President Donald Trump turned into a tree hugger, signing an executive order in October of 2020 detailing the United States commitment to assisting in the global campaign in conjunction with the World Economic Forum in Davos. He and First Lady Melania Trump planted a new tree on the White House Lawn and is quoted saying, “On this special occasion, we are renewing our strong national commitment on conserving the wonder of God’s creation. We’re also honoring our country’s heritage of conservation through the One Trillion Tree Initiative, which is a very big deal” (“Trump

Administration," 2020). Clearly, the Trillion Trees campaign has reached a large audience and entered popular media. It is a straightforward way to think about the benefits of forests in capturing large amounts of carbon. Yet, the scientific study that generated these initiatives has received some significant push back from the scientific community indicating that it is perhaps not as big of a deal as the former President believes it to be.

The initial study that generated so much of the hype for reforestation was published in the journal *Science* on July 15, 2019 with the lead author, Jean-Francois Bastin working from the Crowther Lab in Zurich, Switzerland. The authors used satellite data of currently protected land to build a predictive model using environmental variables to determine where forest restoration may be possible. They found that there is currently 0.9 billion hectares of land that could support reforestation and determined that when mature, these forests could capture and store 205 Gigatons of carbon (Bastin et al. 2019). These findings indicated that a massive amount of carbon could be stored simply through reforestation efforts. To be exact 205 GT would be close to 1/3 of the historic carbon emissions since the dawn of the Industrial Revolution (Veldman et al. 2019). This led to the aforementioned hype train of media that followed the trillion trees campaign. If accounting for 1/3 of human produced CO_2 could be as simple as planting one trillion trees, society wouldn't have to worry so much about the amount of carbon used each year as long as we had trees to suck it right back up. However, these data may have been miscalculated according to a scathing rebuke of the paper published shortly after.

A critique of the paper authored by 45 scientists and published in the journal *Science* a few months after the initial report, with the lead author Joseph Veldman of Texas A&M University, claimed that many of the methods utilized by Bastin et al. were flawed. Specifically, the review disputed the author's quantification of carbon stored in the mature forests, claiming that 205 GtC was 5 times too high. They believed the more accurate amount of carbon that would be sequestered is closer to 42 GtC. The critique also noted that Bastin et al. included afforestation of vast swathes of grassland into their calculations, which through fire regimes and herbivores have historically been free of woody plants, allowing grasses to take over. Planting forests in these areas would not only deplete the biodiversity held in grasslands, but would not even capture more carbon than healthy, intact grasslands (Veldman et al. 2019). The discrepancy in the amount of carbon stored by reforestation highlights the imperative for peer review in the scientific process. With the amount of media attention, the initial article got, there was a massive push for reforestation to help reduce the carbon dioxide in the atmosphere. Whole campaigns were launched on the basis of planting trees. It seemed like an easy and uncontroversial process that could reduce some of the human caused global warming being experienced. Yet, with the data so skewed to suggest such a large amount of carbon could be stored, the campaign to plant one trillion trees may not be so straight forward in its benefits for sequestering carbon.

While forests acting as large carbon sinks is certainty the case, the degree to which they can help mitigate the worst effects of climate change remains to be seen. With the media storm surrounding the trillion tree campaign, the power of plants is being shouted to the world. Yet, this highlights the challenges associated with working towards a decarbonized economy and an atmospheric composition more compatible with historic ranges, ecology and conservation is extremely complex. Undoubtedly forests play a vital role in drawing down carbon out of the atmosphere; but focusing solely on their role in the carbon cycle omits so much of the benefits that forests bestow on the world. Tropical forests are the biodiversity hotspots of the world harboring incredible species of plants and animals, many of which are still to be formally recognized by science. Instead of the mantra of planting a trillion trees to mitigate climate change, more emphasis needs to be placed on protecting the intact forest that remains, as well as protecting the other incredible, unique ecosystems on planet Earth, such as grasslands and deserts. Forests don't need humans to plant saplings to recreate them. Trees have been surviving and reproducing in a constantly changing world for millennia. All nature requires is protection from the long arm of man to be able to reestablish. Thus, perhaps a better campaign for ecological protection is in order.

The 30 by 30 campaign is an international collaboration of conservation groups seeking to preserve 30% of the ocean and land for natural processes by 2030. Spearheaded by the National Geographic Society and the Campaign For Nature along with over 100 other conservation non-profits including the Nature Conservancy, this crusade aims to preserve biodiversity while also mitigating climate change. While the trillion trees website (1t.org) has a resources tab with numerous videos and articles detailing the benefits that forests bring, it does not have quite as extensive a library as the website for the Campaign for Nature, which contains a treasure trove of published papers in major scientific journals arranged by topic ranging from biodiversity to protecting indigenous and local communities ("Science Page" 2021). The inclusion of hundreds of peer reviewed papers, as well as large UN reports shows the scientific credibility behind the benefits of simply protecting wild spaces.

This expansive array of scientific data has clearly caught the eye of some influential figures as President Joe Biden signed an executive order on January 27, 2020 to commit the United States to protecting 30% of land and water for management to preserve biodiversity. The U.S. currently protects 26% of its ocean but only 12% of land, or 389 million acres. To reach 30% by 2030, the U.S. will have to protect an additional 440 million acres for a total of 729 million acres set aside for spaces (Sala, Huey, & Toensing 2021). This ambitious goal is going to be a massive uphill battle as that is an incredible amount of land that needs to be protected. Yet, with many in the country becoming more environmentally conscious, it could become a reality. Regardless of whether Biden or the U.S. Federal Government can actually achieve this lofty goal, it shows a commitment to conservation that has been very much lacking at the Federal level since the environmental movement of the 1960s and 70s. People are finally waking up to the importance of preserving wild spaces and the new administration is taking note.

Forests can act as carbon sinks and be extremely beneficial towards reducing the effects of Anthropogenic climate change. Yet, only valuing forests for their ability to soak up carbon fails to take into account the full role that trees play on the Earth. Advocating for the protection of forests and the reforestation of many areas is terrific and the more publicity that conservation has in the public is phenomenal. However, taking a more nuanced stance to incorporate the ecosystem as a whole is critical in maintaining biodiversity as well as combatting climate change. A comprehensive understanding of the many interactions that happen on the ecosystem level is essential in preserving wild spaces for future generations of humans and the diverse organisms that inhabit this world.

Regrowing the Human Connection to the Natural World

As we have seen, plants are essential to the health of our planet. Yet, plants have the capacity to benefit human lives in very direct, intimate ways. Human beings arose in a world dominated by plants. Our ancestors relied on knowledge of the interactions between species to survive. They utilized the myriad properties of plants, such as the abundance of fruit, nuts and animals that survived in community to find sustenance. This forms the basis of the biophilia hypothesis by ecologist E.O. Wilson, which states that humans have an innate tendency to focus on life and life-like processes. Having an affinity for nature is hard wired into our genes. Yet, modern life largely removes humans from contact with the biologic world and replaces it with human constructed buildings and screens. In modern times, most urban dwellers now spend 80-90% of their time indoors (Deng & Deng 2018), separated from the natural world in which their ancestors arose; a world dominated by plants. The move towards a digital life has only increased thanks to the COVID-19 global pandemic that has turned so much of the global economy and way of life upside-down. A marked shift to a digital environment has only served to increase human isolation from the outdoors and natural processes. The human habitat is now encapsulated by four walls and centralized around a screen. Thus, reexamining the ways that human beings can directly connect with the natural world, dominated by plants, is of tantamount importance for not only increasing human physical health, but also reinvigorating the human spirit and combatting negative mental health.

Cultivating plants indoors can have marked benefits for air quality. Phytoremediation is the process of utilizing plants and their symbiotic microorganisms to remove harmful pollutants. One of the most researched components of phytoremediation is the removal of volatile organic compounds, VOCs, from indoor air. VOCs are commonly found in indoor environments and can lead to serious harm for human health. The five major volatile organic compounds found in indoor spaces are formaldehyde, benzene, toluene, ethylbenzene, and xylene (Kwang et al. 2018). Remediating these compounds through house plants and their associated microorganisms was first researched by NASA scientists trying to create a more livable environment for astronauts leaving Earth's atmosphere. One of the pioneers in the field, B.C. Wolverton, a NASA scientists summed up his report on plant benefits in creating a livable environment by saying, "If man is to move into closed environments, on Earth or in space, he must take along nature's life support system, plants" ("Plants Clean" n.d.). Incorporating plants into indoor spaces has the potential to drastically improve the health of humans.

Different plant species utilize different methods for removing VOCs, some more efficiently than others. The VOCs are typically absorbed through the leaves either through an open stomata or through the compounds sticking to the waxy cuticle, where they are then slowly absorbed into the leaf. Once absorbed inside the plant, VOCs are transported through the phloem with photosynthate to the root systems where they can be metabolized. Benzene, toluene and xylene are broken down into intermediates before reaching fumaric acid, which can be utilized in the TCA cycle. Formaldehyde is changed into formic acid and then CO_2 to be utilized in the Calvin cycle (Kwang et al. 2018). Only a few plant species have been studied in their ability to remove VOCs, with marked differences in efficiency. One CAM photosynthesizing succulent, *Crassula portulacea,* was found to remove benzene at a rate of 724.9 ($\mu g\ m^{-2}\ d^{-1}$) (Liu et al. 2007). Not all plants can break down the VOCs internally, some rely on the associated microbes that live in their root systems to metabolize the pollutants, indicating the importance of symbiosis in plants and their symbiotic microbes. Whether through the enzymes found within the plant leaves or the microbes that live alongside plants, improving indoor air quality through phytoremediation is a cost effective way to generate a more healthy environment for humans to thrive in.

Plants not only have a remarkable ability to create healthy air for humans to live in, they also stimulate our mental well-being, pointing towards our affinity to natural processes. In hospital rooms adorned with plants and flowers, patients reported less pain and felt less anxious than patients that had rooms without any plants. The patients surrounded by plants even had lower cytosolic blood pressure than those without (Park & Mattson 2009). This emphasizes the human need for connection with the natural world.

Interacting with the natural world has tremendous benefits not only to human physical health, but also to mental health. In his most recent book, *Our Wild Calling,* nature write Richard Louv describes the ways animal encounters, especially wild animals, can influence our lives. Louv challenges humanity to connect with our fellow life forms on this planet describing how certain special encounters with wild creatures can release humans from ego, allowing us "a doorway into another world" (Louv 2019, p.6). Louv goes on to describe a myriad of physical and psychological health benefits associated with a connection to the natural world such as an increased attention span, mental health alleviation and better physical condition. In addition, he writes frequently about the ability nature has to "reset our and wonder awe." When one stops to consider the complexity of life, the intricacies and interconnectedness of the biosphere becomes apparent.

Louv highlights many explorers and researchers who have had connections with wild animals that transcended the species barrier to create a momentary or lifelong connection with another sentient being. The connection with nature is essential to creating a more humble attitude. Human hubris, our tendency to view ourselves as the dominant species that has mastery over the world, is what has led us to the challenges we face in the Anthropocene. The disconnect from natural systems and species have led to human caused destruction of natural systems. The decimation of species, denigration of ecosystems and anthropogenic climate change, have grown from a misconstrued notion that humans have dominion over the Earth, rather than being an integral part of its interconnected processes and systems. Humans fail to view themselves as part of the world, not the owners of it. Louv quotes an environmental educator named Norah

L'Eespérance near the end of the book who encapsulates this thinking, "The more I have learned about ecology and the story science tells us of the unfolding universe, the more my language has changed in my teaching. When I talk about the planet Earth, I no longer say, 'we are on the Earth.' Now I talk about 'the planet we are a part of.' It's a small change in words but a big shift in consciousness: we're not separate from everything else on the planet, we are actually, literally, completely a part of it" (Louv 2019, p.264). Rhetoric matters and beginning to deconstruct the ways in which humans view themselves as the center of the world creates a new ethic of a collectivist, worldwide mindset. Placing human action in the context of a dynamic ecosystem of interconnected parts is the vision that future human development must undertake. Only then can human activity begin to progress in a sustainable manner.

Reconsidering the role that plants play in human lives has the capacity to create a richer connection with the natural processes that govern life on Earth. Plants may not be as charismatic as the polar bears or pandas, yet they are essential to life on this planet. We must constantly be reminded of the power within each tiny photosynthesizing cell to create oxygen for humans to breath. Realizing human reliance on other life forms will release humanity from the all-consuming anthropocentric pride. When released from human hubris, we will realize that we are not masters of the Earth, but rather members of a living, breathing community reliant on the unique qualities that sustain different forms of life. Cultivating this sense of humility has the capacity to catalyze human action to consider the interconnectedness of world processes and proceed with actions that are in communion with living systems to support human and non-human life's ability and right to flourish.

Arp, T. B., Kistner-Morris, J., Aji, V., Cogdell, R. J., van Grondelle, R., & Gabor, N. M. (2020). Quieting a noisy antenna reproduces photosynthetic light-harvesting spectra. *Science (New York, N.Y.), 368*(6498), 1490-1495. doi:http://dx.doi.org.dml.regis.edu/10.1126/science.aba6630

Barth, B. (2019, January 03). Congress Finally Passed a New Farm Bill and It Continues to Pay Homage to the Cult of Corn and Soy. Retrieved January 29, 2021, from https://modernfarmer.com/2019/01/congress-finally-passed-a-new-farm-bill-and-it-continues-to-pay-homage-to-the-cult-of-corn-and-soy/

Bar-On, Y., Phillips, R., & Milo, R. (2018). The biomass distribution on earth. *Proceedings of the National Academy of Sciences of the United States of America, 115*(25), 6506-6511. doi:http://dx.doi.org.dml.regis.edu/10.1073/pnas.1711842115

Berner, R. A. (2003). The long-term carbon cycle, fossil fuels and atmospheric composition. *Nature, 426*(6964), 323-6. doi:http://dx.doi.org.dml.regis.edu/10.1038/nature02131

Betts, H. C., Puttick, M. N., Clark, J. W., Williams, T. A., Donoghue Philip, C. J., & Davide, P. (2018). Integrated genomic and fossil evidence illuminates life's early evolution and eukaryote origin. *Nature Ecology & Evolution, 2*(10), 1556-1562. doi:http://dx.doi.org.dml.regis.edu/10.1038/s41559-018-0644-x

Black, C. C., & Osmond, C. B. (2003). Crassulacean acid metabolism photosynthesis: `working the night shift'. *Photosynthesis Research, 76*(1-3), 329-341. doi:http://dx.doi.org.dml.regis.edu/10.1023/A:1024978220193

Calma, J. (2020, January 31). Planting 1 trillion trees might not actually be a good idea. Retrieved January 29, 2021, from https://www.theverge.com/2020/1/31/21115862/davos-1-trillion-trees-controversy-world-economic-forum-campaign

Chapman, R. L. (2013). Algae: The world's most important "plants"-an introduction. *Mitigation and Adaptation Strategies for Global Change, 18*(1), 5-12. doi:http://dx.doi.org.dml.regis.edu/10.1007/s11027-010-9255-9

Christopher, J. (2017). The imperative for regenerative agriculture. *Science Progress, 100*(1), 80-129. doi:http://dx.doi.org.dml.regis.edu/10.3184/003685017X14876775256165

Climate change: Vital signs of the planet. (n.d.). Retrieved February 16, 2021, from https://climate.nasa.gov/

Crowe, S. A., Døssing, L.,N., Beukes, N. J., Bau, M., Kruger, S. J., Frei, R., & Canfield, D. E. (2013). Atmospheric oxygenation three billion years ago. *Nature, 501*(7468), 535-8. doi:http://dx.doi.org.dml.regis.edu/10.1038/nature12426

Deng, L., & Deng, Q. (2018). The basic roles of indoor plants in human health and comfort. *Environmental Science and Pollution Research International, 25*(36), 36087-36101. doi:http://dx.doi.org.dml.regis.edu/10.1007/s11356-018-3554-1

Dellero, Y., Jossier, M., Schmitz, J., Maurino, V. G., & Hodges, M. (2016). Photorespiratory glycolate-glyoxylate metabolism. *Journal of Experimental Botany, 67*(10), 3041-3052. doi:http://dx.doi.org.dml.regis.edu/10.1093/jxb/erw090

Delwiche, C. F., & Cooper, E. D. (2015). The evolutionary origin of a terrestrial flora. *Current Biology : CB, 25*(19), R899-R910. doi:http://dx.doi.org.dml.regis.edu/10.1016/j.cub.2015.08.029

Edwards, G. E., Franceschi, V. R., & Voznesenskaya, E. V. (2004). Single-Cell C(4) Photosynthesis Versus the Dual-Cell (Kranz) Paradigm. *Annual Review of Plant Biology, 55*, 173-96. Retrieved from http://dml.regis.edu/login?url=https://www-proquest-com.dml.regis.edu/scholarly-journals/single-cell-c-4-photosynthesis-versus-dual-kranz/docview/220801615/se-2?accountid=28590

Fischer, W. W., Hemp, J., & Valentine, J. S. (2016). How did life survive earth's great oxygenation? *Current Opinion in Chemical Biology, 31*, 166-178. doi:http://dx.doi.org.dml.regis.edu/10.1016/j.cbpa.2016.03.013

Glibert, P. M., Maranger, R., Sobota, D. J., & Bouwman, L. (2014). The Haber bosch-harmful algal bloom (HB-HAB) link. *Environmental Research Letters, 9*(10) doi:http://dx.doi.org.dml.regis.edu/10.1088/1748-9326/9/10/105001

Glibert, P. M. (2020). From hogs to HABs: Impacts of industrial farming in the US on nitrogen and phosphorus and greenhouse gas pollution. *Biogeochemistry, 150*(2), 139-180. doi:http://dx.doi.org.dml.regis.edu/10.1007/s10533-020-00691-6

Guo, J., Lei, M., Yang, J., Yang, J., Wan, X., Chen, T., . . . Guo, G. (2017). Effect of fertilizers on the cd uptake of two sedum species (sedum spectabile boreau and sedum aizoon L.) as potential cd accumulators. *Ecological Engineering, 106*, 409-414. doi:http://dx.doi.org.dml.regis.edu/10.1016/j.ecoleng.2017.04.069

Haider, N. (2018). A brief review on plant taxonomy and its components. *The Journal of Plant Science Research, 34*(2), 277-292. Retrieved from http://dml.regis.edu/login?url=https://www-proquest com.dml.regis.edu/docview/2158169809?accountid=28590

Keeley, J. E., & Busch, G. (1984). Carbon assimilation characteristics of the aquatic CAM plant, isoetes howellii. *Plant Physiology, 76*(2), 525-530. Retrieved from http://dml.regis.edu/login?url=https://www-proquest-com.dml.regis.edu/docview/733490960?accountid=28590

Keeley, J. E. (1998). CAM photosynthesis in submerged aquatic plants. *The Botanical*

Review, 64(2), 121-175. doi:http://dx.doi.org.dml.regis.edu/10.1007/BF02856581

Keeling, P. J. (2010). The endosymbiotic origin, diversification and fate of plastids. *Philosophical Transactions of the Royal Society of London.Series B, Biological Sciences, 365*(1541), 729-748. doi:http://dx.doi.org.dml.regis.edu/10.1098/rstb.2009.0103

Klatt, J. M., Al-Najjar, M., Yilmaz, P., Lavik, G., de Beer, D., & Polerecky, L. (2015). Anoxygenic photosynthesis controls oxygenic photosynthesis in a cyanobacterium from a sulfidic spring. *Applied and Environmental Microbiology, 81*(6), 2025-2031. doi:http://dx.doi.org.dml.regis.edu/10.1128/AEM.03579-14

Koteyeva, N. K., Voznesenskaya, E. V., Berry, J. O., Cousins, A. B., & Edwards, G. E. (2016). The unique structural and biochemical development of single cell C4 photosynthesis along longitudinal leaf gradients in bienertia sinuspersici and suaeda aralocaspica (chenopodiaceae). *Journal of Experimental Botany, 67*(9), 2587-2601. doi:http://dx.doi.org.dml.regis.edu/10.1093/jxb/erw082

Kwang, J. K., Md. Khalekuzzaman, Jung, N. S., Kim, H. J., Shagol, C., Ho-Hyun, K., & Kim, H. J. (2018). Phytoremediation of volatile organic compounds by indoor plants: A review. *Horticulture, Environment and Biotechnology, 59*(2), 143-157. doi:http://dx.doi.org.dml.regis.edu/10.1007/s13580-018-0032-0

Lara, M., Andreo, C. (2011). Abiotic stress in plants-mechanisms and adaptations. *IntechOpen* DOI: 10.5772/24936

Latowski, D., Kuczyńska, P., & Strzałka, K. (2011). Xanthophyll cycle--a mechanism protecting plants against oxidative stress. *Redox Report : Communications in Free Radical Research, 16*(2), 78-90. doi:http://dx.doi.org.dml.regis.edu/10.1179/174329211X13020951739938

Lin, G., Li, K., Liang, S., Li, Y., Su, Y., & Wang, X. (2020). Compound eutrophication index: An integrated approach for assessing ecological risk and identifying the critical element controlling harmful algal blooms in coastal seas. *Marine Pollution Bulletin, 150*, 110585. doi:http://dx.doi.org.dml.regis.edu/10.1016/j.marpolbul.2019.110585

Liu YJ, Mu YJ, Zhu YG, Ding H, Crystal Arens N (2007) Which ornamental plant species effectively remove benzene from indoor air. Atmos Environ 41:650–654

Louis Pasteur Quotes. (n.d.). Retrieved March 14, 2021, from https://www.brainyquote.com/authors/louis-pasteur-quotes

Lubitz, W., Chrysina, M., & Cox, N. (2019). Water oxidation in photosystem II. *Photosynthesis Research, 142*(1), 105-125. doi:http://dx.doi.org.dml.regis.edu/10.1007/s11120-019-00648-3

Martin, W. F., Bryant, D. A., & Beatty, J. T. (2018). A physiological perspective on the origin and evolution of photosynthesis. *FEMS Microbiology Reviews, 42*(2), 205-231. doi:http://dx.doi.org.dml.regis.edu/10.1093/femsre/fux056

North American Bird Conservation Initiative, U.S. Committee, 2011. The State of the Birds 2011 Report on Public Lands and Waters. U.S. Department of Interior: Washington, DC.

Numata, I., Cochrane, M., Souza, J., Sales, M. (2011). Carbon emissions from deforestation and forest fragmentation in the Brazilian Amazon. *Environmental Research Letters*. 6:4

Olson, J. M. (2006). Photosynthesis in the Archean era. *Photosynthesis Research, 88*(2), 109-17. doi:http://dx.doi.org.dml.regis.edu/10.1007/s11120-006-9040-5

Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., . . . Hayes, D. (2011). A large and persistent carbon sink in the world's forests. *Science (New York, N.Y.), 333*(6045), 988-993. doi:http://dx.doi.org.dml.regis.edu/10.1126/science.1201609

Park, S., & Mattson, R. H. (2009). Ornamental indoor plants in hospital rooms enhanced health outcomes of patients recovering from surgery. *Journal of Alternative and Complementary Medicine (New York, N.Y.), 15*(9), 975-980. doi:http://dx.doi.org.dml.regis.edu/10.1089/acm.2009.0075

Pedersen, O. (2020). Jack of all trades - C4 photosynthesis, CAM and HCO3- use in the same tissue. A commentary on: 'structural basis for C4 photosynthesis without kranz anatomy in leaves of the submerged freshwater plant ottelia alismoides'. *Annals of Botany, 125*(6), iv-vi. doi:http://dx.doi.org.dml.regis.edu/10.1093/aob/mcaa034

Plants Clean Air and Water for Indoor Environments. (n.d.). Retrieved January 30, 2021, from https://spinoff.nasa.gov/Spinoff2007/ps_3.html#:~:text=The%20answer%2C%20according%20to%20a,life%20support%20system.%E2%80%9D%20Plants.

Ragsdale, S. W., & Pierce, E. (2008). Acetogenesis and the wood-ljungdahl pathway of CO(2) fixation. *Biochemical Et Biophysica Acta, 1784*(12), 1873-1898. doi:http://dx.doi.org.dml.regis.edu/10.1016/j.bbapap.2008.08.012

Ranganathan, J., Waite, R., Searchinger, T., & Zionts, J. (2020, September 24). Regenerative Agriculture: Good for Soil Health, but Limited Potential to Mitigate Climate Change. Retrieved January 29, 2021, from https://www.wri.org/blog/2020/05/regenerative-agriculture-climate-change

Sage, R. F., Khoshravesh, R., & Sage, T. L. (2014). From proto-kranz to C4 kranz: Building the bridge to C4 photosynthesis. *Journal of Experimental Botany, 65*(13), 3341-3356. doi:http://dx.doi.org.dml.regis.edu/10.1093/jxb/eru180

Sala, P., Huey, P., & Toensing, P. (2021, January 28). The U.S. commits to tripling its protected lands. Here's how it could be done. Retrieved January 29, 2021, from https://www.nationalgeographic.com/environment/2021/01/biden-commits-to-30-by-2030-conservation-executive-orders/#close

Science Page. (n.d.). Retrieved January 29, 2021, from https://www.campaignfornature.org/science-page

Schuler, M. L., Mantegazza, O., & Weber, A. P. M. (2016). Engineering C4 photosynthesis into C3 chassis in the synthetic biology age. *The Plant Journal : For Cell and Molecular Biology, 87*(1), 51-65. doi:http://dx.doi.org.dml.regis.edu/10.1111/tpj.13155

Sleep, N. H., Bird, D. K., & Pope, E. C. (2011). Serpentinite and the dawn of life. *Philosophical Transactions of the Royal Society of London.Series B, Biological Sciences, 366*(1580), 2857-2869. doi:http://dx.doi.org.dml.regis.edu/10.1098/rstb.2011.0129

Soumare, A., Diedhiou, A. G., Thuita, M., Hafidi, M., Ouhdouch, Y., Gopalakrishnan, S., & Kouisni, L. (2020). Exploiting biological nitrogen fixation: A route towards a sustainable agriculture. *Plants (Basel, Switzerland), 9*(8) doi:http://dx.doi.org.dml.regis.edu/10.3390/plants9081011

Steffen, W., Crutzen, P. J., & McNeill, J. R. (2007). The Anthropocene: Are humans now overwhelming the great forces of nature? *Ambio, 36*(8), 614-21. Retrieved from http://dml.regis.edu/login?url=https://www-proquest-com.dml.regis.edu/docview/207670675?accountid=28590

Sugitani, K., Mimura, K., Takeuchi, M., Lepot, K., Ito, S., & Javaux, E. J. (2015). Early evolution of large micro-organisms with cytological complexity revealed by microanalyses of 3.4 ga organic-walled microfossils. *Geobiology, 13*(6), 507-521. doi:http://dx.doi.org.dml.regis.edu/10.1111/gbi.12148

Tashiro, T., Ishida, A., Hori, M., Igisu, M., Koike, M., Méjean, P., . . . Komiya, T. (2017). Early trace of life from 3.95 ga sedimentary rocks in labrador, canada. *Nature, 549*(7673), 516-518. doi:http://dx.doi.org.dml.regis.edu/10.1038/nature24019

The Editors of Encyclopedia Britannica. (2017). *energy | Definition, Types, & Examples*. Encyclopedia Britannica. https://www.britannica.com/science/energy

The Vision. (n.d.). Retrieved January 27, 2021, from https://trilliontrees.org/about/the-vision

Trump Administration Furthers Commitment to One Trillion Trees Initiative. (2020, October 14). Retrieved January 27, 2021, from https://www.doi.gov/pressreleases/trump-administration-furthers-commitment-one-trillion-trees-initiative

Ulf-Ingo, F., Westhoff, P., & Dario, L. (2016). Recent advances in understanding photosynthesis. *F1000Research, 5* doi:http://dx.doi.org.dml.regis.edu/10.12688/f1000res earch.9744.1

Urte Schlüter, Andreas P.M. Weber (2016) The Road to C_4 Photosynthesis: Evolution of a Complex Trait via Intermediary States, *Plant and Cell Physiology*, Volume 57, Issue 5, Pages 881–889, https://doi.org/10.1093/pcp/pcw009

Veldman, J. W., Aleman, J. C., Alvarado, S. T., Anderson, T. M., Archibald, S., Bond, W. J., . . . Zaloumis, N. P. (2019). Comment on "the global tree restoration potential". *Science (New York, N.Y.), 366*(6463) doi:http://dx.doi.org.dml.regis.edu/10.1126/science.aay7976

Voznesenskaya, E. V., Franceschi, V. R., Kiirats, O., Freitag, H., & Edwards, G. E. (2001). Kranz anatomy is not essential for terrestrial C4 plant photosynthesis. *Nature, 414*(6863), 543-6. doi:http://dx.doi.org.dml.regis.edu/10.1038/35107073

Waters, C. N., Zalasiewicz, J., Summerhayes, C., Barnosky, A. D., Poirier, C., Gałuszka, A., . . . Wolfe, A. P. (2016). The Anthropocene is functionally and stratigraphically distinct from the Holocene. *Science (New York, N.Y.), 351*(6269), 1. doi:http://dx.doi.org.dml.regis.edu/10.1126/science.aad2622

Wellman, C. H., & Strother, P. K. (2015). The terrestrial biota prior to the origin of land plants (embryophytes): A review of the evidence. *Palaeontology, 58*(4), 601-627. doi:http://dx.doi.org.dml.regis.edu/10.1111/pala.12172

What is the Farm Bill? (n.d.). Retrieved January 29, 2021, from https://sustainableagriculture.net/our-work/campaigns/fbcampaign/what-is-the-farm-bill/

Winter, K., & Holtum, J. A. M. (2014). Facultative crassulacean acid metabolism (CAM) plants: Powerful tools for unravelling the functional elements of CAM photosynthesis. *Journal of Experimental Botany*, *65*(13), 3425-3441. doi:http://dx.doi.org.dml.regis.edu/10.1093/jxb/eru063

Winter, K. (2019). Ecophysiology of constitutive and facultative CAM photosynthesis. *Journal of Experimental Botany*, *70*(22), 6495-6508. doi:http://dx.doi.org.dml.regis.edu/10.1093/jxb/erz002