ENVIRONMENTAL IMPLICATIONS OF MODERN FOOD PRODUCTION: AN ANALYSIS FOR THE CONSCIOUS CONSUMER

By

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ABSTRACT

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This project explores the pathways by which agriculture affects the environment and determines which foods have the greatest climate, water, and land impacts. Agricultural effects on the environment are extensive, from loss of habitat and declines in regional biodiversity to disruption of global nutrient cycles and climate change. Global food production accounts for 26-34% of annual anthropogenic greenhouse gas emissions, makes up 38-46% of habitable land, and is responsible for 70% of freshwater extraction. The effect of agriculture on the environment is most significantly dictated by what type of food is being produced. Animal-based food products consistently have the highest impact on water, land, and climate; whereas plant-based foods consistently have the least. This means that the most effective method to limiting food-related environmental impacts is to prioritize plant-based food consumption and limit animal-based foods, particularly ruminant (red) meat and dairy.

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INTRODUCTION

"Eating… is inescapably an agricultural act, and how we eat determines, to a considerable extent, how the world is used."– Wendell Berry

Central to daily human life, food has both cultural and personal significance; and, in its greatest extent, food creates a social imperative that brings people together. Often unseen and undiscussed, the environmental consequences of how we produce food have become a growing problem in the modern world. As we grapple with more acute climate changes, water and land degradation, habitat losses, and declining biodiversity, there is an important story to be told about how modern food production systems contribute to these issues. To meet the unprecedented challenges ahead, everyone has an important role to play in creating a world where sustainability and food security are a reality. Our present situation can be overwhelming to think about, and even a little terrifying. The good news is that we know the causes of climate change and other pressing ecological problems; and communities of farmers, scientists, activists, and politicians are making progress in reducing our impact on the planet.

Industrial agriculture is now the most prevalent type of farming practiced worldwide, born from the development of scientific and technological innovations, economies of scale (mass production), and governmental politics (i.e., global trade, food safety regulations, and food labeling). There are several primary agricultural practices that can be classified as industrial, including intensive livestock production (concentrated animal feeding operations and heavy use of antibiotics and growth hormones), monocultures, high input farming (excessive chemical and nutrient inputs), large scale mechanization and heavy tilling, aquacultures, and genetically modified (GM) crop farming (Horrigan et al., 2002). These intensive farming strategies have helped to maximize efficiency and crop yield, with agricultural production nearly tripling between 1960 and 2015 (Wang & Fugile, 2012). This transformation in food production methods has affected more than just food supply. In tandem with the technological advancements that characterize the past century of agriculture, the distribution and ownership of farms have changed markedly as well. Particularly in higher income countries, the consolidation of farm ownership has transformed the industry to be dominated by predominantly large-scale "megafarms" that practice the highest level of industrial production. Today, it is estimated that around 60-70% of global food production operations are designated as "industrial" (FAO, 2021b). In addition to shifting the agricultural workforce composition, the associated specialization and consolidation of farms has also redefined the types of foods commercially available and affordable to consumers.

While the industrial food complex succeeds at producing large quantities of food with increased short-term efficiency, it also produces negative outcomes that affect the environment at both local and global scales. Widespread aquatic chemical contamination, high greenhouse gas emissions, loss of natural carbon sinks, loss of biodiversity, and degradation of aquatic and terrestrial ecosystems across the globe characterize just some of these negative outcomes (Frison, 2016). Forming an unbiased understanding of the environmental implications of modern agricultural practices is difficult. Being informed about the impact our life habits have on the world around us is a powerful responsibility. Systemic change happens in small increments, beginning on an individual level. Through time, our choices change the world.

The purpose of this book is to reduce misinformation and provide readers with a robust scientific understanding of ecological systems and processes affected by food production. From this cognizant position, we can look more critically at how food production interacts with life on Earth and make scientifically informed decisions about what we want our future to look like. While there are many components of the modern food production system (e.g., production, processing, packaging, distribution, consumption, and waste), this project focuses on the production process, which is the source of most food-related environmental impacts (82%) (Poore & Nemecek, 2018). By the end of this book, it will be clear which foods have the largest and smallest environmental footprints in terms of climate change, water quality, and land use.

We begin in Chapter 1 with an exploration of nutrient cycles (carbon, nitrogen, and phosphorus) and how they are affected by agriculture. Chapter 2 focuses on the ways food production alters the quality, abundance, and distribution of water. Chapter 3 examines how much of the globe is dedicated to food production and the various environmental consequences of agricultural land use. Chapter 4 examines the climate implications of food production and how greenhouse gas emissions can vary significantly by food type. Chapter 5, the final chapter, provides solutions and recommendations to minimize the environmental impacts from the food we eat.

CHAPTER 1: NUTRIENT CYCLES

Nutrient cycles are shaped by the dynamic flow of matter and energy throughout Earth's biological, geological and chemical systems. The global carbon (C), nitrogen (N), and phosphorus (P) cycles are central to the structure and function of Earth. Varying forms and amounts of these three elements are exchanged between the atmosphere, biosphere, and geosphere, including both terrestrial and aquatic ecosystems. Agriculture, including land-use changes and fertilizer production, has profoundly changed all three cycles on global scale. Those changes have compromised the health of terrestrial and aquatic ecosystems and have markedly contributed to the increase in greenhouse gases that cause global heating (Wang et al., 2010). This chapter will explore the carbon, nitrogen, and phosphorus cycles and their roles and implications within food production.

Nutrient cycles are the continuous flow of bioelements, those elements essential for life, among Earth's biophysical systems. Terms commonly used when describing nutrient cycles are pools, sources, sinks, fluxes and transformations. Pools, also called reservoirs, are collections of an element identified by where it is found, e.g., atmosphere or soils (DeAngelis, 2012). A source or sink refers to the location of an element that is released or taken up during a biological or chemical process, such as photosynthesis, respiration, or N fixation (Frissel, 2012). Fluxes describe the movement of elements from one pool to another. Transformations, either biological or chemical, refer to any compositional changes that elements and other chemical compounds undergo (Fowler et al., 2013). Transformations are particularly important when discussing plant essential nutrients and their availability.

The Carbon Cycle

Found in abundance throughout Earth's atmosphere, oceans, soils, crust, and within all living organisms, carbon is the fourth most abundant element on our planet (Janzen, 2004). The carbon cycle comprises the production, movement (flux), transformation, and storage of carbon. One of the most significant roles of carbon is the maintenance of a relatively stable and biologically habitable climate largely controlled by atmospheric CO_2 along with water vapor; together they act as a sort of thermostat for our planet (Madsen, 2011). Throughout Earth's history, varying concentrations of CO_2, in addition to other greenhouse gases and aerosols, have contributed to significant changes in climate (Hart, 1978).

Carbon is often referred to as 'the building block of life", as it is the main element of the organic molecules that compose carbohydrates, proteins, lipids, and nucleic acids, all essential for living organisms. Key to processes like photosynthesis and respiration, carbon is also crucial to the Earth's energy cycle (Scharlemann et al., 2014). The essential industrial and technological uses of carbon must also be acknowledged, as it plays a leading role in activities such as materials synthesis and processing and energy production (Sovacool & Brown, 2010).

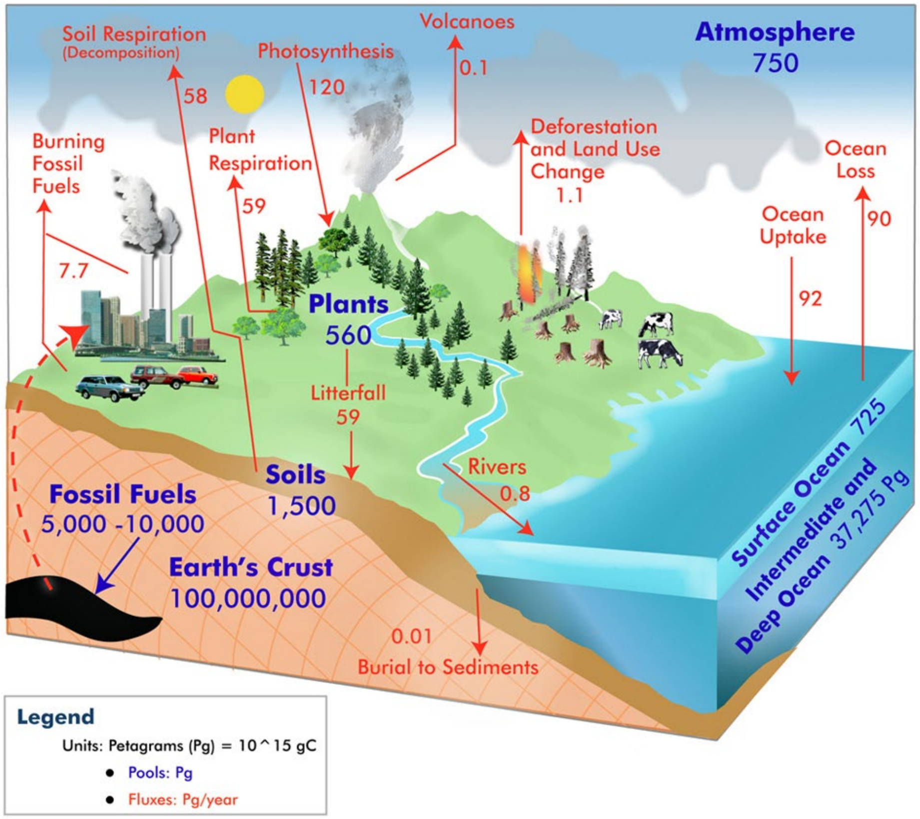

Figure 1. The global carbon cycle, including pools (in blue; Pg) and fluxes (in red; Pg/year) throughout Earth's atmospheric, terrestrial, and aquatic ecosystems. Note that values vary slightly among different sources (GLOBE Carbon Cycle Project, 2017).

Pools and Fluxes

As carbon is cycled throughout the planet, there are several pools where carbon is stored for extended periods of time (Fig. 1; GLOBE Carbon Cycle, 2017). Total carbon is commonly divided into four pools: geologic, oceanic, atmospheric, and terrestrial. Earth's crust, including unextracted fossil fuels, is the largest pool of carbon on Earth; it is estimated to total approximately 100,000,000 Pg C. While this geological pool of carbon is the largest, it generally has a very long residence time, ranging from millions to billions of years (Boyce et al., 2023). However, the length of time carbon is stored in geological systems can vary depending on the type of sequestration process. For example, carbon can be absorbed into the outer layers of rocks and minerals and can be released more quickly than carbon that is mineralized and stored for longer periods of time (Newell & Ilgen, 2019).

More short-term storage and rapid exchange of carbon occurs within the terrestrial biosphere, where it is found largely within soils and plants, but also in animals and microflora. Soils, where the majority of terrestrial carbon exists, contain an estimated 1,500 Pg C. The primary sources of soil carbon are detritus (dead plant matter) and microorganisms. Vegetation constitutes 560 Pg C, most of which is held in the woody tissues of trees. From surface to deep oceans, marine systems contain a total of 38,000 Pg C. The majority of this carbon resides in deeper parts of the ocean in the form of dissolved inorganic carbon (DIC). The atmosphere contains approximately 750-875 Pg C (Friedlingstein et al. 2022; Houghton, 2007), mostly CO_2 but also methane and other compounds. Despite containing less carbon than other pools on Earth, atmospheric carbon via the greenhouse effect is the primary cause of anthropogenic climate change. As such, carbon pools play a critical role in biogeochemical cycling and the regulation of life supporting systems on Earth.

Organic matter in terrestrial ecosystems is stored in both biomass and soils (Houghton et al., 2009). It should be noted that Earth's vegetation is currently a net carbon sink and has increased significantly in size, largely due to forests in the Northern Hemisphere (Potter et al., 2012). One review found that between the 1960s and 2010s, this sink doubled in size (increasing from 1.2 ± 0.5 Pg C yr−1 to 3.1 ± 0.6 Pg C yr^{-1})

(Ruehr et al., 2023). This is largely due to increases in fertilization from rising atmospheric CO_2 combined with the warmer temperatures and increased growing season length (Malhi et al., 2002).

The world's oceans are a significant component of the global carbon cycle, with high flux rates (uptake and emissions) and a large pool in the deep ocean. Through processes of physical CO_2 dissolution, biological uptake, and chemical reactions, oceans absorb about 2 Pg (net) of CO_2 per year (approximately 25-34% of all anthropogenic CO_2 emissions) (Gruber et al., 2019; Keenan & Williams, 2018). Oceans absorb carbon as dissolved inorganic carbon (DIC), dissolved organic carbon (DOC) and particulate organic carbon (POC). The absorption of CO_2in the ocean mostly takes place in surface waters, but longer-term storage occurs deeper, through biological processes like the growth, death, and decay of organisms (Sabine & Feely, 2007). More carbon is stored geologically through the deposition of calcium carbonate ($CaCO_3$) from the shells of marine organisms on the ocean floor that form sedimentary rock (Bachu, 2000).

The most consequential fluxes, with respect to their effects on climate change, are the anthropogenic fluxes of CO_2 from the burning of fossil fuels (7.7 Pg C yr−1) plus those due to deforestation and land use change (1.1 Pg C yr−1). Fossil fuels, even with recent expansions of solar, wind, and other green energy sources, still supply 85% of the world’s energy requirements (EI, 2023). Additionally, land use changes and deforestation release the carbon stored in trees and other vegetation when forests and other landscapes are converted for agriculture (Houghton, 1995). Since the 1750s, atmospheric CO_2 emissions have risen from 280 ppm to over 417 ppm, increasing by roughly 50% (Field

& Raupach, 2004; Fig. 2), and the flux is still increasing. CO_2 emissions from fossil fuel combustion are the dominant cause of global heating (Friedlingstein et al., 2022).

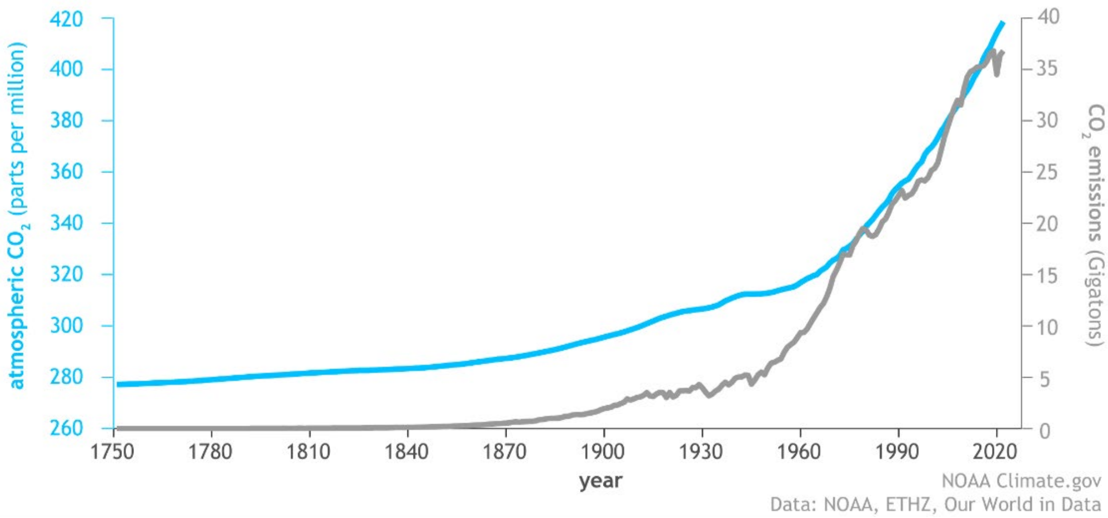

Figure 2: The global atmospheric concentration of CO_2 (blue) compared to the quantity of anthropogenic CO_2 emissions (gray) as they've changed from the mid-1750s to the year 2022 (Lindsey, 2023).

Methane

In addition to CO_2, methane (CH_4) is also an important part of global carbon cycling. Like other greenhouse gases, it contributes to the greenhouse effect and traps heat in the atmosphere. However, methane has a greater global warming potential (GWP) than carbon dioxide, meaning it more efficiently absorbs thermal infrared radiation per unit molecule. On a 20-year timescale, methane per unit molecule is roughly 86 times stronger than carbon dioxide, and 28 times stronger on a 100-year timescale (Jackson et al., 2020). That being said, there is a much higher concentration of CO_2 in the atmosphere than CH_4, and therefore more long-wave radiation is being absorbed by CO_2 overall. Methane also has a relatively shorter residence time in the atmosphere. Carbon dioxide lasts 100-300 years in the atmosphere, whereas methane persists only 8-12 years (Wahlen, 1993).

Nonetheless, methane is an important topic in the conversation surrounding climate change. A variety of natural and human-based activities emit methane, including agriculture, fossil fuel production, and transportation. Within agriculture, the main sources of methane include enteric fermentation from ruminant livestock, rice cultivation, and manure management. Methane constitutes around 16% of greenhouse gas emissions. It is estimated that 40% of global methane emissions come from natural sources (e.g. wetlands, wildfires, termites), and 60% comes from anthropogenic sources (e.g., agriculture, fossil fuels, waste management, landfills) (Karakurt et al., 2012).

The Nitrogen Cycle

Nitrogen is important for all living organisms and ecosystems, existing as a primary component of both protein and DNA structures. Although it is abundant throughout most of Earth’s systems, nitrogen is paradoxically quite scarce in its usable form. Though living organisms only need it in small amounts, it’s often the limiting nutrient and resource for tissue growth and crop production (Stevens, 2019). Nitrogen is integral to the enzymes that mediate important biogeochemical processes like photosynthesis and respiration (Zhang et al., 2020). Farmers commonly supplement their crops with fertilizers that include nitrogen-based compounds. These anthropogenic inputs have profoundly altered the global nitrogen cycle, dramatically increasing the amount of bioavailable nitrogen in terrestrial and aquatic ecosystems (Stein & Klotz, 2016).

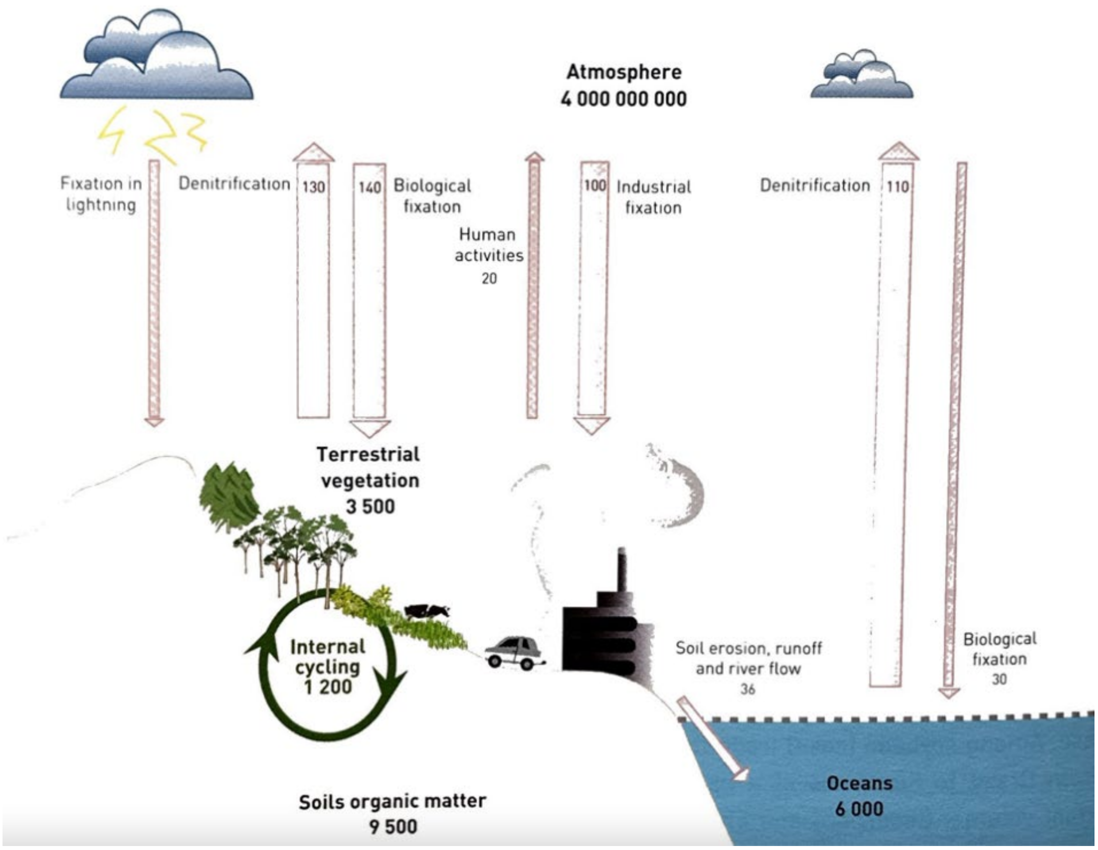

Figure 3: The global nitrogen cycle, with each pool and flux being shown in units of 10^{12} g N per year (Steinfeld, 2006).

Pools

Nearly all of Earth's nitrogen is found in the atmosphere, with less than 1% found in other reservoirs (soils, the oceans, and terrestrial vegetation) (Fig. 3; Steinfeld, 2006). Atmospheric N, mostly in the form of the inert gas dinitrogen (N2), totals 4 x 109 g N

(Trenberth & Guillemot,1994) and makes up about 78% of the atmosphere's volume. It is unavailable to plants and other organisms unless it is fixed (reduced) via biological N fixation or synthetically. In addition to atmospheric nitrogen, the other two main pools of N on Earth are oceans, terrestrial vegetation, and soil organic matter, respectively containing roughly 6 x 1015 g N, 3.5 x1015 g N, and 9.5 x 1015 g N (Prentice, 2008; Post et al., 1985).

In order for N2 gas to be converted into reactive, plant-available forms of nitrogen, it must be transformed through either biological nitrogen fixation or industrial fertilizer production (Anderson, 2022). In biological nitrogen fixation, unreactive nitrogen in the atmosphere is transformed into reactive nitrogen as ammonium-based compounds Wagner, 2011). In industrial nitrogen fixation, the unreactive atmospheric nitrogen is converted into ammonium (NH4) as the initial key ingredient for synthetic fertilizers used in agricultural operations across the world. Industrial synthesis of ammonia works by using high pressure and temperature to break the triple bond between the two nitrogen atoms of N2 gas, which are then combined with hydrogen to form NH3 (Brill, 1977; Galloway et al., 2003). Industrial N fixation has profoundly affected the global nitrogen cycle, nearly doubling global N fixation and, consequently, the amount of reactive N created on the planet every year. Synthetic fertilizers now account for 40% of the nitrogen that crops take up (Smil, 2002). In addition, the high energy costs of producing industrial ammonia emits more CO_2 than any other chemical-making process (Boerner, 2019).

Fluxes

From its fixed form, nitrogen can enter the food chain as it is converted into amino acids and taken up by plants. It can be further transformed within organisms as it moves through the food web. A portion of the nitrogen entering the soil is incorporated as soil organic matter through inputs of plant detritus, e.g., dead leaves, woods, and roots. Nitrogen can also enter the soil as synthetic fertilizers are applied to agricultural fields. Nitrogen is returned to the atmosphere as nitrous oxide (N_2O) through the process of denitrification, which is carried out by microorganisms within anaerobic environments (Knowles, 1982). The emission of N_2O, which is a greenhouse gas, contributes to global warming Approximately 82–130 x 10^{12} g Nyr^{-1} is released by denitrification from land sources, and 110–300 x 10^{12} g Nyr^{-1} is released from denitrification in the world's oceans.

The internal cycling of nitrogen within the terrestrial biosphere involves a series of transformations, including ammonification, where organic matter is broken down by bacteria and fungi. In this process, organic forms of nitrogen are converted back into an inorganic form, releasing ammonium ions (NH_4^+) into the soil which can then be oxidized into nitrite (N_2O^-) and subsequently into nitrate (NO_3^-) by bacterial nitrification (Sharma & Ahlert, 1977; Strock, 2008). Both ammonium and nitrate are readily taken up by plants and used for growth. This flux of nitrogen cycling within terrestrial systems amounts to about 1,200 x 10^{12} g Nyr^{-1} (Steinfeld, 2006).

Excess nitrate that isn't taken up by plants and soil microflora can also be returned to the atmosphere through denitrification or to aquatic ecosystems through leaching and surface runoff. For this reason, the application of nitrogen fertilizers can compromise water quality and impact aquatic communities (Soumare et al., 2020). The amount of nitrogen released by soil erosion, leaching, runoff and river flow totals 36-43 $x10^{12}$ g Nyr^{-1}. Human activities overall are estimated to result in a release of 20×10^{12} g Nyr^{-1} of gaseous N to the atmosphere. The process to produce synthetic nitrogen fertilizers through the industrial synthesis of ammonium is also a significant source of nitrous oxide (N_2O). Agricultural nitrous oxide emissions are estimated to be 6.4–8 $x10^{12}$ g N_2O^- Nyr^{-1} (Reay et al., 2012). Including the N_2O emitted from fertilizer production, livestock management and biomass burning for crop and livestock land expansion, agriculture accounts for 70% of global nitrous oxide emissions (Van Aardenne et al., 2001).

The Phosphorus Cycle

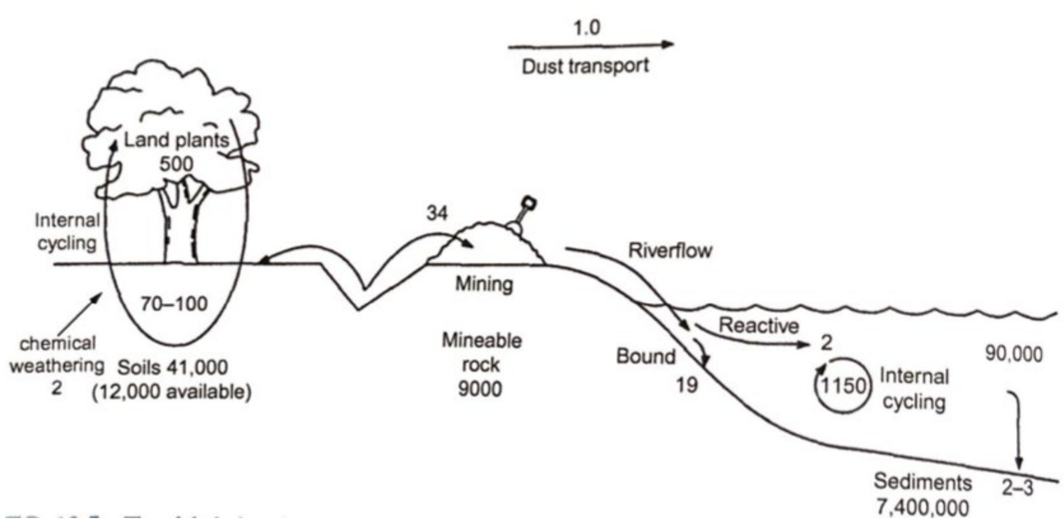

Figure 4: The global phosphorus cycle, showing pools in 10^{12} g P and fluxes in 10^{12} g P per year (Schlesinger & Bernhardt, 2020)

Pools and Fluxes

Phosphorus is an essential nutrient for all biological life forms, playing an important role in the synthesis of DNA and RNA and the production and transfer of energy (Filippelli, 2008). Phosphorus is found throughout terrestrial, aquatic and geological systems (Fig. 4; Schlesinger & Bernhardt, 2020). Geologic sources constitute the largest phosphorus pools and includes phosphorus in deep ocean sediments (7,400,00 x 10^{12} g P) and mineable rock (9000 x 10^{12} g P) (USGS, 2021; Van Cappellen & Ingall, 1996). The next largest phosphorus pool is mineral P released during the decomposition of soil organic matter. The total amount of phosphorus in soils is approximately 41,000 x 10^{12} g P with 12,000 x 10^{12} g P in biologically available forms (Yang et al., 2013; Wang et al., 2010). Land vegetation contains 500 10^{12} g P, most of which is originally derived from chemical weathering and erosion of calcium phosphate minerals (Smil, 2000). The aquatic pool totals 90,000 x 10^{12} g P and primarily includes oceanic phosphorus in the form of dissolved inorganic phosphorus (DIP) plus phosphorus inorganic matter and sediment particles deposited at the bottom of water bodies (Filippelli, 2002; Sundby et al., 1992).

Phosphorus movement and transformation in the biosphere occurs through several processes (Fig. 4; Schlesinger & Bernhardt, 2020). River transport constitutes the main flux of phosphorus in the global cycle, transporting 21 10^{12} gP/yr (Smil, 2000). Another flux is the chemical weathering of rocks and soil minerals, which yields soluble, plant-available phosphorus and supplies phosphorus to terrestrial vegetation (2 x 10^{12} g Pyr^{-1}). Plant uptake makes up another flux, circulating an estimated 70-100 x 10^{12} g Pyr^{-1} into terrestrial ecosystems. The recycling of phosphorus is achieved through plant consumption and the decomposition of organic matter returns it to the soil (Ruttenberg, 2003).

Human activities have greatly influenced the phosphorus cycle. It is estimated that about 34 x 10^{12} g Pyr^{-1} is extracted through mining and used as fertilizers (Yang et al., 2019), which contributes to the amount of phosphorus entering and being carried by river systems. Due to increases in erosion and runoff, the amount of phosphorus transported by rivers today is double what it was 300 years ago, prior to the industrial revolution. In addition, the mining of phosphorus and its modern use in fertilizers has significantly increased the amount of plant available phosphorus on Earth (Metson et al., 2012). It is estimated that 40-60% of agricultural soil phosphorus comes from the application of mineral phosphorus fertilizers (FAO, 2019). Thus, similar to nitrogen, widespread uses of these fertilizers have influenced global cycling of phosphorus and have had various negative implications for the environment.

This chapter has explored the fundamentals of the carbon, nitrogen, and phosphorus cycles and highlighted the important role each of them play in agricultural productivity. We have highlighted how modern human activities, including food production, have impacted these biogeochemical cycles. This foundational information is key to understanding the ways that food production can interact with environmental systems. From here, the following chapters will dive deeper into how imbalanced nutrient cycles can contribute to issues like climate change and water quality degredation.

CHAPTER 2: WATER

Water is essential for life. However, human activities, including agriculture, threaten this precious resource. From freshwater extraction for irrigation and drinking water to water pollution, human impacts on water resources are immense. The depletion and contamination of freshwater resources has had profound implications for biological communities both in aquatic habitats and those adjacent to them. Modern agriculture's dependence on water supply is immense. For crop plants, water is used for irrigation, pesticide and fertilizer application, cooling, and frost control. For livestock, water is used for drinking, cooling, sanitation, and waste disposal (Lovelace, 2009). Understanding the interplay between agriculture and water resources necessitates a closer examination of the way water is obtained and used within food production and how we can support global food production while protecting this precious resource. This chapter will first explore nutrient and chemical agricultural inputs and how they can enter and impact water quality. Following this, we will examine some of the environmental implications of water extraction and use in agriculture and how that affects the quantity and distribution of water resources.

Impacts of Agriculture on Water Quality

Pesticides

Pesticides, an umbrella term that includes insecticides, herbicides, rodenticides, molluscicides and fungicides, are used to safeguard the health and production of plants and livestock (Schäfer et al., 2011). There is often an increased need for pest management in larger-scale industrial or monoculture operations (the practice of growing a single crop on the same plot of land, across consecutive years) due to associated increases in pest populations, reduced crop resistance to pathogens and insects, and greater weed competition (Pimentel & Edwards, 1982). Thus, industrial agriculture relies heavily on pesticides to meet these challenges. In the United States alone, over 400,000 metric tons of pesticides, or 2.54 kg/ha of farmland (FAO, 2022), were applied to croplands in 2020. Without the use of pesticides, we could expect losses of 78% in fruit production and 54% in vegetable production (Tudi et al., 2021). In addition to the benefits of increased agricultural productivity, pesticides have also improved access to affordable food and helped alleviate global hunger. Although highly useful, however, routine application of these chemicals can also harm organisms in nearby water bodies. This section will discuss the benefits and environmental drawbacks of global pesticide use.

Pesticides originated with the use of minerals (e.g. sulfur and copper) and plant extracts (e.g., neem and nicotine) to combat weeds, pests, and diseases in crops thousands of years ago. While these early methods of crop protection were sometimes effective, advancements in the 20th century led to the development of synthetic crop-protective chemicals, among which were DDT and BHC, both hailed for their broad-spectrum effectiveness. In the 1960s and 1970s, environmental concerns about the persistence and bioaccumulation of pesticides or active ingredients in food chains as well as impacts on non-target species led to the banning and improved regulation of such pervasive pesticides (Bertomeu-Sanchez, 2019).

Apart from being categorized by their target organisms, pesticides are often grouped into one of four types: organophosphates, organochlorides, carbamates, and synthetic pyrethroids (Jawale et al., 2017). Application methods include spraying (i.e., broadcast, aerial, directed, and spot application), chemigation (when pesticides are incorporated into irrigation water), or direct application to the soil. The chosen application method is dependent on several factors, such as agricultural setting, target pest, topography and size of the application area, weather conditions, and pesticide form (e.g., liquid and granular). Of course, different application methods have different degrees of environmental risk. For example, over 98% of herbicides and insecticides sprayed on fields reach unintended outside destinations, including water bodies.

Fertilizers

The major plant nutrients needed for tissue growth are nitrogen (N), phosphorus (P), and potassium (K) (Pandey, 2018), which are the majority of fertilizers applied to farms worldwide. Humans have long understood that soil supplements— what is now called fertilizer — can increase crop production (Parr & Hornick, 1992). Several millennia ago, Roman and Asian agriculturalists utilized nitrogen fixing plants and applied wood ash, seaweed, sewage waste, and manure to increase soil fertility (Jones, 2013; Tietz & Von Minckwitz, 2023). Still used by modern farmers today, nutrient supplements can help ensure that soils are fertile, productive, and erosion resistant.

As scientific and technological developments accelerated into the 20th Century, one new technology revolutionized the farming industry, dramatically raised crop yields, and helped catalyze a sharp increase in human population growth. In 1908, German scientists Fritz Haber and Carl Bosch developed the process for converting atmospheric nitrogen gas into inorganic ammonia, which was used for the production of nitrogen fertilizer, as well as explosives and (Erisman et al., 2008). The industrial synthesis of ammonia, also termed the Haber-Bosch Process, quickly became commercialized and was integrated into the industrial agricultural model.

Through additional processing, the ammonia can be converted into nitrogen-containing compounds like ammonium nitrate (35% nitrogen) or urea (46.6% nitrogen), which are forms of nitrogen that can be easily absorbed and utilized by plants (Smil, 2004). These compounds can be used to ameliorate nutrient deficiencies and markedly increase crop yields. Global nitrogen fertilizer application began increasing rapidly enough that by the mid 1990s, global inputs totaled over 50 kg N/ha, a roughly 10-fold increase from how much was applied in the 1950s (Fig. 5). In total, there has been a 125-fold increase in inorganic nitrogen input per hectare across the past century (Kimbrell, 2002).

The industrial manufacturing of nitrogen fertilizers enabled the unprecedented population expansion from 1.6 billion people in 1900 to 8 billion people today in 2023 (Cilluffo & Ruiz, 2019). The Haber-Bosch breakthrough eliminated the largest limitation on crop production, essentially eliminating the primary limitation for human population growth as well. The world was never the same.

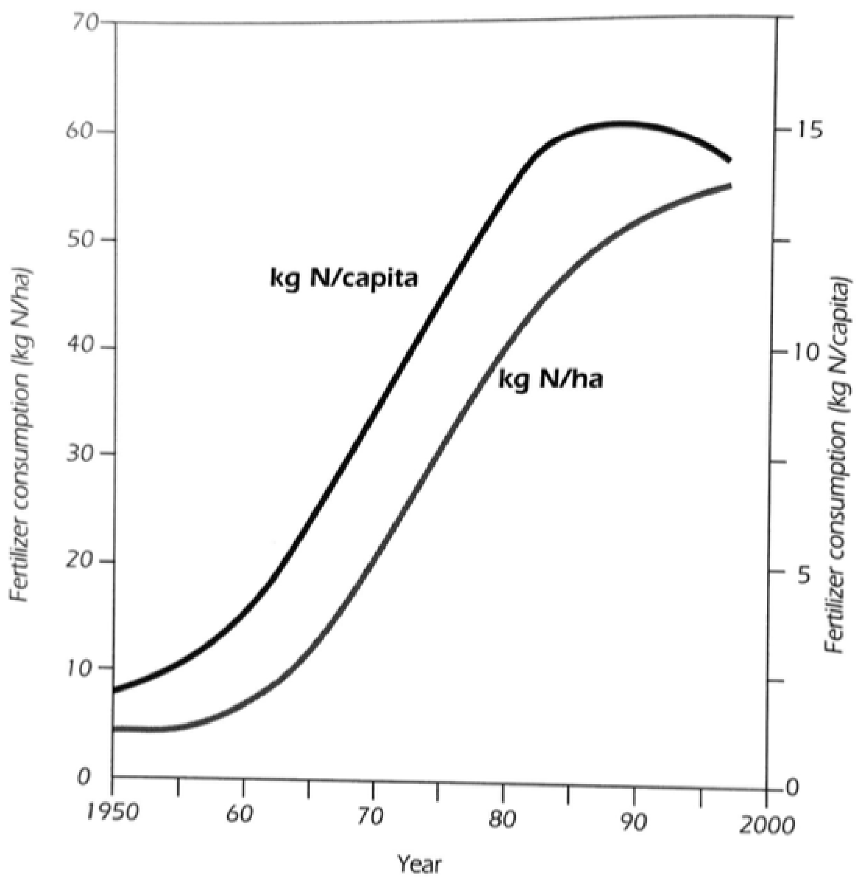

Figure 5: Global fertilizer applications in kg N per hectare and per capita from 1950 to 1996 (Smil, 2004).

Synthetic, inorganic nitrogen fertilizer and organic nitrogen amendments are markedly different with respect to their reactivity, effects on the environment, and commercial availability in large quantities. Organic fertilizers, which are those derived from natural sources such as plant and animal materials, release nutrients slowly as they are broken down by soil microorganisms. This minimizes the degree of nutrient leaching and subsequent issues for water quality (Hazra, 2016). Inorganic fertilizers are taken up rapidly by plants; however, nitrate, which is often a component of fertilizer, is highly mobile. Excess nitrate from farms is one of the primary causes of eutrophication of surface waters. Organic fertilizers generally improve soil health via an increase in soil organic matter that promotes improved soil structure, increased plant available water, and microbial diversity and function. In contrast, inorganic fertilizers offer no soil-related benefits (Chen, 2006).

Farmers consider several factors when choosing between organic or inorganic fertilizers, including cost, availability, equipment requirements, crop type, climatic conditions, and soil type. Like anything in life, there are benefits and drawbacks of both types of fertilizers. Within these two groups, fertilizers can be defined as single nutrient, multi-nutrient, binary (NP, NK, PK), or NPK (nitrogen, phosphorus, or potassium-based fertilizers), or balanced NPK fertilizers. There are several types of synthetic, inorganic fertilizers including nitrogen (slow, fast, and controlled release), ammonia (NH3), potassium, or phosphorus. Alternatively, organic fertilizers are made up of any plant, animal, or otherwise naturally occurring product or byproduct of natural biological processes. This includes sources like compost, bone, fish emulsion, coco peat, peat moss, mulch, or even sewage (Bi et al., 2010).

Increased crop production is mostly dependent on the method of fertilizer application. How fertilizers are applied depends on the crop type, soil conditions, weather, and fertilizer type. Broadcasting, which is a common practice for field crops like wheat, corn, or soybeans, involves spreading dry or granulated fertilizer across soil surfaces using mechanical equipment (Shahena et al., 2021). While this method provides a more uniform application, it creates a higher risk for nutrient loss through runoff or volatilization. Band placement concentrates bands of fertilizers in rows or at the base of plants, which optimizes nutrient uptake and reduces nutrient loss. This is commonly used in crops like maize and potatoes (Wang et al., 2018). Topdressing involves applying fertilizers directly to topsoils surrounding already established plants, like fruit trees. In foliar application, fertilizers are sprayed onto the plants themselves and can be useful in rapidly addressing nutrient deficiencies or diseases (Żarski & Kuśmierek-Tomaszewska, 2023). Drip irrigation delivers nutrients directly into the root area through injection of liquid fertilizers, allowing for greater precision. This method is common in greenhouse or horticultural settings. Fertigation is a method that combines irrigation and liquid fertilization delivered via drip or sprinkler, which offers greater efficiency and precision of application (Liu, 2023). Fertilizers can also be incorporated directly into seed mixes prior to planting, which can support early growth stages of crops, particularly small-seeded plants (Rocha et al., 2019). Some fertilizers can also be incorporated into soils during tilling processes, while others utilize subsurface placement to directly target roots (Afzal et al., 2020).

Generally speaking, the application methods that are better for the environment include drip irrigation and fertigation, band placement, and subsurface placement. Broadcasting is the least precise method of fertilizer application and therefore carries the greatest potential for environmental harm. Topdressing and foliar application pose similar potential risks if not properly managed. The overuse or improper management of any of these methods can have deleterious ecological consequences, including nutrient contamination of water bodies and increased emissions of greenhouse gases (e.g., nitrous oxide) (Savci, 2012).

Contamination Pathways

Agricultural inputs aren't always well contained. When farmers apply fertilizers or pesticides to their fields, a portion of them inevitably enter and move through adjacent land and into water bodies, affecting the organisms there (Chaney & Oliver, 1996). Due to their connective and widespread nature, freshwater systems are particularly vulnerable to this type of pollution. Deeply interconnected, nutrients, chemicals, and organic materials are continuously exchanged between aquatic and terrestrial systems through the movement of organisms, flow of water, and precipitation and erosion events within the watershed (Chapin et al., 2009). The nature of these dynamic systems means that inputs from agriculture can easily pollute and degrade aquatic ecosystems.

Leaching, Runoff & Erosion

Specific pathways that fertilizers and pesticides take to leave farmland soil and enter aquatic ecosystems include leaching into groundwater, erosion, and runoff into surface waters. Leaching can occur when water from irrigation or precipitation percolates down through soils, taking any added dissolved nutrients or water-soluble pesticides with it. This process can carry inputs deep into the soil profile, past the root zone, and into groundwater. It's more common for this to happen in croplands with well drained soils and higher water tables. For instance, studies have estimated that more than 50% of applied fertilizers are not taken up by crops and end up leaching into surrounding environments (Ayuob, 1999). In general, pathways of nutrient and chemical loss vary in different geographic areas due to spatio-temporal and agro-meteorological variability across regions (Schulte et al., 2006). This means that different farms will face different risks of nutrient loss. Environmental parameters like slope, soil type, drainage, and climate influence the movement of fertilizers and pesticides. For example, leaching of fertilizers is generally greater in humid climates than dry ones. For this reason, nutrient management and efforts to reduce nutrient loss will look different from farm to farm.

The risk of leaching for nutrients depends upon their solubility and the charge and size of the component molecules. The most mobile ones are small molecules with a net negative charge. Nitrate (NO_3^-), due to its negative charge and relatively small size, is among the most easily leached. Compared to nitrate, phosphate, due to its larger size, is less mobile and has a lower probability of leaching (Lehmann & Schroth, 2002). Soil pH, or alkalinity, is a large determinant of leaching rates. A low pH (indicating more acidic soil conditions) can increase solubility and mobility, potentially leading to greater amounts of leaching (Neina, 2019). Conversely, soils with a high pH (indicative of alkaline conditions) can reduce solubility of some nutrients, reducing the risk of leaching (Kerle et al., 1994). With respect to pesticides, mobility and leaching rates are largely dependent on the specific chemical composition of the pesticides. For instance, more alkaline soils may cause certain herbicides to degrade quicker, thus reducing their lifetime and leaching potential (Nicholls, 1988).

Surface runoff, another pathway of transport, occurs when excess water from either rainfall or irrigation carries dissolved and particulate fertilizers, pesticides, or other crop residues into adjacent land and surface waters. Surface runoff describes the mobilization of water and pollutants across land surfaces and generally occurs when the rate of water input exceeds the infiltration capacity of the soil. As a result, water is forced to flow in accordance with topography, flowing downhill until it reaches surface waters or a low point or catchment on the landscape (Xia et al., 2020).

Soil erosion often occurs in conjunction with surface runoff, as excessive rainfall or irrigation detaches and transports topsoil rich in fertilizer into adjacent and downhill surface waters bodies. Soil lost through runoff can also transport pesticides into nearby aquatic ecosystems. A number of factors can increase the likelihood of such events, such as intensive tillage practices or lack of adequate soil structure that supports and anchors vegetation. Erosion of topsoil also plays a substantial role in riparian sedimentation (the formation of sediments in river and stream ecosystems). However, runoff and erosion of pesticides and nutrients aren't the only way that water quality can be degraded by agricultural pollutants.

Livestock Waste Management

Since the 1950s, a large portion of animal production in developed countries like the United States has transitioned to concentrated animal feeding operations (CAFOs). Starting in the chicken industry and later practiced by pig and cow farmers in the 1970s and 1980s, CAFOs have become a hallmark of the industrial animal production system (Burkholder, 2007). However, the expansion of CAFOs has resulted in respiratory problems for people in nearby communities and pollution of ground and surface waters (Thorne, 2007). In some Midwest locations, CAFOs have also increased groundwater nitrate concentrations high above the EPA drinking water standard.

Animal-based nutrient pollution originates from the high concentrations of nitrogen and phosphorus found within livestock waste; whether animal excrement is stored in waste pits, ponds or dispersed over croplands as manure, it can create an oversaturation of nutrients and potentially contaminate nearby water systems. In addition to excessive nutrients, animal waste may also contain veterinary pharmaceuticals, including antibiotics, antiparasitics, prophylactics, vaccinations, and growth promotants (most prominently used in beef cattle) (Khan et al., 2008). It is common practice in industrial animal production to supplement animal feed with these types of drugs in order to protect animal health and wellbeing, but they can pose environmental health risks as well (Bradl, 2005).

Other contaminants in livestock waste include pathogens and heavy metals such as zinc and copper (Gerba & Smith, 2005). Antibiotics administered to farm animals for meat production and therapeutic uses account for approximately 80% of all antibiotics (including those for human use) sold in the United States, a country that makes up 46% of the global antibiotic market (Bartlett et al., 2013). These pharmaceuticals are primarily used to prevent infection, treat illnesses, and promote tissue growth to increase the overall efficiency of animal production (Wright, 2010). Cows and pigs receive the majority of antimicrobial drugs in the U.S., at an estimated 41% and 42%, respectively. Animals raised for human consumption are primarily given these drugs in their food (64%) and water (30%), the majority of which is excreted in their waste and subject to transport into the environment (FDA, 2021). Although they play a vital role in human and animal disease prevention, medical pharmaceuticals have many unintended side effects for freshwater ecosystems. Hormone and antibiotic pollution can cause acute and chronic toxicity in microbial, invertebrate, and fish communities; such contaminations can negatively impact respiration rates, growth, reproductive success, and enzyme activity (Bartelt-Hunt et al., 2011; Cheng, 2020). However, accurate assessment of the environmental consequences of antibiotic use is impossible, in part due to the large area in which these contaminants are dispersed into the environment.

Livestock production can pose serious risks to aquatic ecosystems in the same way that nutrients and pesticides can, through surface runoff, leaching, erosion, and deposition. The primary pathways in which pollutants from livestock can enter aquatic ecosystems include improper management of animal waste products, feedlots, and grazing areas. Surface runoff can carry manure, urine, pharmaceuticals, and other contaminants into water bodies. Furthermore, soil erosion resulting from livestock grazing and trampling can transport even more of these contaminants. Depending on location and husbandry practices, livestock may have access to water bodies, where they can introduce waste products and their nutrients and pathogens directly into the water.

Impacts to Aquatic Ecosystems

Freshwater systems have been, and continue to be, profoundly altered by humans. The 2022 Global Living Planet Index (LPI) reported that freshwater vertebrate species population sizes have declined by an average of 83% worldwide from 1970 to 2018 (Westveer et al., 2022). Though not to the extent that freshwater populations have, marine vertebrate population sizes have also declined, with losses of 44% between 1970 and 2016 (Reid et al., 2019). The LPI identified the loss and degradation of habitat as the most prominent threat to biological populations. In that regard, current agricultural practices, including animal waste management and pesticide and fertilizer use, significantly contribute to the degradation of aquatic ecosystems.

Nutrients, primarily nitrogen and phosphorus, are transported from agricultural operations into aquatic ecosystems via leaching or surface runoff where they stimulate aquatic plant growth (Withers & Haygarth, 2007), a process defined as eutrophication. Nutrients that contribute to eutrophication can also result from urban runoff as well. Eutrophication can be highly negative for the health and sustainability of freshwater ecosystems. For most freshwater and coastal marine ecosystems, such nutrient enrichment has become the primary issue impacting water quality and aquatic ecology at every trophic level, from plants to herbivores to predators (Smith & Schindler, 2009). The biological consequences of eutrophication include the growth and spread of toxic algal species, oxygen depletion, mass die offs of fish and other aquatic organisms, and general habitat degradation. Ultimately, eutrophication disrupts food webs and community composition.

The process of eutrophication and mechanisms of these consequential impacts begins with increased primary production from the excess nutrients within the water (Dudgeon, 2006). The nutrients promote growth of phytoplankton and macrophytes (aquatic plants), often resulting in extensive algal blooms throughout the system. An abundance of photosynthesis produces large amounts of oxygen in the water, but once photosynthesis ceases after nightfall, continuous plant respiration and microbial decomposition consumes that oxygen as organic matter is broken down. By morning, the quantity of dissolved oxygen is normally depleted and, in some cases, creates hypoxic conditions (low oxygen, less than 3 milligrams O2 per liter of water) (Withers et al., 2014). Hypoxia can be detrimental to aquatic life, and if depletion continues to the point of anoxia (absence of oxygen, 0 milligrams O2 per liter water), it can quickly kill fish and invertebrates who need it for respiration (Reay, 2015). Hypoxic or anoxic conditions can have serious ramifications, such as declines in biodiversity, alterations to food webs, and mass fish die offs (Harper, 1992). Oxygen depleted areas, colloquially called “dead zones", have the ability to completely transform entire ecosystems in which the majority of biotic life cannot survive, particularly sessile organisms such as benthic invertebrates (Tilman et al., 2002).

Anthropogenic eutrophication of surface waters has become a global problem. Areas like the Gulf of Mexico now experience annual eutrophication episodes that result in a benthic hypoxic zone spanning 10,000 km2 (NOAA, 2021). The result is over four million acres of habitat that is now functionally unavailable, primarily for bottom dwelling fish and invertebrates. It is estimated that 78% of global eutrophication is caused by terrestrial food production activities (Bouwman et al., 2002). As of 2017, the U.S. Environmental Protection Agency has estimated that over 46 percent of rivers and streams in the United States are classified as being in "poor biological condition" (EPA, 2017). This is due in part to eutrophication but also to other factors such as low hydrologic flows, substrate homogenization and lack of complex habitats, and associated higher stream temperatures and greater stress conditions for fish and invertebrates. An estimated 24% of lakes in the U.S. are hypereutrophic, with exceptionally high nutrient concentrations occurring seasonally or year-round (Kuntz, 2022).

Sediments and Pesticides

The ecology and health of surface waters can also be reduced by soil and pesticide inputs from farms. Elevated levels of suspended sediments, resulting from inputs of eroded soils from nearby farms, increases turbidity (reducing water clarity and light level), thereby lowering the photosynthesis rates of aquatic plants (Kemp et al., 2011). In addition, fish spawning grounds and benthic habitats for invertebrates can be compromised or eliminated by sediment buildup (Chapman et al., 2014). Reduced visibility, due to higher turbidity, can interfere with the ability of fish to acquire food and, in extreme cases, fish may suffocate if their gills are damaged or clogged with sediments (Henley et al., 2000). Sedimentation and turbidity, therefore, can significantly alter the structure and function of aquatic ecosystems through their effects on food availability, physiological function, and reproductive success.

Nearly 50% of all groundwater and well water reserves in the U.S. are contaminated with pesticides (Pimentel & Burgess, 2014; Kolpin, et al., 2000). The mobility of pesticides depends on the pesticide's chemistry, soil properties, weather conditions, application practices, and the use of buffer zones. Variations in solubility and persistence of individual pesticides can determine how easily they can leach or run off into surrounding water bodies. Generally, the higher the solubility of pesticides, the greater the mobility and risk of leaching through soil and into groundwater (Cheng et al., 2023).

Agricultural pesticides are toxic to non-targeted aquatic organisms, including fish, amphibians, invertebrates, and plants. The degree of toxicity varies by pesticide type, dosage, exposure time, and lifetime in the environment. Even at low concentrations, many of these chemicals can be harmful to aquatic organisms due to what is called bioconcentration. Bioconcentration is the accumulation and increased concentration of pesticides, which are resistant to metabolism, as they move up the food chain. If not present at an immediately lethal level, pesticides can have a variety of sublethal effects on fish and invertebrates, including diminished reproductive success, greater susceptibility to diseases, weight loss, hormonal disruptions, social behavioral alterations, sterility, and reduced predator avoidance (Helfrich et al., 2009). Herbicides act similarly on aquatic plants and can lead to a loss in vegetation that serves as crucial habitat, particularly as nursery and protective spaces. These impacts can affect species at all trophic levels as well as their interactions with one another. Reduced water quality due to pesticide contamination can lower the fitness and resilience of fish and invertebrates, leading to food web disruption and systemic losses of biodiversity (Helfrich et al., 2009; Relyea, 2009).

Impacts to Water Quantity and Distribution

As concerns increase globally about the availability and quality of water, agricultural water use is receiving heightened attention. Even as farmers have adopted accurate, advanced methods for both determining soil moisture and irrigating fields efficiently, conflicts among water users in agricultural regions are now commonplace. Disputes over water use have risen between farmers, ranchers, homeowners, and municipalities. The availability and quality of water will continue to decline as global heating worsens.

As of 2015, the United States ranks first worldwide in total annual water withdrawals, extracting over 300 billion m3/year. For context, the second leading country is China, withdrawing 140 billion m3/year, roughly half the United States total (Fig. 6). It is estimated that global food production accounts for approximately 70% of global freshwater extraction, and closer to 90% in more arid regions like the Middle East and North Africa (Gleick, 2014; Mekonnen & Hoekstra, 2012).

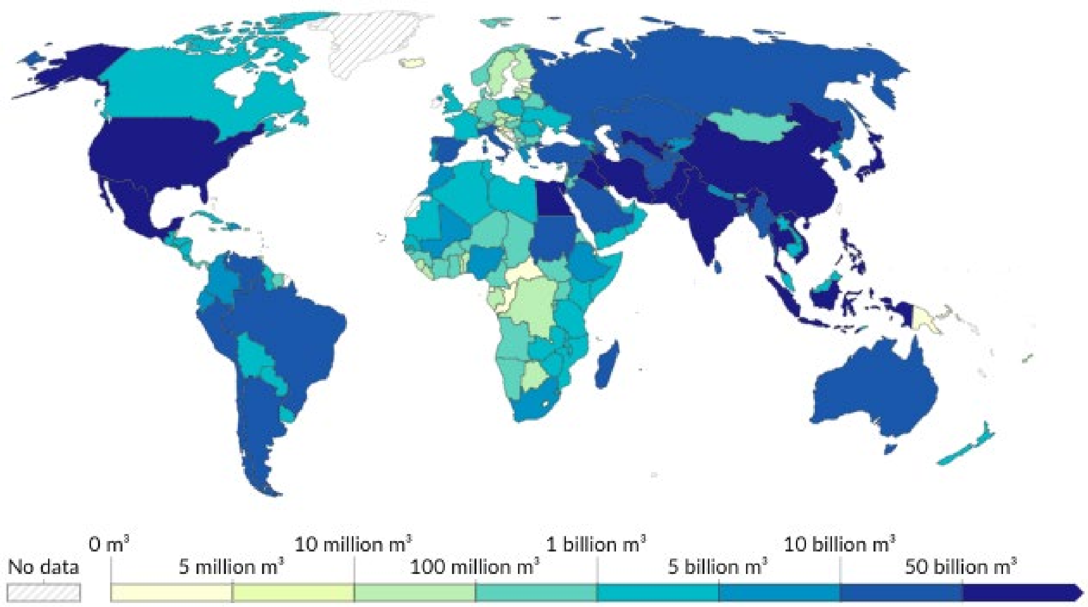

Figure 6: Total agricultural water withdrawals for the year 2015, measured in m3 per year. Quantity of water includes that which is withdrawn for irrigation, livestock and aquaculture purposes (Ritchie & Roser, 2017).

Water Use in Agriculture - Overview

Water has a vast range of uses and functions in modern agriculture, including washing and maintaining equipment and facilities, cooling machinery and animals, and irrigation for crops and animal production. Most of these activities require water withdrawal, or water abstraction, which describes the action of directly extracting freshwater from sources underground or on the surface. Comparatively, extraction describes the larger process of not only direct freshwater withdrawal, but also the transportation, storage, and delivery of water for human uses. Natural water sources like rivers and lakes are often used, but impoundments, like reservoirs or dams, have also been constructed for more significant or long-term withdrawals. Through collecting and retaining water from rivers, streams, or rainfall, impoundments can control water flow in riparian ecosystems and ensure a reliable and consistent source of irrigation water (FAO & UN Water, 2021).

Irrigation is the artificial delivery of water to crops when natural precipitation is insufficient. In many regions, irrigation is essential for crop production. The percentage of irrigated lands, including both arable and grazing land, varies considerably by region and country (Fig. 7). Irrigation is most prevalent in Middle Eastern and Asian countries, where water is applied to more than half of the agricultural areas.

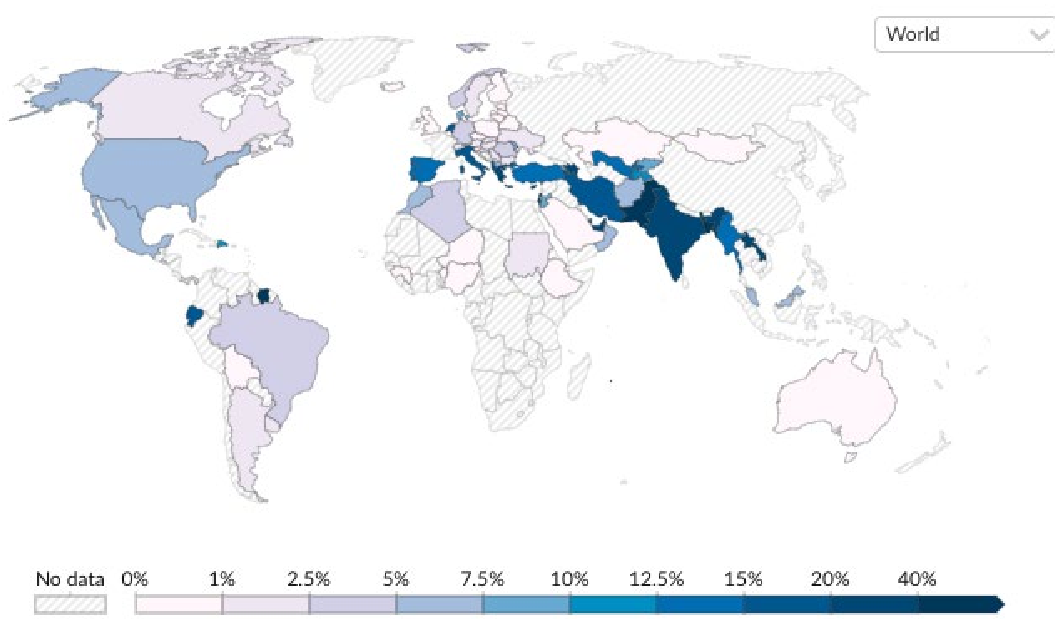

Figure 7: Percentage of total irrigated agricultural lands, including a combination of both crop (arable) and grazing land (Ritchie & Roser, 2017).

Common methods of irrigation include surface, drip, sprinkler, center pivot, flood, and fog and mist irrigation. Irrigation occurs in four phases: water source control (capturing water from natural sources), water delivery (transportation of water to the area of application), water use (precisely what techniques are employed to deliver this water), and water drainage (the management of excess water) (Kelly, 1983). Gravity surface irrigation directly applies water to surfaces such as furrows created between rows of crops or basins surrounding individual plants. This method utilizes gravity for flow and is useful in ensuring root infiltration (Chavez et al., 2020). Drip irrigation, which is considered one of the most efficient methods, involves sending water directly to the root zone through tubes and piping; this minimizes overall water waste, but is more complex and time intensive to install (Camp, 1998). Subsurface irrigation works in the same way, except the tubing that carries the water is installed beneath the soil, further reducing risk of evaporation and runoff. Sprinkler irrigation describes the spraying of water above crops to mimic rainfall. It is easy to modify this method for various crops but, depending on the time of watering, can increase water evaporation. Similarly, center pivot irrigation uses mounted sprinklers on moving towers that enable irrigation of more extensive fields (Evans, 2001). However, the inherently high application rates of sprinklers can increase the risk of runoff and topsoil erosion (Kincaid, 2005). More delicate crops often do better with fogging and misting applications, which involve spraying finer water droplets that are absorbed primarily by leaves rather than roots. A less precise and efficient method used in select regions is flood irrigation, which involves inundating crops with water, allowing for deeper infiltration. The method of water delivery chosen in agricultural operations depends on numerous factors, such as financial cost, local climate and freshwater availability, crop type, and personal preference (Green et al., 1996).

Animal Agriculture

Raising livestock is inherently more complicated than crop production and involves a number of additional steps and water requirements. Water is essential for the health, well-being, and productivity of animals raised for food production. Providing access to clean drinking water is crucial for all animals, as adequate hydration is required to regulate body temperature and digest food (Meehan et al., 2015). In hot and arid climates, both indoor and outdoor housing facilities often include cooling systems, such as misters and fans, to prevent risks of heat stress and related illnesses. Water is also needed in the preparation of animal feed, particularly when producing pellets, rehydrating forages, or simply to mix with grains to create a slurry for improved digestibility (Schlink et al., 2010). When evaluating variations in water requirements, the amount of fresh water directly consumed (freshwater intake, or FWI) should be distinguished from the total water intake (TWI), which includes any water from feed as well (Parker & Brown, 2003).

A large portion of the water footprint of animal products is the amount needed to produce animal feed. It is estimated that up to 80% of the water needed to produce animal products is attributed to feed production alone (Mekonnen et al., 2010). Approximately 37% of global cereal grain production goes to feeding livestock (FAO, 2011). Global TWI for livestock production accounts for approximately 33-41% of total agricultural water consumption (Heinke et al., 2020; Mekonnen et al., 2012). Aside from these common uses, water is also needed for cleaning and sanitizing animal housing units. The regular washing of stalls and barns is critical for hygiene and reducing pathogen-related illnesses within animal groups. Dairy operations are among the most water intensive livestock operations due to cleaning and sanitation needs of milking parlors, milking equipment, and animal hygiene maintenance (Blümmel et al, 2014). Other animal operations that are water intensive include poultry and aquaculture. It should be noted that water requirements of different foods depend on a number of factors, from the animal's physiological conditions to their diet and conditions of their surrounding environment.

Water Requirements of Different Foods

The water requirements of specific foods depend on whether we consider them in terms of protein content, caloric density or weight (Figs. 8-10; Poore & Nemecek, 2018). By protein content, the foods with the highest water requirements are meat, dairy and nuts; those requiring the least water are poultry and pulses, such as beans, peas, lentils, and chickpeas (Fig. 8). With respect to water consumption by calories, prawns, fish, tomatoes and dairy are the highest consumers and plant-based foods like root vegetables, bananas, and grains are lowest (Fig. 9). Based on weight alone, cheese, nuts, fish, prawns, and beef are highest on the list, with plant-based foods like root vegetables, fruits, and even wine being the least consumptive (Fig. 10). The majority of foods with the highest water resource requirements are almost exclusively animal-based products. This is due to the compounding water requirements of growing animal feed in addition to growing animal tissues, producing water-rich byproducts like milk, and maintaining general health and wellbeing of the animals.

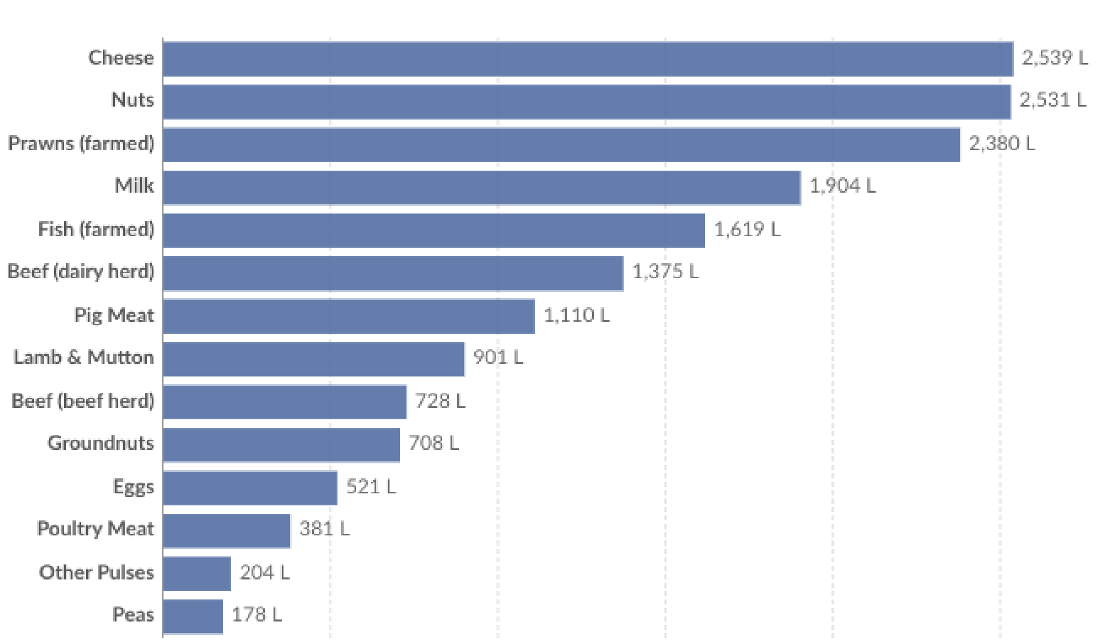

Figure 8: Freshwater withdrawals of a variety of different protein sources per 100 grams of protein (Ritchie & Roser, 2015).

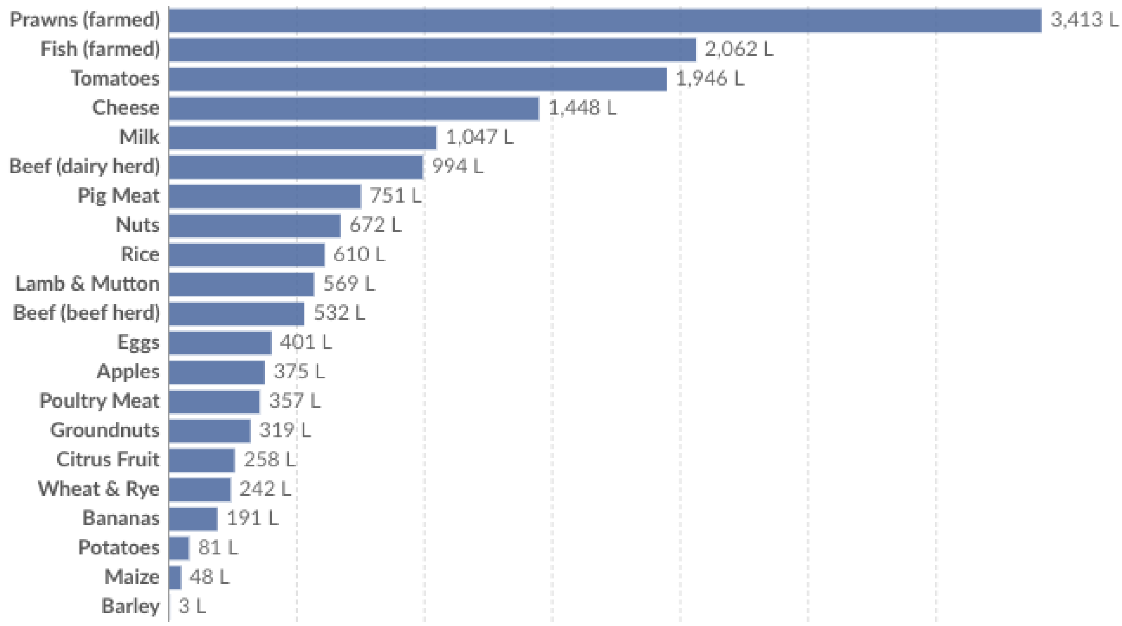

Figure 9: Freshwater withdrawals of a variety of different foods per 1000 kilocalories (Ritchie & Roser, 2015).

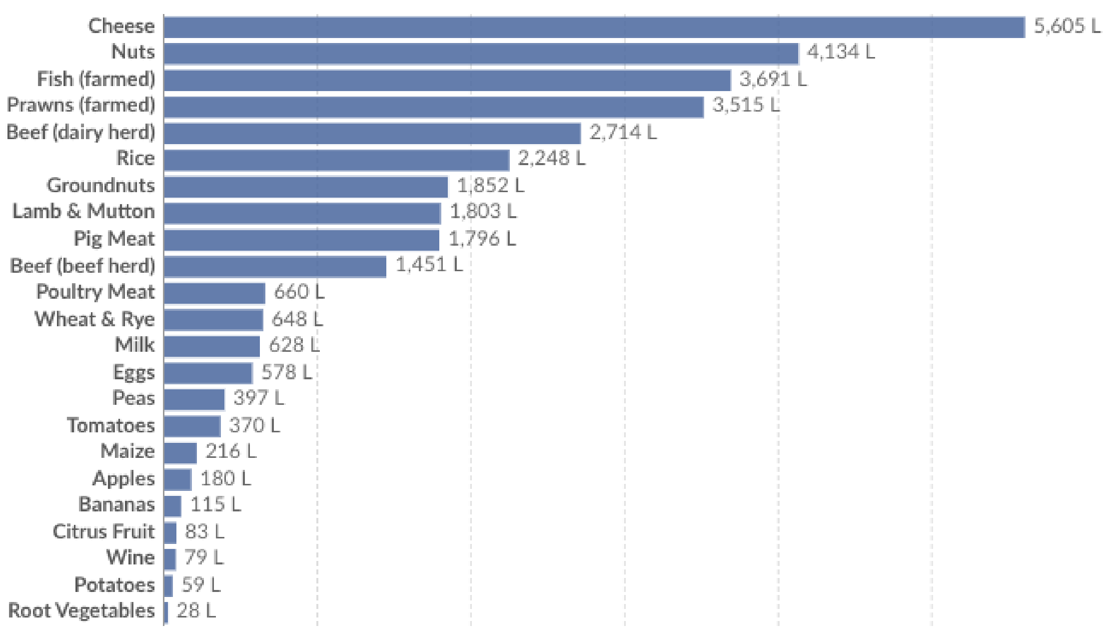

Figure 10: Freshwater withdrawals of a variety of different foods per kilogram of food product (Ritchie & Roser, 2015).

Overall, agriculture affects water resources in several primary ways. First, conventional practices of fertilizer and pesticide application can significantly reduce water quality, as pollutants can enter aquatic ecosystems via runoff or leaching. Nutrient contamination of water bodies can trigger chronic and episodic eutrophication, leading to oxygen depletion and compromising the health of aquatic ecosystems. Pesticide contamination can also compromise aquatic habitat and disrupt endocrine systems, leading to population declines in vulnerable species such as amphibians (USEPA, 2005). Furthermore, the management of livestock waste can pose additional problems through runoff and leaching of soluble organic matter and pathogens into ponds, lakes, streams, and rivers. Nutrients and chemicals can be transported and affect downstream ecosystems as well. Second, agricultural operations can lead to depletion of surface and groundwater as well as changes in water flow and distribution. The extensive use of water for irrigation across various climates and landscapes has altered natural hydrological patterns and contributed to the decline in global freshwater reserves (Eliasson, 2015; Rosegrant et al., 2002).

CHAPTER 3: LAND

Land is the foundation of agriculture. The productivity and sustainability of food systems largely depends on the results of land use practices that facilitate a consistent global food supply. Many farming practices, however, are detrimental to soil structure and fertility, surface and belowground waters, biodiversity, adjacent ecosystems, and the atmosphere. In order to minimize these negative effects, how we use agricultural land must be re-envisioned. Greater adoption of environmentally responsible land use practices can ensure long term agricultural success and foster economic and public health.

Since the dawn of agriculture, around 10,000-12,000 years ago, the developments of human civilizations have led to a radical transformation of biomes around the world (Montgomery, 2012). Since the early 1700s, the expansion of agricultural land has resulted in a terrestrial biosphere that is now primarily anthropogenic. Due to this expansion, global farmland area has increased sixfold over the past 300 years (Ellis et al., 2010; Poore & Nemecek, 2018). There are more than 570 million farms worldwide, the vast majority of which are small-scale, often family-owned and operated farms. Although 72% of all farms are small-scale (less than 1 hectare), they control only 8% of global agricultural land space. Conversely, 1% of global farming operations are greater than 50 hectares (industrial), and they represent more than 65% of global agricultural land (FAO, 2014). Today, it is estimated that around 60-70% of global food production operations are designated as "industrial" (FAO, 2021b). In addition to shifting the agricultural workforce composition, the associated specialization and consolidation of farms has also redefined the types of foods commercially available and affordable to consumers. The industrial revolution of agriculture changed humanity on political, economic, and cultural levels (Kimbrell, 2002; MacDonald, 2013).

Through the improvement of crop yields and expansion of crop and pasture lands, enough food has been produced to enable a four-fold increase in the global human population over the past century (Steinfeld, 2006). The strategies and successes of our current agricultural model cannot be denied; however, the environmental consequences of agriculture need to be considered in order to build a sustainable food system. The substantial development of Earth's land cover has had important consequences for the Earth's biogeophysical systems (Pongratz et al., 2008). Habitat destruction and fragmentation, disruptions to food web structure, altered ecological and biological functions, loss of carbon sequestration capacity, and even manipulation of evolution and genetics are all ways that agricultural land use can impact Earth's systems (Dale, 1997).

The term "land use" is used to describe any permanent or periodic human intervention practiced in order to develop, distribute and manage habitable land-based spaces (Foley et al., 2005). The ecology of land includes vegetation, soils, topography, and climate. Land management encompasses various activities, including agriculture (such as tillage, irrigation, crop arrangement, and grazing), forestry, conservation efforts, and the development and management of land for industrial and residential purposes. The creation of agricultural land generally involves the conversion of natural ecosystems into rangelands, pastures, or croplands, as well as the utilization or modification of vegetation, soil structure, water, and nutrients. Direct impacts include fertilizer and pesticide applications, tillage, and irrigation (Vink, 2013). This chapter delves into the various components of modern land-based farming and examines the resulting biological and environmental impacts.

Agricultural Land Extent

Food production is a major use of land and is by far the most significant driver of global deforestation. Agricultural land makes up at least 38-46% of global ice-free land (Ellis et al., 2010), with croplands making up one third and livestock production two-thirds for a total of 5 billion ha of agricultural land worldwide (FAO, 2021a). Livestock grazing alone utilizes roughly a quarter of global habitable land surfaces, and production of livestock feed makes up around one third of global arable land (Smil, 2013). The remaining undeveloped, “natural” land is composed of 38% forests and 14% grass and shrublands. Prior to the industrial revolution, agricultural areas grew steadily though slowly and remained below 1 billion hectares. However, agricultural land area increased by about 660% from 1600 to 2016 and continues to grow, though now at a reduced rate (Goldewijk et al., 2017; Taylor & Rising, 2021). This expansion has varied by geographic region, particularly between developed and developing countries. With over 1.19 billion ha, Africa has the greatest amount of arable and pastureland worldwide; China holds the second largest share with 630 million ha; following that is Asia (excluding India and China) with 510 million ha, and Latin America and the Caribbean with nearly 484 million ha; the United States possesses the fifth largest amount with at least 410 million ha (Fig. 11). The conversion of forests, grasslands, and shrublands to farmland has increased global greenhouse gas emissions, reduced terrestrial carbon sequestration, and degraded ecosystems and biodiversity worldwide.

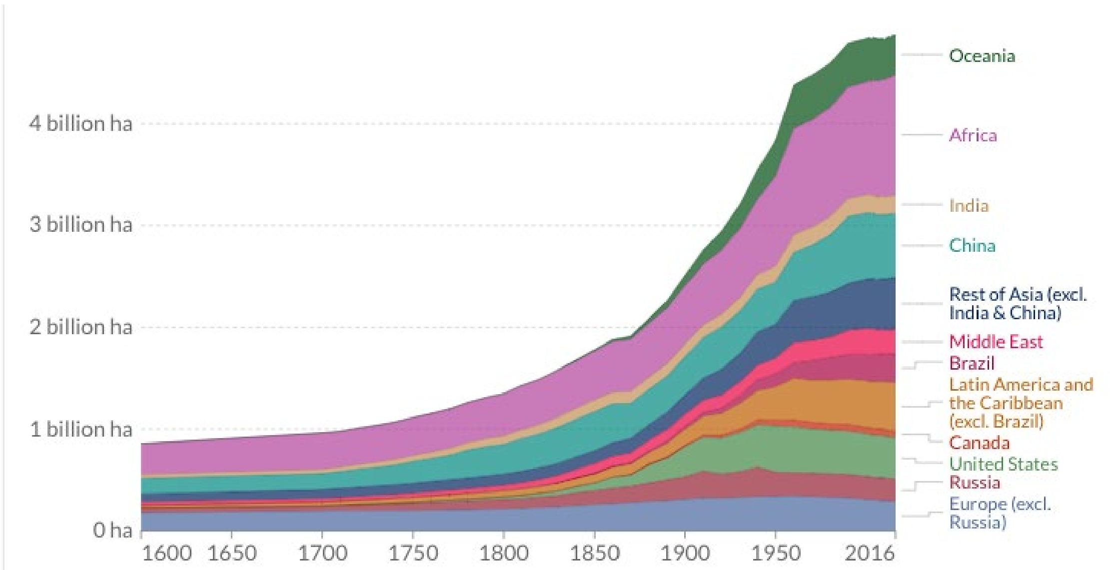

Figure 11: Total agricultural land area, including both cropland and grazing pasturelands and permanent meadows (data from Goldewijk et al., 2017; graphic produced by Ritchie & Roser, 2019).

<u>Arable Versus Grazing Land</u>

The two primary uses of agricultural land include pastureland, which describes livestock rearing areas (including permanent meadows), and croplands, also called arable land, which is used to grow both long term (perennial) and temporary (annual) plants. In total, 31% of global agricultural land is dedicated to growing crops, while 69% is used to produce livestock (including permanent meadows and pastures for grazing). However, if croplands used for feed production are included, then approximately 77% of global agricultural land is used to produce livestock, while only 23% is used for producing crops for human consumption (Ritchie, 2021a; Williams, 2003). Global meat production has increased by over 44% since the year 2000, rising from 103 million metric tons to 337 million metric tons produced annually (Coimbra et al., 2020; FAO, 2021a). The countries with the greatest proportion of arable land include those in South Asia and Europe, with up to 53% of their total land area being used for crop production (Figure 12). Conversely, those with the greatest proportion of livestock-production land include countries in Africa and Central Asia, led by Saudi Arabia (80%), Mongolia (72%), and South Africa (69%) (Figure 13).

Occupying over one third of global land surfaces, the impacts of food production and land management are an issue of regional and global importance. Recall that industrial agriculture, practiced upon roughly 60% of global agricultural land, is characterized by intensive livestock production (concentrated animal feeding operations and heavy use of antibiotics and growth hormones), monocultures, high input farming (excessive chemical and nutrient inputs), large scale mechanization and heavy tilling, aquacultures, and genetically modified (GM) crop farming (Horrigan et al., 2002).

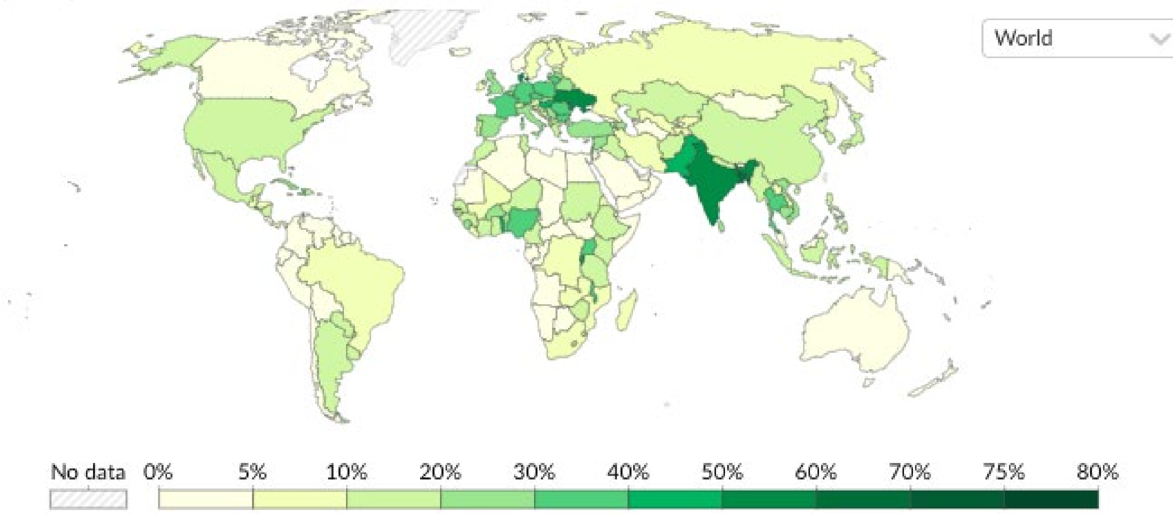

Figure 12: Percentages of total land area used for arable agriculture within each country, including temporary croplands and meadows, gardens, and temporarily fallow lands (Data from FAOSTAT; figure produced by Ritchie & Roser, 2019).

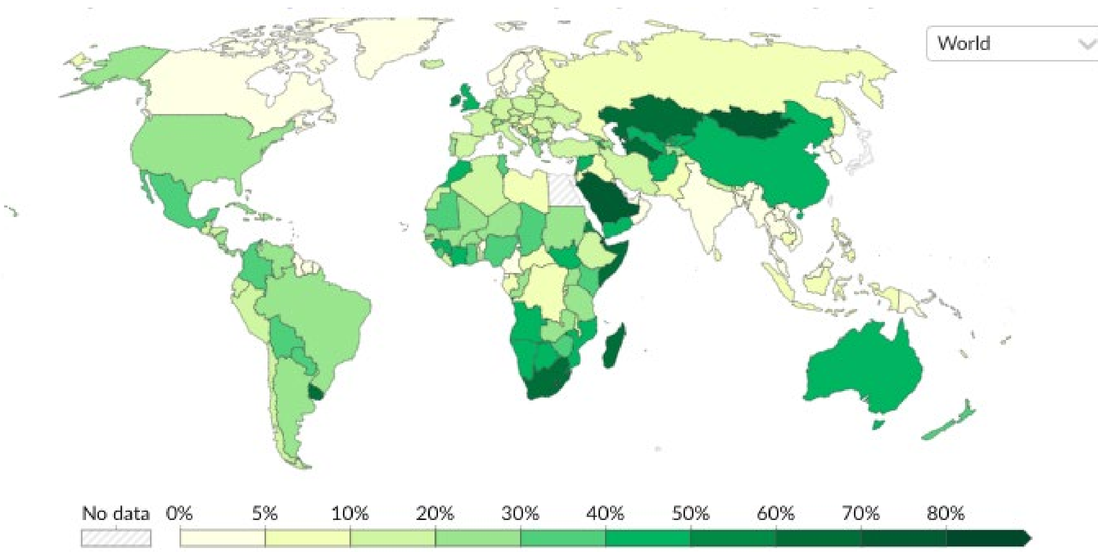

Figure 13: Percentages of total land area used for livestock rearing within each country, including permanent meadows and pasturelands (Data from FAOSTAT; figure produced by Ritchie & Roser, 2019).

Agricultural Land Conversion

Forests cover almost one third of the Earth's ice-free land and provide numerous ecological services, supporting and regulating the hydrologic cycle, maintaining soil structure, sequestering carbon, and hosting a large amount of global biodiversity (Chakravarty et al., 2012). Despite their critical importance to the biosphere, a significant portion of forests and are lost to human activities each year. Since the last ice age, the world has lost over one fourth of its forests; in alignment with many other anthropogenic impacts, the degree of impact has increased with development and the rise in human population. Roughly 10,000 years ago, Earth's habitable land was composed of 57% forests (6 billion hectares) and 42% wild grass and shrublands (4.6 billion hectares) (Krump et al., 2004). Forests now, based on recent reports (FAO & UNEP, 2020), make up less than 38% of global habitable land (4 billion ha). Similarly, while grasslands and shrublands once made up 42% (4.6 billion ha) of the global ice-free landscape, today they now account for less than 14% (1.74 billion ha). In total, approximately 46% of lands once designated as forest, grasslands, or shrublands have now been converted to agricultural land (Fig. 14).

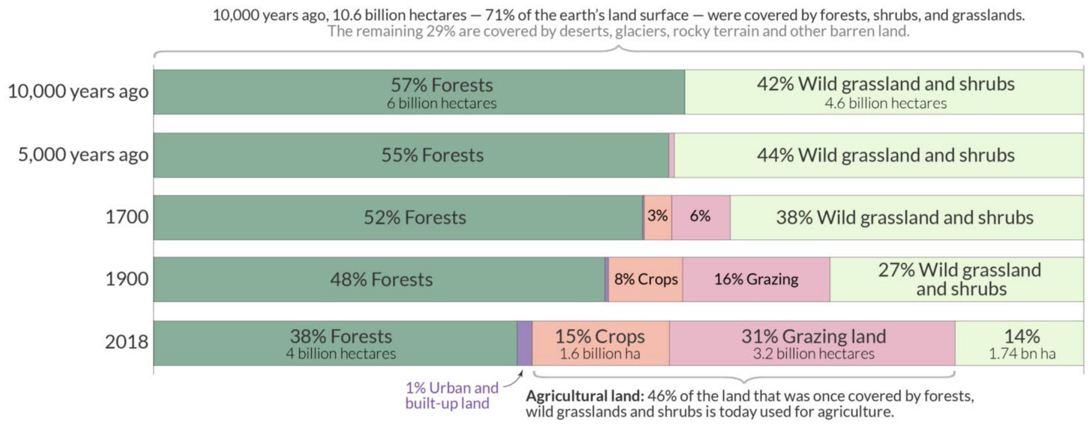

Figure 14: Estimates of how Earth's surface has changed over the past 10,000 years (from the end of the last ice age to present day) in terms of forested, grassland, and shrubland ecosystems with respect to agricultural land conversion (Ritchie, 2021a)

The United Nations Food and Agriculture Organization's (FAO) 2020 Forest Resources Assessment estimated that the world has lost over 178 million ha of forested land since the 1990s, though the rate of deforestation has been gradually slowing. Net forest loss from 1990 to 2000 was approximately 7.8 million hectares per year and declined to about 4.7 million hectares per year between 2010 and 2020 (Fig. 15; FAO, 2020). The vast majority of deforestation over the past two decades has occurred in Brazil, Indonesia, and Tanzania (Fig. 16; FAO, 2020; Keenan et al., 2015). Of the total 5.4 million hectares of tropical forests cleared in 2019, 33% took place in Brazil, and 19% in Indonesia (Pendrill et al., 2019).

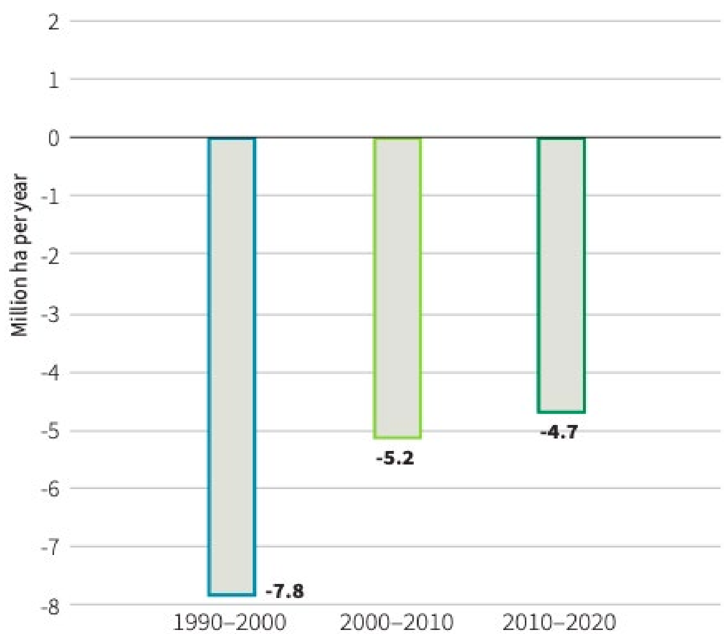

Figure 15: Annual net changes in global forested area across the past three decades (FAO, 2020).

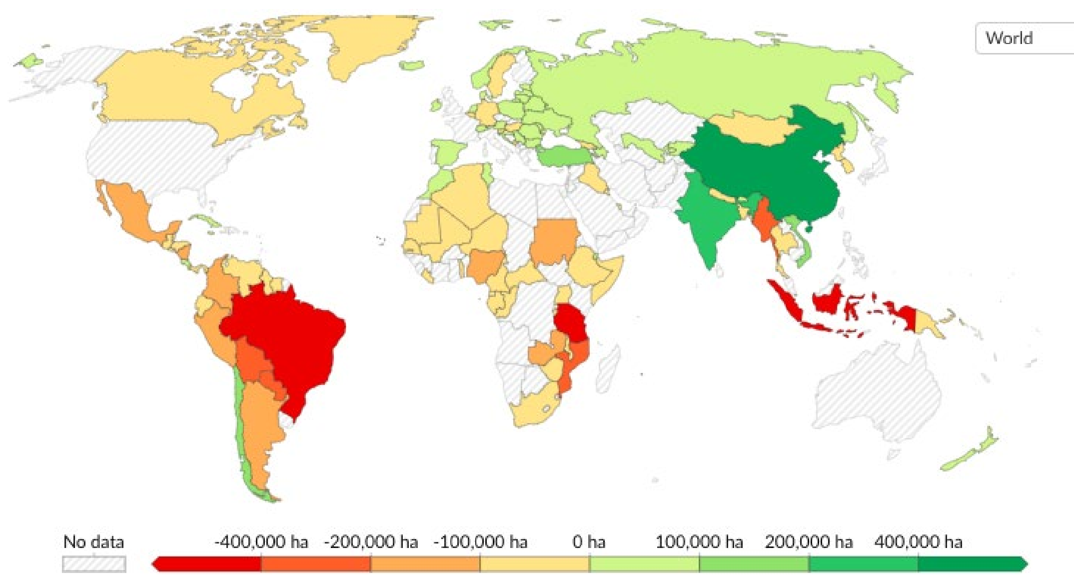

Figure 16: Annual net change in forested cover across the world, calculated as the amount of forest lost minus the amount of forest gained each year (Data from FAO Global Forest Resources Assessment, 2020; graphic created by Ritchie, 2021a).

Agricultural land expansion is the primary driver of deforestation as well as grassland and shrubland losses worldwide (Houghton, 1990). The term deforestation is commonly used to describe the complete and permanent removal of large forested areas. According to the Food and Agriculture Organization (FAO), deforestation more specifically refers to “the conversion of forest to other land uses (regardless of whether it's human induced)” (FAO, 2020). Therefore, deforestation does not include logging on land that is left to re-grow afterwards. Forest area net change describes the sum of all losses and gains in forested areas, which is useful in understanding how global forest coverage changes over time. Though deforestation facilitates the acquisition of land for urban or agricultural development, it has significant negative effects on ecosystems and biodiversity.

It was previously estimated that agriculture is responsible for approximately 70-80% of all global deforestation (FAO, 2016; Gibbs et al., 2010; Hosonuma et al., 2012). However, as of 2021, it is estimated to be closer to 90-97% based on data from 1840-1990 (FAO, 2021b; Geist & Lambin, 2002). Nearly three quarters of deforestation in the tropics is specifically due to beef (41%) plus soybean and palm oil production (~19%) (Pendrill et al., 2019; USDA PSD Database, 2022).

It is a common misconception that soybeans are one of the leading drivers of deforestation worldwide, and that they are worse for the environment than beef or dairy production. In fact, only 7% of global soybeans are produced for human consumption, while over 77% is produced for livestock feed (Ritchie, 2021b; USDA PSD Database, 2022). The remainder is used in biofuels, vegetable oils, and other industry uses. Having more than tripled in the past 50 years, global meat and dairy production has become the leading cause of agriculturally based biological impacts, deforestation being only one (FAO, 2021c). At least 25% of all vertebrates are estimated to be threatened by the volume of modern global meat consumption, simply due to the greater land requirements of animal products (Coimbra et al., 2020). Lamb and mutton require the greatest amount of land to produce (184.8 m2/100g protein), with beef and cheese requiring the second largest amount (164 m2/100g protein and 39.8 m2/100g protein). Excluding aquaculture, the foods with the lowest land use requirements include peas, groundnuts, and grains (Fig. 17; Poore and Nemecek, 2018).

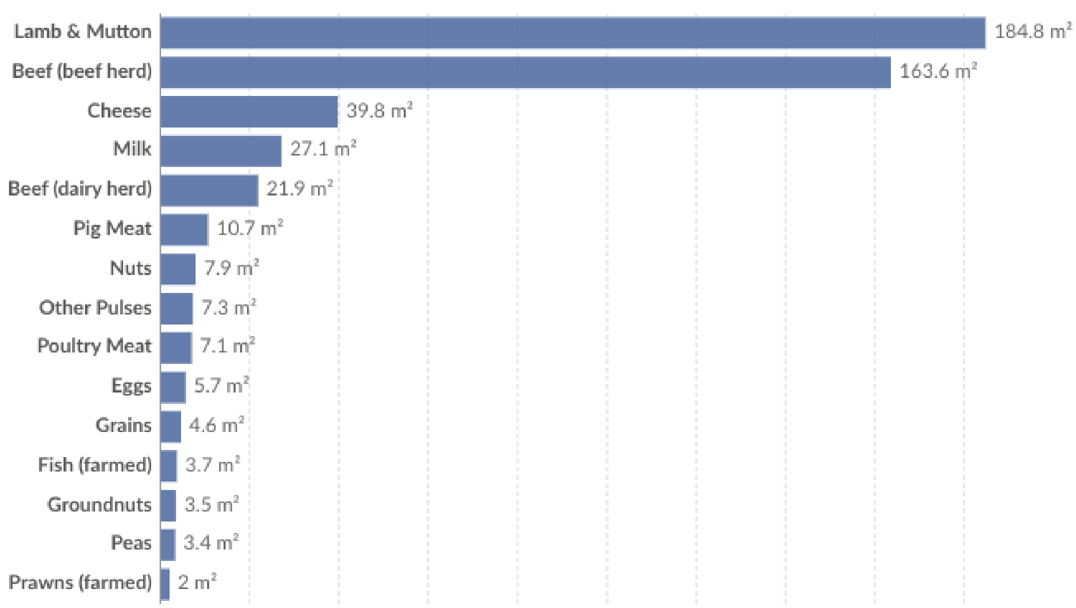

Figure 17: Land use requirements of various foods. Units are in m^2 per 100 grams of protein (Data from Poore & Nemecek, 2018, graphic produced by Ritchie & Roser, 2013).

Implications

To successfully feed a growing global population of more than 8 billion people, modern food production relies on the development and management of large areas of land for growing crops and raising livestock. Deforestation impacts Earth's systems through loss of habitat, displacement of species and loss of biodiversity, climate change, disruption of hydrological cycles, increased soil erosion, and loss of soil fertility (Bennett, 2017). The process of converting forest to agricultural land generally involves cutting and burning large areas of trees and vegetation to make way for crop or livestock production. In addition to degrading and breaking up segments of forested ecosystems, displacing local fauna, lowering ecological resilience, and eroding biodiversity, these actions also contribute to climate change through disruptions to the carbon cycle. Through the removal and burning of living biomass, processes like respiration and carbon sequestration are adversely affected. As discussed in earlier chapters, trees are photosynthetic organisms that sequester carbon in their biomass. During the process of photosynthesis, trees take up carbon dioxide (CO_2) from the atmosphere and, with the addition of water, convert it into glucose and subsequently to other organic compounds. Carbon is stored in biomass, and oxygen is released into the atmosphere (Tubiello et al., 2015). Until the industrial revolution, a balanced carbon cycle helped maintain a stable climate.

Of the 861 gigatons of carbon stored in the world's forests, the majority is contained in soils (44%) and above and belowground live biomass (42%), with the remainder found in dead wood (8%) and leaf litter (5%) (World Resources Institute, 2022). In addition to the release of carbon from above ground carbon pools, soils that are exposed after forest clearing experience raised temperatures from incoming solar radiation, thereby increasing the microbial decomposition rate of soil organic matter, leading to further carbon emissions (Ontl & Schulte, 2012).

Covering only 7% of global ice-free land, tropical rainforests support more than half of all species on Earth. Between the years 2015 and 2017, tropical deforestation released an average of 4.8 Gt CO_{2eq}/year, responsible for 8% of global CO_{2eq} emissions (Herzog, 2009). In fact, if the cleared tropical land were in a single country, it would rank as the world's third greatest emitter of greenhouse gas emissions.

Aside from the species lost when a specific area is deforested, the habitat fragmentation and biogeophysical disturbances to their ecosystems create cascading effects on the adaptability and resilience of biological communities (Vijay et al., 2016). Species extinction rates and the risks of extinction are much higher now than previously in human history. According to The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), more than 1 million species of plants and animals are currently threatened with extinction due to anthropogenic land-use changes (Montanarella et al., 2018). At current rates of deforestation and degradation, the Earth could experience extinction rates hundreds of times greater than those of the past four mass extinction events (Giam, 2017).

Cropping Practices

There are a variety of different crop management practices employed by farmers, each with its own benefits and drawbacks. In this section, we will explore the different cropping types and how they can negatively or positively impact the surrounding environment.

Monocropping is the practice of growing a single crop on the same land across multiple years; it's common in modern industrial farming systems, both in conventional and organic farming, and offers several benefits for farmers (Gebru, 2015). Monocropping can increase planting and harvesting efficiency, reduce the type of equipment and laborers required, lower costs, and allow for development of a more specialized farming skill set (Altieri, 2009a). For these reasons, monocropping can often be more efficient at larger scales. Roughly 85% of the world's 1.5 billion hectares of farmland is designated as monocultures, primarily in corn, soybeans, rice, and wheat (Altieri, 2009b; Altieri & Nicholls, 2020).

Less intensive farming approaches, which have lower environmental impacts, are practiced on smaller spatial scales. Polycultures, which involve growing multiple crop types on the same land, involve alternative cropping systems such as double cropping, intercropping, strip cropping or relay cropping. Outside of the scope of plant arrangement, there are also several non-conventional types of land management that integrate different food systems within one production operation. One example is alley cropping, which is a method used in agroforestry where crops are planted in "alleys" between trees and shrubs (Nair, 1993).

Agroforestry is collectively described by the International Council for Research in Agroforestry as any land use system or practice that deliberately integrates woody perennials into crop rotation or livestock production systems (Leaky, 1996). This technique allows crops to take advantage of the ecological services that trees and shrubs provide, like shade and wind protection, ultimately providing a variety of systemic biological benefits. This method of growing food can increase biodiversity, improve nearby water quality, stabilize soil structure and nutrients, and even enhance carbon sequestration (Ramachandran, 2009).

While alternatives to monocropping can definitely work at larger spatial scales and offer a host of ecological benefits, they do require more complex and sometimes expensive planning and management. However, such diversified operations can also provide an opportunity to increase farm revenue through the incorporation of other saleable crops like fruit trees. Because the primary focus of food production is centered around achieving maximal crop productivity at minimal cost, monocropping is more productive and profitable in the short term. However, the sequential planting of one crop on the same land can have negative environmental and biological consequences.

Consequences of Monocropping

When farmers grow the same crop repeatedly over an extensive area of land, the continuous and repeated uptake of specific nutrients by only one species can lead to nutritive imbalances within the soil (Liu et al., 2018). As such, monocultures typically require synthetic fertilizers to maintain soil fertility and crop yields. While fertilizers provide macronutrients like nitrogen (N), phosphorus (P), and potassium (K), they often lack the micronutrients that decomposing plant residues typically supply (Shete et al., 2016). Over time, the persistent lack of natural organic matter inputs can cause synthetically fertilized soils to become deficient in certain trace minerals and lose fertility (Galt, 2008).

Monoculture systems and industrial farming practices can also disrupt organic matter development and reduce microbial diversity. Soil organic matter is crucial for a resilient and balanced ecosystem, as it provides substrate and nutrients for microorganisms, including bacteria, that are responsible for nutrient cycling (Altieri, 2009b). The low level of plant residues in monoculture systems and the subsequent reduced soil fertility then requires the addition of fertilizer inputs for sufficient plant growth (Rychcik et al., 2006). Soil structure can also be negatively affected by monocropping due to a lack of diverse root structures, which can also reduce water retention and increase the risks of erosion.

Tillage aerates the soil and mixes crop inputs, fertilizers, and pesticides into the mineral soil. Tilling breaks up soil aggregates that protect organic matter from microbial decomposition. As soils become more oxygenated, decomposition rates increase, increasing losses of carbon from soils (Nobakht et al., 2011). Soil organic carbon (SOC) is one of the most important indicators of soil quality and also plays an important role in carbon sequestration and carbon-based soil processes. Due to modern tillage practices, it has been estimated that between 30% and 50% of SOC contained within U.S. soils have been lost since the establishment of agriculture (Haddaway et al., 2017). Similar to other industrial land use practices, like the extensive use of heavy machinery and intensive grazing, conventional tillage has also been found to increase compaction of soils below the plough layer (Shah et al., 2017). These activities can increase soil density with a decrease in porosity, aggregate stability, and the storage and supply of water and nutrients. Compaction thereby reduces soil fertility and diminishes overall crop production efficiency (Hamza & Anderson, 2005). For these reasons, there is a growing interest in alternative soil management methods within the farming community, such as conservation tillage or no till practices (Ogieriakhi & Woodward, 2022).

Because they consist of only one plant species, monocultures are inherently more vulnerable to pests and diseases that target the cultivated plant. To protect their crops, farmers often use chemical pesticides, but regular applications can be harmful to beneficial insects, birds, and mammals (Mahmood et al., 2016). Their degradation can compromise nutrient cycling and soil fertility. Furthermore, as discussed in previous chapters, pesticides can leach into groundwater or runoff into nearby surface waters, reducing water quality and harming aquatic organisms. The use of these chemical inputs can create further problems as crop plants can become pesticide resistant, requiring larger application amounts to control weeds and unwanted animals and insects (Alain, 2017).

Agricultural lands are ecosystems too, defined by the resident biological communities and their interactions with and within the environment. Stretching over sometimes thousands of acres, monocultures often replace diverse habitats with much more homogeneous ones. Many species are dependent on one another and offer services to the entire ecosystem, such as water quality maintenance, dispersal of pollen and seeds, regulating ‘pest’ populations, nutrient supply and processing, and climate regulation (Mergeay & Santamaria, 2012). With a drastically simplified ecological matrix, monocropping erodes local biodiversity and creates ecosystems that are more fragile and vulnerable to pests, diseases, and adverse environmental events (Pereira et al., 2012). Thus, anthropogenic land use methodology has the potential to influence the overall sustainability of modern food production.

This chapter has highlighted the extent that agricultural lands have expanded and impacted natural ecosystems, as well as what types of food consume the most land to produce. On average, animal products required more land than plant-based foods. Agricultural land expansion has resulted in significant losses of forest, grassland, and shrubland ecosystems, leading to habitat fragmentation and declines in biodiversity. Furthermore, the growing prevalence of monocropping practices has degraded soil structure and nutrients as well as depleted local biodiversity and led to an increasing need for fertilizer and pesticide inputs. These issues highlight the importance of prioritizing more sustainable land management that focuses on diversifying crop rotation, incorporating regular organic inputs, and practicing more selective tillage strategies.

CHAPTER 4: CLIMATE

About the Atmosphere

Earth's atmosphere functions as a life support system for our planet. With its multiple protective layers akin to those of an onion, it serves as a barrier against the harsh conditions of outer space while also facilitating the transfer and distribution of energy and other resources between different physical systems. The composition of the atmosphere is also the primary controller of Earth's climate. As a result, it influences the quality and availability of life sustaining resources such as food, water, and biological habitat. Critical to Earth's climate are biogeochemical cycles, particularly the circulation of elements like carbon, nitrogen, and phosphorus, between water, land, and atmospheric systems. The dynamic nature between these entities is fundamental to the operations of the natural world, as the movement of various elements through biological, geological, or chemical processes support all living systems (Schlesinger & Bernhardt, 2020). However, many of these biogeochemical cycles have faced significant perturbations from human activities, particularly those following the industrial revolution. These disturbances include not only not only land-use changes that have dramatically altered the composition of the Earth's surface, but also the flux of greenhouse gases to the atmosphere from fossil fuel combustion and other industrial activities (Jackson et al., 2020). Modern food production has contributed to these issues and profoundly altered the Earth's biogeochemistry, largely due to synthetic fertilizers, livestock production, tillage, and the conversion of tropical forests to agricultural land.

Atmospheric Composition

While the atmosphere may appear invisible and inconsequential to the human eye, it is, in fact, a complex and interconnected system of unique gaseous layers, held in place by gravity and operating as a dynamic entity. The air in the atmosphere is composed of 78% nitrogen (N_2), 21% oxygen (O_2), and 0.1% argon (Ar) (Schlesinger & Bernhardt, 2020). The remaining <1% consists of a combination of trace gases, including NO, N_2O, HONO, HNO_3, SO_2, NH_3, dimethyl sulfide (DMS), biogenic volatile organic compounds (VOCs), O_3, CH_4, and N_2O, as well as particulates of organic and inorganic chemical origin (categorized as primary or secondary aerosols, sized between 1 nm-10 μm) (Fowler et al., 2009). In addition to the gaseous components, particulate concentrations also play an important role in Earth's climate. These particulates can come in a variety of forms, originating from the soil, the ocean, the biosphere (e.g., pollen, plant matter, fungal spores, microorganisms), and volcanoes (Després et al., 2012; Sigl et al., 2015).

Present day measurements of these gases and aerosols are made possible by modern scientific instruments but understanding the atmospheric composition and climate of the past requires other lines of evidence, such as proxy data from ice and sediment cores, geological formations, and the fossil record (Tierney et al., 2020). It is important to note that throughout its 4.5-billion-year history, the Earth's atmospheric chemistry and climate have changed frequently and sometimes abruptly (Hart, 1978).

However, for the first time in the Earth's history, human activities over the past two centuries have significantly altered the atmosphere's chemical composition, resulting in alarming changes to the Earth's climate (IPCC, 2013). While industrialization has brought numerous constructive changes to the world, it has also resulted in environmental damage from the local to global scale. This chapter will focus on how modern agriculture affects the atmosphere and how it thereby contributes significantly to climate change.

The Greenhouse Effect

The theory of climate change was first described 166 years ago in the August 1856 issue of The American Journal of Science and Arts in a paper called "Circumstances Affecting the Heat of the Sun's Rays", written by Eunice Newton Foote (Sorenson, 2011). Foote had observed the relationship between atmospheric gas composition and radiant energy absorption. She reported that trapping a surplus of carbon dioxide in our atmosphere would trap more heat and thus gradually warm surface temperatures of the Earth (Foote, 1856). The implications observed in Foote's experiment are now being realized, as excessive global fossil fuel consumption since the industrial revolution has led to pronounced global heating. Industry, electricity generation, transportation, home and commercial heating, and agriculture, are strongly dependent on fossil fuels and have resulted in massive additions of greenhouse gases to the atmosphere (Allan et al., 2021). There is a strong relationship between economic development and energy consumption; as standards of living increase, so do food and energy use and the attendant fossil fuel emissions that drive climate change (Martinez & Ebenhack, 2008).

Greenhouse gases, predominantly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), are the major drivers of anthropogenic (human-caused) climate change. Through the trapping solar radiation in the atmosphere, greenhouse gases act as an insulating blanket that maintains the Earth's average surface air temperature (Kweku et al., 2018). Thus, greenhouse gases are central to the Earth's energy balance (Fig. 1).

Of the incoming solar radiation, less than one third (30% or 107 Wm^{-2}) is reflected back to space, with the Earth's surface absorbing 50% (168 Wm^{-2}) and the atmosphere absorbing the remaining 20% (67 Wm^{-2}) (Lindsey 2009). The majority of this outgoing long-wave radiation is first captured by atmospheric greenhouse gases, including water vapor, and the energy subsequently is radiated both back to the Earth's surface and to outer space (Kiehl & Trenberth, 1997).

The absorption and re-emission of most of that longwave radiation is what drives the greenhouse effect. When the quantity of incoming solar energy is balanced by that of outgoing heat, Earth reaches a state of radiative equilibrium, leading to a relatively stable global surface temperature (Trenberth et al., 2009). Without the greenhouse effect provided by our atmosphere, Earth's average surface air temperature, which is currently 14°C (57.2°F), would be -19°C (-2.2°F), approximately 33°C (91.4°F) lower (Le Treut et al., 2007). This demonstrates the strength and importance of the greenhouse effect, particularly with regard to the survival of most biological life. However, increasing atmospheric greenhouse gas concentrations has changed the Earth's energy balance and intensified the greenhouse effect, resulting in a warming planet that is not currently in equilibrium. Instead, the Earth is releasing slightly less energy than it receives (~1wm^{-1}) due to the high concentrations of greenhouse gases.

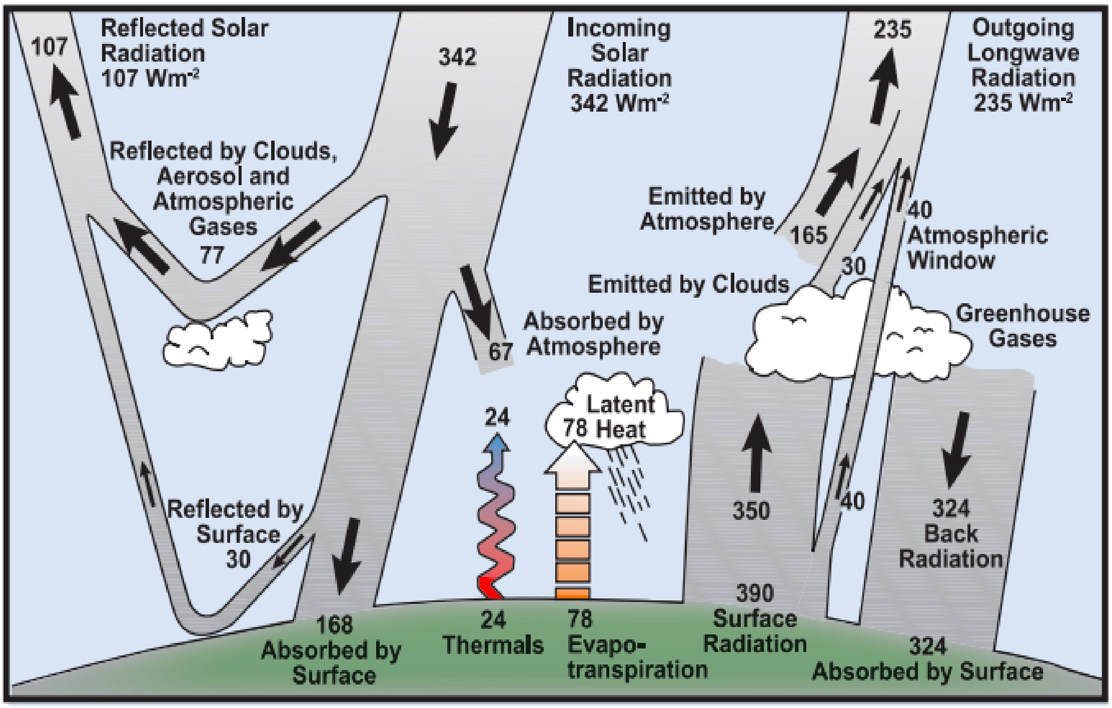

Figure 18: Estimations of Earth's annual mean energy balance (in Wm^{-2}), where there is a long-term equilibrium between the amount of solar radiation being absorbed and the amount of longwave radiation being released by Earth and the atmosphere (Kiehl & Trenberth, 1997)

<u>How Climate Has Changed</u>

Average global surface temperature rose +0.08°C per decade from 1880 to 1980 and subsequently has risen recently to +0.18°C per decade (Lindsey & Dahlman, 2021). In 2022, the U.N. Intergovernmental Panel on Climate Change (IPCC) reported that Earth is currently on track to surpass the global climate target of preventing warming greater than 1.5°C (2.7°F) above pre-industrial temperatures by the year 2100 (Pörtner, 2022).

The ambition to prevent such a detrimental rise in average surface temperatures was endorsed by 195 countries during the 21st Conference of Parties, of the United Nations Framework Convention on Climate Change (UNFCCC) (Rhodes, 2019). This temperature threshold was collectively agreed upon by scientists to prevent the worst consequences of climate change (Zhongming et al., 2018). Failing to meet the goals of the Paris Agreement and effectively mitigate climate change is predicted to have several negative consequences for life on Earth. Some of the potential impacts include mass migration events, significant loss of biodiversity, sea level rise of up to 4 meters, ocean acidification of up to 150% and the anticipated loss of >90% of coral reefs, and serious threat to global food and freshwater security (Allan et al., 2021; Pörtner et al., 2022; Rhodes, 2018).

Emissions

How the Industrial Revolution Changed the Atmosphere

To discuss the evolution of anthropogenic climate change effectively, we must first look back to one of the most transformative revolutions in human history. The first industrial era, later named the Mechanical Revolution, began in the mid-18th century and was marked by technological advancements in new energy sources together with the mechanization of what were previously handicraft and agrarian-dominated societies (Shu et al., 2021). This was a major turning point in human history, as it impacted much of everyday life across the globe through changes in the economy, transportation, and medicine. It also set off a cascade of further qualitative advancements. Many historians also describe the succession of three more industrial revolutions that took place up until the 21st century— the Electrical, Automated, and Digitized Revolutions— that saw further advancements in the use of synthetic and natural resources, automatic machinery and information accessibility (Groumpos, 2021). These systemic changes ended up radically transforming societies, cultures, economies, and, unbeknownst at the time, the integrity of the biological world as well. Among other changes, these developments gave way to industrialized food production systems characterized by heavy synthetic pesticide and fertilizer inputs, monocultures, concentrated animal feeding operations (CAFOs), and use of heavy machinery. While these modern food production methods have numerous advantages (e.g., increased food production capacity, greater cost efficiency, and improved food distribution) they also have contributed to climate change.

Carbon dioxide is the primary greenhouse gas responsible for anthropogenic climate change and accounts for the majority of emissions from agriculture, deforestation, and fossil fuel combustion. With the growth ofindustrialization, the carbon cycle has undergone an unprecedented and influential transformation. Along with other industrial activities, the combustion of fossil fuels has increased the amount of CO_2 in the atmosphere by 51%, from approximately 277 parts per million (ppm) at the start of the Industrial Era to 419 ppm in 2023 (Gulev et al., 2021; Lan et al., 2023). Whereas annual CO_2 emissions in 1750 totaled 9.35 million metric tons, emissions in 2021 amounted to 37.12 billion metric tons (Friedlingstein et al., 2022). The concentrations of other major greenhouse gases in the atmosphere have increased during this period as well. From 1750 to 2019, atmospheric methane (CH_4) increased by 156% (1137 (± 10 ppb) to 1915 ppb).

From 1750 to 2023, nitrous oxide (N_2O) increased by 23% (62 (± 6 ppb) to 336 ppb) (NOAA, 2023). To give some historical perspective, the changes in atmospheric greenhouse gas concentrations over the past 270 years exceed those during the previous 800,000 years (Gulev et al., 2021).

How Modern Agriculture Contributes to Climate Change

To provide a comprehensive understanding of how global agriculture contributes to greenhouse gas emissions, CO_2 equivalent emissions (CO_{2eq}) can be used to describe emissions of CO_2 as well as other greenhouse gases weighted by their 100-year warming potential. Using CO_{2eq}, it is estimated that global food production collectively produces between 26% and 34% of global anthropogenic greenhouse gas emissions, contributing between approximately 13.7 and 17.9 billion metric tons CO_{2eq} to the atmosphere each year (Crippa et al., 2021; Poore & Nemecek, 2018).

Agriculture produces greenhouse gas emissions through several processes. Largely, these sources of emissions can be broken down into those resulting from land use change (24%), crop production (27%), supply chain (18%), and livestock and fisheries (31%) (Fig. 19). Emissions from land use change are dominated by land conversion for livestock production, which generates double the greenhouse gas emissions compared to land converted for crops grown for human consumption. Emissions from crop production arise primarily from fossil fuel use, nitrous oxide emissions from fertilizer application, and methane emissions from rice cultivation (via anaerobic digestion). Livestock and fisheries emissions are largely composed of the methane released during the digestion of ruminant animals (enteric fermentation), but also include manure and pasture management and the fossil fuels used to operate fishing vessels.

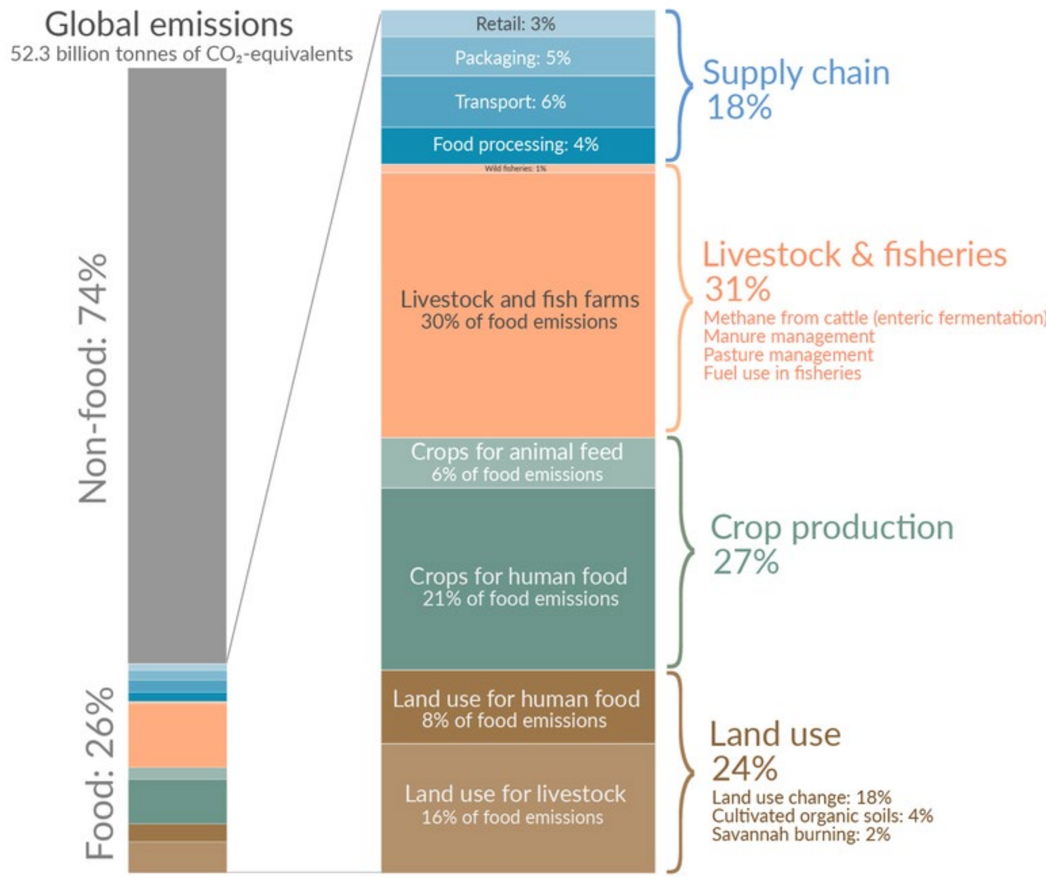

Figure 19: Global annual greenhouse gas emissions from various sectors of food production (in CO_{2eq}), including that from supply chain, livestock and fisheries, crop production, and land use. Crop production illustrates emissions from direct production of food Crop production illustrates emissions from direct production of food resulting from fertilizer production and use and machinery operations. Livestock and fisheries emissions are primarily from ruminant digestion and manure, but also include machine operations and pasture management. Land use describes emissions that result from land conversion as well as land-based management practices (Ritchie, 2019).

While CO_{2eq} is a useful tool in getting a broader understanding of total global emissions, distinguishing between different greenhouse gases is also valuable because they each have a unique climate impact based on their warming potential and lifetime in the atmosphere. To go into specifics about the top greenhouse gases, aside from carbon dioxide, global food production is estimated to also be responsible for 52% of methane and 84% of nitrous oxide emissions (Smith et al., 2008). Compared to carbon dioxide, both methane and nitrous oxide have higher global warming potentials per molecule, meaning they are more potent greenhouse gases in terms of their ability to warm the planet. Global warming potential specifically describes how much energy 1 ton of a given greenhouse gas will absorb over a period of time (typically a 100-year period is used and compared relative to 1 ton of CO_2). Therefore, if CO_2 has a warming potential of 1, then over a 100-year period the warming potentials of CH_4 and N_2O are approximately 25 and 300 times higher than that of CO_2, respectively (Jackson et al., 2020; Reay et al., 2012). The length of time each of these gases remain in the atmosphere also differs. While CO_2 molecules can remain for hundreds to thousands of years, methane typically lasts only about 12 years and nitrous oxide lasts closer to 114 years before breaking down into other compounds (EPA, 2023). Carbon dioxide, though it absorbs less long-wave radiation per unit molecule than methane and nitrous oxide, is the primary cause of global warming due to its much higher concentration.

Global GHG emissions from the production of food is estimated at 17,150 ± 1,760 Tg CO_{2eq}/year; meat production, including livestock feed, contributes 58%, and the production of plant-based food contributes 29%. The remaining 13% of emissions are caused by other utilizations (e.g., food spoilage, transportation, and processing) (Xu et al., 2021). The impacts to Earth's climate are among the most significant drawbacks of modern food production. To dive further into how agriculture significantly contributes to climate change, it's helpful to consider what we're producing and how we're producing it, as different types of foods can have vastly different environmental impacts. Some of the differences in emissions by food type are due to variation in land use requirements, agricultural management practices, resource requirements in terms of inputs and their efficiency, and byproducts of production such as animal waste.

In a study comparing 40 different types of foods and their respective variations in greenhouse gas emissions, eutrophication, terrestrial acidification, and threat to water scarcity (based on freshwater extraction requirements), it was found that foods with the greatest emissions impact were primarily animal products (Poore & Nemecek, 2018). Major comparison groups included protein rich foods, alcoholic beverages, milks, starches, oils, vegetables, fruits, sugars, and stimulants (like chocolate and coffee). Most notably, the greenhouse gas emissions for producing beef exceed those of any other food product by a significant margin, with beef emitting approximately 99.48 kg CO_{2eq} per kilogram of weight (Figs. 20-22; Ritchie et al., 2020). For comparison, the next greatest emitter per kilogram is lamb and sheep at 39.72 kg CO_{2eq} contributing less than one fourth the emissions of beef.

In addition to analyzing food types based on their weight, comparing emissions of different foods in terms of protein or calories can provide a more comprehensive picture of how we feed the world. In terms of greenhouse gas emissions per kilogram of food product, beef is the greatest animal-based contributor (99.48 kg CO_{2eq} per kilogram), while rice is the greatest plant-based contributor (4.45 kg CO_{2eq} per kilogram) (Fig. 20). In terms of emissions per unit of protein, beef is again the greatest animal-based contributor (49.89 kg CO_{2eq} per 100g of protein), while bananas are the greatest plant-based contributor (9.56 kg CO_{2eq} per 100 g of protein) (Fig. 21). Lastly, in terms of kilocalories, beef is the greatest animal-based contributor yet again (36.44 kg CO_{2eq} per 1000 kilocalories), with tomatoes being the greatest plant-based contributor (11 kg CO_{2eq} per 1000 kilocalories) (Fig. 22).

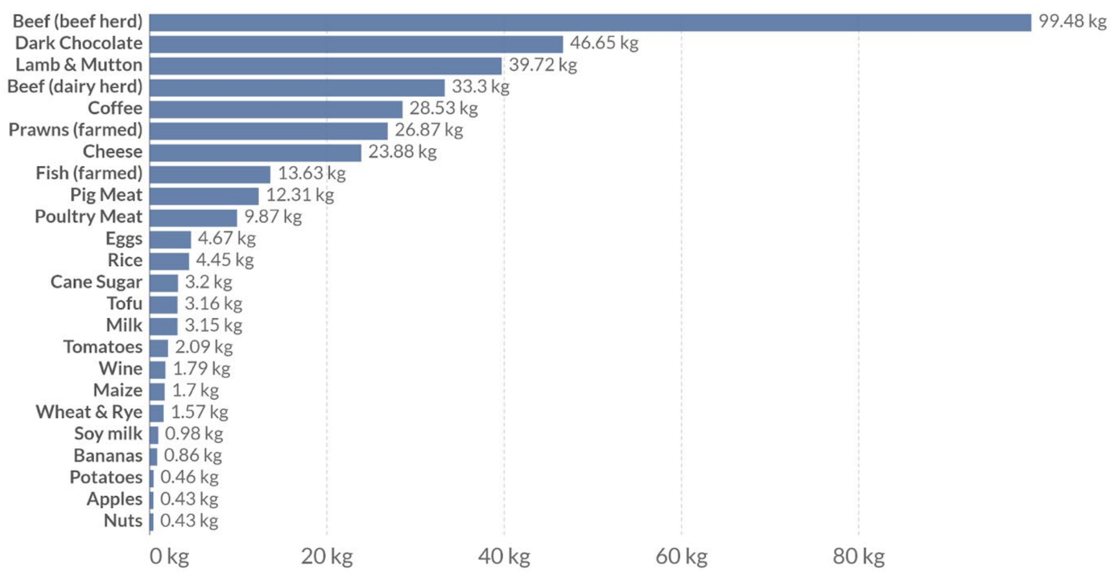

Figure 20: A comparison of greenhouse gas emissions (measured in CO_{2eq}) per kilogram for a variety of common foods (Ritchie et al., 2020).

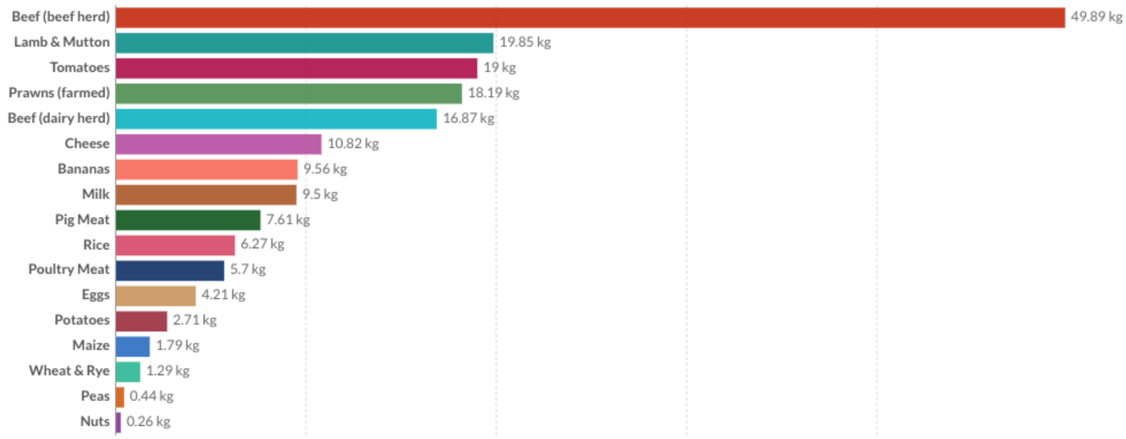

Figure 21: A comparison of greenhouse gas emissions (measured in CO_{2eq}) per 100 g of protein for a variety of common foods (Ritchie et al., 2020).

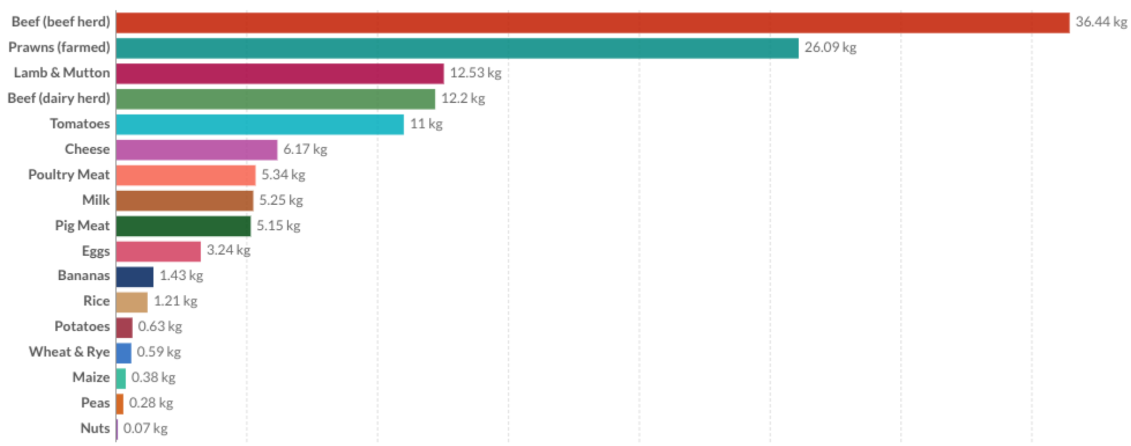

Figure 22: A comparison of greenhouse gas emissions (measured in CO_{2eq}) per kilocalorie for a variety of common foods (Ritchie et al., 2020).

Variation Between Foods

A common tool used to evaluate the environmental impacts of a product throughout its lifetime is a life cycle assessment (LCA). This framework offers a universal and systematic methodology to calculate impacts from the raw material extraction stage, through production and use, to its disposal management stage. LCAs demonstrate the cause and effect relationship between Earth's biological systems and modern human activity, considering parameters like resource requirements, energy consumption, emissions and waste generation (Hellweg et al., 2014).

Through analysis of 52 LCAs, Nijdam et al. (2012) compared the land use and climate impacts of animal versus plant-based sources of protein. Most notably, while ruminant meat and fisheries-based seafood production have the largest impact in terms of emissions, they also have the largest range of impacts depending on production methods (Ziegler & Valentinsson, 2008). Of the twelve foods analyzed in the study, emissions, in kg CO_{2eq} per kg protein, vary depending on numerous factors (Fig. 23) For example, emissions from beef production vary depending on whether the meat came from beef or dairy cows and whether those cows were raised intensively or extensively. While the variation between these methods exists, they still have a greater climate impact overall compared to plant-based protein sources. Of all animal-based protein sources, those with the lowest emissions impact include eggs, milk, poultry, and aquaculture-based seafood.

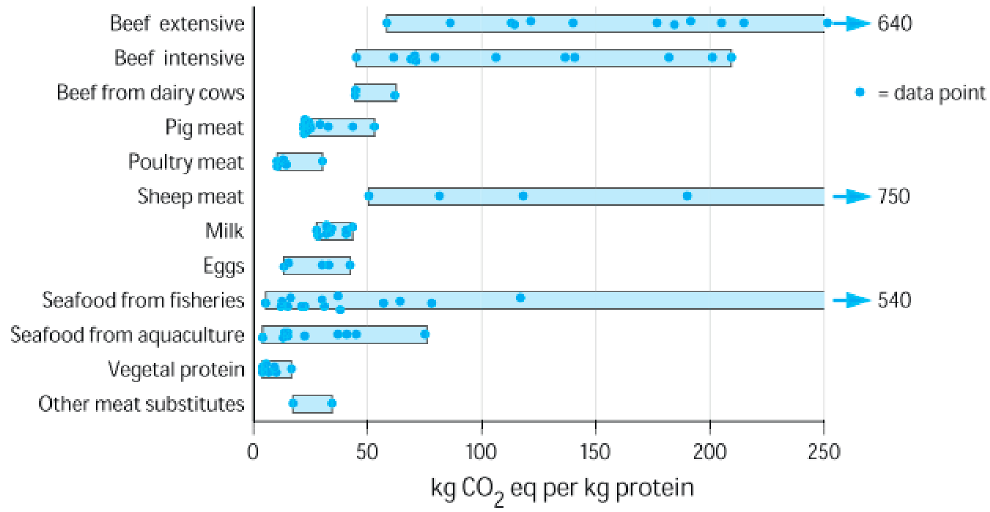

Figure 23: A visual comparison of data is synthesized from 52 studies that each examined the range of biological implications of producing different foods, from production to consumption (Nijdam et al., 2012).

Overall, animal products generally have a greater climate impact than compared to plant-based alternatives due to the energy and variety of high warming potential greenhouse gases emitted from animal feed production, enteric fermentation, manure, and the use of diesel and electricity to operate industrial machinery (Garnett, 2010). Studies in Japan and Ireland estimated that the carbon footprint of beef is composed of 60-61% enteric fermentation, 18-27% fertilizer/feed production, 10-12% manure production, 8% industrial concentrate production, and 4% in mechanical energy expenditure (Casey & Holden, 2006; Ogino et al., 2007).

One way that emissions from animal products vary is in feed production methods and feed composition. Generally speaking, raising animals on high-energy feed, also known as concentrate feed or simply grain-based feed, produces higher greenhouse gas emissions than those raised on pasture-based feed, more inclusively called forage-based feed (Galloway et al., 2007). This difference is largely due to NH_3 volatilization from synthetic fertilizers used in intensive coarse grain production, the primary source of concentrate feeds, and the variations in the feed-to-food conversion efficiency. This refers to the efficiency with which animals convert their food into animal products such as meat and milk. When considering forage-based feed, non-ruminants have a higher feed conversion efficiency than ruminants and produce lower emissions overall. However, when considering concentrated feeds between ruminants and non-ruminants, the difference in their conversion efficiency is virtually non-existent, and substantially lower food output efficiency is found across the board (Gilson et al., 2020).

Pig meat production has a lower carbon footprint than beef, though it still remains on the high end of the emissions spectrum, where conventional production results in 5-12.3 kg CO_{2eq} per kg of meat produced (Poore & Nemecek, 2018). The majority of pork emissions primarily result from the fertilizers used in feed. Compared to conventionally raised pigs, pasture-raised pig operations actually produce 20% more greenhouse gas emissions for similar reasons to cattle operations (Basset-Mens & Van der Werf, 2005). Compared to cow and pig production, conventional chicken production has a much lower emissions impact, totaling approximately 3-6 CO_{2eq} per kg for meat production and 1.7-5.5 CO_{2eq} per kg for egg production. Again, the carbon footprint of free-range egg and poultry production is estimated to be 10% larger compared to the industrial, concentrated alternative (Mollenhorst et al., 2006).

The climate impacts of different foods vary according to food production practices. They may include organic versus non-organic farming or grass-fed versus conventional livestock production. Livestock production operations range from highly intensive, concentrated animal feeding operations (CAFOs) to highly extensive pasture-based operations. Compared to other livestock, beef production exhibits the highest variation in emissions, and the debate about whether grass-fed or conventional beef is better for the environment is still ongoing. In terms of emissions, some scientists argue that conventional beef raised in CAFOs actually has a lower climate impact compared to grass-fed (Nijdam et al., 2012). For example, reducing the space for beef cows cumulatively reduces their energy expenditure and creates a more efficient system of meat production that requires less time and resources per animal. However, other scientists argue that, despite taking longer, grass-fed beef can have lower emissions when grazing is managed properly to improve soil carbon sequestration. Regardless, beef is still by far the most energy intensive and environmentally harmful food to produce. Considering the variation of impacts among other animal products, pork and poultry demonstrate the most homogeneity in emissions across different methods of production.

Anthropogenic climate change is a complex and nuanced topic, and while there is no food devoid of environmental impact, we can reduce those impacts by being selective about what we eat. Animal products generally emit significantly more greenhouse gas emissions per kilogram, gram of protein, and kilocalories. Therefore, to reduce the environmental impact of their food production, consumers should prioritize plant-based foods and limits animal-based foods.

CHAPTER 5: SOLUTIONS AND RECOMMENDATIONS

The goal of this project is to provide a broad overview of the environmental impacts of modern agricultural practices, so that the reader can make scientifically informed decisions about food choices. This chapter identifies consumer-based solutions to reduce those impacts. As the ultimate arbiters of the food economy, consumers wield significant power in shaping modern agricultural practices. Recall that about 38% of the world's habitable ice-free land is occupied by agriculture (Ritchie & Roser, 2020). Identifiable by intensive land and water use, monocropping, chemical inputs, and the conversion of tropical forests to pastures and tilled lands, many aspects of modern industrial agriculture threaten the integrity and resilience of terrestrial and aquatic biomes. Deforestation increases greenhouse gas emissions, degrades soils, disrupts food webs, and diminishes local biodiversity. The use of fertilizers and pesticides can lead to contamination of water bodies, degrading aquatic habitats and harming fish and invertebrate populations. In many areas, the water withdrawn for irrigation and animal husbandry has depleted rivers, groundwater, and aquifers (Konikow & Kendy, 2005). Greenhouse gas emissions from worldwide food production are a significant contributor to climate change, accounting for 26-34% of all global greenhouse gas emissions (Crippa et al., 2021; Poore & Nemecek, 2018). With modified agricultural practices and changes in consumer demand, that number could be reduced. By 2050, it has been estimated that food production will need to increase by 50-70% to sufficiently feed the anticipated 10 billion people on Earth (Aune, 2012; Wise, 2013). If no changes are made to our agricultural system and collective dietary choices, food-related activities could make up more than half of global greenhouse gas emissions by 2050 (Willet et al., 2019). This chapter will identify specific ways in which your individual environmental impacts from agriculture can be reduced through dietary choices, including the top foods to avoid.

Consumer-Based Solutions (listed in order of importance)

Determining the environmental impacts of our food choices is not easy. While nutritional information on food product labels is standard in developed countries, information about the greenhouse gas emissions and environmental practices used to produce the food is much less common. There are certifications and labels that can indicate a higher degree of environmental responsibility; however, it can often be confusing or even misleading (Grunert et al., 2014). With food making up 10-30% of individual household greenhouse gas emissions (CO_{2eq}), our food choices are an opportunity to make positive changes in the world (Jones & Kammen, 2011). Due to markedly different agricultural practices, including fertilization, irrigation, and pesticide applications, the environmental impacts of different foods vary greatly and depend on the environmental factor considered.

1. Eat More Plants and Less Meat

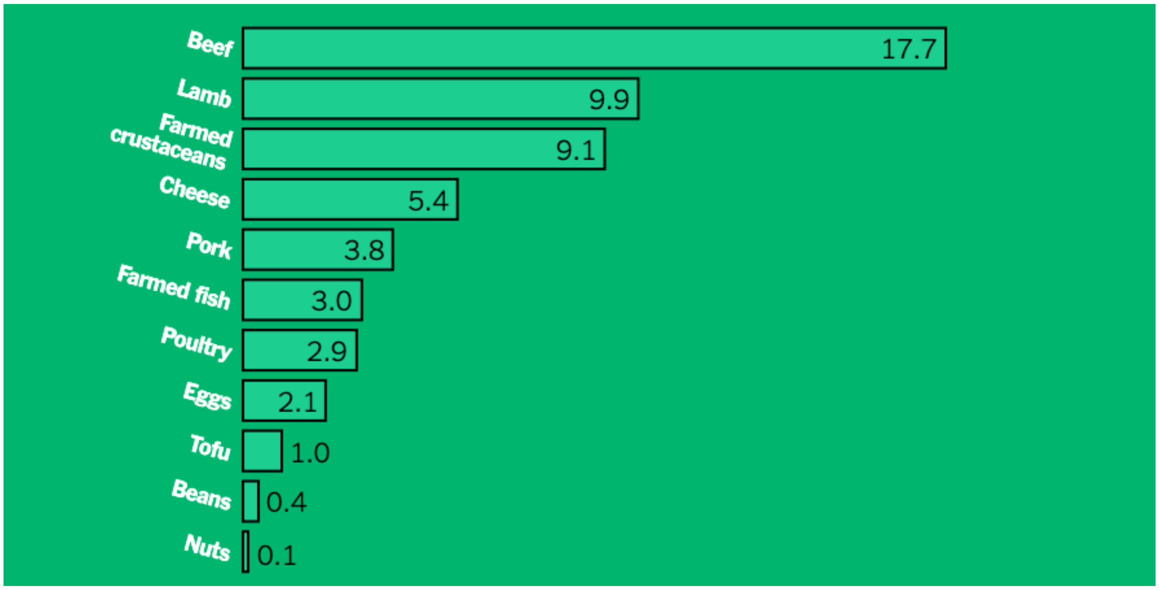

Figure 24: The relative differences in food-related greenhouse gas emissions (in kg CO_{2eq}/capita/year) per 50 grams of protein, or roughly the daily requirement. (Aleksandrowicz et al., 2016; graphic by Nadja Popovich).

As examined in previous chapters, the explanation for animal products' greater environmental impact relates back to the inefficiencies of their production. While animal products offer a rich source of protein and mineral nutrients and while livestock can eat crop residues and grasses not palatable to humans, animals, compared to crops, still require more resources overall (Ritchie & Roser, 2027). Ruminant animals, which provide red meat, produce the greatest greenhouse gas emissions primarily due to digestive enteric fermentation, fertilizer and feed production, and manure production. Ruminants include cows (beef and veal), pigs, lamb and sheep, goats, horse, and wild game like deer, elk, or bison (Broucek, 2014). Therefore, an emissions-friendly diet would prioritize plants and potentially also include a small amount of poultry, fish and eggs, much like the Mediterranean diet.

While recent literature has confirmed that reducing one's meat and dairy intake can significantly reduce the amount of land, water, and energy consumed, a vegan diet results in an even greater reduction (Dussiot et al., 2023). Note that while vegetarianism excludes the consumption of meat only, veganism excludes the consumption of all animal products, including fish, eggs, dairy products, and, for some, even honey (Chai et al., 2019). A meta-analysis of 34 life cycle assessment studies (Kustar & Patino-Echeverri, 2021) found that a vegan lifestyle sharply reduces land use (50-86%), water consumption (22-70%), and GHG emissions (21-70%).

Prioritizing organic foods is a great way to reduce the impact that food production has on the environment. The USDA organic certification standards require the integration of cultural, biological, and mechanical practices that support effective nutrient and resource cycling, biodiversity, and balance within ecosystems. Organic certifications also forbid the use of most synthetic fertilizers and pesticides, sewage sludge, irradiation of food, and genetic engineering of any kind (USDA, 2023). When it comes to growing crops, opting for organic growing practices means eliminating the use of harmful substances in the agricultural landscape (Hazra, 2016). By extension, purchasing organic animal products is also more environmentally responsible, as the USDA requires animals to be fed a 100% organic diet and restricts hormone and antibiotics administration. When it comes to raising non-ruminants (e.g., chickens), feed production has a greater environmental impact than other aspects of livestock management. In general, organic crop and livestock operations reduce greenhouse gas emissions and water quality degradation (Boggia et al., 2010).

Organic farming is, with respect to many indicators, more environmentally friendly than conventional farming (Rabes, 2020). While prioritizing organic foods is an effective way to help support farming practices that reduce degradation of terrestrial and aquatic ecosystems, it should be recognized that organic foods, which are commonly more expensive, may not be affordable or a priority for many consumers. Comparatively, reducing meat and dairy intake represents a greater opportunity to reduce both agriculture's environmental impacts and a shopper's grocery bill.

2. Prioritize Local and Seasonal Foods

A common recommendation you may hear is to eat locally and seasonally, meaning you purchase foods from farms in your area and avoid eating foods out of season. However, how much does this actually reduce a consumer's environmental impacts? Notably, transportation accounts for only about 9-11% of global agricultural greenhouse gas emissions, whereas production accounts for around 68%. (Weber & Matthews, 2008; State of Oregon, 2017). This might be surprising considering how much of the food in our grocery stores is regularly transported from across the country and sometimes across the world. As countries grow in wealth, consumers develop a higher demand for imported gourmet products, not to mention foods out of our immediate season and climate. Many tropical products, such as coffee, cocoa, bananas, and other fruits, are staples in the everyday life of an American. This puts into context the sheer size of greenhouse gas emissions resulting from agriculture. However, flying food all around the world only accounts for a small portion of the total carbon footprint for commercial food. Eating locally may be good for other reasons (e.g., helping the local economy and having a closer connection with food production), but it only slightly reduces greenhouse gas emissions. From a purely environmental perspective, it is far more important to concern yourself with what foods you eat, rather than where they come from (Ritchie & Roser, 2023).

3. <u>Be Informed About Labels</u>

Understanding the various certifications and labels within the food industry can be challenging. For example, in the egg industry in the United States, "free-range" means that birds are provided an indoor shelter with continuous access to outdoor areas, whereas "cage-free" birds are not offered outdoor access but are freely roaming within larger indoor rooms or buildings. Additionally, there are no USDA standards for "pasture raised" animal products, though this label is commonly applied to poultry products. Furthermore, there are "humane" and "natural" labels, which, respectively, mean animals are raised humanely and with minimal processing and artificial ingredients. However, the verification of these claims is largely subjective, without universal standards or regulations (USDA, 2023). Nonetheless, knowing which certifications you trust and prefer is an important step to becoming a more informed consumer.

4. Maintain a Connection to Food

Another valuable approach to reducing environmental impacts is to grow our own food, or at least a portion of it. Whether you live in a city apartment or out in the countryside, there are opportunities to grow food. If you live somewhere where you can grow a substantial garden, you can adopt sustainable practices, such as using organic fertilizers and avoiding herbicides and pesticides. In addition, by replacing a monoculture lawn with edible or native plants, you can support pollinators, biodiversity, habitat connectivity, and the resilience of the land around your home.

Final Takeaways

Food production is one of the main ways modern human life impacts the environment. As we choose what foods to eat throughout the day, we have an opportunity to support specific production methods over others. One of the most important things anyone can do to take action against the global climate emergency and expanding environmental degradation is to continue asking questions and learning with an open mind. Maintaining a healthy curiosity of the impact behind our everyday decisions, like those we make several times a day at mealtime, is important. Arguably most important is the ability to think critically and know which sources of information about food and agriculture are trustworthy.

In the global effort of environmental conservation and climate mitigation, consumers emerge as potent agents of change through their everyday choices. Individual choices help determine our collective future. In this text, I have walked you through how modern agriculture affects nutrient cycles, land, water, the atmosphere, and climate. With this knowledge, you now have a better understanding of the impact of different food choices.

From seed to soil, to being watered and nurtured with nutrients, harvested and transported, to being packaged and processed to arrive on the shelf in our local shops, the journey that food takes can be long and involute. The steps taken to get there dictate the impact of food on the natural world, and there is always an impact. From the marketplace to the dinner table, consumers yield transformative power. The impact of individual decisions throughout the day is felt on a societal and cultural level, and changes in those decisions can lead to paradigmatic shifts that reframe our relationship with food and the planet. Our food choices have never been more important to environmental and planetary stewardship.

Through actionable steps like embracing a more plant-based diet, supporting sustainable farming practices, and prioritizing local, organic, and low water consuming foods, consumers can help foster an environmentally conscientious future. The waves of systematic agricultural change begin as ripples of mindful consumption, and flow into the decisions of policymakers, scientists, farmers, and activists, holding the potential to establish a greater harmony between human progress and the well-being of the natural world.

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