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Ghanian African Dark Earths as an Alternative to Nitrogen-Based Fertilisers

A Master's Thesis submitted for the degree of
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Affidavit

I, **VICTORIA KEOGH, MA**, hereby declare

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Abstract

Nitrogen-based fertilizers produce crops which sustains half of the global population. While they are intrinsic for human life, excess nitrogen from fertilizer use has a negative impact on air, soil, and water quality. Furthermore, these fertilizers can gradually degrade the fertility of soils, and the production of nitrogen-based fertilizer consumes and emits large quantities of fossil fuels. Fertilizer use cannot be removed but could potentially be replaced.

This thesis focuses on African Dark Earths in Ghana and discusses the feasibility of using these soils as an alternative for nitrogen-based fertilizer. This question has been examined through an overview of available literature and data regarding known anthropogenic soils in both the Amazonian Basin and West Africa. Given research into West African Dark Earths is a burgeoning field, information from Amazonian Darks Earths have been used to fill any potential knowledge gaps, considering that the two soils are considered analogous. Between research completed on these two forms of anthropogenic soil, Dark Earths are discussed in terms of how they are made, why they are made, what chemical properties they contain, and what impact they have on soil fertility and agricultural yield. Ghana is taken as a case study to contextualise these soils and examine how they are made and used in a contemporary setting.

This thesis then discusses whether the impact these Dark Earths have on the local communities within which they are created could be extrapolated to industrial-scale farming. Given the time, cultural and spatial constraints of Ghanaian African Dark Earth production, it was determined they cannot be feasibly scaled-up to be of any significant impact on contemporary industrial farming. However, for local communities, this method of soil production may have positive and long-lasting benefits. This thesis concludes by discussing other substitutes to nitrogen-based fertilizers, resolving that while research and development into these technologies is in its nascent phase, there is reason to be optimistic about the future of food production.

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Acknowledgements

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To my "papa", thank you for your love of academia, engagement in my studies, and enthusiasm for knowledge and learning. May this thesis bring us a lively discussion in the future.

1. Introduction

By 1913, Carl Bosch had formalised Fritz Haber's method for nitrogen fixation, allowing the production of ammonia on an industrial level. The Haber-Bosch process, as it has become known, produces ammonia for use in nitrogen fertilisers which is used to grow the food that sustains 50% of the global population. However, while this monumental achievement has led to increases in food productivity and yield, the increased dependence on artificial fertilizer have led to concerns over the long-term sustainability of its use. The pollutants of anthropogenic nitrogen fixation have had an impact on water quality, air quality, green house balance, biodiversity, and soil quality. This does not account for the further concerns over the socio-political ramifications of the fertiliser industry, and the additional environmental burden of having to transport fertiliser internationally (Roy, 2001).

Sensing a need for a move away from nitrogen-fertiliser, increased research is being undertaken regarding organic alternatives. Specifically, there has been a surge of interest in Anthropogenic Dark Earths which have been detected in the Amazon rainforests. These soils are linked to sites of former inhabitation, and it is believed that the remnants of human civilisation (pottery, ashes from fires, vegetative and food wastes) have been key in giving these soils its additional nutritional potency (Lehmann et al., 2003). Furthermore, these soils are being viewed as an example of an early type of organic fertiliser, which was intentionally created and used within the community. This thesis will focus on the potential of anthropogenic Dark Earths as a viable solution to long-term sustainable agriculture. However, this study will concentrate on the lesser-known African Dark Earths (AfDE) which has become a burgeoning field after research in Ghana and Guinea have uncovered similar soil types to those found in the Amazon. Like the Amazonian Dark earths (ADEs), AfDE indicate intentional anthropogenic behaviours have created, and continue to create high quality soils which are reused within the community as an organic fertiliser for agriculture. These soils have been produced up to the present day; so, this paper will use AfDE as a contemporary example to study how small, local communities create organic fertiliser to use in place of nitrogen-based chemical fertilisers. To this end, Ghana is taken as a case study to contextualise these soils and examine how they are made and used in-situ.

Using Ghana as a case study, this thesis will address the main questions of how AfDE is created, what is its composition and to what extent it is possible to scale-up these processes to be applicable for industrial-scale agriculture. In particular, the purpose of this work is to discover if AfDEs are a feasible alternative to nitrogen-based fertilisers.

To answer this question, this work has been divided into four chapters:

1) An overview of nitrogen-based fertiliser, how they are made, and what impact a high nitrogen input can have on the environment: This chapter dedicates itself to determining why contemporary agricultural-industries have become reliant on nitrogen-based fertiliser, and the history behind ammonia synthesis. This chapter concludes with an analysis of the multi-faceted impact of nitrogen pollution.
2) An examination of ADE: ADE is used as a basis to understand the chemical composition and soil dynamics of anthropogenic Dark Earths, since this style of research has only recently emerged for AfDEs. ADEs will also be discussed from the perspective of how they are made, and the beneficial impacts they have had on the soils in the Amazonian Basin.
3) An examination of AfDEs: This chapter will look at AfDEs across West Africa. Given AfDE formation is a contemporary process, this chapter will focus on how these soils are formed, and the known impacts they have on the highly weathered Ferralsols of West Africa. This chapter will focus on the State of the Art for AfDEs but will continue to draw on Chapter II "ADEs" to bridge any gaps in knowledge.
4) A case study of Ghana, industrial AfDE applications and alternative methods: The final chapter will focus on Ghanaian AfDEs to try and answer the ultimate question of whether these soils can somehow be replicated on an industrial level. Alternative options to nitrogen-based fertilisers will also be discussed.

1.1 Research Design

The crux of this work is the interlink between human behaviour, and the soil processes which occur both naturally and as a by-product of anthropogenic intervention. Thus, a combination of literature has been used to strike a balance between scientific studies, and studies examining humans' role in the creation of AfDE.

AfDE has been subject to a burgeoning field of research. However, given its relative obscurity and novelty in comparison to Amazonian Dark Earths, studies are still discontinuous and comparably scarce. Fraser et al.'s (2014) work is a foundation of this thesis, as it discusses how anthropogenically altered soil is a process which continues up to the present day in countries like Liberia, Sierra Leone, Guinea and Ghana. This separates it from Amazonian Dark Earths which are no longer actively produced but are remnants of long-gone settlements. Duflo (2006) concentrates on the economic development perspective of fertiliser use in rural communities, and Amanor (2012) discusses how gender has influenced the creation of AfDEs, given that "dumping sites" are often the responsibility of women. The commonality between these researchers is their focus on the socio-political context of AfDE, rather than the biological and chemical processes of soil formation. These sources are important as the socio-political component of these "anthropogenic" soils cannot be ignored and is essential in discussing the human role in soil alteration- whether intentional or accidental. However, other literature such as Chen et al. (2019), Flavell-While (2010) and lectures given by Mark Sutton (Móring, 2018), have been included as their focus is purely scientific and describes the chemical and biological mechanisms of Dark Earth formation.

Given that AfDE research in West Africa is relatively new, studies completed on ADE have been included, in order to fill the knowledge gap of the bio-chemical processes which create Dark Earths. Based on the assertion by Frausin et al. (2014), it is the agreement of this thesis that, within reason, studies completed on ADE are comparable to AfDE. Steiner et al. (2007) and Lehmann (2009) are essential for their contributions to the anthropogenic component of Dark Earth formation. In particular, Lehmann outlines the importance of biochar (a by-product of human settlement), and its role in improving soil's nutrient retention rate. As proposed by Noguera et al. (2011), Van de Voorde et al. (2014), and Steiner et al. (2007), given certain soil types are more susceptible to nutrient loss, biochar may prove to be a realistic alternative to nitrogen fertilisation. This is one of the main innovations to be pursued by this work. Maezumi et al. (2018) bridges the gap between science and anthropology by linking the exceptionally rich *Terra Preta de Indio* soils found throughout the Amazon to sites of former human habitation and expands on the work of Noguera et al. (2011) in their analysis of the nutritional composition of Dark Earth Soil.

A series of literature dedicated to the nitrogen cycle has also been included to demonstrate the long-term impacts of nitrogen fertilisation; and to emphasise the need to find alternative agricultural practices and resources. The literature by Gruber and Galloway (2008) is a purely scientific work which outlines how the Haber-Bosch process is outpacing the availability of naturally produced nitrogen. The need for an organic alternative to chemical fertiliser is not a new idea but has been suggested for decades. In a 1907 study conducted in Guinea, Baillaud acknowledged the excessive use of chemical fertiliser could have a negative impact on crop productivity. Furthermore, by 1986, organic fertiliser was already being publicised as a cheaper and better option to chemical fertilisers (Anon, *Dubious Plans*, 1986). More contemporary research, such as a report by the European Nitrogen Assessment, has linked increased nitrogen fixation to degrading air, soil and water quality, as well as a loss of biodiversity and increased greenhouse gases (Nitrogenscientists, 2011). Furthermore, Roy (2001) points out there are wider environmental and socio-political consequences of the fertiliser industry, such as wage inequality, loss of resource, and the environmental costs of the international trade and transport of fertiliser.

Issues to be resolved in this work is the lack of scientific sources regarding AfDE. Thus far, works on western Africa have been scarce and decentralised. In order to fill this knowledge gap, researchers such as Duflo (2006), who focused their works on other African regions, will be used in order to draw generalisations. Furthermore, this thesis has been written after numerous discussions with Dr. Samuel Nettey of the University of Ghana to gain a better- and more local- understanding of these soils.

2. Nitrogen

2.1 A Basis for Life

Nitrogen is a building block for all life. It is a key component in amino acids which form proteins and enzymes in plants and animals. Even the nuclear basis of DNA contains nitrogen. In plants, nitrogen is an essential part of the chlorophyll molecules which makes photosynthesis possible. Therefore, without nitrogen, life could not survive.

For plants, their source of nitrogen comes from the soil. This nitrogen is made available in the soil either by nitrogen-fixing bacteria, which draws directly on N_2 in the atmosphere and fixes it to become a form useable for plants, or the mineralisation of plant and animal matter in soils. Nitrogen is mainly taken up in the form of nitrates (NO_3^-). Finding a way to input available nitrogen into soils to increase plant uptake/growth is the aim underlying the production of fertiliser. In fact, approximately half of the world's population is alive today due to food grown with the use of nitrogen-based fertiliser (Erisman et al., 2008). While the natural nitrogen cycle can supply reactive nitrogen in the soil from the concentrations in the air and degraded organic material, this supply would not be enough to produce the food required for the Earth's growing population. Therefore, finding an alternative and accessible source of nitrogen has been a historical challenge throughout human history. While mankind relied on organic sources of fertiliser for most of its history – such as manure - a breakthrough 100 years ago has enabled the global population to explode and has allowed farmers to keep pace. The creation of nitrogen-based fertilisers changed the world.

Despite its intrinsic importance for all life, nitrogen is the "*Godfather of environmental pollution*" (Sutton, The Nitrogen Cycle). Artificially creating reactive nitrogen has had a series of environmental consequences, which have thrown into question the benefits of chemical fertiliser versus the impact it is having on the world. Given that half of the world's population is dependent on fertiliser for survival, it is impossible for its use to stop or wane. Yet, it is important to understand the impact chemical fertilisation is having on the environment – and to begin discussing solutions. This chapter will address how nitrogen-based fertilisers are made, and the environmental problems their overuse creates.

2.2 Nitrogen Cycle

The Earth's atmosphere is 78% nitrogen. The nitrogen cycle describes how this element is naturally moved between the earth's soil, water, and atmosphere. The natural nitrogen cycle is shown in Figure 1. There are two ways by which nitrogen can be introduced into soils. First, nitrogen-fixing bacteria in the soil can draw on N_2 from the atmosphere and convert this nitrogen into ammonia (NH_3). This process is called bacterial nitrogen fixation, and these bacteria can be found in soil, water, or in plants themselves (known as "symbiotic bacteria"). This ammonia then undergoes nitrification to form nitrates (NO_3^-), a form which is available for plant uptake (Gouda et al., 2018). Secondly, nitrogen is also sourced in soils in the form of organic nitrogen. Plants can be eaten by animals or humans and returned to the soil through excrement which include organic nitrogen compounds. Alternatively, decomposed plant and animal matter in the soil can mineralise into ammonium and then nitrify into nitrates. Nitrogen at this point in the cycle can also escape into the air through denitrifying bacteria which convert nitrates back into N_2. The cycle is closed by nitrogen-fixing bacteria which draws on N_2 in the atmosphere and the cycle repeats.

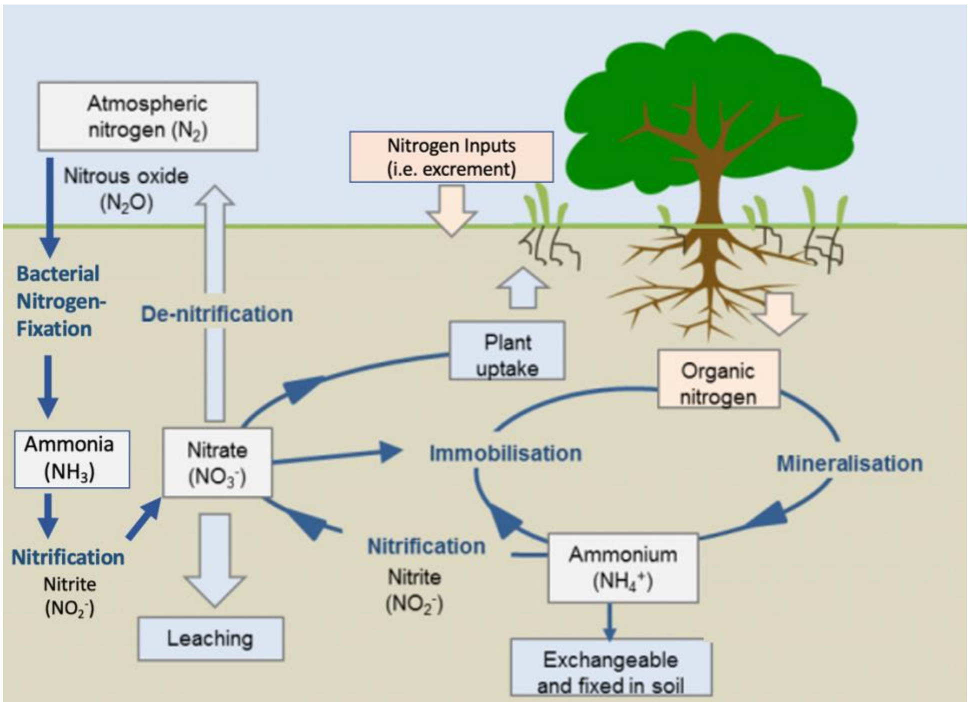

Figure 1: Nitrogen Cycle
Source: Modified from Department of Primary Industries and Regional Development, 2017.

While the marine-nitrogen cycle is not the focus of this thesis, it is notable to mention as nitrogen excess from fertiliser can also impact the natural nitrogen cycles of the seas. The oceans are one of the largest sinks of nitrogen. The presence of nitrifying bacteria removes N_2 from the air which can then be precipitated into sedimentary rock at the bottom of the oceans. Nitrogen is then released by the weathering of these rocks over time, or by denitrifying bacteria which also releases nitrogen back into the air as N_2 (Galloway, 2008). This is the natural nitrogen cycle- excluding all human impacts such as fertilisation. In this way, the nitrogen cycle ensures a continual supply of nitrogen is moved between the soil, sea, and air.

As has been mentioned, the concentrations of nitrogen naturally produced is not enough to grow the quantities of crops needed to feed the current global population. Approximately 250 Tera-grams of nitrogen are fixed or absorbed naturally by the nitrogen cycle every year (Galloway, 2008). However, the need to wait for these natural processes to take place is not compatible with the need to supply food to a growing global population. For this reason, fertiliser has always been used to capture and reuse nitrogen for plant uptake. Having discussed the natural cycle of nitrogen, this work now turns to a way by which ammonia can be artificially produced.

2.3 Haber-Bosch Process

Mankind has always searched for a form of nitrogen to exploit. While nitrogen is abundant in the Earth's atmosphere, it is not readily available. The triple bond of N_2 in the atmosphere makes it very stable and difficult to "fix" (Sutton, The Nitrogen Cycle). Before the synthesis of ammonia, Guano, Salpeter and ammoniac extracted from coal had been sources of fertiliser used to feed the world. However, these sources are not reliable – and are often finite. In the case of Guano, overexploitation led to the collapse of a bird species, and an exhaustion of the resource- demonstrating just how fragile these natural reservoirs can be. Therefore, a more stable and sustainable source of nitrogen was needed. This was accomplished with the discovery of how to "fix" or artificially activate nitrogen in the atmosphere to create ammonia. The synthesis of ammonia is a cheaper, more reliable, and more efficient means to obtain nitrogen than former sources or relying on what is naturally produced. Currently, more than 80% of global ammonia production is used in nitrogen-based fertilisers (Chen et al., 2019 and Erisman, 2008). This ammonia is synthesised using the Haber-Bosch process.

Fritz Haber in 1909 discovered a way to artificially "fix" nitrogen. This procedure required a high-pressure environment (around 175 atmospheres) and temperatures of 550°C, using a catalyst of osmium and uranium. Subjecting dinitrogen and dihydrogen to these conditions created small concentrations of ammonia – and his initial experiments yielded ammonia concentrations around 15%. However, the yield was too small to be used industrially, and expensive to create. Furthermore, the technology was simply not available to enlarge this procedure to increase the concentration yields. Yet, Haber's ability to create artificial nitrogen had such important implications for the agricultural and military fields (ammonia is a key component of dynamite) that his discovery attracted much interest and attention. So, in 1913, Carl Bosch was given the task of finding a way to scale up this process.

Bosch did this by slightly altering Haber's method. First, he introduced water-gas as a synthesis gas which was cheaper than Haber's use of dihydrogen and dinitrogen and feasible to scale-up. (Flavell-White, 2010). Second, the catalyst was changed from osmium and to an iron-oxide compound which performed just as well and was a cheaper substitute. Third, Bosch needed to design a reactor which would be able to withstand the high temperatures and pressures required by this reaction. This resulted in the creation of the first lined reactor which allowed hydrogen to both enter and exit the reactor chamber – preventing the potential for a build-up and explosion. The first plant with these new parameters in place opened in Oppau in 1913, forever changing the agricultural – and military – landscape. For their accomplishment, Haber was awarded the Nobel Prize in 1918 and Bosch in 1931 (Flavell-White, 2010).

Over the past 100 years, the process has not changed drastically asides from being further optimised, and advancements in machinery catching up to the high pressure and temperature requirements of the Haber-Bosch process. Figure 2 shows a schematic of the process of modern-day ammonia synthesis plants. Nitrogen and hydrogen are circulated over the iron-oxide catalyst at 500°C at a pressure of 150-200 atmospheres to create ammonia on an industrial scale (Chen et al., 2019). Currently, the process is only about 50% efficient with each ton of ammonia produced containing 5 MWh of energy (Boerner, 2019).

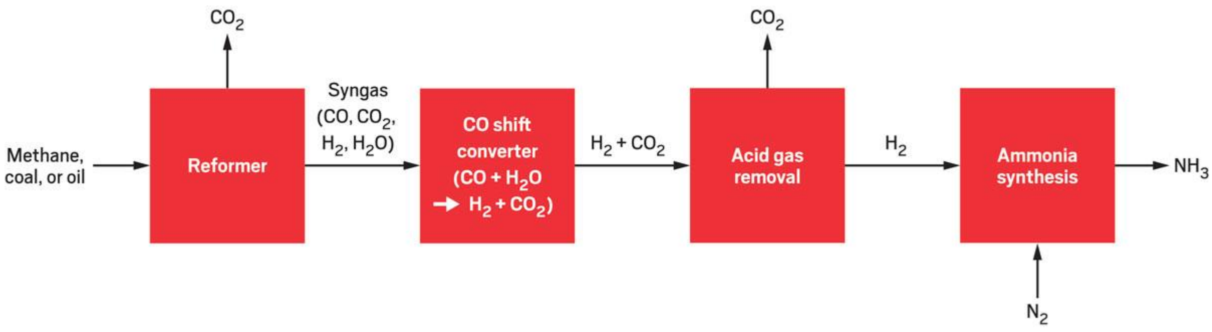

Figure 2: Summary of the Haber-Bosch Process
Source: Boerner, 2019.

While the Haber-Bosch process synthesises ammonia, it is important to distinguish that is does not create *fertilizer*. Rather, it creates one of the key components of fertilizer. Once ammonia has been produced, it is oxidised with air to produce nitrogen dioxide (NO_2) which is then absorbed in water to create a liquid solution of nitric acid (HNO_3). This nitric acid is then converted into ammonium nitrate (NH_4NO_3), or urea ammonium nitrate (Fertilizers Europe, 2021 and Grande et al., 2018). These are the forms in which nitrogen is usually applied to soil – rather than ammonia in its pure form. Other popular forms of fertilizer include NPK fertilizer (nitrogen – phosphorous - potassium), and potassium- or phosphorous-based fertilizers.

Figure 3 shows the impact of nitrogen-based fertilizer on the nitrogen cycle. Fertilizer contributes ammonia and nitrates to the soil. Ammonia (NH_3) when applied to the soil reacts to form ammonium (NH_4^+) which then nitrifies to form nitrates (NO_3^-) (CTAHR, 2021). Nitrates produced from fertilizer are then available for plant uptake. As can be seen in Figure 3, fertilizer does not alter or change the nitrogen cycle. Rather, it represents a high input of nitrogen forms, making it easier for plants to uptake the nitrogen they need to grow. However, there are limitations to the amount of nitrogen that plants can uptake or use- especially within a given time frame. Fertilizer does not increase nutrient retention – it simply provides more nutrients to the soil. Without increased nutrient retention, excess nitrogen will not be used and can be lost and create environmental concerns.

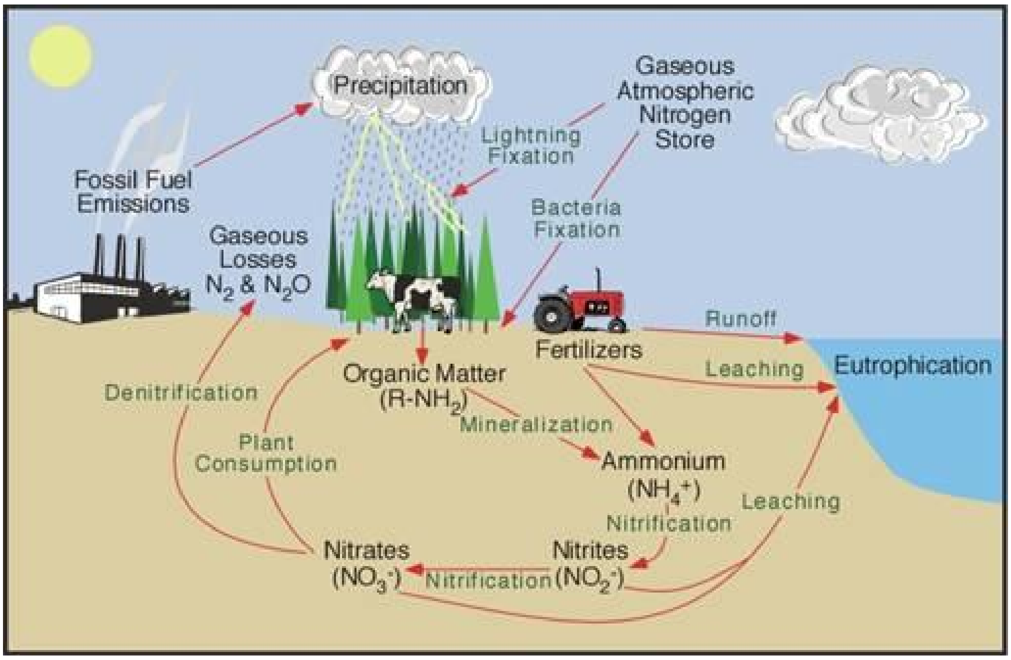

Figure 3: Nitrogen Cycle with Fertilizer
Source: CTAHR, 2021, https://www.ctahr.hawaii.edu/mauisoil/c_nutrients01.aspx.

As can be seen from Figure 3, fertilizer additions can lead to runoff and leaching of excess nitrogen, which can cause eutrophication. Yet, losses because of nitrogen excess are not the only impacts chemical fertilizers have. Figure 4 details the way in which nitrogen-based fertilizers can acidify the soil. The introduction of ammonium to the soil means more H^+ ions than would naturally be produced in the nitrogen-cycle (University of Adelaide, n.d.). If these ions are not taken up by plants, they accumulate in the soil, leading to long-term acidification. This depletes the quality of the soil which impacts plant diversity (as individual plant species have specific ranges of pH within which they can grow) and leads to decreased microbial diversity (Kamaa et al., 2011).

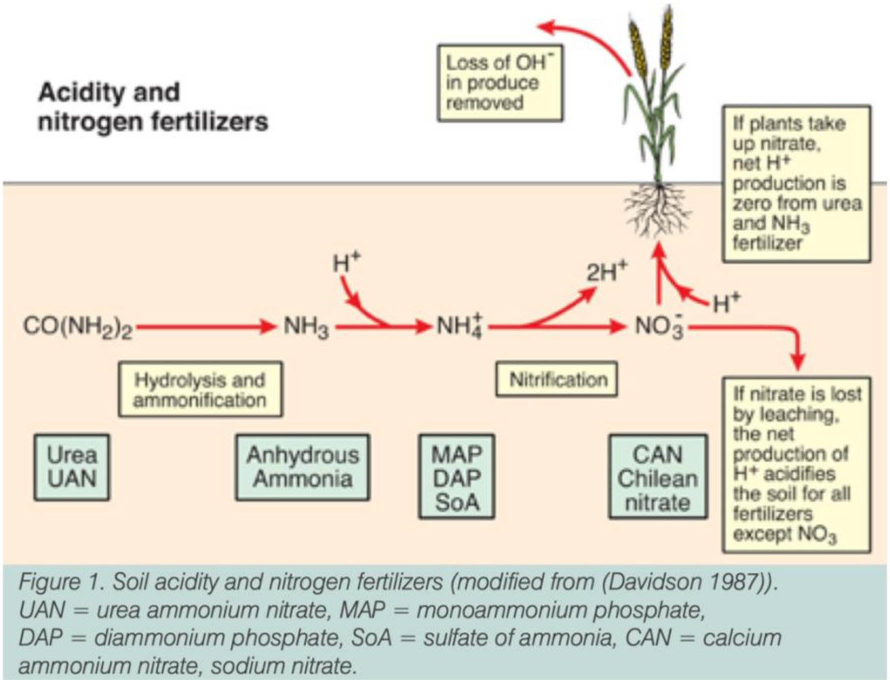

Figure 4: Soil Acidification by Fertilizer
Source: University of Adelaide, n.d.

The demand for fertiliser is increasing, as is the concentrations of ammonia needed to be synthesised for fertiliser production. This demand is driven by the rising population and decrease in arable land. Nitrogen-rich fertiliser means the crop yield per hectare can be increased, offering a hopeful solution for future problems of food shortages. Furthermore, ammonia is also in demand for the burgeoning field of biofuels and the subsistence of animals which are fed using crops grown with fertiliser (Erisman, 2008). For all these reasons, the Haber-Bosch process has changed the world. Approximately 100 Tera-grams of the nitrogen created by the Haber-Bosch process annually is used in agriculture. Yet only 17 Tera-grams of nitrogen are consumed by humans in crops and animal products. This disparity between the amount of nitrogen produced and the amount consumed via final products indicates a problem of large-scale nitrogen excess or loss. The types and impacts of this nitrogen surplus will now be addressed (Ibid.).

2.4 The Problem

In 2019 the United Nations launched the "Colombo Declaration" which aims to halve all nitrogen waste by 2030. This global initiative seeks to address the problems of nitrogen pollution and find a way to sustainably manage nitrogen use. While acknowledging that all life is dependent on nitrogen, the UN recognises the compounding problems caused by its overuse which is beginning to take its toll (UNEP, 2019). As Kanter points out, the ability of nitrogen to take on many different chemical forms (NH_3, NO, NO_2, NO_3, NO_X) means it can easily exacerbate any pre-existing environmental problem (Kanter et al., 2020). Nitrogen wastes impacts air quality, water quality, soil quality, ecosystems and biodiversity and the Greenhouse Gas balance (Sutton, The Nitrogen Cycle, and European Nitrogen Assessment, 2011). The effects of nitrogen on these parameters will be addressed below.

Air Quality: The main source of anthropogenic nitrogen in the atmosphere comes from the combustion of fossil fuels, and losses in fertiliser use. Specifically, ammonia when applied in its pure form in fertiliser is susceptible to escape the soil surface and be released into the air (CTAHR, 2021) and losses may also be due to leaching, which will be discussed below (Erisman, 2008). Combined, these two sources of loss contribute approximately 160 Tera-grams of nitrogen into the atmosphere every year. As a comparison, 110 Tera-grams are naturally fixed by the land, and 140 Tera-grams of nitrogen are absorbed by the sea annually (Galloway, 2008). This emission of nitrogen from anthropogenic sources represents over half of what can be processed naturally by earth-systems. This is alarming given that N_2 emissions from natural nitrogen cycles have not been considered here. Due to this, nitrogen-related Greenhouse Gases (NOx and N_2O) are forming at higher concentrations, causing air pollution which has led to an increase in respiratory diseases (UNEP, 2021). According to the American Lung Association (2021), emissions of Nitrogen Dioxide (NO_2) from fossil fuel use have been connected to asthma in adults and children, and cases of lung cancer. Additionally, these nitrogen-based emissions are linked to problems such as acid rain, increased tropospheric ozone and low visibility (EPA, 2016).

Water Quality: Nitrates are highly mobile in the soils – meaning they are more susceptible to leaching with ground and rainwater. As these compounds are available for plant uptake, their loss not only affects the fertility of the soil, but it is also an economic loss for farmers using fertiliser. The nitrogen in these compounds can end up in potable drinking water reservoirs or be leached into water bodies such as lakes or rivers. This is problematic as increased nitrogen concentrations can affect the quality of the water (CTAHR, 2021). Excessively high nitrogen concentrations in drinking water can cause reproductive and development problems for humans and can even be fatal for infants (EPA, 2019). Furthermore, nitrogen is a known cause of eutrophication and leads to large algae blooms (Galloway, 2008). Thus, mismanagement or misuse of fertiliser can have an impact on ecosystems and communities outside of the agricultural area where it was applied.

Soil Quality: Fertiliser is also linked to changed pH levels in soil over multiple applications. If a fertiliser contains high ammonium levels, it can decrease the soils pH levels – acidifying the soils. This impacts microbial diversity in soils, as bacterial and fungal biodiversity were found to decline with consecutive chemical fertilisation. Microbial communities in soil enable nutrient cycling and decomposition of organic matter (Nakhro and Dkhar, 2010). As an indirect cause of inorganic fertilisation, decreased microbial communities lead to decreased Soil Organic Matter (SOM), which in turn further depletes the soils' microbial communities (Kamaa et al., 2011). These fertilisers require increase concentrations of "lime" or calcium carbonate, to mitigate the impacts of this acidifying component (CTAHR, 2021). For this reason, the type of fertiliser and the frequency of its use can have an impact on the quality of the soil. This impact may not necessarily be bad- as fertiliser is used to improve the nutritional concentration in soil. However, given its ability to have such a drastic impact on the pH levels, microbial communities and nutrient concentrations of its surroundings, its use must be carefully regulated. Soils which have become too degraded are difficult to save and, ironically, the fertiliser used to save it may cause more harm than good.

Ecosystems and Biodiversity: On land the changing pH levels can also have an impact on the species of plant which could be grown (CTAHR, 2021). According to a 2015 report by the USA Environmental Protection Agency, nitrogen waste causes 6.5 million USD of losses annually in different US states due to eutrophication, algal blooms, and the loss of aquatic life. This had a detrimental impact to commercial fishing as states recorded reduced shellfish, shrimp and crab harvests, fish poisoning, and bed closures due to pollution. For this reason, artificially created ammonia can have an adverse impact on the ecosystem and biodiversity of plant species. Depending on the type of fertiliser used, the nitrogen compounds may hinder plant and animal growth and diversity.

Financial Considerations: Nitrogen waste has a knock-on effect for other industries. A decline in the quality of water or air decrease property values of residences located near water bodies or places of industry. Furthermore, areas which have been polluted (i.e. experience eutrophication) can lose revenue from tourism if they rely on water-based recreation – or must pay for costly restoration projects. Having a polluted source of water, air or soil also leads to increased health expenditures and costs of potable drinking water. Increased funds must be channelled to treat water from local sources before it is fit for human consumption (EPA, 2015).

Dynamite: These problems are all related to ammonia. Another problem with the synthesise of nitrogen is the compounds produced are major components of dynamite and other explosives. Not only has this reactivity been exploited for military purposes, but it has also caused widespread damage in other ways. For example, the 2020 Beirut explosion was caused by the unsafe storage of ammonium nitrate. This explosion killed 200 people and caused between 10-15 billion dollars of damage (BBC, 2020, *Beirut Explosion*). This is a very recent example of the threat posed by artificially produced ammonia. Nitrogen is a double-edged sword. As explained by Erisman (2008, p. 636), "*millions of people have died in armed conflicts over the past 100 years, but at the same time, billions of people have been fed*."

Energy Requirement: The process of creating active nitrogen also creates environmental concerns. As can be seen from Figure 2, ammonia synthesis is reliant on fossil fuel feedstocks. The ability to maintain a reaction at such high temperatures requires huge quantities of energy, and ammonia synthesis consumes approximately 1% of the world's total energy production. Given the use of fossil fuels as the source of this energy, ammonia synthesis is also responsible for the emission of 451 million tons of CO_2 into the atmosphere- which accounts for about 1% of the world's annual CO_2 emissions. And within these emissions, half of the total CO_2 output is derived from the energy requirements to produce hydrogen (Boerner, 2019). Creating ammonia is a highly polluting and energy-intensive process. Additionally, given the reliance on fossil fuels, fertiliser can be expensive – and represents a 100-billion-dollar industry (CTAHR, 2021 and AIChE, 2016). The lack of access to fertiliser on account of its pricing will be discussed in Chapter III "AfDEs." Optimising the Haber-Bosch process to minimise its environmental impact has been suggested to mitigate the impact of ammonia synthesis. For example, certain "green ammonia plants" have begun to substitute renewable energies or biofuels in place of fossil fuels to power the reaction – or use hydrogen from purge gas. Some improvements have been made to improve energy efficiency; however, plants now consume closer to 30-40 GJ/megaton, rather than the 60 GJ/megaton of the older versions of the plants. While this is a substantial decrease, it still entails a hefty energy consumption (AIChE, 2016). Such solutions will be addressed in Chapter IV "Applications."

The Colombo Declaration is only one of 2,726 policies across 186 countries which concerns nitrogen regulations – a good indicator of how severe of a problem is posed by nitrogen overuse (Kanter et al., 2020). Understanding how fertiliser use can cause financial and environmental problems explains the desire to find an alternative option to increase agricultural yield and nutrient concentrations of soils. One option which is increasingly investigated is to replicate the formation of the highly nutritious African Dark Earth soils. These anthropogenic soils may hold the key of how to increase soil fertility in a natural way. An exploration of these soils will form the basis of this work.

3. Amazonian Dark Earths

3.1 ADEs as a Comparison to AfDEs

AfDEs were "discovered" relatively recently, meaning in comparison to ADEs little is known about their chemical composition or structure. For this reason, this thesis offers an examination of ADEs as analogous soils to fill potential gaps in knowledge. ADEs have been subject to intense research since the 1960s given their fertility and contemporary use by South American farmers (Fairhead and Leach, 2009). Much is known about how they are formed, and how they function, making them a useful proxy for lesser known AfDEs.

ADEs are thought to cover between 1-3% of the total forested portion of the Amazonian Basin and have been definitively recorded in multiple Basin countries (Oliveira, 2020). Unlike this work's exploration of AfDEs, when discussing ADEs no singular country or location will be pinpointed for analysis. Rather, ADEs in general will be used as a comparison to AfDEs with the understanding the scientific community supports the claim they are analogous (Frausin et al., 2014), and it is scientifically sound to extrapolate chemical data and apply it to AfDEs.

To demonstrate the compatibility of this comparison, this work offers a brief comparison of Accra, the capital of Ghana, and Manaus, the capital city of the Brazilian state of Amazonas- which is in the Amazonian Basin. The longitudinal difference between the two can be shown in Figure 5 below:

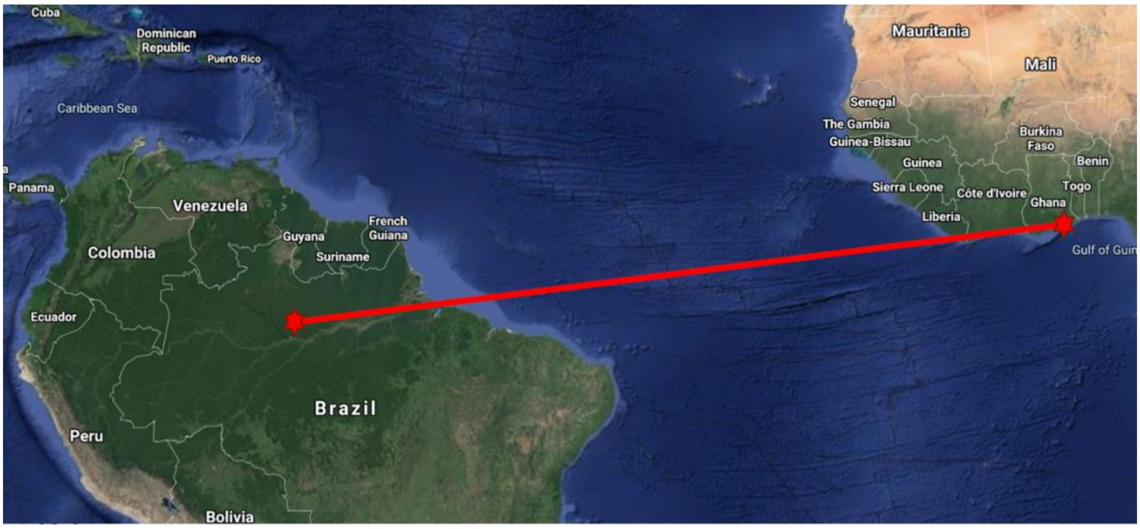

Figure 5: Satellite Image Showing Manaus, Brazil and Accra, Ghana
Source: Google Maps, https://www.google.com/maps (Accessed April 22, 2021).

Manaus and Accra are 6,715 miles apart with an 8° latitudinal difference. Table 1 shows annual average temperature and precipitation of the two cities. While the temperatures are congruent, there is a vast difference in the annual and monthly precipitation. This distinction must be kept in mind when comparing ADE and AfDEs, as these two soils are similar, but are not formed in identical climates. Thus, while this comparison is accepted by scientists, and while this thesis will demonstrate that the formation and effects of ADEs and AfDEs are synonymic, the comparison is not without fault. And, as will be discussed in Chapter III "AfDEs," Ghana suffers from different climatic problems than Brazil.

Table 1: Comparison of Temperature and Precipitation between Accra and Manaus.

Sources: Climate-Data.org, https://en.climate-data.org/ (Accessed April 22, 2021).

Weatherbase, http://www.weatherbase.com/weather/weather.php (Accessed April 22, 2021).

Annual Average Temperature (Celsius)												
Accra												
Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Annual Average
27	28	28	28	27	26	25	25	26	26	27	27	27
Manaus												
Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Annual Average
27	26	27	27	27	27	27	27	28	28	28	27	27
Annual Average Precipitation (mm)												
Accra												
Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Annual Average
17	19	31	54	129	183	75	39	50	65	54	32	62.3
Manaus												
Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Annual Average
322	331	395	385	334	200	133	114	133	159	193	302	250.1

3.2 Formation of ADEs

Anthroposol soil is an ancient innovation. Diving into the depths of the Amazonian rainforests, researchers have found anthropogenically-modified landscapes dating back 4,500 years (Maezumi et. al, 2018). Research into human modification of the environment did not start as a scientific question, but rather a historical one. The early South American colonisers of the 15^{th} and 16^{th} centuries wrote accounts of cities with populations numbering in the millions, and archaeological excavations of Pre-Colombian civilisations are well recorded (Oliveira, 2020). The question remained of how the dense, nutrient-poor soils of the Amazon were able to support such large numbers of people. The answer came in the 1960s when an excavation site at the Amazon, Rio Negro and Madeira rivers led to the discovery of *Terra Preta de Indio* (Schmidt, 2014).

Terra Preta is unique for several reasons. First, they have a singular characteristic which can be observed by the naked eye as they are a much darker colour than surrounding soil sites – *Terra Preta* means "dark earth" in Portuguese; a literal indication of how these soils can be identified (Lehmann, 2009). Furthermore, ADE sites are demarcated by a distinct biodiversity which is more diverse than surrounding soils and favors edible plants and tree species- a notable indication of their former use (Robinson et al., 2020). ADEs are usually found in a fixed and intentionally created area, often demarcated by fortifications with canals (Oliveira, 2020). Moreover, Amazonia Brown Earths (ABEs) (a form of ADE where the biochar was not completely pyrolyzed) are found on the peripheries of ADE sites as a transition between unaltered soils and ADEs (Lehmann, 2009). Their appearance around ADE indicates these soils were deliberately concentrated in certain areas (Robinson et al., 2020). Therefore, the effects of ADEs must have been known, and purposely used.

A primary characteristic of ADEs is their composition. ADEs are composed of a wide range of organic, inorganic, cultural materials, and biochar. Typical components of ADE include bones and remnants of burial activities, animal and human excrement, waste from human habitation (ceramics, remnants from buildings, straw or palm leaves, oil, dyes) (Lehmann, 2009), plant and animal residues and ashes and charcoal (Bento et al., 2020). This eclectic mix is indicative of natural by-products and waste of quotidian life, implying the original formation of ADEs may have been unintentional before it was intentionally incorporated into agricultural activities. Schmidt (2014) believes the incorporation of biochar may initially have been mixed with human waste in lavatories to prevent the spread of infectious diseases. He goes on to propose human waste was a key source of fertilizer, and therefore biochar was a way to ensure it would be preserved until transported to the fields. While this may be a contributing factor to the presence of biochar in ADE, it is more commonly accepted that biochar was formed by pyrolysis, either as a waste-management strategy (Bento et al., 2020) or a soil-management strategy to renew the soil for the next cultivation (Souza et al., 2018). This addition of biochar is the key indication these soils were the result of human production.

The dark colour, concentrated soil sites, eclectic composition, and incorporation of biochar are the main characteristics of ADEs. While the intentional production of these soils is not unanimously accepted, this work points to the sites demarcated by ABE and canal fortifications as evidence ADE was intentionally produced. To understand why these soils were heavily used by Pre-Colombian populations, and why they are highly sought after today, this work now turns to the impact the composition of this soil has on its fertility.

3.2.1 Methodology

A review of all relevant literature regarding the soil composition of ADEs was completed. Efforts have been made to ensure all literature reviewed was up-to-date and valid. However, older articles (such as Lehmann, 2003) are considered foundational to the subject, and are still widely cited in contemporary literature. For this reason, some literature which is older has been included as it is still considered relevant.

The discussion of ADEs will make use of information from countries throughout the Amazonian basin. Distinction will be made of where the study was conducted, but all Amazonian Basin ADEs will be considered as analogous to be used as a comparison to AfDEs. The literature regarding this topic is largely unanimous when it comes to the chemical composition, and effects, of ADEs. The main point of debate revolves around the question of intentional or unintentional creation of ADEs. However, as this is not a key consideration for this chapter, this thesis expresses its opinion that ADEs were intentionally created and does not dive further into this debate.[1]

The data presented below is derived from this literature review and does not represent original fieldwork. A standard procedure of soil sampling, collection and preparation was followed in most studies. This included collecting soil samples at ADE sites and control sites (mixed-soils/ferrous soils/etc) at a range of 0-20cm depth. Samples were then dried (either air-dried or oven-dried) and sieved to prepare them for characterisation (Corrêa et al., 2020, Almeida et al., 2020, Asare and Afriyie, 2020, Oliveira, 2020). The method to analyse these samples was not identical as each study differed in their research question.

[1] Oliveira offers a concise overview of the relevant literature concerning this debate as of 2020. For more information regarding this discussion, please refer to his bibliography.

3.2.2 ADE Principal Processes

ADEs are defined by two clear and distinct processes. First, increased concentrations of nutrients are inputted into the soil through the anthropogenic addition of vegetative wastes, ceramics, bones, and biochar (which is added in the form of ashes from fire or created in-situ through pyrolysis of wastes). Second, the introduction of biochar increases the overall pH of the soil, which in turn activates microorganisms and increases the soil's cation-exchange capacity ("CEC"). The CEC allows for nutrients with cationic charges to be held in the slightly negatively charged soil, leading to an increased nutrient retention, and an overall increased soil fertility (Brown and Lemon, 2021). Furthermore, increased activity and reproduction of microorganisms means more nitrates are assimilated by microorganisms, rather than lost through leaching (Lehmann, 2009). This is the foundation of all anthropogenic Dark Earth soils; anthropogenic input followed by an overall soil improvement due to increased nutrient retention. These processes are summarised in Figure 6. When comparing the nitrogen cycle with Dark Earths to the naturally occurring nitrogen cycle, the cycle itself does not change. Rather, the main difference is there are increased nutrient inputs, less losses, and increased nutrient retention.

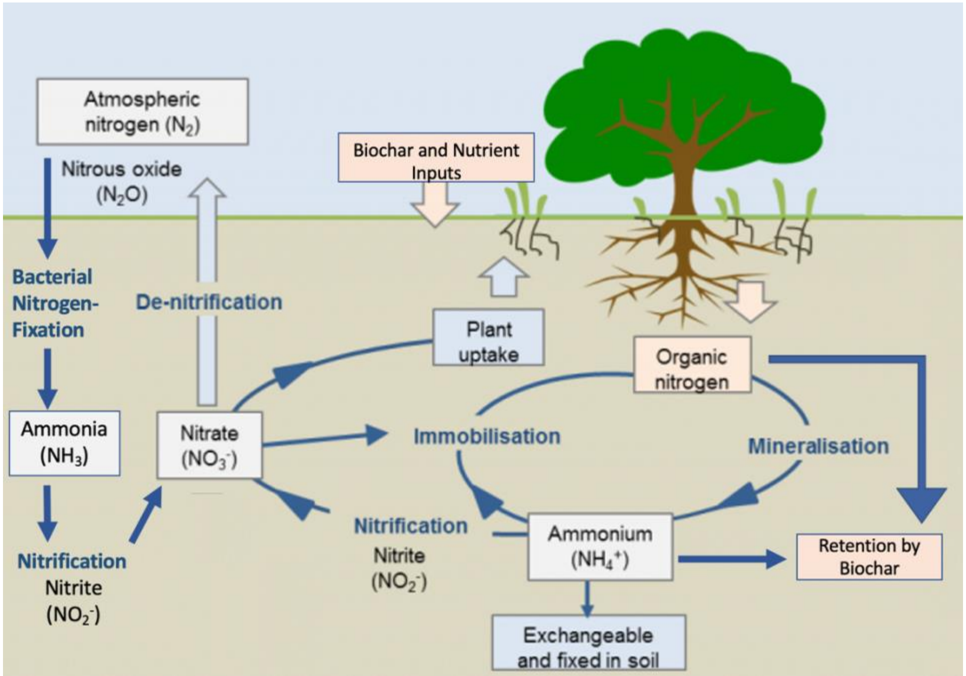

Figure 6: Dark Earth Nitrogen Cycle
Source: Modified from Department of Primary Industries and Regional Development, 2017.

ADEs are surrounded by Ferralsols or other mixed soils which act as control sites for studies. This soil type if characterised as yellowish white, highly weathered, nutrient poor, and clay-like with a low cation exchange capacity (FAO, 2015), low fertility and a low concentration of Soil Organic Matter (“SOM”) (Lehmann, 2003). Immediately, as a comparison, ADE stands out for its high SOM, high nutrient concentrations, and its fertility and agricultural yield. The differences between these soils will be broken down into individual characteristics for the ease of the reader.

3.2.3 Nutrients

To discuss nutrients in ADE, this thesis will briefly explain what these nutrients are and what role they play in soil. This thesis focuses on “available” nutrients. These are nutrients which are in forms available for uptake by plants such as Nitrate (NO_{3-}) and ammonium (NH_{4+}). These nutrients are distinct from the “total” nutrients, which are concentrations of nutrients which are found in the soil but are not in forms available for plant uptake. Total nutrients are converted to available nutrients through processes such as decomposition by microorganisms or weathering of rocks (Welkes and Fyles, 2005). Nutrients in plants can also be broken down into “macro” and “micro” nutrients. Macro nutrients are those which are required by plants in larger concentrations. Table 2 presents an overview of these macro and micronutrients, and their role in plants.

Table 2: Micro/Macro Nutrients and Their Role in Plants.
Source: Boundless, 2021.

Macro and Micro Nutrients in Plants			
Macronutrients	**Role**	**Micronutrients**	**Role**
Carbon	Formation of carbohydrates, proteins, nucleic acids	Iron	Chlorophyll synthesis
Hydrogen	Formation of organic compounds, water	Manganese	Chlorophyll synthesis
Oxygen	Cellular respiration, Formation of water	Boron	Carbohydrate transport; metabolic regulation
Nitrogen	Formation of proteins, nucleic acids, vitamins	Molybdenum	Convert nitrates into available compounds
Phosphorus	Synthesis of nucleic acids, conversion of light energy into chemical energy	Copper	Formation of enzymes
Potassium	Regulates stomatal opening and closing	Zinc	Chlorophyll synthesis

Calcium	Regulates nutrient transport	Chlorine	Supports osmosis and photosynthesis
Magnesium	Supports photosynthesis process		
Sulfur	Formation of amino acids, electron transport during photosynthesis		

Table 3 offers a summary of the element levels found in a collection of soil samples taken by Robinson et al. in the Bolivian Amazon. In ADEs, the levels of nitrogen, manganese, and potassium are elevated when compared to the adjacent control soils – with levels of phosphorus and calcium being particularly high. A clear transition in nutrient content can be observed as the samples move from the yellow white Ferralsols, through the ABE and finally onto the ADE.

Table 3: Total Element Concentrations in ABE, ADE and Control

Source: Robinson et al., 2020.[2]

Average Total Element Levels in ABE, Control and ADE Bolivian Soils (All Values in mg/kg)										
ABE										
Copper	Zinc	Barium	Iron	Aluminium	Calcium	Magnesium	Manganese	Phosphorus	Potassium	Sodium
17.2	17.4	10.6	43155.7	72765.8	561.9	102.6	68.0	321.5	107.0	18.2
Control										
Copper	Zinc	Barium	Iron	Aluminium	Calcium	Magnesium	Manganese	Phosphorus	Potassium	Sodium
14.2	11.7	9.9	40312.5	71862.8	35.9	39.1	23.0	127.5	101.1	16.6
ADE										
Copper	Zinc	Barium	Iron	Aluminium	Calcium	Magnesium	Manganese	Phosphorus	Potassium	Sodium
11.6	21.6	48.6	8778.3	25781.1	2892.4	227.3	287.1	1620.0	135.8	12.2

The reason for this elevated nutritional content is rooted in the high SOM – where most of these nutrients are stored. This SOM takes the form of kitchen wastes (i.e. vegetative wastes or by-products of crop processing), excrement, bones, ceramics, ash, charcoal, and any other "pure" (i.e. not manufactured or processed) inputs. The SOM contributes to a high CEC, which is given increased efficacy by the higher pH values of ADE soil (to be discussed below) (Lehmann, 2003). As demonstrated in a study by Almeida et al. (2020), the high SOM content and CEC led to ADE high sorption and low desorption rates. Table 4 shows a side-by-side comparison of CEC values recorded by Almeida et

[2] Data obtained from an open source excel sheet attached to Robinson et al.'s article. Data is from the site described in the study. Calculations were completed by the author. This table shows the averages derived from 14 ABE samples, 14 control samples, and 21 ADE samples. This datasheet can be accessed here: https://onlinelibrary.wiley.com/doi/10.1002/gea.21839.

al. (2020) and Robinson et al. (2020) respectively when compared to controls. In both studies, it can be seen the CEC is significantly higher than the adjacent nutrient poor-soils, indicating this to be a prime factor in the different nutritional compositions. And, as stated by Schmidt (2014), a high CEC prevents leaching of positively charged nutrients contributing to the higher nutrient content.

Table 4: CEC and pH Values of ADE and Control Sites.
Sources: Almeida et al., 2020 and Robinson et al., 2020.

Comparison of ADE and Control Samples from Studies Conducted by Almeida et al. and Robinson et al.		
	Almeida et al. Collection Site: Santarém, Brazil	
	ADE	Control
Average CEC (meq/100g)	10.8	4.2
Average pH	7.2	6.7
	Robinson et al. Collection Site: Laguna Versalles, Bolivia	
	ADE	Control
Average CEC (mmol/dm3)	16.4	2.2
Average pH	6.5	4.4

One explanation for this phenomenon is proposed by Lehmann (2003) who suggests this higher SOM content has more exchange sites due to the presence of pyrolyzed carbon in the form of biochar. However, this is only a possible explanation, but no formal research has been done to substantiate this claim. It is regardless, accepted that higher organic matter concentrations lead to an increase capacity for adsorption of nutrients. And, as ADEs are characterised by a high SOM, they have a higher nutrient retention, which directly contributes to their renowned fertility.

The question remains as to the connection between anthropogenic activity and this high nutrient content. Lehmann (2003) takes the predominate presence of inorganic phosphorous to imply this intense nutrient composition is not a result of human activity. Due to nitrogen fixation and the weathering, dissolution, and mineralisation of phosphorous, these elements do occur naturally throughout the world. However, he is contradicted by Robinson et al. (2020, p.11) who explicitly links the high values of P, Ca, and Mg to "*accumulation of waste from food production and consumption.*" This standpoint will later be supported by discussing the unique biodiversity of ADEs, and the increased concentration of edible plant species found on these soil sites. The recurrence of anthropogenically useful plant species appears to hint at their former purpose, and imply their composition is not entirely natural and by chance. It is, after all, human modification which led to the development of ADEs, meaning the separation of its nutrient composition from any anthropogenic activity seems unlikely. However, it is agreed that the presence of biochar is a direct result of human activity, and this plays a primary role in ADE formation.

3.2.4 Soil Organic Matter

As mentioned, Lehmann (2003) has suggested the unique CEC, SOM and nutritional contents are the effects of dynamic soil chemistry, rather than any intentional alterations by Pre-Colombian communities. However, it is undeniable that the anthropogenic addition of biochar played an inextricable role in the creation of ADEs. With this mind, this work turns to an examination of biochar and carbon content in ADE soil.

Large concentrations of biochar were discovered in ADE soils. In some ADE sites, carbon concentrations can be 70 times higher than in surrounding soils (Glaser et al., 2001, p. 37). They were thought to be one of the key factors impacting ADE fertility, though it was originally not clear how. Ash and charcoal were common inputs into midden holes, or dumpsites which gave rise to ADE soils (Robinson et al., 2020). Biochar is a product of pyrolyzing raw materials without oxygen at high temperature (Almeida et al., 2020). As can be seen from Robinson et al.'s 2020 study, the difference between ABE and ADE soil colour is an indication of the amount of charcoal combusted, and how complete that combustion process was in the formation of anthropogenic soils.

It is a misconception that biochar in-and-of-itself provides additional nutrition to the soil. Biochar is predominantly carbon, and therefore does not contain the growth-limiting nutrients necessary for plant survival. There are limited nutrients available in the ash which integrate into the soil, but this contribution is minimal (Steiner et al., 2007, pp. 3-4). Rather, the secret of biochar lays in its chemical structure and interactions with soil. To begin, charcoal amendments to soil act as a stabilising agent in ADE. In a study completed by Steiner et al. (2007, p. 12), three types of soil were tested – soil with charcoal amendments, soil with organic fertilisation amendments (such as compost), and a control soil. According to the study, charcoal containing soil was the most resilient only losing 4-8% of its soil, as compared to 27% and 25% respectively for the other two soil types. The key to biochar is then its work as a stabilising agent. Rather than working to contribute nutrients to soil, biochar is instead a key component in nutrient retention.

Biochar's adsorption capacity demonstrates the role of its addition in soils. As explained by Schmidt (2014, p. 118), *"Biochar is an extremely porous substance with a highly specific surface that has a surface area of up to 300 m^2 per gram. Due to the high porosity of biochar, it is capable of soaking up to five times its own weight in water as well as adsorbing large amounts of the therein dissolved nutrients."*

The oxidation of the biochar surface form carboxylic groups which promotes increased organo-mineral interactions which in turns increases the CEC of ADE (Steiner et al., 2007, p. 12, Bento et al., 2020, p. 1). Increased CEC in turns prevents the leaching of positively charred nutrient ions increasing the fertility of the soil (Schmidt, 2014, p.118). Additionally, this biochar forms an optimal habitat for the growth of microorganisms such as nitrogen-fixing bacteria or mycorrhizal fungi (Steiner et al., 2007, p. 12).

Bento et al. proposed SOM in ADE underwent two stabilisation processes: hydrophobic stabilisation and organo-mineral stabilisation. The top SOM layer of ADE displays more hydrophobic tendencies than surrounding Ferralsols. These hydrophobic tendencies meant as organic matter dissolved and moved deeper into the soil over time, they were largely insoluble, and therefore stabilised in the soil with mineral interactions and protected from dissolution and erosion by rainwater. Bento et al. (2020, pp. 1632-1633) suggests this hydrophobic tendency may have stemmed from fire-management by Pre-Colombian populations as fire created SOM which was more dehydrated and condensed- in turn making them more hydrophobic and more stable and resistant to degradation. The study continues by pointing out soils surrounding ADE has less access to organic matter due to a lack of anthropogenic additions, and constant addition of litter is the main vehicle by which non-ADE receive their nutrients. Without these additional stabilisations, which are catalysed by human actions, surrounding soil does not have the same nutrient retention and stability, and therefore is more highly weathered, and quickly loses its nutrients through degradation, mineralisation, and erosion.

For these reasons, biochar is what distinguishes ADE from Ferralsols. According to Glaser et al. (2001), the presence of aromatic and carboxylic carbon is the only significant distinction between ADE and surrounding soils. Had Pre-Colombian populations manually added additional organic material to soil, without biochar amendments, the natural processes of leaking, erosion, mineralisation and dissolution would occur. It is the addition of biochar as a stabilising agent, and a medium to retain nutrients which allows for the increased fertility and higher agricultural yields of ADEs.

3.2.5 Cause and effect of increased pH

As seen in Table 3, metals such as aluminium and iron are notably present in ADEs at lower concentrations. However, in the ABE soil, these concentrations are higher, implying the chemical composition of ABE with its partially pyrolyzed charcoal seems to adsorb many metallic micronutrients which may be absorbed from Ferralsols, or, conversely, act as a catchment for metals which are leached from ADEs.

As seen in Table 4, pH impacts the chemical interactions which improve soil CEC and nutrient content. These higher pH values have multiple implications for ADEs. The higher pH is likely caused by the anions in the remnants of ash deposited by Pre-Colombian civilisations when they burnt vegetation, or cropland to prepare the soil for new cultivation (Souza et al., 2018). This ash has been incorporated into the soil, along with its composition of basic salts and their anions such as calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$). This hypothesis accords with the elevated Ca and Mg levels recorded in ADEs in Table 3. The contribution of these salts altered the overall pH of ADE, making it more basic and less acidic. It has been suggested "*higher pH values enhance activity and reproduction of microorganisms and alter species composition*" (Lehmann 2009, p. 1). For these reasons, a higher pH level contributed to greater nutrient resilience. Nutrients are susceptible to be lost in acidic media. Such acidic conditions can be observed in the surrounding Ferralsols, which are nutrient-poor. The protection provided by this more basic soil allowed for increase of the CEC and the bioaccumulation of nutrients (Bento et al., 2020). And, as was discussed in 3.2.3, the increased nutrient concentrations, and higher CEC, are primary causes for the increased fertility and agricultural yield of ADEs. This is supported by data from Robinson et al. (2020), who has recorded a transition from a higher to lower pH as the collected samples moved from ADEs, to ABEs and finally and the ferrous control soils.

3.2.6 Structure

ADE is also notable for its unique soil structure and texture which allows for the high nutrient retention rates and protects against degradation and mineralisation. According to Bento et al. (2020, p. 1623), "*ADE soils are highly fertile because the SOM is present in recalcitrant and reactive forms, which is attributed to the presence of carbon nanoparticles (2-8 nm) with a graphitelike core and oxidized surface. Thus, graphite-like structures prolong the amount of time that the carbon is in the soil and the oxidized surface promotes the increased cation exchange capacity of the soil, thereby increasing the retention of nutrients.*"

Therefore, it is the very matrix of ADE which contributes to its fertility.

Corrêa et al. (2020) took a different approach to examining ADE stabilization, focusing instead on particle size distribution (PSD). According to the study, PSD facilitates movement of water, heat, air, and nutrients in the soil as aggregates create a more porous soil. The study found ADEs across the Amazonian Basin are predominantly made of clay, sand, and silt with an emphasis on coarser particles due to ceramic and lithic additions. There are differences in which of these concentrations are predominate (I.e., Corrêa et al. [2020] suggests ADE is more sand-silt whereas Lehmann [2003] proposes it is more clay-silt) but it is generally agreed this soil structure plays a key role in ADE formation. As an example, clay content plays a role in aggregate formation and carbon stabilisation by forming organo-mineral complexes (Lehmann, 2003, p. 110). The higher the clay content, the higher the fractal dimension (particle size), meaning increased aggregate formation and soil stability by forming increased organo-mineral complexes. This clay content, and the presence of increased organo-mineral interactions are connected to increased stabilization in ADE, and a strong carbon retention (Jones and Singh, 2014). This is noteworthy as aggregates are more likely to protect the soil against the impacts of erosion and degradation as they are stronger than fine particles (Corrêa et al, 2020). Being able to withstand erosion and degradation means preventing nutrient loss, contributing to ADEs greater fertility.

3.2.7 Biodiversity

As a last point, ADE is also characterized by its biodiversity. Flora, fauna, and bacterial communities within ADE soil are highly diversified when compared to surrounding Ferralsols as increased soil richness facilitates the growth of a wider range of plant species. The diversity of flora and fauna species in an area can change and indicate the presence of ADEs. As an example, Oliveira's 2020 study recorded that ADEs contained a significantly higher proportion of edible plants than surrounding Ferralsols. This observation was also supported by a study by Maezumi et al. (2018) which also recorded increased concentrations of edible plants and a richer biodiversity. Not only does this observation indicate another empirical way in which ADE's can be observed, this also serves as an indication of ADE's former agricultural use by pre-Colombian populations.

While not visible on an empirical basis, this phenomenon is continued on the microscopic scale. Within ADE soil, microbial communities are enriched and more diversified (Souza et al., 2018). These bacterial communities support plant growth and nutrient uptake, contributing to the overall fertility of ADEs. Symbiotic bacteria imbed in the rhizosphere and fix free nitrogen into ammonia for the uptake by plants. One such bacteria found in ADE is Rhizobacteria, which is a plant-growth related bacteria associated with increased nitrogen-fixation, nodulation, phosphate solubilisation and the production of enzymes (Gouda et al., 2018). As an additional benefit of microorganisms in ADE, Souza et al's 2018 study identified that increased diversity in Rhizobacteria showed great potential to be a cultivator of new natural antibiotics. This means ADE soils may now serve a function almost greater than innovating agricultural yield and may be a key to future medicinal developments. ADEs may play a future role in preventing pathogen attacks (Souza et al, 2018, p.1985).

These discoveries give rise to a "chicken or egg" style debate. Is the increased biodiversity the reason for the ADEs fertility? Or does ADE fertility foster an environment which allows for greater species diversification? The answer seems to lie somewhere in the middle. With every factor that increases ADE fertility, those impacts are amplified leading to a knock-on effect of fertility, biodiversity, and nutritional value. As stated by Fairhead and Leach (2009, p. 269) "*it is quite probable that among them will be interactions between biochar and the microbial (bacterial) and soil fauna (e.g. worm, termite, ant) communities involved in nutrient recycling and organic matter turnover.*"

3.3 ADE Summation

This chapter has introduced ADE as a model for the formation, chemical composition, and effects of anthropogenic soils. As ADEs are a well-researched, and more widely known field of Anthrosols, ADEs will be used as analogous soils by which to examine AfDEs. This chapter has demonstrated that the two climates, and soils are familiar enough to extrapolate chemical data from ADEs and apply them to AfDEs. Furthermore, this chapter has overviewed some of the key characteristics of ADEs, which define them as "dark earths." ADEs are a human-made soil, with distinct empirical and chemical characteristics which identify it as a highly nutritious soil with massive impacts on agricultural yield and fertility. This chapter has supported the argument these soils were made intentionally, and human actions had a direct impact on their fertility. Having reviewed AfDEs Amazonian precursors, this work now turns its attention to AfDEs themselves, and the implications they could have for modern day agriculture.

4. African Dark Earths
4.1 Introduction to AfDE

In 1903, Emile Baillaud, a Frenchmen, arrived in Guinea and attempted to create a banana plantation modelled after the European agricultural style. Drawing on the use of chemical fertilisers and large-scale planting, M. Bailluad wrote, "*I came to the conclusion the soil of Guinea was not rich enough to allow any hope of extensive plantations yielding a sufficient return to make them worth undertaking*" (Baillaud, 1907, p. 271). This simple phrase in a century-old text is poignant given the continued problems with nutrient-poor Ferralsols in West Africa.

Africa is currently undergoing massive demographic changes which is placing increasing burden on the continent's agricultural production. Diminishing arable land, a booming population, and a decrease in the percentage of the population engaged in the agricultural sector all play a role in stressing agricultural capabilities (Tadele, 2017, p. 3). As will be discussed, for many smallholding farmers, fertiliser (organic or chemical) is not an option to increase crop yield (Duflo, 2003). And, to date, the amount of nutrient per capital and the amount of nutrient per agricultural land is lowest in Africa (as a continental average) (Tadele, 2017). For all these problems, AfDEs offer a potential solution.

AfDEs are a form of carbon-rich anthropogenic soil which is created by West African communities through waste disposal of organic material, ash, and char - as well as by other inorganic additions such as bones, manure, and ceramics (Frausin and Fraser, 2014). Additionally, AfDEs are notable (and distinct from ADE) as more research has been done relating to the type of organic matter which is inputted into community "dumpsites." Gendered practices, and the different crops which are grown (i.e., for consumption vs. for sale) add another layer to AfDE which has thus far been absent from ADE research.

The previous chapter addressed the precursors to AfDEs – ADEs, their composition, formation, and benefits. In terms of lessons to be learned from anthropogenic soils, much research into ADE revolves around making educated guesses of Pre-Colombian routines, diets, agricultural practices, and (un)intentions in the creation of Dark Earth

Soil. The distinguishing feature of AfDEs is its contemporary formation. ADE formation is an ongoing process and has been practiced for over 500 years by populations throughout West Africa (Camenzind et al., 2018). Interviews, observations, and classical scientific studies have all been used to learn more about this burgeoning field of research. And the contemporary nature of this soil type creates hope and optimism that AfDEs can help find innovations for the future of agriculture.

As a transition from a conversation about ADEs to AfDEs, Fairhead and Leach (2009, p. 267-268) proposed in their work three core points which link the two anthropogenic soils:

1) The soil context in which the two soils are created are similar; the Dark Earths are both surrounded by low-nutrient, highly weathered, and leached Ferralsols or Oxisols, and are themselves highly nutritious with notably increased fertility,
2) In both the Amazonian rainforest and the West African communities which create AfDEs, populations live in highly nucleated villages and have continued "traditional" lifestyles as concerns agricultural production, hunting, farming, etc,
3) The climate and ecosystems – especially the forests – have been highly influenced by climate changes throughout history. This means agricultural practices in these communities have had to develop in parallel to changing environments and climates.

These three "connections" will be addressed in the following discussion. Other parallels to ADE can be found in the distinctive colour in AfDEs, the anthropogenic nature of their creation, and the benefits enjoyed by the communities which makes use of these soils. Furthermore, Chapter II introduced ADEs as a medium by which the chemical composition of AfDEs could be better understood. In turn, AfDEs, given their contemporary nature, provide a window into researching how ADE formation may have taken place, and the quotidian patterns of life for Pre-Colombian populations.

AfDEs are not exclusive to Ghana, rather they are found throughout West Africa; Liberia, Guinea, and Sierra Leonne all have studies recording Dark Earth. For this work, Ghana has been chosen as a case study to explore AfDE formation in depth. As a note, in comparison to ADE, AfDEs are a relatively new and emerging field. Therefore, this chapter has drawn on a wider range of literature- such as historical, sociological, and anthropological, sources – to create a more holistic understanding of AfDE. These sources have been supplemented by classical scientific studies. And, as has been mentioned, any gaps in knowledge as regards the chemical composition of AfDEs will be filled from what is known about ADE.

4.2 Formation of AfDEs

When asked about AfDEs by researchers, the Loma people of Liberia responded, “God made the soil, but we made it fertile” (Frausin et al., 2014, p. 696). Like in the Amazonian Basin, Dark Earths are not naturally created. The Ferralsols of West Africa are known as “red soil.” While this category encompasses several different soil types, in general, “red soil” is known as the soil which is wide-spread, low in nutrients and highly weathered. This soil can be rocky, clay-like and sandy – depending on its exact location – and susceptible to nutrient leaching (Frausin et al., 2014). An additional factor to consider is poor soil management and the removal of crop residues from fields which also contribute to the decreased fertility of “red soil” (Tadele, 2017).

Local understanding of soil does not make a more detailed differentiation between these soil types, apart from their colour. What is understood is “red soil” is nutrient-poor and infertile; and it can be transformed into the rich “black soil” with human intervention. Such intervention includes activities like food preparation and disposal, middening (creating deliberate waste disposal sites), craftwork and agriculture production and processing (Asare and Afriyie, 2020, p. 13).

Like with ADEs, there are also questions concerning the intention behind AfDE – that is, is this a natural by-product of traditional lifestyles, or is there a conscientious effort made to produce AfDE. Given the interviews conducted by Frausin et al. (2014) the self-awareness of interviewees that they are responsible for turning red earth to black earth seems to indicate the anthropogenic role in AfDE formation is well-known. And, as will be discussed, spatial organisation and gender dynamics in AfDE formation show an intentionality behind Dark Earth creation.

AfDEs must be viewed in a different historical context than ADEs. Chemical fertilisation was not an option for Pre-Colombian populations, meaning the creation of their own organic fertiliser was the only way to increase soil fertility. West African communities benefit from the modern-day knowledge of artificial, nitrogen-based fertilisers – but these are not widely used in West Africa. In a study conducted by Duflo (2003, p. 8), the use of chemical fertilisers was not opposed by farmers across West Africa. Rather, fertilisers were considered too expensive for 98% of farmers interviewed. Therefore, while anthropogenic Dark Earth is touted as a more sustainable and eco-friendlier alternative to chemical fertilisers, the producers of AfDE themselves do not seem to be opposed to the idea of their use. It is rather a lack of access which prevents them from doing so. The impact and degradation of using chemical fertiliser is a topic which has already been addressed in Chapter II “Nitrogen”, and therefore will not be considered here.

4.2.1 Gender Organisation

Esther Duflo (2003) studied West African communities from a standpoint of developmental economics. While her research focused on questions of income and economic models, her study has useful results for the question of gendered division of labour and its contribution to AfDE formation. Duflo observed men and women have responsibility over different spaces. Women have domain over kitchen gardens, where they primarily grow vegetable for domestic consumption, and which are seasonal based on rain patterns. Men, however, focus their attention on cash crops, and tend to grow tree species (pp. 3-4). This observation has multiple implications. Not only does it indicate a spatial aspect of AfDE formation, but it indicates gendered spaces create different kind of SOM inputs.

“Dumpsites” are restricted spaces where kitchen waste, and waste produced in crop processing is deposited- along with ash, biochar, ceramics, or other inorganic wastes produced in day-to-day life (Frausin et al., 2014). This differentiates them from what is known as compost heaps as “dumpsites” encompass a wider range of inputs whereas compost heaps are usually more exclusive to kitchen or garden wastes. “Dumpsites” are used for the disposal of all by-products of daily life, with the presumption that the communities which form these sites do not dispose processed or manufactured items such as plastics or metals.

AfDE soils are formed by and then removed from these centrally located dumpsites and used for crop cultivation. Women are more active in the "transformation" of red soil to AfDEs. The proximity of kitchen gardens to dumpsites indicates women also play a larger role in the maintenance and upkeep of community "dumpsites." Furthermore, as ash and char from kitchen fires are a key source of biochar in AfDE, the primary contributors of this resource are women who traditionally handle the cooking. However, the products of these dumpsites (AfDEs) are not shared equally between men and women. While women play a more important role in the "transformation", men are the benefactors of what is produced. Men will take the dark earth produced from these dumpsites and move them to sites used to grow tree species and other cash crops (Frausin et al., 2014).

While women are responsible for the creation of "dumpsites", men are responsible for the creation of AfDE patches where agricultural production takes place (Fraser, Leach and Fairhead). Women are responsible for the dumpsites, but men are responsible for the maintenance of the AfDE site. Thus, there is a disparity present in AfDE which has not been considered in ADE research. The site of "black soil" production is not the same place as where the Dark Earth is used. This adds a spatial dimension of AfDE which will be discussed below.

4.2.2 Spatial Organisation – War and History

When discussing ADE, Robinson et al. (2020) argued the presence of ABE and fortified canals denoted ADE patches were intentionally created within an artificial boundary. Spatial considerations play a similarly important role in AfDE research, as similarly demarcated sites indicate the intentionality behind AfDE formation. However, as has been indicated, spatial organisation is more complex based on what is known of Dark Earth production in West Africa.

The discussion of gendered roles carries over into the space in which AfDE is formed. Women maintain kitchen gardens, and maintain the community dumpsites (Frausin et al., 2014). The waste from kitchen gardens, be it vegetable waste, ash from cooking fires, broken ceramics, or other household trash, would be added to dumpsites, and is the key input of SOM into AfDE (see "Composition" for a more detailed discussion). The proximity of dumpsites to kitchen gardens supports the argument that "dumpsites" form because of daily activities, and the waste comes as a by-product of everyday life.

"Dumpsites" are intentionally created by communities. The Loma word for AfDE is "tulupole" literally meaning "dumpsite soil" – indicating that Loma people have created a distinguished space which is associated with Dark Earth (Fraser, Leach and Fairhead, 2014, p. 1232). These dumpsites are an example of "landmarks of the Anthropogenic Landscape" - a phrase coined to denote these human-made modifications to the natural world (Fraser, Leach and Fairhead, 2014). These also include larger infrastructures such as towns, villages and homes, and smaller features such as gardens, midden pits or demarcated agricultural fields. By breaking down the landscape into anthropogenic spaces, it is easier to map AfDEs and their formation on a spatial scale.

This is congruent with what was observed with ADE. Soils surrounding abandoned or contemporary human settlements demonstrated increased fertility (Asare et al, 2020). This was supported in a study conducted by Asare et al. (2020) at the Ziavi–Galenkuito settlement in Ghana. This was the site of a former German-British fort which had been abandoned in 1957 once Ghana gained independence. During its habitation, the site was used for all expected day-to-day activities like pottery-making, medicinal practice, some trade, cooking, etc. Over the past 70 years, during its abandonment, AfDE soils were found to have formed around the site, indicating AfDE formation may be much more rapid than we previously believed. With human intervention, AfDE could take only a few generations to create. Furthermore, the presence of increased nutrients around old building/midden pits/cooking fires, when compared to the control sites located further away from the settlement site, also links AfDE formation to designated sites of human activity. According to Asare and Afriyie (2020, p. 20) the size of the settlement, intensity of settlement activities and longevity of the settlement all contribute to an increase bioaccumulation of nutrients.

This was further supported by Solomon et al. (2016) who identified three main types of AfDEs: those surrounding kitchens and palm-oil production sites, those surrounding current settlements, and those surrounding abandoned settlements. In other words, AfDE encircles loci of human habitation, and is interspersed amongst buildings, gardens, and fields.

Leach (2009) recorded ADE and AfDE sites shift over time according to long-term changes. This is supported by research from Duflo (2003) which suggests, naturally, that crop production alternates seasonally, based on rainfall, or based on fluctuating market prices for certain goods. The climate-economic argument is not new and is rather intuitive.

However, Fraser, Leach and Fairhead (2014) observed West African AfDE sites also change based on the historical and political situation of the country. Their 2014 study based in Liberia examined the impact of the Liberian Civil War from 1990-2003 on changes in AfDE production. The Civil War greatly impacted the "traditional lifestyles" which Leach (2009) suggested was a connection between AfDE and ADE. The war led to the destruction of nuclear villages, and the fracturing of social groups from a sense of community to a focus on the nuclear family. Traditionally, a village would have one AfDE site which was overseen by an elder, and communally worked on by the men in the village in the production of cash crops. The War meant young men lost their communities, and therefore created a generation of men who missed community production. Following the end of the Civil War, men started creating their own individual AfDE patches, rather than invest in a community site - breaking the former homogeneity of AfDE production. While the sites of AfDE did not change in terms of their location to dumpsites or human settlement, the range of sites increased as did the number of AfDE patches, albeit the size of each individual patch diminished. This was accompanied by a shift of kitchens further away from town. As each farm had less labour, individual dumpsites and farm-specific sites of food production made more sense than the journey to a dumpsite in town (Fraser, Leach and Fairhead, p. 1234-12355). Ideas of proximity changed. History and politics play just as much of a role in the creation of AfDEs as does considerations of climate or market value of crops. This is a phenomenon which is only understood thanks to the contemporary formation of AfDEs.

This observation changes the understanding of AfDE formation into something more complex. It is a living and ongoing process – meaning it is not as simple as the current understanding of ADEs, which were confined within designated areas for agricultural and logistical reasons. This realisation will have an impact on the wide-scale use of AfDEs, as the nuanced nature of formation has repercussions for how this soil could be applied on a more industrial scale (see Chapter V "Applications" for a more detailed discussion).

4.3 Composition of AfDEs

The composition of AfDE is almost identical to ADE. Table 5 demonstrates how AfDEs in both Ghana and Liberia keep with trends observed in ADEs. In comparison to surrounding Ferralsols, carbon, nitrogen and phosphorous are present in higher concentrations. Additionally, the CEC for Dark Earth soils were at least 0.1 mmolc cm^{-3} greater in both AfDEs.

Table 5: Comparison of Ghanaian and Liberian AfDE
Source: Camenzind et al., 2018, p. 5.

AfDE Nutrient Concentrations, pH and CEC in Ghana and Liberia						
		pH	**C (mg cm^{-3})**	**N (mg cm^{-3})**	**P (mg cm^{-3})**	**CEC (mmolc cm^{-3})**
Ghana	**AfDE**	6.5	49.5	3.17	0.187	0.187
	Control	6.36	27.1	2.33	0.036	0.087
Liberia	**AfDE**	5.63	47	2.7	0.287	0.155
	Control	4.39	24.1	2.12	0.091	0.072

For this reason, AfDE composition will not be addressed in detail, as the information would be repetitive to what was discussed in Chapter III "Amazonian Dark Earths." Instead, the composition of AfDEs will be discussed in terms of a more detailed understanding of the exact materials which are inputted into dumpsites, and which are transformed into AfDEs. The contemporary formation of AfDEs allows researchers to observe first-hand what SOM, biochar and other additions are discarded as waste. This is beneficial as this information is impossible to know as concerns ADEs.

Studies observing the gendered and spatial aspect of AfDE formation also provides information about the organic matter inputted into dumpsites. The main source of nitrogen is vegetative wastes from kitchen gardens or by-products of cash-crop processing. This is paired with bone, ash, and manure to create the unique AfDE composition. Organic waste interacts with the bacterial and fungi communities which play a role in transforming the inputted organic matter into nutrients which are available for uptake by plants. According to a study conducted by Camenzind et al. (2018) Dark Earth sites tend to have unique bacterial and fungal communities – which can be attributed to the pH, organic matter input and notably the availability of phosphorous which is singular to AfDE. As phosphorous is a growth-limiting nutrient, its elevated levels in AfDE may partially explain the remarkable fertility of these soils. This phosphorous is a product of anthropogenic inputs- such as bones- which are rich in calcium phosphates. The presence of anions in biochar raises the pH so that organic phosphate is more easily mineralised, and inorganic phosphates in the soil are more soluble – increasing the availability of phosphorous in the soil (Solomon, 2016). Additionally, AfDE recorded an increased abundance of fungal communities – which were linked to AfDEs improved nutrient cycling, carbon sequestration, and higher nutrient retention and CEC (Camenzind et al., 2018).

AfDEs contain 200-300% more organic carbon, and 2-26 times more pyrogenic carbon than surrounding Ferralsols (Solomon et al., 2016, p. 72). Biochar plays an important role in the creation of AfDEs. The benefits of biochar are increased carbon sequestration, increased nutrient retention, increased availability of phosphorous, increased fertility and increased CEC (Solomon et al., 2016). As was discussed in Chapter III "ADE", biochar's role in ADE and AfDE are identical enough to be considered analogous. Therefore, biochar's interactions with SOM, and its role in AfDEs will not be addressed here as the discussion would be redundant. However, a point to note is, unlike ADEs, researchers have been able to determine the exact nature of inputs of charred organic materials. According to a 2014 study, there were three primary forms of biochar additions: char and ash as a product of cooking fires, char by-products in the production of potash and charred palm kerns resulting from oil production (Fraser, Leach and Fairhead, p. 1228).

4.4 Heavy Metals

AfDEs are not exclusive to rural communities. AfDE sites can also be found in urban areas where dumpsites still result in the creation of Dark Earth. Urban dumpsites can either be remnants of old settlements which used to be on the same site before urbanisation repurposed the land for new uses or may be a result of urban populations using the sites as dump heaps without a consideration of what is inputted. Either way, soils around these dumpsites are still used for agricultural production – in both rural and urban areas (Agbeshie et al., 2020). Because of this, heavy metal concentrations in urban waste have become a topic of concern.

Heavy metals are naturally occurring elements which are found in the earth's crust. They include lead, mercury, arsenic, cadmium, chromium, iron, copper, nickel, and zinc. Traces of these elements are normal, and some, such as iron, are important for plant growth. However, higher concentrations are the result of anthropogenic activity (Agbeshie et al., 2020). These elements are not easily biodegradable, and therefore can have huge impacts on soil quality. This is the case of urban dumpsites, where heavy metal concentrations have exceeded naturally occurring levels as a result of increased consumption of manufactured goods -particularly the increased consumption of E-Waste (Mensah et al., 2017 and Magaji, 2012). Examples of heavy metal wastes are paints, batteries, plastics and discarded phones and electronics.

E-waste, in particular, deserves special comment. According to a study conducted by Mensah et al. (2017), the majority of E-waste in Africa is informally recycled by burning, meaning certain materials containing hazardous components are not properly disposed of. As this burning often takes place locally on-site, and with minimal tools, there is a risk fires do not reach higher enough temperatures or reacts with enough O_2 to fully combust. This, in addition to the type of materials being burned, can create hazardous by-products. These include products containing polycyclic aromatic hydrocarbons, chlorofluorocarbons, and polybrominated diphenyl. Fumes created from burning can contain hazardous compounds which impact air quality as they are transported and then precipitated onto surrounding soils, causing knock-on effects for both human and animal health. The impact on soil quality will be discussed below.

While heavy metals naturally occur as traces in soil, an imbalance of heavy metals (either too much or, in some cases, too little) can lead to soil degradation. One of the main impacts of heavy metal pollution is an increased pH in situations where concentrations are too high. Across several studies, pH levels in soils surrounding dumpsites were more basic, which was taken as a direct consequence of metallic pollution in leachate from dumpsites (Magaji, 2012, Mekonnen, Haddis and Zeine, 2020, Agbeshie et al, 2020 and Mensah et al., 2017). Soils are the part of the ecosystem around dumpsites most susceptible to pollution because of seepage of leachate through water (Magaji, 2012). Increased pH levels influence the soil's reaction, and results in an increased mobilisation of heavy metals in the soil. With an increase of heavy metal concentrations, soils around urban dumpsites are at risk of being unsafe for agricultural production, and the benefits of AfDE soil is negated (Agbeshie et al, 2020). The leachate from dumpsites does not only pollute the soil but has a wider ecosystem-impact by also affecting the quality of nearby water bodies or (as in the case of burning E-waste) air quality (Mekonnen, Haddis and Zeine, 2020). According to a study by Agbeshie et al. (2020, p.9), heavy metal leaching may impact an area up to 40m from the dumpsite. Therefore, since AfDE formation is a contemporary and ever-evolving process, these kinds of trends must be taken into account when considering the role AfDE may play in agricultural innovation. Unlike ADE which is frozen in time, AfDE is constantly evolving, and the impact of inorganic, and manufactured waste will need to be addressed as it becomes an ever-increasing reality.

4.5 Lessons Learned – Benefits and Cautions

Having discussed AfDE formation and composition, this work now considers other factors of AfDEs which have not yet been addressed. The benefits of AfDEs are constantly touted – increased fertility, increased agricultural yield, and an independence from chemical fertilisers. Yet, to seriously discuss the wide-spread application of AfDEs, some concerns must be addressed.

Fulton suggests in her 2016 National Geographic article that AfDEs may not be as beneficial as previously believed. She suggests the downside of AfDE formation revolves around the necessity to gather organic wastes from large swathes of land, and concentrate them in a very small, intensely cultivated area. Given that "red soil"

Ferralsols are nutrient poor, in order to create "Dark Earth", nutrients must be intensely recycled, and reused on the same AfDE patches. Thus, Fulton suggests communities which practice AfDE formation are actively robbing nutrients from the rest of their land to focus on small, intensively cultivated spaces. There is also the more general concern that open-dumping could be a vector for disease-carrying flies and mosquitos and constitute a health concern for nearby populations (Magaji, 2012). Considering the example of Ghana, the risk of infectious disease is "very high" according to the CIA Factbook (Ghana, 2021). Therefore, a study into a connection between disease carriers and urban and rural dumpsites is needed before AfDEs are considered seriously for industrial use.

AfDE may also be an irresponsible use of nutrients. According to a study conducted in Malwai by Tadele (2017, p.15), of the 324 smallholder farmers interviewed, only 20-40% of them used an organic form of fertiliser given that organic waste such as crop residue and manure were put to better use as a source of fuel or livestock feed. In this study, not all SOM was recycled and reused on AfDE patches, leaving gaps in the idea that whatever is taken out of the ground needs to be put back in (Schmidt, 2014). As this study was conducted in Malawi, it is outside the region of interest for this work. However, it does propose an interesting thought-puzzle of the balance of AfDE composition. If certain SOM inputs were used for other purposes, would this disrupt the production or fertility of AfDE? And, if so, this raises wider questions regarding the fragility of AfDE soils.

This delicate soil is also dependent on an absence of chemical fertilisation. As was mentioned, farmers abstain from using fertiliser due to a lack of access, rather than a lack of desire (Duflo, 2003). This means AfDE formation may decline or become a hybrid form of agriculture with artificial fertiliser if prices drop in the future. This may negatively impact AfDEs as chemical additions could degrade the quality of the Dark Earth. For example, Camenzind et al. (2018) suggests inorganic fertiliser has a negative impact on Arbuscular Mycorrhizal Fungi. AfDE relies on "pure" inputs – additions to the dumpsites which do not involve any form of manufactured good. As has been seen by the discussion of heavy metals, globalisation and increased consumerism across the world may witness the introduction of processed or manufactured substances into traditional lives of West African communities – therefore disrupting the inputs into AfDE dumpsites.

5. Applications

AfDE is being increasingly touted in publications as a promising solution to problems of climate change (Guilbert, 2016). Having discussed ADE and AfDEs in terms of their composition and formation, this thesis now goes to the crux of the problem and considers how feasible it truly is to apply AfDE production on a wider scale as an alternative to nitrogen-based fertilizers. In order to do so, this work will start with a case study of Ghana, and then consider alternative solutions to optimise soil fertility.

5.1 Case Study – Ghana

Ghana is a West African country which practices AfDE production. Agriculture plays a crucial role in Ghana's economy, employing over half of its workforce, accounting for 20% of its total GDP and 69.1% of its total land usage. However, Ghana also suffers from problems such as drought, deforestation, soil erosion or overuse, and a lack of clean/potable water (Ghana- CIA Factbook, 2021). These problems are compounded by a growing population and, more specifically, a growing urban population, meaning less people in the agricultural sector and more people to feed. According to Solomon et al. (2016, p. 72), most smallholder famers practice low-input subsistence agriculture. Thus, while the majority of Ghanaian land and workforce may be employed in agriculture, this does not mean they are prepared to handle climate change or a growing population – particularly not if that population will be concentrated in urban areas. Nevertheless, the main exports of Ghana are crude petroleum (from palm-oil) and cocoa related products (OEC, Ghana).[3] Agriculture then plays an important role for the financial economy of the country, in addition to the subsistence of its own population. For these reasons, Ghana is an interesting case study as it represents a country with both agricultural problems and a potential solution.

[3] As of 2019.

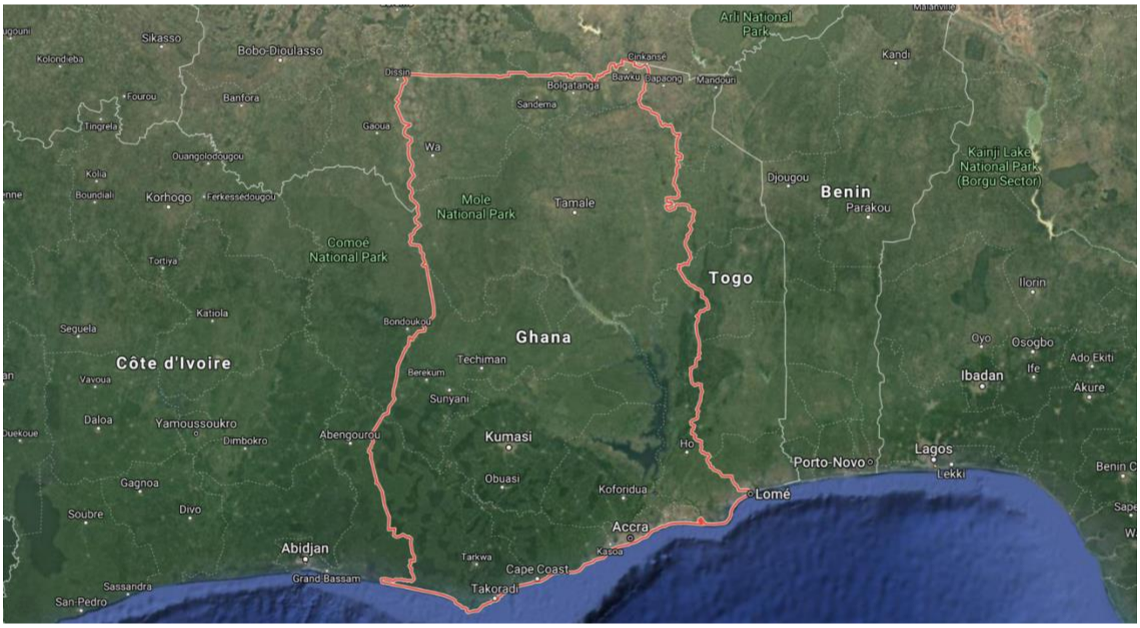

Figure 7: Arial View of Ghana

Source: Google Maps, https://www.google.com/maps (Accessed May 2, 2021).

As was discussed in Chapter III "ADE," Ghana's climate is similar to the Amazonian Basin, with a much smaller annual precipitation. As a result of AfDE formation, Ghanaian forests are deciduous woods, with a high biodiversity, rich soil, and an increased concentration of edible and domesticated plants located around "mosaics of human interventions" (Amanor, 2012, p. 75).

According to interviews with local farmers in the Ashanti and Brong-Ahafo regions of Ghana, soil management is well understood, as farmers intentionally transform "red soils" (Ferralsols) to "black soils" (AfDEs). There is an active awareness of AfDEs' increased fertility and nutrient content. Those interviewed also understood what inputs were needed by dumpsites to create these soils, such as SOM, char, and ash (Solomon et al., 2016). Because of this, these interviews also revealed a strategy of AfDE use. What is meant by this is both AfDEs and Ferralsols are used for crop production. There is not enough AfDE produced to supply all the crops necessary for community subsistence *and* agricultural production for financial gain. For this reason, the use of AfDE must be selective. The crops grown in "red soil" were more likely to be used in household consumption, such as rice and beans. On the other hand, one interviewee stated that cash crops such as cocoa and banana did not grow well in "red soil," meaning AfDE soil was prioritised for these species (Solomon et al., 2016, p. 74). This innocuous comment has wider implications of the wide-spread application of AfDE. Even the creators of AfDE must exercise selectivity when using Dark Earths. The prioritisation of using AfDE soil for cash crops may simply be attributed to the need to ensure a good harvest for economic and financial security. However, there may other reasons as well. Taking the example of the cocoa bean, while West Africa is the world's leader in cocoa production, the cocoa bean is *not* indigenous to West Africa. Rather, it was originally grown in South America, and introduced to British West Africa in the second half of the19th century. Therefore, the use of AfDEs for cash crops may be because these plants species are not always local, and therefore are not well adapted to Ghanaian "red soil", requiring the more nutrient-rich "black soils" to thrive (World Cocoa Foundation, 2018 and Howes, 1946).

In summary, these interviews imply AfDEs are finite, and therefore must be carefully allocated for the growth of certain crops. Therefore, wide-scale application of AfDEs may prove to be difficult as even locally they cannot be used for all household consumption and economic production.

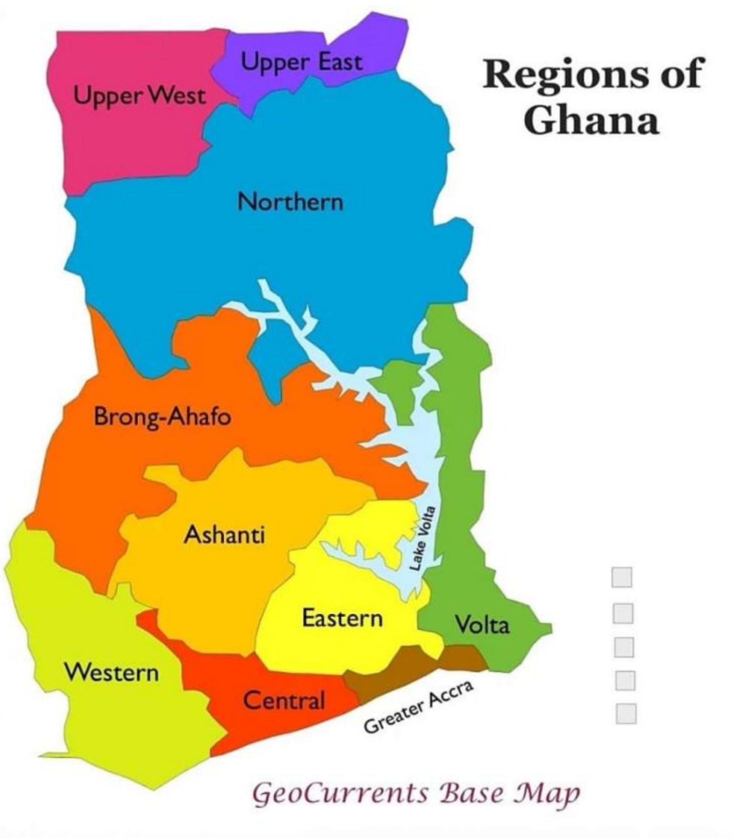

Figure 8: Regional Map, Ghana

Source: Abudlai, Modern Ghana, 2019.

Moving to the Volta region of Ghana, further lessons can be learned from the Ziavi–Galenkuito hillfort. As was discussed in Chapter III "ADE", this site demonstrates the rapidity by which AfDEs can form- as Dark Earth soil was produced within a 70- year time span (Asare et al., 2020). This study is not a perfect example of AfDE formation as research was completed at an abandoned settlement and does not discuss on-going Dark Earth production. However, in order to discuss the Ghanaian example in depth, it provides a good foundation to discuss soil nutrition and fertility. Table 6 presents a summary of the AfDE data collected on-site at four excavated locations of human settlement at the Ziavi-Galenkuito hillfort. As can be seen, in comparison to the control site, AfDE patches demonstrate higher levels of all nutrients and elements, and a higher pH. This is in keeping with the findings for ADEs in Chapter III and AfDEs in Chapter IV. In terms of heavy metals, the data from the Ziavi-Galenkuito site were congruent with other AfDE findings showing concentrations of Cu, Zn, Mn, Sr and Rb were higher in AfDEs due to a bioaccumulation of SOM caused by human settlement activities (Asare and Afriyie, 2020).

Table 6: Elemental Concentrations in AfDE from Ziavi-Galenkuito Site

Source: Asare et al., 2020.[4]

AfDE Nutrient and Element Concentrations From Ziavi-Galenkuito Site								
	pH	**Organic C (%)**	**Total N (%)**	**P (%)**	**K (%)**	**Ca (%)**	**Fe (%)**	**Al (%)**
AfDE A	6.6	4.5	0.32	0.51	1.31	4.67	2.72	4.25
AfDE B	6.5	4.63	0.29	0.3	1.33	3.61	2.27	4.29
AfDE C	6.2	3.54	0.23	0.33	1.28	2.17	2.5	4.26
AfDE D	6.3	3.91	0.26	0.32	1.31	2.17	2.56	4.29
Control	4.3	1.76	0.09	0.01	0.06	0.17	1.16	3.43

This information is congruent with former chapters, and therefore is not in and of itself new data. However, what is more interesting is the history of Ziavi-Galenkuito. The AfDE soil on this site were used to grow cash crops (Asare and Afriyie, 2020). Again, AfDE soil is prioritized for the use of tradeable and financially beneficial crops, rather

[4] Data provided in Asare et al., 2020, p. 11. Data was taken from 4 Loci within excavated building sites as well as a control site, and 3 sites at the building's foundation. Data was collected at three soil depths (0-10cm, 10-20cm, 20-40cm). For simplicity, the table has been composed of averages for all loci across all soil depths.

than the cultivation of foodstuffs for the household. Therefore, to speak about using AfDE production on the scale of industrial agriculture for domestic consumption is an idea which has not even been put into practice by producers of AfDE. While those interviewed by Solomon et al. (2016) had a clear knowledge about the benefits of creating Dark Earth, it appears food production for local use still largely relies of Ferralsols. Therefore, there is not currently a study showing a community setting the precedent to use AfDE for local agricultural sustainability- which is the solution this work had hoped to prove.

Moving from the past to the present, different lessons can be gleaned from the contemporary use of AfDEs in urban Ghana. Ghanaian dumpsites in both rural and urban areas are used for Dark Earth creation, and agricultural production (Agbeshie et al., 2020). This tells us the tradition of dumpsites live on- though in urban areas they may take on a different role. As was discussed in Chapter IV, a new challenge in the form of heavy metal concentrations in soils now threaten the purity of AfDEs, particularly in urban areas. This also begs the question of what defines AfDEs. Is it their composition or formation? And can these urban dumpsites, with manufactured and industrial inputs be categorized in the same way as their rural counterparts. As was discussed, the presence of heavy metals, fertilizers, pesticides, and urban wastes such as plastics or manufactured goods, are less biodegradable, and prone to bioaccumulation in soils. To note, while rural AfDE sites, such as Ziavi-Galenkuito, show higher heavy metal concentrations, these soils still fall within FAO and WHO limits of what is safe for human consumption. Conversely, urban dumpsites encounter problems of heavy metal concentrations exceeding thresholds which are safe for human consumption (Agbeshie et al., 2020 and Mensah et al., 2017). This was explored in a study conducted at Ghanaian urban dumpsites in Accra, where the presence of E-waste was found to significantly alter the composition of soils by inducing higher concentrations of heavy metals and increased levels of toxicity (Mensah et al., 2017). Therefore, soils surrounding urban dumpsites may not have the same nutritional capacity which is characteristic of AfDEs. We must then consider whether the definition of AfDEs needs to change, or, if the term AfDE can simply not be attributed to these urban soils.

In a study conducted by Camenzind et al. (2018), AfDE soil samples were collected from the Ashanti and Brong-Ahafo regions to research their Arbuscular Mycorrhizal fungal communities. The results of this study are in keeping with what was discussed in Chapter IV "AfDEs"- and these soils exhibited increased fungal abundance, paired with an improved nutrient recycling, C-sequestration, and overall fertility. At present, what is more important is to consider the study's findings that use of inorganic fertiliser was detrimental to fungal communities (p. 8). The impact of inorganic fertilizer on fungal and bacterial communities was discussed in Chapter II "Nitrogen," therefore this finding is not unsurprising. Like what was discussed regarding increased concentrations of heavy metals, chemical fertilisation negatively impacts the microbials which create the defining fertility of AfDEs. Looking at the case of Ghana, currently, all fertilisers used in the country are imported (FAO, Fertilisers in Ghana). There is not a consistent trend in fertiliser use, with the amount imported fluctuating over the years. However, in general, the consumption of fertiliser has increased over the years, albeit in a disjointed manner. As of 2018, 29.4 kilograms per hectare were used in Ghana (Knoema, Ghana). This is high in comparison to Sub-Saharan Africa (17 kg per hectare) but it well below the world average (135 kg per hectare) (AFAP, 2020).

What does appear to be consistent about Ghanaian fertiliser consumption is how they are used. According to the FAO, the majority of fertiliser is used in cash crop industries like tobacco, cotton, or oil-palm. However, it also makes mention of 700 rural fertiliser distributers, indicating at least some demand from smallholder farmers. Regardless, Ghanaian agricultural still records a deficit in nutrient deficit – meaning more nutrients are lost rather than returned to the ground (i.e., as fertiliser). According to the FAO, this average deficit means Ghana's soils are increasingly becoming more impoverished.

In a 2019 report, the Besome Freho district of the Ashanti region of Ghana made mention that their soils were ideal for the cultivation of "*cocoa, oil-palm, tubers, cereals and other food and cash crops*." The "dark colour of the surface soil" indicated its fertility and capability to sustain animal and crop production (Ministry of Food and Agriculture). According to the report, the average commercial farm is shrinking in size due to pressures on land. Agriculture is described as one of the most promising sectors to ensure economic prosperity for the district and, importantly, ensure future employment for young people. For these reasons, this report advocates a focus on cash crop production. In order to facilitate this, there is a push for government support to modernize farming techniques, and crop yields. This includes gaining access to stronger crop varieties and using insecticides/pesticides to combat diseases. The only mention of fertilizer throughout this report is in relation to a program which sells cocoa fertilizer to farmers to increase their yields – with cocoa being one of the main cash crops. AfDE is not mentioned by name, nor by the analogous term of *Terra Preta* – with only the dark colour of the soils being mentioned in passing. This article is important to understand the current mindset of Ghanaian agriculturalists. Agriculture is still the dominant industry in Ghana – although this demographic is slowly changing. Nonetheless, the report places an emphasis on optimizing soil fertility and crop yields. This report supports the viewpoint of the farmers in Solomon et al's 2016 study – economically prosperous crops are to be prioritized, especially when it comes to fertile soil. What differs from Solomon's report is the interest in modern agricultural techniques – including pesticides, herbicides, insecticides and, if available, fertilizer. The truth of Ghana's relationship with its soil may therefore lie somewhere in between the urban dumpsites of Accra and the rural smallholders in Ashanti. Ghana is a country heavily dependent on its agricultural sector. Dark Earth soil is beneficial, and still formed in parts of the country. Yet, commercial farming shows an openness, if not a willingness, to modernize. And, for purely economic reasons, AfDE production may be sidelined for the sake of agricultural progress and economic prosperity.

5.2 Application

The question remains; from what has been discussed about Dark Earths – how they are made, what they are made of, and what benefits they bring – can these soils be integrated into industrial farming to reduce the dependency on nitrogen-based chemical fertilizers?

There are number of ways to answer this question. From one standpoint, research into AfDEs and ADEs demonstrate what is already known. Nutrient recycling, in as pure of a form as possible, yields the most fertile soil. Putting back into the ground whatever you take out is the best way to ensure nutrient concentrations remain high, and the soil does not become degraded or impoverished. And, as has been seen, the benefits of AfDE in terms of its fertility, nutrient retention, CEC, and crop yield lends itself in favour of wide-scale use. However, the practical application is a different matter.

From a logistical standpoint, it seems unlikely that AfDE can offer a solution for industrial farming. AfDE is formed in intensively cultivated patches of land, where SOM and biochar additions are constantly added over long periods of time. The quickest formation discussed in this work has been the 70 year-period in which AfDE formed at the Ziavi–Galenkuito hillfort. The soils which are produced from these efforts are then carried to their final location, but not necessarily integrated on site. This poses a very simple problem of how industrial farms could gather enough SOM in a centralized location, maintain the sites of Dark Earth formation, and then transport it to fields, in a way that would be economically beneficial and even realistic. This might be feasible in Africa, where the average farm across the continent is 2.4 hectares, but in regions like North or South America, it would be extremely difficult to collect enough nutrients to create enough soil to fertilise farms ranging from 100-180 hectares (Global Agriculture, 2018).

Instead of trying to find a way to directly replicate AfDEs, their role in improving modern-day agricultural production is instead in what lessons we can learn from them. As much organic waste as possible need to be recycled, and in as pure a form as possible. Biochar or similar charcoal amendments are a cost-effective and very feasible addition to soils, and can improve soil fertility, even without additional SOM inputs. The AfDE model – at least vis-à-vis Asare and Solomon- use small communities as their examples. In confined areas, it is easier to catch nutrients. Therefore, AfDEs may indicate that industrial farming is an inefficient mode of agriculture, and smallholder farming, on a local scale, should be the preferable substitute. Of course, this is an idealistic proposition, and would involve a complete upheaval of how food is produced today. Obviously, this is not a global solution- but from a scientific standpoint, it may be the best way to prevent soil degradation and produce enough food to support the world's growing population.

One of the biggest wastes, then, are urban areas. However, the "dumpsite" model cannot be applied everywhere without limitation. The risk of breeding disease is still very prevalent (Magaji, 2012). This thesis did not find any information on how rural communities prevent pathogen spread in their dumpsites. This would need to be researched before any proposal of implementing more dumpsites could be supported. Furthermore, there is the question of plastics and heavy metals which can be found in urban dumpsites. The ideal dumpsite is one which only contains organic and naturally produced substances, and is free from any manufactured, industrialized, or processed goods. As is seen by the urban dumpsites which have been discussed in this thesis, the ideal dumpsite is increasingly difficult to find or maintain as plastics – especially microplastics – will impose an increasing threat to the "purity" of dumpsites.

In short, while AfDEs can offer many lessons about how farming should be done to ensure the best soil fertility and crop yield, the ability to apply AfDE formation on an industrial scale is unlikely. Instead, the world needs to look to other methods of improving soils. Some of these alternatives will be discussed below.

5.3 Alternatives

Dark Earths have been discussed from the standpoint of their formation, composition, and possible applications. This work has concluded that given the complexity of Dark Earth formation, and the limited quantity of Dark Earth soil which is generated, using the AfDE model on an industrial scale is logistically unfeasible. However, the global need to reduce dependence on chemical fertilisers cannot be dismissed, even if the AfDE route is not possible Therefore, this work proposes other methods by which the agricultural sector could reduce its dependency on chemical fertiliser.

5.3.1 Macroscopic Soil Amendments

First, there is an idea to use certain soil amendments to increase soil nutrition. The addition of biochar has already been discussed as a beneficial input into soils. Another such input would be earthworms. According to Noguera et al. (2011), biochar and earthworms work well in tandem. Biochar acts to increase nutrient retention whereas earthworms increase mineralisation. In their study, these supplements were tested in samples both with and without fertilisers. In all cases, the biomass yield of rice was higher with the use of these supplements, as well as the concentrations of nitrate and ammonium. Additionally, there was a higher biomass yield in the scenarios where earthworms and biochar were used without fertilisation than with it (p. 2352). This implies these additions can stand on their own as means to increase agricultural yields and can operate independently of fertilisers. Thus, soil supplements are an optimistic means by which to increase soil fertility, without the necessity of chemical additions.

Of note, Noguera et al's study places an emphasis on the importance of crop breeding. Crop-breeding has become increasingly important in contemporary-agriculture, meaning plant genotypes are being bred to have certain traits and characteristics. This is the same for soil supplements, which are being developed to be more resistant to pathogens and diseases. Thus, for the addition of soil supplements to work, the plant species which is being considered must also be bred to be responsive to the soil supplement. According to the study, crop species and soil supplements have become increasingly selectively breed, meaning that the natural response of crops to soil additions, or the ability of these additions to work naturally, is becoming more difficult and artificial. In fact, certain supplements have been intentionally bred to grow using high levels of fertilisation (Nogeura et al, 2011, pp. 2353-2355). In short, this alternative method to increase soil fertility is promising, but not as simple as adding biochar to soil, or increasing the population of earthworms. As was seen in Chapter III, AfDEs function because of the "pure" nature of dumpsites. Randomly adding supplements to crop fields – especially if those fields have been intentionally bred – means the supplements may not have the same beneficial effects.

A study conducted by Pandey et al. (2021) investigated the use of biochar to mimetize Dark Earth soils, without the complex and elaborate formation processes discussed in relation to ADE/AfDE. This study aimed to replicate the structure of carbons in Dark Earths, to achieve the same level of nutrient retention and cation exchange capacity. To do this, biochar was created from a myriad of materials (castor beans presscake, sugarcane bagasse, pequi shells and sewage sludge) and pyrolyzed at different temperatures (p. 2). These biochars were activated by three different agents (nitric acid, phosphoric acid, and potassium hydroxide) to determine how, and to what extent, the structural and chemical composition of Dark Earth could be replicated. The results of this study yielded several materials (mostly notable the biochar created from castor beans presscake) which were similar to Dark Earths. This indicates it may be possible to synthesise ADE/AfDE. In this case, the creation of a Dark Earth alternative for industrial use may be feasible. Further research would be required by monitoring the effects of this synthesised biochar in-situ, to see if its impact would be congruous to ADE/AfDE.

One major drawback of soil supplements is they need to be added in conjunction with SOM. ADE/AfDEs derive their fertility from both the additions of biochar, and the additions of organic matter. Earthworms may increase mineralisation but require organic matter/plant residue to eat and survive. Furthermore, biochar works to retain nutrients in soil, but these nutrients need to be added separately (Kamaa et al., 2011, and Noguera et al., 2011). This begs the question, where do these organic inputs come from? Soil supplements work well in small, centralised communities where most nutrients can be captured and recycled. Trying to export these techniques to industrial-scale farming would require not only large concentrations of soil supplements (i.e. large quantities of biochar, earthworms, etc), but an equally large input of organic matter. Given industrial farming does not necessarily focus on production for local use, the nutrients taken out of the ground will not necessarily stay in the local area. Especially crops consumed in urban areas are most likely to be lost, and not returned to the soil. In order to successfully implement practices of organic/natural soil supplements in industrial-scale farming, there would need to be a system-wide change in the way food is produced and consumed. Farms, small communities, and especially urban areas would need to be conscientious about catching nutrients and returning them to agricultural fields. This topic is worthy of a thesis in its own right. Yet, while it is not discussed in detail here, it is important to remember given the loss of nutrients from contemporary agricultural and consumption patterns, without system-wide changes soil supplements are still in their nascent phase of development.

5.3.2 Microscopic Soil Amendments

Earthworms and biochar are a macroscopic alternate to chemical fertiliser. Another option is to discuss the use of microscopic soil supplements– such as fungi and bacteria. Microtechnology is the use of matter on a microscopic scale for industrial purposes. The use of such technology to increase soil fertility and productivity has an optimistic future. The impact of microbials on soil have been briefly discussed in Chapters III and IV when discussing the role of Rhizobacteria in ADE (Souza et al., 2018) and fungal communities in AfDEs (Camenzind et al., 2018). The idea underlying microtechnology would be to stimulate and cultivate certain microbes in soils, based on the known benefits of these communities. For example, phosphorus is an essential nutrient for plant growth, but 95-99% of this element in soil is present in insoluble, or immobilised forms, meaning it is not available for plant uptake (Gouda et al., 2018, p. 133). Certain plant growth promoting Rhizobacteria – such as *Arthrobacter* – have phosphorus-solubilising traits, meaning that a promotion of these bacterial colonies in soil could assist with phosphorus uptake, without the need for chemical fertilisers. Bacterial species exhibit a wide range of traits. The bacteria *Rhizobium* sp works in symbiosis with plants to activate atmospheric N_2 in soil, *Bacillus mucilaginosus* can assist in Potassium solubility, and *paenibacillus polymyxa* can prevent fungal disease. An abridged list of known plant-growth promoting Rhizobacteria and their effect on soils and plants can be found in Table 7, demonstrating the wide variety of benefits microtechnology could have.

Table 7: Bacterial Amendments and their effects
Source: Gouda et al., 2018, pp. 133-134.[5]

Microbe	Known Effect
Azospirillium brasilence	Increase resilience to polycyclic aromatic carbons
Azospirillium lipoferum	Promotes the development of root systems
Azotobacter chroococcum	Stimulates plant growth Increases Phosphate solubilisation
Azotobacter aceae	Increases Nitrogen fixation
Bacillus subtilis	Increases Nickel accumulation
Paenibacillus polymyxa	Alleviates the effects of drought Prevents fungal disease
Pseudomonas aeruginosa	Stimulates Potassium and Phosphorous uptake

Thus, this study offers an innovative alternative to macroscopic supplements. Rather than focusing on what to input into dumpsites, or how to form Dark Earths, microtechnology altering soil fertility on a microscopic level. Like with earthworm populations, the introduction and cultivation of a specific bacterial community – if it became self-sustaining in the soil – could be a natural way to ameliorate soils,

[5] The effects of the different bacteria were discovered by several different studies, and summarised in a table by Gouda et al. The individual studies which examined these individual bacteria can be found in the bibliography of Gouda et al.'s work.

independent of chemical fertilisation. Of course, this option would require a heavy investment into biotechnology, agrotechnology, chemical engineering and material science (Gouda et al.). Thus, while this is a promising alternative, it is not as simple as AfDE or ADE formation as a large investment into research and technology would be required for this option to become feasible.

5.3.3 Changes in Fertilizer Use and Production

Another alternative would be to explore a more sustainable use of fertiliser. For example, Roy (2001) discusses in his article that one tonne of fertiliser produces ten tonnes of food. Fertiliser has had an indisputable role in history by allowing for the yield of crops on an exponential level which can match rapidly growing populations. It sustains 50% of the worlds current population and attempting to eliminate the role of fertiliser in agriculture may have disastrous, if not deadly results. Therefore, rather than looking for a means to wean industrial agriculture off of fertiliser, Roy advocates a more responsible creation and use of fertiliser. For example, he suggests the real main environmental impact of today's agricultural field is the international transfer of foodstuffs. In his article, he argues it is environmentally and financially better to import fertiliser rather than food. Food should, as much as possible, be grown locally. And an even more beneficial move would be to follow the ADE/AfDE model and create organic fertilisers using local materials – like the biochar created by Pandey et al. (2021). His article considers other fertiliser inputs outside of nitrogen – such as coal or other organic additions. Rather than look to completely end the fertiliser industry, he advocates redefining what fertiliser is and how it is used. Why not experiment with different kinds of fertilisers, and shift focus to minimizing the impact and need of international transport? While this alternative is not in-and-of itself a scientific proposal, it does raise interesting suggestions of what the future of industrial-scale agriculture could look like.

Continuing with the theme of finding innovative ways to use fertilisers, another option would be to try and optimise the Haber-Bosch process to minimize the environmental impact. One study suggests a way to fix nitrogen using electrochemical dinitrogen activation (Chen et al., 2019, pp. 35-37). Such methods include the use of liquid instead of solid electrolytes, synthesis using molten salts as electrolytes, and the use of different solid electrolyte systems. These methods are still under development and are not yet ready to be deployed wide scale. If they are optimised, however, they could contribute to a reduced energy consumption, less CO_2 output, and a sustainable way by which to synthesise ammonia.

5.4 Outlook

This chapter has been dedicated to the application of AfDEs and the feasibility of their use on the industrial scale. A case study was conducted using Ghana as a sample country, which revealed AfDEs are a optimistic alternative to chemical fertilisers on a local level. However, it was determined the formation of AfDE – both the space and time requirements and the quantity of Dark Earth produced – means AfDE in their traditional sense are not suitable on the industrial-scale. Where possible, they can be employed to improve the soil of small communities but replicating these soils for industrial farming would be difficult. This chapter then reviewed other alternatives to nitrogen-based fertiliser, such as microtechnology or alternative forms of ammonia synthesis. While these alternatives are promising, they are in their nascent stage of development. And, even with a successful development of an alternative to nitrogen-based fertilizers, this thesis still does not address the other problems of contemporary agriculture such as the use of heavy machinery, problems of mono-cropping, and the conversion of natural land to agricultural fields. Nevertheless, there is good reason to hope one of these substitutes will develop into a feasible and successful alternative to nitrogen-based fertilisers in the future. The question is how long will it take, and will it be ready in time?

6. Conclusion

This work has dedicated itself to the exploration of AfDEs as a substitute to nitrogen-based fertilisers. Given the wide-ranging environmental impacts nitrogen can have when it is overused in fertiliser, anthropogenic soils are a burgeoning field of research as they represent a hopeful solution to the problem of ecosystem degradation by chemical fertilisation, soil nutrient exploitation, and the loss of soil fertility under agriculture.

This work began with an overview of fertiliser and the nitrogen cycle – to discuss how the products of the Haber-Bosch process has outweighed natural nitrogen fixation – tipping the balance of what the earth's soil is able to absorb and use. The excess nitrogen is lost through emissions or leaching and has had a number of environmental impacts such as a deteriorating air, water and soil quality, as well as increased Greenhouse Gas emissions and an impact on plant biodiversity and ecosystems.

This work then considered the example of ADEs- millennia-old soil which is noticeably richer in nutrients than the surrounding Ferralsols which are considered standard for tropical rainforests. Since tropical soils are susceptible to nutrient loss and weathering, further studies were conducted to understand why ADEs demonstrated a richness which it has maintained over thousands of years. The answer was that these soils were created as a by-product of human activity, and inputs of SOM and biochar into agricultural fields which altered the soil's composition and enabled increased nutrient retention. These soils have been subject to extensive a wide-range of studies, meaning the soil dynamics and chemical composition of these soils – and the effect this has on soil nutrition – is well understood. Yet, as these soils were created by Pre-Colombian civilisation, gaps in knowledge of how this soil was made, and the implication it may have on the modern agricultural industry, remained unclear.

For this reason, this work turned to focus on the analogous AfDEs. The chemical composition and soil dynamics of these soils were parallel to ADEs, meaning their effects on agricultural yield and fertility were also observed in Africa. The key difference is AfDEs are formed in contemporary, ongoing processes in several parts of West Africa – meaning they reveal how these soils are made in the present day, and how they can be applied locally.

Ghana was taken as a case study to draw conclusions on the implications AfDEs have on modern-day agricultural. This work concluded that AfDEs have greatly benefitted the local communities in which they are made by providing a more fertile soil type for the growth of cash crops, which financially benefit the farmers. However, interviews with local planters indicate that AfDE soil is scarce and must be used selectively- with cash crops usually given the priority. This implies that the creation of AfDE is demanding in terms of time, space, and SOM input. It is not a process which can be completed quickly, and the AfDE yield is finite. It is therefore unlikely this method could be replicated to produce enough AfDE to replace nitrogen fertiliser on industrial farms.

This work finally addressed other alternative to nitrogen fertilisers, and discussed the lessons learned from Anthropogenic Soils. While the complete AfDE process may not be replicable, AfDEs have inspired researchers to try new cultivars to improve soil fertility or focus on nanotechnology to replicate the same soil dynamics. These developments offer hope to a future which is not dependent on nitrogen-based fertiliser- even though AfDEs may not be the answer.

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