ASSESSING THE POTENTIAL TO IMPROVE AGRICULTURAL AND PUBLIC HEALTH OUTCOMES IN TOGO THROUGH ECOLOGICAL SANITATION

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ABSTRACT

Togolese farmers' traditional soil fertility management practices are no longer adequate to maintain fertility under intensive cultivation, and synthetic fertilizers are applied at rates too low to balance nutrient exports from harvest and erosion. Simultaneously, Togo has one of the highest rates of open defecation in the world, and the prevalence of exposed human feces contributes to a rate of under-five mortality nearly double the global average. Ecological sanitation, a suite of sanitation technologies that aim to reduce the negative environmental outcomes of traditional sanitation systems while facilitating the reuse of human excreta for agriculture, may be an effective approach to resolve these twin agricultural and public health crises.

This paper will discuss the agricultural and public health context in Togo, examine historical methods of maintaining soil fertility in the region and the ways in which these methods have broken down, and review the literature on the safe reuse of human excreta for agriculture. Using existing population and spatial data, along with estimates of the nutrient content in human excreta, I evaluate the potential to improve Togolese farmers' access to soil fertility amendments through the promotion of ecological sanitation technologies. This analysis reveals that human excreta nutrient concentration per hectare of cropland from ranges from a high of 65.0 kg N ha^{-1}, 11.5 kg P ha^{-1}, and 16.1 kg K ha^{-1} in the Maritime region to a low of 4.8 kg N ha^{-1}, 0.9 kg P ha^{-1}, and 1.2 kg K ha^{-1} in the Centrale region. This suggests that nutrient recapture and reuse may be more viable in more densely populated areas of Togo.

BIOGRAPHICAL SKETCH

Whitman Barrett received his Bachelor's of Arts from Oberlin College, where he majored in history. He became interested in the connections between humans and the environment through his coursework in history and geology. After completing his bachelor's degree and serving in AmeriCorps, he received a Master's of Urban and Regional Planning degree from the University of Minnesota—Twin Cities, where he focused on housing and community development. He then served as a volunteer in the United States Peace Corps in Togo from 2016-2019, working alongside farmers in Yobo-Sedzro (Maritime), Naki-Ouest (Savanes), and Tadjan (Centrale).

Dedicated to all those in Togo who worked with me, laughed with me, and took care of me.

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1. Introduction

Negative nutrient balances have drained fertility from soils in Sub-Saharan Africa. Forty percent of soils in Africa are degraded (FAO 2018). This poor soil fertility is a primary constraint on agricultural productivity on the continent (Giller et al., 2006) While low yields of the main food crops in the region reduce the export of nutrients from harvests, extremely low levels of fertilization are inadequate to balance even these modest exports. Given that the population in the region is expected to rise by 100% by 2050 (from 1.1 B to 2.2 B) (Suzuki, 2019) and cereal demand is expected to increase by 300% in that period (van Ittersum et al., 2016), drastic changes in soil fertility management are needed to ensure that food security is not imperiled further. Several studies suggest that organic and ecological methods of soil amendment (e.g., compost, animal manures, green manures) cannot increase yields to the levels needed to satisfy the projected population increase's demand (Dawson and Hilton, 2011; Drechsel et al., 2001)—though these studies may not consider the nutrients added via human excreta. They indicate that chemical fertilizers will be essential to fill the yield gap. However, even high rates of chemical fertilizer application have uneconomic effects on yield on soils with very low levels of soil organic carbon (SOC) (Marenya and Barrett, 2009), suggesting the importance an integrated approach to soil fertility management that makes use of both chemical and organic soil amendments.

Even as food security in West Africa is endangered by stagnant low yields, public health is put at further risk by high levels of diarrheal diseases transmitted due to the frequency of open defecation in much of the region. Rates of open defecation (OD) are 20% in Sub-Saharan Africa and 48% in Togo (World Bank, 2017), and likely to be even higher in rural areas far from urban sewerage networks. Due in part to OD, Togo has a rate of mortality for children under 5 years old that is nearly double the global average (World Bank, 2019).

Ecological sanitation may be a means of reducing yield gaps and improving public health. Ecological sanitation (Ecosan) is a term used to describe a variety of practices for reducing the negative environmental effects of sanitation systems (such as eutrophication from nutrient runoff to waterways) while also recapturing some of the benefits of materials previously thought of as wastes. Ecosan can also include the capture and reuse of human excreta[1] (Dickin et al., 2018). Such treated excreta can then be used as a soil amendment, providing moderate quantities of nutrients while also increasing levels of soil organic matter (SOM). The promotion of ecosan in West Africa and in Togo in particular can improve both sanitation and agricultural outcomes simultaneously.

By making modest alterations to existing sanitation programs, governments and non-governmental organizations (NGOs) can create new streams of high-quality soil amendment available at low or no cost to smallholder farmers while also improving access to improved sanitation facilities and thus reducing the rate of OD, its concomitant diarrheal diseases, and death. In this paper, I will evaluate the environmental and agricultural context in Togo to better understand the reasons why chemical fertilizer and Green Revolution-based agricultural reforms have largely been inadequate to maintain and improve agricultural yields. I will then describe the historical use of human excreta and evaluate its potential for sustainably reducing yield gaps in Togolese agriculture. I will conclude with a plan to maximize excreta capture efficiency in different settings along the rural-urban gradient. Animal manure will not be quantified and

[1] Following Harder et al. (2020), I will avoid the use of the term “waste” and “wastewater” to refer to sources of usable, and valuable, nutrients, instead using the term “excreta.” “Excreta” refers to both urine and feces simultaneously.

evaluated as a soil amendment, because it is assumed that a significant portion of such manures are already used in Togolese agriculture (UN FAO 2018).

2. Importance of Nutrient Balances

Every person has a vested interest in ensuring that agricultural systems are sustainable. Humans rely on soil-based agriculture for nearly all of the food we eat (Holleman, 2018). Humanity could not continue to exist if unsustainable food production practices render our arable land unproductive. Measuring sustainability, however, is difficult due to the immensely broad range of agricultural practices and their complex interactions with edaphoclimatic factors. What is sustainable in one climate and soil context may not be in another. The nutrient balance, a measure of the difference between nutrient outputs and nutrient inputs (Cobo et al., 2010), allows researchers and agricultural practitioners to measure the sustainability of a system by providing an easily interpreted metric that can be readily compared across sites. A negative nutrient balance means that cropping demand for nutrients (coupled with losses of nutrients due to erosion, leaching, etc.) exceeds the amount of nutrients applied via chemical and organic fertilizers and deposition. A negative nutrient balance is sometimes referred to as nutrient mining because the excess nutrient output reflects nutrients removed from soil nutrient stocks (Drechsel et al., 2001), thus gradually reducing the soil's natural fertility. Negative nutrient balances predominate at most scales in sub-Saharan Africa, with the exception being certain subsections of farms that receive relatively large amounts of inputs (Smaling et al., 1996). Compounding these net negative nutrient balances in West Africa are the region's low mineral nutrient stocks in soils due the age of the region's soils and strong weathering (Rhodes et al., 1996). Agroecosystems with low nutrient stocks and negative nutrient balances can be considered unsustainable (Smaling et al., 1996).

Cropping of land necessarily increases the rate of nutrient outflow because significant (though varying) quantities of soil micro- and macronutrients are contained in the harvested portion of crops (Vitousek et al., 2009). For example, one study determined that a 10 Mg ha^{-1} cassava (*Manihot esculenta*) harvest exported 50 kg N ha^{-1}, 12 kg P ha^{-1}, and 100 kg K ha^{-1} (Carsky and Toukourou, 2005). Another study of potassium exports in maize found that 12 years of cropping exported a total of 100 kg K ha^{-1} contained in the grain and an additional 254 kg K ha^{-1} contained in crop residues (Poss et al., 1996). In order to maintain such increased outflows over long periods of time, these nutrient losses must be balanced by corresponding inflows of nutrients. These inputs and outputs need not be balanced during every cropping cycle or every year, though they must balance over longer time scales (Smaling et al., 1996). Fallows are effective methods of reducing nutrient outflows if they are practiced frequently enough and for long enough (Smaling et al., 1996). Biological nitrogen fixation by leguminous trees and other plants during fallows can increase nitrogen nutrition while deeply-rooted plants can draw nutrients from the subsoil and deposit them in topsoil, making them accessible for future crops (Smaling et al., 1996). Additionally, nutrient rich soils can be cultivated for longer periods, even under net-negative nutrient balances, as their stocks are gradually depleted (Cobo et al., 2010).

Although soil degradation is a major issue in sub-Saharan Africa and one of the major causes of inadequate food production on the continent (Sanchez, 2002; Tittonell and Giller, 2013), it may receive inadequate attention from farmers due to the larger time scales and lack of immediately-visible effects of nutrient mining (Smaling et al., 1996). Continued soil degradation leaves soils unable to respond to inputs of fertilizers and negates the benefits of planting genetically-improved plant varieties (Tittonell and Giller, 2013). Such unresponsiveness means that soil degradation may trap some farmers into poverty because the typical strategies to improve incomes (by improving agricultural production) are ineffective on their farms (Tittonell and Giller, 2013). Several studies have noted that agricultural production in Sub-Saharan Africa cannot keep pace with projected population increases and increased food demand without the use of chemical fertilizers (Dawson and Hilton, 2011; Drechsel et al., 2001), however, we have seen that even chemical fertilizers may not be effective at improving yields on the ever-growing portion of the region's land that is degraded.

Manure can help to restore degraded land by improving levels of soil organic matter (SOM) and soil organic carbon (SOC) and potentially by increasing the soils' buffering capacity and water holding capacity (Haynes and Naidu, 1998). Livestock play a major role in concentrating nutrients onto cropped fields (Giller et al., 2006), they graze biomass over relatively large areas and then their manure fertilizes inner fields where they are corralled or where farmers apply collected manure. Manures improve crop production by fertilizing crops directly. Manures contain varying quantities of nutrients. Manures also improve growing conditions for crops by improving soil texture (i.e., reducing bulk density, and decreasing surface crusting), and water dynamics (i.e., improving infiltration and hydraulic conductivity) (Haynes and Naidu, 1998). The effects of manure on increasing water holding capacity are mixed and positive effects may be overstated (Minasny and McBratney, 2018). This may result in part because both field capacity and wilting point increase with additions of organic material like manure, meaning that the gap between the two (i.e., available water) expands little (Haynes and Naidu, 1998). Manure application also improves the effectiveness of other organic soil amendments, e.g., by alleviating phosphorus deficiencies and thus promoting the growth of legumes and increasing their associated biological nitrogen fixation (BNF) (Giller et al., 2006) which otherwise may fix lower amounts of nitrogen on highly degraded land. Manure also tends to improve microbial biomass and earthworm populations, which in turn have benefits for soil porosity and aggregation (Haynes and Naidu, 1998)—though these benefits are not universal, and earthworms can sometimes have negative effects on tropical soils if the soil macrofauna is not sufficiently diverse (Chauvel et al., 1999; Lavelle et al., 2001).

Microbial activity is an indicator of soil health (Lehmann et al., 2020) and it reflects the soil's ability to effectively cycle nutrients. Higher microbial activity may also indicate greater nitrogen immobilization, meaning that nitrogen amendments are protected from being lost from the soil due to leaching (Watts et al., 2010). Manure additions tend to shift the microbial community in the soil and to promote greater microbial diversity overall (Toyota and Kuninaga, 2006). Manure contains N, but it may also contribute significantly to soil nutrient cycling by promoting BNF through the addition of P and K (which may otherwise be limiting). Manure promotes arbuscular mycorrhizal fungi (AMF) growth because it provides an unbalanced mixture of nitrogen and phosphorus, meaning that plants may still require AMF infection to acquire adequate phosphorus (Ngosong et al., 2010). AMF can provide additional benefits to crop plants by expanding their access to soil nutrients (Ryan et al., 1994). Amending soils with manure may increase total SOC more than the addition of chemical NPK fertilizers alone (Francioli et al., 2016). Contributions of composted manure to SOC are higher than when the manure is applied (Haynes and Naidu, 1998). The magnitude of benefits of increasing SOC vary by soil texture, with sandy soils responding more to such additions than clayey soils (Minasny and McBratney, 2018). Livestock populations may not be adequate to sustain soil fertility in sub-Saharan Africa (Tittonell and Giller, 2013) except for those wealthier farmers who are likely to have more livestock and manure (Giller et al., 2006).

3. Historical Methods of Maintaining Soil Fertility

Maintaining and improving soil fertility are central to any sustained agricultural system. Soils whose fertility is allowed to be depleted gradually (or rapidly) lose their capacity to support agriculture. Dramatic examples of such failures abound, from the Dust Bowl in the Great Plains of the United States to massive erosion in the Loess Plateau region of China (Holleman, 2018; Zhao et al., 2013) Declining soil fertility is thought to have contributed to the downfall of the Roman Empire (Montgomery, 2012). Although soil degradation may not yet risk the downfall of modern civilization, it costs the global economy $400 billion dollars per year and imperils food security in many parts of the world, including West Africa (UN FAO, 2016).

Historically, soil fertility in West Africa was maintained through a variety of techniques, including lengthy fallows and the regular addition of organic matter in the form of animal manure and household wastes (White and Gleave, 1971). Prior to colonialization, much of West Africa practiced either shifting cultivation or a system of extended bush fallows (White and Gleave, 1971). Both systems restore soil fertility and productive capacity through the slow regeneration of soil organic matter through biomass growth, along with the deposition of nutrients through wind and rain (Ehui et al., 1990). In both systems, farmers clear trees from fallowed land areas, burn woody biomass that would interfere with cultivation, and then use the field for cropping for several years until its fertility begins to decline, at which point the land is allowed to fallow again. The distinction between the two systems lies in the length of the period of cultivation and the length of the fallow and thus the quantity of biomass that is able to grow during the fallow period: shifting cultivation typically allows forest-like levels of biomass to return before cultivation recommences, which may take many years. Under shifting cultivation, land may be cropped for as few as one or two years before being allowed to fallow again

(Hopkins, 2019). Bush fallows, as the name suggests, allow for significant biomass regrowth but not complete forest reestablishment, and typically last five to ten years (White and Gleave, 1971). Both fallow systems allowed agriculture to continue sustainably for hundreds or thousands of years in West Africa, though they have been threatened by rising population density in recent decades. Both systems have significant benefits to the maximization of output per person since much land clearance labor is saved by the use of fire rather than mechanical cultivation (Hopkins, 2019).

Several authors have identified a gradient of cropping intensity in West African agriculture: the most intensively farmed plots lie closest to the household where they can receive household scraps and animal manures from paddocks in order to maintain production on short or no fallows (Giller et al., 2006; Rhodes et al., 1996; Tittonell and Giller, 2013). Beyond these so-called *champs de cases* (household fields) lie the *champs de village* (village fields) in a ring around the village, which receive some soil amendments but less than the inner-most fields (Rhodes et al., 1996). Finally, the *champs de brousse* (bush fields), relatively distant from the household and village, receive little or no soil amendment and are instead fallowed regularly to maintain their fertility (Giller et al., 2006; Tittonell and Giller, 2013). Soil amendment in the *champs de case* and *champs de village* include household wastes such as kitchen scraps, ash from cooking fires, and animal manure (White and Gleave, 1971).

Mainstays of soil fertility management, organic soil amendments and fallows, have dramatically declined in importance relative to chemical fertilizers in recent decades. In developed countries like the US, farmers fallow infrequently and for short durations, instead maintaining positive or neutral nutrient balances through the application of large amounts of chemical fertilizers (Doberman and Cassman, 2002). Indeed, chemical fertilizers (combined with high yielding varieties and chemical pesticides) form the backbone of what are known as Green Revolution technologies, a group of technologies promoted by NGOs and governments worldwide as the most effective means of feeding growing populations in the Global South. In West Africa, however, long fallows were not replaced with adequate levels of chemical fertilizer application, leading to sustained negative nutrient balances and the steady degradation of soils in the region (Vitousek et al., 2009). Given these negative nutrient balances in the region, Vitousek et al. (2009) conclude that agricultural yield declines are kept modest through nutrient mining of once fertile soils. In Sub-Saharan Africa, farmers apply on average only 9 kg ha^{-1} of chemical fertilizers (Marenya and Barrett, 2009) compared to a global average of 136.8 kg ha^{-1} (World Bank, 2018). Even this low average number masks considerable variation in application rates between countries (farmers in Burkina Faso applied an average of 17.6 kg ha^{-1} of chemical fertilizers in 2018 where Togolese farmers applied only 5.8 kg ha^{-1}) and between crops in each country (World Bank, 2018). For example, while cotton crops in Togo received an average of 5 kg N ha^{-1} in 2010, maize crops received only 1.1 kg N ha^{-1} (Rosas, 2012). Relatively few people in Togo have access to chemical fertilizers (Koffi-Tessio et al., 2003). Additionally, export-oriented cash crops tend to receive more fertilizer than food crops grown for subsistence, which has implications for food security. Numerous governments in Sub-Saharan Africa (e.g., Malawi, Nigeria, Ethiopia) subsidize fertilizers for farmers or provide lines of credit to purchase such inputs, especially for the production of cash crops like cotton (Gray, 2005; Sheahan and Barrett, 2017). Such subsidy programs are not universal throughout the continent, and fertilizers cost, on average, 2-6 times more money in Africa than in Europe or North America (Sanchez, 2002).

The variability in fertilizer application masks even more profound issues in soil fertility management and the feasibility of economic development through agricultural development in

Sub-Saharan Africa. Once soils have been degraded to a certain threshold, even high levels of investment in chemical fertilizers may not be enough to ensure adequate yields (Marenya and Barrett, 2009). Kintché et al. (2010) identified a feedback loop that occurs when poor soil leads to poor crop and biomass production, which in turn reduces SOC and prevents soil quality from improving. Barrett and Bevis (2015) found that some soils of very low fertility could not be improved with the addition of chemical fertilizers. Additionally, synthetic fertilizers had higher marginal yield responses on more fertile soils (i.e., those with higher levels of SOC) (Barrett and Bevis, 2015). Soil degradation may thus constitute a poverty trap, since a farmer's means of earning income to improve her soil is reduced by the low fertility of the soil (Barrett and Bevis, 2015; Kintché et al., 2010; Tittonell and Giller, 2013). Degraded soils imperil agricultural development in Sub-Saharan Africa by reducing the effectiveness of the standard tools of the Green Revolution: high yielding varieties and chemical fertilizers.

Due to these constraints on the effectiveness of chemical fertilizers on degraded soils, coupled with the high price of chemical fertilizers in sub-Saharan Africa (Barrett and Bevis, 2015), chemical fertilizers cannot be the primary means of restoring the soil nutrients to soils in the region or of ensuring the long-term sustainability and productivity of soils. Such fertilizers must instead be only a single component of an approach to integrated soil fertility management (Smaling et al., 1996) that also accounts for improving SOM/SOC through a variety of techniques. Increased use of animal and human excreta as manures should be a component of such an approach.

4. Agricultural and Public Health Context in Togo

Soil fertility management in Togo, as in much of West Africa, has broken down. Historically, farmers in Togo relied on regular bush fallows and shifting cultivation to maintain fertility in their main fields (*champs de brousse)* while applying limited manure and household organic wastes to inner-ring fields (*champs de case* and *champs de village*) (See Section 4). Over the past 150 years, since the beginning of the colonial period in the country, the agricultural system has undergone several shifts which, combined with reductions in fallowing due to population growth, have broken down traditional fertility management systems, degraded soils, and contributed to massive yield gaps in the country.

Yields of the food crops in Togo (i.e., maize, millet, rice, sorghum, and yams) have stagnated or fallen (UN FAO, 2019) even as the country's demand for food has risen along with population growth. Today, Togo has some of the lowest yields of cassava of any country in West Africa (Boansi, 2017). This demand for food, coupled with stagnant yields, has forced farmers to expand onto new land—crop production area has risen to unprecedented levels (UN FAO, 2018b). In a country as small as Togo, these trends of urbanization and agricultural extensification have inexorably led to corresponding losses of forest land and, as agriculture reaches the limits of the total arable land, to unsustainable increases in cropping intensity (a measure of the number of crops obtained from an average plot annually). The average cropping intensity in Togo rose from 0.6 in 2007 to 0.8 in 2017 (UN FAO 2018b).

The decline of Togolese agricultural sustainability began with colonization. Prior to colonization, farmers practiced a variety of low-impact systems using extensive fallows to maintain fertility while growing food crops for subsistence. European colonizers—first the Germans from 1884-1914, and then the French until independence in 1960—shifted the focus of

Togolese agriculture from subsistence to cash crops for export to satisfy metropole demand or to offset the cost of the colonial administration (Cornevin, 1962; Smith, 1978). European colonial officials frequently perceived African agriculture as backward and underdeveloped, in part due to the large tracts of land intentionally left fallow as part of shifting cultivation systems, as well as the absence of plows (Hopkins, 2019). European colonizers failed to understand the usefulness of shifting cultivation for maintaining yields over the long term in challenging conditions (Hopkins, 2019). The German colonizers wasted no time establishing a cotton research station (1889) and had built a network of cotton processing plants in the southern half of the territory by 1906 (Cornevin, 1962). Coffee and cocoa production were limited to the relatively small mountainous region in the southwest of the country, but cotton grows throughout, from south to north. The Germans exported significant quantities of cotton during their control of the territory and these exports, coupled with those of palm oil products, coconut, sisal, etc. allowed Togo to be one of the few profitable colonies in the German empire (Smith, 1978). The French continued most of these industries, eventually establishing parastatal marketing boards to facilitate the extraction of surplus value from Togolese agricultural producers (White and Gleave, 1971; Cheru, 1992). The colonial era imperative to pay taxes undermined agricultural sustainability by forcing farmers to alter cropping systems to farm cash crops and also by forcing many men of working age to leave farming communities to seek wage labor rather than farm for subsistence (Logan, 2016).

Independence in 1960 continued these trends toward commodification and cash cropping, though the underlying political justification shifted from the colonial extractive imperative to the independent government's need to satisfy the neocolonial debtholder institutions like the International Monetary Fund (IMF) and World Bank (WB), that imposed a system of structural adjustment programs (SAP) on Togo in the early 1980s (Toporowski, 1988). Reliance on agricultural export commodities (whose price is determined by global markets) for government revenue drives environmental degradation in sub-Saharan Africa as farmers exchange the natural capital of soil and undegraded arable land for ever-shrinking revenues (Cheru, 1992). Such has been the case in Togo. The SAP era increased the nation's dependence on agricultural cash crop exports even as the concurrent austerity gutted public expenditures, including a 20% reduction in 1979 (Toporowski, 1988). Government funding for agricultural research in Togo fell from nearly $6 per capita in 1981 (before SAP) to under $2 per capita in 2005 (Stads and Labare, 2010). This decline suggests that Togo is less able to respond to agricultural crises today than it was 40 years ago, despite the ever-increasing magnitude of those crises.

Nutrient management strategies in Togolese agriculture have not changed adequately to adapt to the land constraints imposed by ever-increasing population (Poss et al., 1996). Extensive fallow regimes are no longer practiced due to the lack of adequate land, cropping frequency has increased, but other fertility management practices (e.g., chemical fertilizers) have not taken their place (Poss et al., 1996). Rather than improve nutrient management (and thus improve yields), production area has increased to meet increased demand for food (Folberth et al., 2013; UN FAO, 2019). Consequently, yield gaps in Togolese agriculture are extensive (Mueller et al., 2012).

Although water scarcity and precipitation variability are increasingly becoming drivers of the yield gap in Sub-Saharan Africa, research in Togo indicates that nutrient scarcity due to nutrient mining remains one of the primary causes of low yields in the country (Poss et al., 1996; Adiele et al., 2020). Phosphorus (P) deficiency is the most common nutrient deficiency in West Africa, where soils tend to be highly weathered and organic matter decomposes rapidly

(Nziguheba et al., 2016; White and Gleave, 1971), but potassium (K) deficiency may have a stronger limiting effect on yields in Togo, especially in the maize-cassava systems common in the southern third of the country. As previously mentioned, maize and cassava each export significant quantities of K during their harvest, exceeding the 5.8 kg ha^{-1} of chemical fertilizer applied on average to Togolese farmland (World Bank, 2018). Exports are particularly high due to the importance of crop residues as animal fodder and as fuel.

Despite a long-running fertilizer subsidy program (Andre, 1990; Schwartz, 1989), rates of chemical fertilizer application remain extremely low in Togo. Application rates range from 13.7 kg ha^{-1} in 2016 to 5.8 kg ha^{-1} in 2018 (World Bank, 2018). However, the aggregate average numbers mask large variability in chemical fertilizer applications to different crops. As in many Sub-Saharan African countries, the largest amounts of chemical fertilizer applications are applied to non-food cash crops such as cotton (Andre, 1990). Cotton represented 52% of all fertilized land in Togo in 1987 despite cereal crops occupying nearly 9 times more surface area—in some areas of the country, cotton cropland represented up to 75% of all land receiving synthetic fertilizer (Andre, 1990; UN FAO, 2019). In Togo, this disparity results in part from programs to offer credit to cotton producers that facilitate purchases of inputs at the beginning of the cropping season, which farmers then pay back with the proceeds from their harvest at the end of the season (Andre, 1990). Fertilizer subsidies in Togo have fallen significantly since the 1970s, when they ranged from 75-90%—by 1984, the subsidy had fallen to 12% for cotton fertilizer and 50% for staple crop fertilizers (Falgon, 1988).

Cotton-associated inorganic fertilizers produce spillover benefits, either in harvests of food crops from land previously sown with cotton and fertilized or because some cotton-associated fertilizers are diverted and used to fertilize food crops (Gray, 2005). Regardless, Togo's low levels of chemical fertilizer application in aggregate do not supply enough macronutrients to offset the nutrient export from grain and cassava identified by Poss et al. (1996) and Adiele et al. (2020), let alone export due to residue removal. Lack of access to inorganic fertilizers may also exacerbate issues with parasitic weeds like *Striga* spp. which are particularly problematic in degraded soils and which can be treated by improving soil nutrient levels (especially N) (Jamil et al., 2012; Tippe et al., 2020). Fertilizer application rates even for cotton production may fall below the recommended rates, leading to a negative nutrient balance (Djagni, 2003).

Additionally, these aggregate statistics mask disparities in chemical fertilizer application rates between wealthier farmers and poorer ones, as the latter group may be less willing or able to participate in cotton input loan schemes (Gray, 2005). Such wealth disparities also arise in application rates for organic soil amendments such as animal manure since wealthier farmers may have more livestock and thus greater access to manure (Gray, 2005). New, more equitable sources of soil amendment are urgently needed to counteract the effects of negative nutrient balances in Togolese agriculture.

4.1 Urban Agriculture

With the increasing level of urbanization in Togo, urban and peri-urban agriculture represent a significant source of food (especially vegetables) and income for a significant sector of the population (Kanda et al., 2009). Urban and peri-urban market gardens in Togo have been extensively studied, perhaps due to their proximity to the *Université de Lomé*. In Lomé, these studies have found an intensive form of agriculture relying on frequent inputs of inorganic fertilizers and other agrochemicals, including a range of pesticides banned in Togo, such as

Aldrin, Dieldrin, Endrin, and Lindane (Kanda et al., 2014). Although these urban farms are at risk due to the rising land values in the city, they still represent significant quantities of intensively farmed land, providing large amounts of *Solanum sp., Lycopersicum*, etc., to urban markets (Kanda et al., 2014). Additionally, they represent a source of employment (17,000 jobs in 1995), largely young people, in a country where youth unemployment is endemic (Kanda et al., 2009). Research in other West African urban areas has identified farmers making extensive use of excreta streams to fertilize urban farms (Abdulkadir, 2013) These streams often contain large quantities of agricultural macronutrients and their use can even lead to overapplication of N and P (Qadir et al., 2015). However, no mention of such sources in Togolese urban or peri-urban agriculture was found, perhaps because of Lomé's coastal location and lack of major rivers or streams.

The main constraints facing these urban farms tend to be related to pests (the populations of which build up steadily in continually cultivated monocultures) and land (which is becoming more scarce and more expensive as urban populations rise) (Kanda et al., 2014). Although a comprehensive urban agriculture strategy is necessary to ensure the continued survival of this critical source of nutritious vegetables for urban markets, improved human excreta recapture and reuse should be a part of such a strategy. Improving soil texture and fertility through low-cost organic soil amendments like human excreta would reduce farmer expenses while improving the agricultural and economic sustainability of urban gardens.

4.2 Food Insecurity in Togo

Food insecurity in Togo remains elevated and largely unchanged in recent decades. Although the proportion of the population suffering from undernourishment declined from ⅓ in

1994 to ⅕ in 2019 (Kouvounou, 1999; UN FAO, 2018b) the absolute number of undernourished people remained constant. Childhood malnutrition is similarly high, affecting roughly 29% of children in 2017 (UN FAO, 2018b). This is close to average for West Africa but suggests that the country's recent economic growth is not improving conditions for the poorest and most vulnerable. Steady increases in the country's agricultural productivity seem to keep pace with population increases (UN FAO, 2019). Cereal imports have risen over 1,700% over the past fifty years, from roughly 20,000 Mg in 1970 to 348,000 Mg in 2019 (UN FAO, 2019). The increasing reliance on imported food further endangers food security due to the risk of price fluctuations in global commodity prices (Carney, 2008). The urban poor are particularly vulnerable to these food price variations because they already spend large portions of their income on food and have no alternative to purchasing food since, unlike rural populations, they have no land to farm (Carney, 2008; Moseley et al., 2010).

Compounding the existing threats to food security in Togo is the specter of climate change. Rising global temperatures and increased variability of precipitation will have immense impacts on agricultural production in Togo and on the price of cereals in global markets that provide an ever-increasing proportion of Togo's total food supply. Current models differ on whether West Africa will become drier, but generally agree that temperatures will rise in the region (Sultan et al., 2013; Sultan and Gaetani, 2016). A study on projected millet and sorghum yields in West Africa found that even increased precipitation would not counteract the negative effect of rising temperatures, and that yields of the two cereals should be expected to decline by up to 41% by the end of the century (Sultan et al., 2013). These declines are expected to be more severe in the Sudanian zone (which includes Togo) than in the Sahelian zone to the north because of the risk of significantly higher temperatures (Sultan et al., 2013). Similarly significant yield declines are projected for other major crops. Boansi (2017) modeled cassava yield response in Togo to a variety of climate and non-climate factors and estimated that a 10% increase in mean temperatures during the southern third of the country's small rainy season would decrease cassava yields by 55% over the long term. This extreme decline is due to water and heat stress due to the low precipitation : temperature ratio in this shorter rainy season (Boansi, 2017). Maize is the most important cereal in Togo, representing 60% of total cereal consumption (Didjeira, 2007, cited in Gadédjisso-Tossou et al., 2020). Maize is particularly vulnerable to the effects of climate change, with global maize yields declining by 7% for each degree-Celsius increase in global mean temperature—compared to declines of 3% for rice and 3% for soybeans (Zhao et al., 2017). Clearly, Togolese food security will be significantly endangered by climate change, putting millions more people at greater risk of hunger and malnutrition.

Malnutrition in Togo results not only from lack of access to adequate quantity and diversity of food, but also from high diarrheal disease burden that causes people, especially children, to have problems absorbing and retaining nutrients. According to the World Bank (2019), the mortality rate of children under 5 years old in Togo is 66.9 per 1,000 live births in 2019. This represents significant improvement over recent decades but is still well above the global average of 37.7 deaths per 1,000 live births (World Bank, 2019). Lack of access to improved sanitation is one of the primary causes of diarrheal diseases and thus of premature death. Without access to improved sanitation facilities such as latrines, people practice open defecation. Open defecation contaminates water and soil, leading to elevated levels of giardiasis, helminthiasis, etc., all of which disproportionately impact children. These diseases have significant, and often permanent, effects on children's cognitive and physical development (Mara, 2017). These significant and often permanent impairments have significant implications for quality of life and the potential for eliminating poverty. Rates of open defecation in Togo remain high, 48% in 2017, though there has been marked improvement since 2000, when the rate was 59% (World Bank, 2017). The global eradication of open defecation is one of the targets of the UN’s Sustainable Development Goals, though recent research shows that the current rate of progress is inadequate to meet the goal of eradication by 2030 (Mara, 2017).

5. Use of Human Excreta in Agriculture

For the thousands of years that agriculture was practiced before the advent of synthetic fertilizers (most notably nitrogenous fertilizers derived using the Haber-Bosch process), humans used a variety of techniques to ensure the sustainability of their agricultural production. As previously discussed in Section 4, fallows, and the incorporation of organic matter in the form of animal manure, crop residues, and household wastes were among the most prominent means of maintaining soil fertility. Many cultures around the world also made use of human excreta (i.e., urine and feces) to restore nutrients to their agricultural land (Ferguson, 2014; Harder et al., 2019 King, 1911). Much of the nutrients exported from farms during the harvest of crops make their way to humans and thus to human excreta through our consumption of those crops. The recapture and reuse of those streams of nutrients in human excreta formed one of the cornerstones (along with compost production and animal manure use) of the highly productive agricultural lands of eastern and southern Asian countries of China, Japan, and India (Ferguson, 2014; King, 1911). The American agronomist F.H. King, visiting East Asia in the early 20th century, attributed the sustainability of these high levels of production in China, Japan, and Korea, over thousands of years to the scrupulous reuse of organic materials, including human excreta (King, 1911). He observed the collection and transportation of human excreta from cities to the agricultural hinterland and discussed the practice with agricultural officials (King, 1911). In Japan in 1908, 24.3 Mt of human excreta were applied to farms, the equivalent of 4.5 Mg ha^{-1} (King, 1911). This human manure contributed 36% of the total N applied to Japanese farms via manure in the early 20th century (Ferguson, 2014).

In place of septic sewers that have come to dominate urban areas around the world, many Japanese, Chinese, and Indian cities had complex organizations of labor to ensure the regular collection of human excreta from urban homes, for the eventual application to cropland (Ferguson, 2014). In Osaka in the late 19th century, separate professional guilds of urine and feces collectors operated within the city (Ferguson, 2014). While, initially, households were willing to give away their excreta for free or to trade it in exchange for produce or other goods, by the early 18th century, Japanese households recognized the value of their excreta and were accepting only cash payments (Ferguson, 2014). These practices allowed both farmers and urban dwellers in these countries to benefit from a material that would otherwise have been perceived as a waste product to be disposed of with expensive labor or infrastructure (King, 1911). Indeed, in European cities, where the recapture and reuse of human excreta was not practiced to the same extent, massive amounts of excreta were discharged directly into the streets even in the late 18th century (Ferguson, 2014). These elaborate systems of excreta recapture and reuse kept feces from polluting urban water sources, leading cities like Tokyo to have cleaner water than London in the late 19th century (Ferguson, 2014).

The recapture and reuse of human excreta allowed Asian agricultural yields to surpass European yields (Ferguson, 2014). Due to the extensive use of human excreta, Chinese farmers applied human and animal manure totaling 13.8-22 Mg ha^{-1} compared to 9.9-13.8 Mg ha^{-1} in Europe (Ferguson, 2014). In India's Shah Jahan Era (mid-17th Century), sugarcane fields could receive 12.3 Mg ha^{-1} of combined manure (Ferguson, 2014). In contrast, European farms regularly experienced N shortages prior to the widespread use of imported guano fertilizers and synthetic fertilizers (Ferguson, 2014). Europeans began to improve human excreta recapture and reuse as grain prices and population rose in the late 18th century, but these efforts were superseded by imported mined and synthetic fertilizers and never reached the same levels as in China, India, and Japan (Ferguson, 2014).

5.1 Current Wastewater Disposal Paradigm

Despite the agricultural and public health benefits of human excreta recapture and reuse, disposal via pit latrines or sanitary sewers to be treated in a wastewater treatment plant (WWTP) and discharged into waterways is the norm today in much of the developed world. Rather than capture the significant amount of nutrients, including nutrients like phosphorus that are finite and increasingly scarce, we allow those nutrients to be lost via dilution, often at great cost in expensive infrastructure and environmental degradation. However, this trend is currently being countered at two opposite ends of the development spectrum: extremely wealthy countries that are beginning to renovate existing WWTP infrastructure with recapture technology to create usable biosolids and urine-based fertilizers via technological sterilization and transformation and poorer, underdeveloped countries, which, rather than building only expensive and wasteful sewerage networks are experimenting with smaller-scale, decentralized recapture and reuse systems such as Urine Diverting Dry Toilets (UDDTs). Vast swathes of Sub-Saharan Africa have little access to centralized sewerage systems outside of major cities (Armah et al., 2018). However, these areas need not be pressured to adopt an expensive technology that has inferior outcomes. Consider the proliferation of cellphone networks in Sub-Saharan Africa, which has greatly surpassed landline coverage in recent years (Pew Research Center, 2015). Few would argue in favor of spending more money to get less telecommunications coverage, so why promote the antiquated WWTP paradigm that mandates expensive infrastructure and largely wastes the very nutrients that agriculture in Sub-Saharan Africa so urgently needs?

Modern Ecological Sanitation (ecosan) technologies have contributed to the use of human excreta in agriculture in sub-Saharan African countries like Burkina Faso (Dickin et al., 2018). The complexity of the ecosan technology varies based on the scale of the recapture, ranging from large tanks for urine storage to small 25-liter jerry cans that can be used for household urine diversion from latrines. Levels of open defecation are extremely high in Sub-Saharan Africa, where 27% of the population, on average, defecates in the open (Mihelcic et al., 2011). Thus, any improved sanitation technology which can reduce the contact that humans have with excreta can improve both public health and sanitation simultaneously. Sub-Saharan African countries currently spend 0.26% of their GDP per year on water and sanitation programs (van Ginneken et al., 2012). These sanitation programs are overwhelmingly housed within health ministries, which may limit the amount of collaboration between sanitation project leaders and agriculture ministry officials. This siloing of sanitation projects may lead to less-than-optimal outcomes for both public health and agriculture. Research on the sustained use of UDDT latrines in Burkina Faso found that households were much more likely to use their latrine if they had been trained on the agricultural benefits of the recapture of excreta contained in the latrines instead of only being trained on the public health benefits of latrine use (Dickin et al., 2018).

The recapture and reuse of human excreta will likely face cultural barriers in Togo. As in much of the world, West African cultures often have strong aversion to the sight and handling of excreta, especially feces (Dickin et al., 2018; Mariwah and Drangert, 2011). Though in some West African cultures this may not rise to the level of a strict taboo (Mariwah and Drangert, 2011). Even strong cultural barriers should not be seen as insurmountable, however: economic and food security benefits can also be strong motivators for human behavior. Indeed, one economic barrier to the adoption of latrines and toilets is that, while improved sanitation has significant economic benefits at the community level through improved health, those benefits tend not to be apparent at the household level, leading to underinvestment (Mara et al., 2010).

Ecological sanitation, especially the recapture and reuse of human excreta for agriculture, could prove to be transformative for both agriculture and public health in developing agricultural economies like Togo's. Togo's low rate of improved sanitation access, particularly in rural areas, contributes to its high rate of diarrheal diseases and, ultimately, to higher mortality (especially for children under 5 years old). Sanitation improvement is one of the most cost-effective public health interventions, costing roughly $11.15 for each disability adjusted life year (DALY) loss averted (Mara et al., 2010). Improving sanitation would not only reduce the major diseases that cause diarrhea, but also Neglected Tropical Diseases (NTDs) like trachoma, helminthiasis, and schistosomiasis, which kill fewer people but cause enormous numbers of DALY losses by disabling people (Mara et al., 2010). Each of these three NTDs has an excreta-linked transmission pathway affected by improved sanitation: for trachoma, improved sanitation reduces fly populations dramatically, reducing the prevalence of trachoma by 30% (Mara et al., 2010). Schistosomiasis reproduction requires feces or urine to contact the environment and many helminthiases are transmitted from soil-borne helminths because of open defecation (Mara et al., 2010). Despite these clear benefits to sanitation improvement, most trachoma and helminth eradication programs focus on medication distribution (Mara et al., 2010).

The agricultural benefits of improving manure application rates are clear. Manure has broad benefits to soil health and to crop productivity. Manure, unlike simplified inorganic fertilizers, contains both macronutrients (including sulfur, often lacking from composed fertilizers sold in Sub-Saharan Africa) and micronutrients like iron, manganese, copper, and zinc (Bayu et al., 2005). Manure moderates the pH of both acidic and alkaline soils, increases CEC, and improves physical characteristics such as aggregate stability, infiltration, structure, and erosion resistance (Bayu et al., 2005). The main limitations of fertility management regimes centered on manure are the inadequate quantities of animal manure typically available to smallholder farmers, and the high labor cost of transporting and applying manure (due to its relatively low nutrient concentrations) (Bayu et al., 2005). Human excreta manure could address both of these limitations by expanding the quantity of manure available and by concentrating that manure in the household, where it can be easily applied to the *champs de case* and *champs de village* (unlike animal manure, much of which is deposited on distant *champs de brousses* as livestock graze). Even more severe constraints limit the use of chemical fertilizers, including high cost, transportation barriers, and lack of supply, leading researchers like Bayu et al. (2005) to call for "alternative soil fertility replenishment technologies." Increased use of human excreta could play a role in such approaches and can complement existing applications of animal manure and chemical fertilizer. These technologies are not mutually exclusive, and all should be combined to face the threat of declining soil fertility.

The benefits for human health of human excreta reuse extend beyond the effects of improved sanitation on reducing the disease burden of diarrheal diseases and NTDs. By some accounts, human excreta may provide better soil amendment than animal manure (Ferguson, 2014). By improving soil fertility and thus crop production, human excreta recapture and reuse can contribute to reductions of malnutrition. Human excreta can also play an important role in the cycling of important micronutrients like selenium, which humans typically obtain from the soil through the food we consume (Barrett and Bevis, 2015; Harder et al., 2020). More generally, food grown on more fertile soils tends to have higher protein and nutrient value than food grown on poor soils, thus every contribution to soil quality also contributes to improved human nutrition (Lal, 2009).

Equity is often overlooked in discussions of soil fertility management practices. Wealthier farmers have greater access to most means of improving soil fertility: they have more land; thus, they can fallow longer and more frequently; they have more cash, and thus greater access to inorganic fertilizers and the labor to apply both inorganic and organic soil amendments; they also have more livestock and thus more manure (Cobo et al., 2010; Giller et al., 2006; Gray, 2005). Poor soil fertility constrains all farmers, but wealthier farmers have the resources to improve their soils' fertility to escape the vicious cycle of low yields and low income (Gray, 2005). Wealthier farmers start out from a more favorable position: they tend to have higher N and P balances than poorer farmers (Cobo et al., 2010). Given these disparities in access to the traditional means of amending soils, human excreta recapture and reuse may be a means of improving soil fertility outcomes for the most disadvantaged farmers. Poorer farm families may have fewer head of livestock, and thus less animal manure, but such families may be larger than wealthier families, meaning that they may produce a greater quantity of human excreta. If this excreta is recaptured and reused, poor farm families may have improved soil fertility outcomes on their farms (Dickin et al., 2018).

Although human excreta may represent a small fraction of the organic matter mass needed to truly remediate depleted tropical soils (one study, Zingore et al., 2008, suggests that such soils need 17 Mg ha^{-1} $year^{-1}$) even small amounts of manure can have significant effects on yields when applied following precision agricultural principles (Aune et al., 2017). Microdoses of manure (200 g $pocket^{-1}$, the equivalent of 2 Mg ha^{-1}) combined with low levels of inorganic fertilizer have significant positive effects on yields (Aune et al., 2017). The effects of manure application can last years (Aune et al., 2017). Combining organic and inorganic soil amendments provides better yield maintenance than inorganic fertilizers alone (Diels et al., 2002). Bayu et al.

(2005) found that the combination of inorganic fertilizers with organic amendments was more effective than inorganic fertilizers alone. Rather than dismiss human manure as a soil amendment due to the relatively low total quantities produced, agronomists and extension agents should strive to maximize the effectiveness of the limited quantities of manure (both human and animal) and inorganic fertilizers available to poor smallholder farmers. As Cobo et al. (2010) argue, policies in Africa should support both the search for additional external inputs, and the building of soil organic matter. Merely waiting for the day when farmers will magically have 200 kg ha^{-1} of synthetic N fertilizer to apply is a recipe for continued declines in soil fertility and food security in countries like Togo.

6. Methods

A variety of methods were used in the present study, including literature review, spatial analysis of existing secondary data, and qualitative interviews (although, due to time and logistical constraints, only one interview was completed and thus there is insufficient data to report here). A large range of studies exist on sanitation improvement, ecosan, the safe recapture and reuse of human excreta. The literature review was performed by building off some keystone articles, notably Trimmer et al. (2017), combined with numerous searches using Google Scholar and Web of Science for terms such as: "ecological sanitation," "human manure," "soil health," "nutrient balance," etc. These search terms provided a wide range of results, many of which were relevant to the Sub-Saharan African context.

To complement the literature review, which provided relatively few results specific to Togo, I devised a key informant interview scheme. I intended to conduct interviews with a range of officials in the Togolese ministries of agriculture and public health, using the questionnaires (see Appendices 1-4). However few email addresses of ministry officials were publicly available and only one interview was completed. To maintain the anonymity of this respondent, the findings from that interview will not be discussed here.

The final component of the present study is the analysis of secondary data (See Appendices 5-8). The literature review revealed several papers which quantify the concentrations of macro- and micro-nutrients in human excreta, such as Drangert (1998), Makaya et al. (2014), Rose et al., (2015), and Winker et al. (2009). Using the QGIS software (QGIS Association, 2021), these results were combined with existing United Nations population data and United Nations Humanitarian Data Exchange (2021) administrative boundary shapefiles to create maps to estimate the total quantities of nutrients available in various geographical subdivisions of

Togo (See Appendices 9-12). The area of cropland within each region was estimated in QGIS based on data compiled by Ramankutty et al. (2008). Some mismatch between the population data and GIS map files occurred, perhaps because of the recent creation of several new prefectures.

The quantity of nutrients excreted depends considerably on the quantity and diversity of the diet consumed by each person. The average N excretion of a person in Nigeria was found to be half or a third of that of an average person in Sweden, due to vastly higher protein consumption in Sweden (Egun & Atinmo, 1993, and Atinmo et al., 1988, cited in Drangert, 1998). The N estimates used in the present study are conservative and closer to the values of the average Nigerian in Drangert (1998). The latrine technology used also affects the percentage of nutrients that are lost prior to recovery (Orner and Mihelcic, 2018). For example, ventilated improved pit (VIP) toilets lose up to 70% of total N due to denitrification (Orner and Mihelcic, 2018). A large portion of nutrients collected from excreta is also likely to be lost during composting, processing, and storage—this could amount to losses of 70% in feces composting, though urine may only lose 20% when properly stored (Heinonen-Tanski and van Wijk-Sijbesma, 2005). Despite these limitations, the estimates in this study should provide reasonable approximations of the quantities of nutrients present in human excreta in Togo and some indication of the spatial arrangement of these nutrients.

7. Excreta Recapture Plan

In order to maximize the recapture and reuse of human excreta along the urban-to-rural gradient, a range of different ecosan technologies should be considered to fit the appropriate technology to the scale of the intervention. Although Togo is rapidly urbanizing, a sizable portion (58% in 2019) of the population lives in rural areas (World Bank, 2019b). Accordingly, effective solutions will be needed for both dense urban areas—with little agricultural activity—and sparsely-populated rural areas, where most inhabitants participate in agriculture. Since human excreta, like other manures, contains a relatively low concentration of nutrients, large quantities are needed to effectively fertilize fields. A primary constraint on the use of human excreta currently is the cost of transportation (Semiyaga et al., 2015). Given the vast quantities of excreta produced daily in urban areas like Lomé, a robust and cost-effective system is needed to handle large amounts of material at the lowest possible expense. The particular ecological sanitation technology promoted in a given area will need to be capable of efficiently reacting excreta-derived products appropriate to both the location and scale.

Ecological sanitation (ecosan) encompasses a wide range of technologies, from improved nutrient recapture and wastewater treatment plants through struvite precipitation, improved large-scale fecal sludge management for on-site sanitation (i.e., latrines), and down to very low-tech approaches like the arborloo. The most effective and appropriate scale and type of technology to choose will depend on a range of factors (e.g., available capital, existing infrastructure, cultural considerations) and important contextual factors, such as the site's position along the urban-to-rural gradient. These factors must be considered to ensure that the proper technology is capable of handling the volume of material it will be required to process given the number of users, and that the resulting excreta-derived product will be in an appropriate form given the proximity to agriculture. In urban settings with limited urban agriculture (and relatively far from agricultural areas), excreta may need to be processed to lower weight and volume and higher nutrient concentrations to allow for economically viable transportation to agricultural regions. In contrast, technologies in rural areas need not emphasize processing and concentration since the latrine or toilet may be quite close to the field, thus minimizing transportation costs.

Sanitary sewers are often considered the most modern technology, but such systems often fail to truly protect public health given the extremely low percentage of sewage effluent that is fully treated, which can be as low as 8% in some regions of the developing world (Orner and Mihelcic, 2018; Drangert, 1998). Such centralized systems are exceedingly expensive to construct and their implementation often lags behind demand, especially in rapidly urbanizing areas. Only 19% of urban households in Sub-Saharan Africa were connected to a sewer in 2004 (Hall and Lobina, 2008). Given the potential for water scarcity as climate change intensifies, avoiding water-hungry sewer systems may be wise to reduce the threat of drought severely impacting urban dwellers' health and sanitation: already 38% of the population of Sub-Saharan Africa lives in water-scarce areas, and demand for water in the region is expected to rise by 283% between 2005 and 2030 (Orner and Mihelcic, 2015).

Sewer access in Sub-Saharan Africa is exceedingly low. Only 7% of the population has access to centralized sewer systems whereas 49% rely on on-site sanitation technologies like pit latrines (44%) and septic tanks (5%) (Orner and Mihelcic, 2015). Luckily, such contained excreta management systems lend themselves more readily to excreta recapture than those that follow the "flush and discharge" paradigm (Drangert, 1998; Orner and Mihelcic, 2015). In the latter paradigm, which relies on sanitary sewers, excreta are flushed from the household using water, to be discharged elsewhere (oftentimes, at least in Sub-Saharan Africa, without adequate treatment) (Orner and Mihelcic, 2015). The system has its roots in the early days of modern sanitation when the main objective was to prevent disease outbreak by removing potentially pathogenic material from the city as quickly as possible (Semiyaga et al., 2015). The drawbacks of such systems typically appear downstream, where untreated effluent damages ecosystems (Semiyaga et al., 2015). In contrast, in "drop and store" systems (Drangert, 1998) like pit latrines, little or no water is used (typically the only water used in pit latrines is for anal cleansing) and excreta remains in place, limiting the negative effects of wastewater pollution on water sources. Pit latrines can be emptied to prolong their useful life, though many users are not aware of this fact (for example, 74% of latrine users surveyed in Blantyre, Malawi did not know they could empty their latrine pits) (Grimason et al., 2000, cited in Orner and Mihelcic, 2015). 80% of urban residents in Sub-Saharan Africa use on-site sanitation technologies (like pit latrines and septic tanks) but only a small minority (20%) of the resulting fecal sludge is treated adequately (Semiyaga et al., 2015). Recapture and reuse of these immense quantities of fecal sludge can have important agricultural and health benefits.

In addition to ensuring that the ecological sanitation technologies are appropriate to the population density and land use of a particular setting, care should be taken to adjust sanitation improvement projects to social characteristics of the target community to use resources more efficiently and ensure the highest possible rate of adoption. Morales et al. (2014) interviewed city dwellers in a Buenos Aires neighborhood to determine their attitudes toward sanitation and excreta. They used these interviews to define what they called the "urban sanitation imaginary": a set of principles held by city dwellers regarding sanitation. Sanitation (including ecosan) in urban settings must attempt to follow these principles to be acceptable to urban dwellers:

> *(1) An urban citizen does not engage physically or mentally with their shit or its management; (2) an appropriate urban sanitation system requires flushing; (3) systems that require user's engagement with their shit and its management signify rural, underdeveloped, and backward lifestyles; and (4) urban sanitation is a state responsibility, not a local one.* (Morales et al., 2014)

SOIL, an American NGO operating in Haiti, provides ecosan latrines in the urban areas of Port-au-Prince and Cap-Haïtien. SOIL's EkoLakay latrine program provides an example of how these principles can be effectively applied to provide ecological sanitation technologies in a densely populated urban setting. Although the sanitation technology provided by SOIL is a simple receptacle with no flush mechanism, the latrines are designed to be attractive to the end-user (Remington et al., 2016). Additionally, their streamlined design eases maintenance and cleaning, reducing the potential for negative visual and odor cues that might otherwise discourage people from using the latrine. Perhaps most importantly, the user of the latrine is not responsible for emptying it: SOIL employees visit on a regular basis (up to twice a week) to empty urine and feces receptacles (Remington et al., 2016). This ensures that the user need not handle (or even think about) their excreta after they have used the latrine. Although the state is not responsible for SOIL's latrines implementation and excreta collection system, the fact that the organization is tackling sanitation on a larger scale by targeting multiple urban areas may also satisfy Morales' fourth principle by taking control of sanitation to a higher-than-local scale. Although SOIL's model is not free to latrine end-user, it is proven to be inexpensive enough to be affordable for many households in their target locations, reflecting urban dwellers' willingness to pay for improved sanitation technologies that meet their sanitation needs while also being convenient and requiring no interaction with excreta by the end-user (Remington et al., 2016).

The largest expense in SOIL's latrine construction, collection, and processing chain is the composting and processing of excreta, which requires significant levels of infrastructure and labor to perform (Remington et al., 2016). These processes could likely be performed more slowly or using more space (and thus more cheaply) in a rural location, but SOIL's urban setting requires this more expensive approach to effectively process the high concentrations of excreta generated. Clearly, excreta recapture and processing should be pursued differently in a different, and more rural, setting but this model might be appropriate in densely populated areas of Togo, especially the larger cities, such as Lomé, Atakpamé, and Sokodé. In smaller cities, closer to agricultural hinterlands, less intensive processing may be feasible, with excreta being moved to adjacent rural farming areas in a less-processed form. This may be appropriate for cities such as Aného, Vogan, Dapaong, Bassar, Sotouboua, Guerin-Kouka, etc., where farming communities are closer to the city.

7.1 Urban Areas: Lomé and other large cities

Given the high cost of transportation of heavy, unprocessed excreta, the key to improving recapture and reuse in urban areas will be finding ways to process and use excreta locally in urban and peri-urban agriculture. As discussed in Section 6, Lomé and other Togolese cities have vibrant urban agriculture, although urban farms and gardens are under threat from rising property values and uncertain land tenure. It is unlikely that urban farms alone could absorb the thousands of tons of excreta produced in Lomé. However, these human manures could potentially be profitably transported to peri-urban farms within short distances of the city, e.g., along the Kpalimé-Lomé and Lomé-Aného roads. Another potential avenue for use of human excreta in urban agriculture is to produce black soldier fly larvae (BSFL, *Hermetia illucens*) to be used as feed for livestock such as poultry (Lalander et al., 2019). Urban poultry production is common in urban areas throughout West Africa (Amado et al., 2012), and it is common for households to have a few chickens. While it may be impractical for each household to raise their own BSFL, this represents an opportunity for local entrepreneurs to generate income through the collection of excrement, production of BSFL, and resale to poultry farmers and household chicken producers at a neighborhood scale, thus minimizing transportation costs. Improved access to high quality and low-cost organic soil amendments may also improve the economic sustainability of urban agriculture. Since the purchase of inorganic fertilizers is a major expense for urban market gardeners, they may be able to reduce expenses by substituting excreta-derived soil amendments.

7.2 Rural Areas

Rural communities represent an entirely different context for ecological sanitation implementation. In these areas, a higher percentage of the population is involved in agriculture, and thus more households have a direct use for the soil fertility amendments resulting from ecological sanitation latrines. The lower population density also means that there is more space to use for excreta processing, if necessary, or for the implementation of low-tech solutions like the arborloo, which would not be feasible in a densely populated town or city. This lower population density may also prevent the formation of economies of scale for ecological sanitation provision, making the construction and maintenance of ecosan latrines relatively more expensive in these areas. Jenkins and Cairncross (2009) studied communities in the rural areas surrounding the twin cities of Abomey and Bohicon in Benin and created a typology of villages characterized by their distance to the city, population density, and levels of trade and contact with other communities (e.g., proximity to paved or improved roads). They argue that improved sanitation projects should be tailored to be appropriate to the particular rural context. For example, in rural communities closer to paved roads or immediately adjacent to Abomey-

Bohicon, residents had relatively high exposure to improve sanitation and thus were more aware of its benefits and how to obtain a latrine of their own (Jenkins and Cairncross, 2009). In contrast, in more isolated communities further from improved roads and with little market activity, residents were less aware of improved sanitation and communities lacked the materials and artisans needed to build latrines (Jenkins and Cairncross, 2009). Programs that merely subsidize the purchase of latrine construction materials may not be effective in such communities where people are not already strongly motivated to acquire latrines or where, even with cash assistance, they are unable to locate the materials or artisans necessary. In such communities, much more attention should be paid to motivating community members to acquire simple, low-cost, latrine solutions which require little to no specialized materials or knowledge to construct.

In rural areas of Togo, a large proportion the population is engaged in agriculture in some form. In such settings, the reuse of human excreta should be even more simple and straightforward. As noted previously, the average person produces enough excreta annually to fertilize 250 kg of cereals (Wolgast, 1993, cited in Heinonen-Tanski and van Wijk-Sijbesma, 2005). Farmers in rural settings are best positioned to make use of this excreta directly by applying their household excreta production to their fields. Given the relatively low level of improved sanitation access in rural Togo, additional efforts by public health and agriculture officials will be needed to ensure that these populations have access to the equipment and the knowledge that they need in order to safely recapture and reuse excreta.

Appropriate ecosan technology for rural areas includes dry composting toilets (UDDT) and the arborloo. Standard pit latrines and VIP latrines are common in Sub-Saharan Africa (Nakagiri et al., 2016), but these complicate excreta removal and cause high N losses due to denitrification in the pit (Orner and Mihelcic, 2018). Arborloos are a low-tech intervention appropriate in areas where cultural aversion to handling of excreta is particularly intense. In the arborloo system, a relatively shallow unlined pit is dug, a temporary platform and shelter are built on top of the pit using local materials, and the latrine is then used until full (generally less than a year depending on family size, anal cleansing material, and pit dimensions) (Morgan, 2007). Once filled, the shelter and platform are removed, the pit is topped with soil, and a tree (generally a fruit tree to supplement household nutrition) is planted in the soil (Morgan, 2007). This system obviates the need to handle human excreta while still ensuring that public health is protected by keeping feces out of the reach of flies and other insects, and nutrients are retained in place and contribute to household food security and income generation. The disadvantage of the arborloo is that the nutrients cannot be used to fertilize cereals and other row crops that provide the majority of household calories unless it is removed from the pit and spread on the field.

Even on a brief trip through the Togolese countryside, one can easily find abandoned and derelict composting toilets constructed as part of NGO-funded projects. Such concrete monstrosities often cost significantly more to construct than a simple pit latrine or VIP and yet have fallen into disrepair and neglect. The key for future sanitation improvement projects must be to implement ecological sanitation technologies that are simple enough to be maintained with locally available tools and materials and which meet household needs so that latrine owners are motivated to use and maintain them.

7.3 Intermediate Villages and Towns

Small towns and larger villages include larger numbers of the population who are not directly involved in agriculture, although perhaps the majority remain involved. In such settings, a combination of ecosan approaches is appropriate. Those who farm could collect and reuse their own excreta directly. There could be opportunities for entrepreneurs to earn a living by collecting the excreta of those not involved in agriculture for BSFL production or for resale to farmers as a soil amendment. The increased density of such towns and large villages means that economies of scale for the transformation of excreta could be reached, as in urban areas. Many larger towns, despite having high population densities, lack wastewater treatment plants and centralized sewer systems; this represents an opportunity to save the cost of constructing expensive sewer infrastructure by instead investing in on-site sanitation and simultaneously promoting nutrient recapture and reuse.

7.4 The Role of CLTS in Ecological Sanitation

Considerable time and money have been invested in programs like Community-Led Total Sanitation (CLTS) which aim to shame communities into pursuing improved sanitation by forcing people to confront the feces littering their community due to open defecation (Galvin, 2015). The effects of these programs have been mixed: with some studies showing significant effects on sanitation adoption following these programs and other short studies showing little or no effect (Crocker et al., 2017; Venkataramanan, 2018). In the context of ecological sanitation, CLTS may detract from the promotion of human excreta as a sustainable soil fertility amendment. CLTS operates by shaming participants by drawing their attention to the proximity of feces to the places they cook and eat, thus further reinforcing the conception of feces as inherently dirty and disease-ridden, which may reduce people's willingness to recapture and reuse excreta. Ecosan promotes the safe recapture, treatment (usually through composting or long storage) and eventual reuse. Organizations promoting ecosan should avoid reinforcing the simplistic approach to sanitation inherent in CLTS. Instead, promoters of ecosan should emphasize the agricultural benefits of the safe recapture and reuse of excreta. The risks of improperly stored or utilized excreta cannot be ignored, but these risks should be contextualized and methods for safe treatment and reuse thoroughly explained to households. Research in Burkina Faso demonstrated that rates of ecological sanitation latrine use and emptying were higher when users were trained on the agricultural benefits of the resulting excreta and not only in the community health benefits of latrine use (Dickin et al., 2018). Although Jenkins and Cairncross (2009) argued that some very rural communities were not good candidates for traditional improved sanitation projects, ecological sanitation may be particularly appropriate in these ultra-rural settings in which population densities are low and a high proportion of the population participates in agriculture. In such communities, ecological sanitation could be presented primarily as a source of free high quality soil amendment rather than emphasizing its health benefits (which, as discussed previously, may not be readily apparent to individual households). The key in such isolated and resource-scarce settings will be presenting technologies that use only locally available materials, and which have minimal costs to build and maintain. Simple ecosan latrines can be constructed using only cheap plastic buckets and plastic jerrycans for urine diversion. A low- or no-cost shelter can then be built if the household prefers to remove the latrine from the immediate vicinity of the home. If cultural factors make the users unwilling to handle excluded as a soil amendment, the arborloo is an effective solution.

7.5 Best Practices

Every proposed ecological sanitation project should be founded upon the best practices identified by researchers such as Heinonen-Tanski and van Wijk-Sijbesma (2005). These include the importance of separating urine and feces. As previously discussed, urine contains far fewer pathogens than feces and can be used with little health risk if it has not been contaminated by feces. Additionally, separating urine and feces reduces the odor of both: when combined, fecal bacteria promote ammonification of the urea in urine and the added moisture creates anaerobic conditions, both of which create unpleasant odors (Drangert, 1998). Urine separation also reduces the rate at which latrine pits fill, thus reducing the frequency of the unpleasant task of emptying pits (Heinonen-Tanski and van Wijk-Sijbesma, 2005). Excess water in fecal sludge in urban areas greatly increases the cost and complexity of its reuse because it adds to the weight of fecal sludge (thus increasing transportation costs) and fecal sludge often must be dewatered to be processed (e.g., by vermicomposting) which may require the addition of relatively expensive dry materials such as sawdust (Semiyaga et al., 2015). If feces are to be composted (which it should be for health reasons, although this can entail nitrogen losses of up to 70%) it should be protected from rainwater and kept moist but not wet (Heinonen-Tanski and van Wijk-Sijbesma, 2005). The compost should feel moist to the touch but should not expel water when squeezed (Heinonen-Tanski and van Wijk-Sijbesma, 2005). Other materials such as kitchen scraps and wood ash can be added to the composting feces to improve the composting process and absorb excess moisture (Heinonen-Tanski and van Wijk-Sijbesma, 2005). Urine-diverting dry latrines are ideal from a nutrient recapture perspective, as they lose considerably less nutrients than other common sanitation technologies such as VIPs and septic tanks (Orner and Mihelcic, 2015). VIPs and septic tanks promote anaerobic decomposition, increasing the rate of methane production (Orner and Mihelcic, 2015), which should be avoided unless biogas recapture is important to the project.

Sanitation projects should use the most simple and cost-effective technology available. Given the urgent need to reduce the prevalence of open defecation to protect human health, governments' and NGOs' limited resources should be used to reach as many people as possible rather than spending large amounts of cash to build expensive concrete UDCTs. A set of buckets and jerry cans that can be purchased at any market in Togo for a few dollars can be combined with a shelter made of locally available materials such as *banco* (mud bricks, typically unfired) or *claies* (panels made from the stems of palm fronds), yielding a serviceable composting toilet for under $10. The benefits of the proliferation of such low-cost improved sanitation will be readily apparent in both public health outcomes and yields on Togolese farms, reducing malnutrition by reducing the burden of diarrheal diseases and by improving per capita calorie supply.

8. Results: Magnitude of Nutrient Availability in Human Excreta in Togo

The data analysis in this report (as described in Section 6—Methods) used population data and estimates of per capita excreta production to derive estimates of nutrient product production at the sub-national scale in Togo. Population centers and agricultural land are not evenly distributed throughout the country (Table 1): Lomé is by far the largest city in the country and, along with its Metropolitan area, makes up a large proportion of the most populated region, the *Maritime* region. In contrast, the *Savanes* region has few urban areas, and none approach the size of the major cities like Lomé, Atakpamé, Sokodé.

Table 1: Population and cropland (in hectares) by region of Togo.

REGION	TOTAL POPULATION	Pop (% of Total)	CROPLAND (ha)	Cropland (% of Total)
Centrale	760,046	10.0%	834,500	31.9%
Kara	946,784	12.4%	393,500	15.1%
Maritime	3,217,371	42.2%	260,600	10.0%
Plateaux	1,686,476	22.1%	884,400	33.8%
Savanes	1,006,609	13.2%	240,500	9.2%
TOGO	**7,617,286**	**100.0%**	**2,613,500**	**100.0%**

Similarly, cropland is not evenly distributed: over 2/3 of the nation's croplands are found in the regions of *Centrale* and *Plateaux*, though those regions have only ⅓ of the national population. These dynamics will lead to a large amount of excreted-derived nutrients per hectare of cropland in some regions and a much lower rate in others. I will now examine each region's results in turn, from south to north:

Maritime

The *Maritime* region has a plurality of the nation's population (42%) but the second smallest share of cropland (10%). This contributes to a high rate of human excreta-derived nutrients per hectare of cropland. These rates may even meet or exceed the recommended nutrient application rates defined by the government for crops like maize, which suggest an NPK application of 45-7-12 kg NPK ha^{-1} for cereals (Kintché et al., 2010). The low estimates of nitrogen derived from excreta is 52.2 kg N ha^{-1}, the high estimate is 65.0 kg N ha^{-1}. Even the low estimate would make a large difference in yields for staple crops, especially for smallholder farmers who currently apply limited amounts of fertilizer.

Table 2: Total (Mg) and per hectare (kg ha^{-1}) amounts of carbon and major nutrients present in human excreta in the Maritime region. Estimates are derived from nutrient contents estimated by Harder et al. (2019), Makaya et al. (2014), Rose et al. (2015), and Winker et al. (2009) (See Appendix 8).

	C	N (Low Estimate)	N (High Estimate)	P (Low Estimate)	P (High Estimate)	K (Low Estimate)	K (High Estimate)
Total (Mg)	17,027.9	13,614.1	16,949.3	1,521.9	3,006.3	3,508.9	4,190.0
Per Hectare (kg ha^{-1})	65.3	52.2	65.0	5.8	11.5	13.5	16.1

Lomé is Togo's largest city, and its location on the coast and the border with Ghana limits the amount of cropland in its immediate vicinity. Despite these limitations, there may be up to 25,700 ha of cropland within a 25 km radius of Lomé (Appendix 12).

Plateaux

In the *Plateaux* region, the ratio of people to cropland is lower than in *Maritime*, meaning there will be a lower concentration of human nutrients in excreta per hectare of cropland. Indeed, the high estimate of nitrogen in *Plateaux* is less than ⅙ that of *Maritime*, 10 kg N ha^{-1}. While this may seem low, it is likely still worth capturing and reusing given the low levels of fertilizer use. Additionally, these nutrients may be spatially concentrated around the cities of Atakpamé, Kpalimé, Notsé, and Anié, thus providing higher per hectare nutrition to peri-urban farms in those areas.

Table 3: Total (Mg) and per hectare (kg ha^{-1}) amounts of carbon and major nutrients present in human excreta in the Plateaux region. Estimates are derived from nutrient contents estimated by Harder et al. (2019), Makaya et al. (2014), Rose et al. (2015), and Winker et al. (2009) (See Appendix 8).

	C	N (Low Estimate)	N (High Estimate)	P (Low Estimate)	P (High Estimate)	K (Low Estimate)	K (High Estimate)
Total (Mg)	8,925.7	7,136.2	8,884.4	797.8	1,575.8	1,839.3	2,196.3
Per Hectare (kg ha^{-1})	10.1	8.1	10.0	0.9	1.8	2.1	2.5

The large cities in the *Plateaux* region tend to be surrounded by moderate amounts of cropland (Appendix 12). Approximately 44% of the land within a 25 km radius of Notsé (84,000 ha) is cropland, along with 38% of the land around Atakpamé (70,700 ha).

Centrale

The *Centrale* region has a similar amount of crop into the *Plateaux* region—834,500 hectares, but less than half the population, thus contributing to the lowest per hectare excreta-derived nutrients in Togo: 4.8 kg N ha^{-1} (high estimate). In the *Centrale* region, it will be especially important to maximize the efficiency of recapture and reuse around urban areas like Sokodé and, to a lesser extent, Pagala-Gare, Tchamba, and Sotouboua.

Table 4: Total (Mg) and per hectare (kg ha^{-1}) amounts of carbon and major nutrients present in human excreta in the Centrale region. Estimates are derived from nutrient contents estimated by Harder et al. (2019), Makaya et al. (2014), Rose et al. (2015), and Winker et al. (2009) (See Appendix 8).

	C	N (Low Estimate)	N (High Estimate)	P (Low Estimate)	P (High Estimate)	K (Low Estimate)	K (High Estimate)
Total (Mg)	4,022.5	3,216.1	4,004.0	359.5	710.2	828.9	989.8
Per Hectare (kg ha^{-1})	4.8	3.9	4.8	0.4	0.9	1.0	1.2

Sokodé is one of the largest cities in Togo. Despite its size, it is located in an area of relatively high cropland density (Appendix 12). Approximately 60% of the land within a 25 km radius of Sokodé is cropland, representing around 112,300 ha of cropland. This proportion of cropland is almost double the average proportion of cropland for the *Centrale* region. This suggests significant potential for agricultural reuse of nutrients recaptured from human excreta in Sokodé.

<u>Kara</u>

The *Kara* region has neither the population nor the high level of cropland of the central region. Its concentration of nutrients, 12.7 kg N ha^{-1} in the high estimate, is close to the national average (Appendix 5). The city of Kara is the primary center of population in the region, and excreta derived from this city could be concentrated in the urban and peri-urban agriculture.

Table 5: Total (Mg) and per hectare (kg ha^{-1}) amounts of carbon and major nutrients present in human excreta in the Kara region. Estimates are derived from nutrient contents estimated by Harder et al. (2019), Makaya et al. (2014), Rose et al. (2015), and Winker et al. (2009) (See Appendix 8).

	C	N (Low Estimate)	N (High Estimate)	P (Low Estimate)	P (High Estimate)	K (Low Estimate)	K (High Estimate)
Total (Mg)	5,010.9	4,006.3	4,987.7	447.9	884.7	1,032.6	1,233.0
Per Hectare (kg ha^{-1})	12.7	10.2	12.7	1.1	2.2	2.6	3.1

Due to urban sprawl and mountainous terrain, there is relatively little cropland within 25 km of the city of Kara. Only 23% of the land within a 25 km radius of the city is cropland, representing approximately 41,500 ha (Appendix 12).

Savanes

The *Savanes* region, like the *Maritime* region, has a greater share of national population than national cropland, leaving it with a more favorable quantity of excreta-derived nutrients per hectare than the *Plateaux*, *Centrale*, or *Kara* regions. The high estimate of nitrogen from excreta is 22 kg N ha^{-1}, which, while not meeting recommended fertilizer application rates for crops such as maize, is a significant quantity of nutrients an effort should be made to ensure that these nutrients are returned to croplands in the region.

Table 6: Total (Mg) and per hectare (kg ha^{-1}) amounts of carbon and major nutrients present in human excreta in the Savanes region. Estimates are derived from nutrient contents estimated by Harder et al. (2019), Makaya et al. (2014), Rose et al. (2015), and Winker et al. (2009) (See Appendix 8).

	C	N (Low Estimate)	N (High Estimate)	P (Low Estimate)	P (High Estimate)	K (Low Estimate)	K (High Estimate)
Total (Mg)	5,327.5	4,259.4	5,302.9	476.2	940.6	1,097.8	1,310.9
Per Hectare (kg ha^{-1})	22.2	17.7	22.0	2.0	3.9	4.6	5.5

Although Dapaong is not as large as cities such as Sokodé and Kara, it is increasing in size and there may be increasing potential to recapture nutrients from human excreta in the city for reuse in the surround agricultural areas. There is approximately 60,500 ha of cropland within 25 km of Dapaong (Appendix 12).

Conclusion

Due to variation in the proportion of population by region, excreta-derived nutrient concentrations vary considerably from region to region, from a low of 4.8 kg N ha^{-1} (high estimate) in *Centrale*, to a high of 65 kg N ha^{-1} in *Maritime* (high estimate). The *Maritime* region's estimated excreta-derived nutrient concentrations would meet or exceed the recommended rates of fertilizer application for cereals, 45-7-12 kg NKP ha^{-1} (Kintché et al., 2010). Even using a higher level of nutrient application (80 kg N ha^{-1}) to compensate for low levels of soil fertility, 65% of cropland in the *Maritime* region and 22% of cropland in the *Savanes* region could be fully fertilized (Table 7). Although any additional quantities of nutrients added to nutrient-scarce Togolese agriculture are likely to be helpful to smallholder farmers, scarce ecological sanitation improvement resources might most effectively be focused on the regions of *Maritime* and *Savanes*, which both possess a higher proportion of the country's population than of its cropland, leading to more favorable concentrations. The *Maritime* region, due largely to the presence of Lomé and surrounding urban areas, is perhaps the greatest potential concentration of human-derived nutrients in the country, and great efforts are warranted to ensure that those nutrients are returned to cropland.

Table 7: Number and proportion of hectares of cropland in each region that could be fully fertilized (i.e., receiving 80 kg N ha-1).

Region	Total Cropland (ha)	N Low Estimate (Mg)	Hectares Fully Fertilizable (80 kg N ha^{-1})	Proportion of Cropland Fully Fertilizable (80 kg N ha^{-1})	N High Estimate (Mg)	Hectares Fully Fertilizable (80 kg N ha^{-1})	Proportion of Cropland Fully Fertilizable (80 kg N ha^{-1})
Centrale	834,500	3,216.1	40,201.2	4.8%	4,004.0	50,049.5	6.0%
Kara	393,500	4,006.3	50,078.3	12.7%	4,987.7	62,346.3	15.8%
Maritime	260,600	13,614.1	170,176.6	65.3%	16,949.3	211,865.7	81.3%
Plateaux	884,400	7,136.2	89,202.9	10.1%	8,884.4	111,055.4	12.6%
Savanes	240,500	4,259.4	53,242.6	22.1%	5,302.9	66,285.8	27.6%
TOGO	**2,613,500**	**32,232.1**	**402,901.6**	**15.4%**	**40,128.2**	**501,602.6**	**19.2%**

APPENDICES

Appendix 1: English Questionnaire for Agriculture Ministry Officials

General Agriculture Project Information

1. What do you see as the primary agricultural problems facing the country?

2. What are the current Ministry priorities for agricultural improvement projects?

3. What strategies is the Ministry using to improve access to organic and inorganic fertilizers?

Ecological Sanitation

4. Tell me about your understanding of the history of ecological sanitation in Togo: who initiated such projects, when, with what goals?

5. Tell me about an ecological sanitation project that you believe was successful. What made it successful?

6. Tell me about an ecological sanitation project that you believe was unsuccessful. What made it unsuccessful?

7. What barriers do you foresee in increasing use of ecological sanitation technology? In increasing the use of human excreta in agriculture?

Collaboration Between Health and Agriculture Ministry Officials

8. Do you know of any current or former collaboration between Health Ministry officials and officials in the Ministry of Agriculture on sanitation improvement projects?

9. How do you personally collaborate with members of the Ministry of Health on improved sanitation or any other activities?

10. What barriers do you foresee in improving collaboration between Health Ministry and Agriculture Ministry officials on sanitation projects?

11. What benefits do you foresee in improving collaboration between Health Ministry and Agriculture Ministry officials on sanitation projects?

Appendix 2: French Questionnaire for Agriculture Ministry Officials

Informations générales sur les projets agricoles

1. Quels sont, selon vous, les principaux problèmes agricoles auxquels le pays est confronté ?
2. Quelles sont les priorités actuelles du ministère pour les projets d'amélioration agricole ?
3. Quelles stratégies le ministère utilise-t-il pour améliorer l'accès aux engrais organiques et inorganiques ?

Assainissement écologique

4. Parlez-moi de votre compréhension de l'histoire de l'assainissement écologique au Togo : qui a initié de tels projets, quand, et avec quels objectifs ?
5. Parlez-moi d'un projet d'assainissement écologique qui, selon vous, a été couronné de succès. Quoi a fait son succès?
6. Parlez-moi d'un projet d'assainissement écologique qui, selon vous, n'a pas abouti. Qu'est-ce qui l'a rendu infructueux ?
7. Quels obstacles prévoyez-vous pour accroître l'utilisation de la technologie d'assainissement écologique? En augmentant l'utilisation des excréments humains dans l'agriculture?

Collaboration entre les fonctionnaires du ministère de la Santé et de l'Agriculture

8. Connaissez-vous une collaboration actuelle ou ancienne entre des fonctionnaires du ministère de la Santé et des fonctionnaires du ministère de l'Agriculture sur des projets d'amélioration de l'assainissement ?
9. Comment collaborez-vous personnellement avec les membres du ministère de la Santé sur l'amélioration de l'assainissement ou toute autre activité ?
10. Quels obstacles prévoyez-vous pour améliorer la collaboration entre les fonctionnaires du ministère de la Santé et du ministère de l'Agriculture sur les projets d'assainissement ?
11. Quels avantages prévoyez-vous pour améliorer la collaboration entre les fonctionnaires du ministère de la Santé et du ministère de l'Agriculture sur les projets d'assainissement ?

Appendix 3: English Questionnaire for Public Health Ministry Officials

General Sanitation Project Information

1. What do you see as the primary public health problems facing the country?

2. What are the current Ministry priorities for sanitation improvement projects?

3. What strategies is the Ministry using to improve sanitation access in urban areas? Rural areas?

Ecological Sanitation

4. Tell me about your understanding of the history of ecological sanitation in Togo: who initiated such projects, when, with what goals?

5. Tell me about an ecological sanitation project that you believe was successful. What made it successful?

6. Tell me about an ecological sanitation project that you believe was unsuccessful. What made it unsuccessful?

7. What barriers do you foresee in increasing use of ecological sanitation technology? In increasing the use of human excreta in agriculture?

Collaboration Between Health and Agriculture Ministry Officials

8. Do you know of any current or former collaboration between Health Ministry officials and officials in the Ministry of Agriculture on sanitation improvement projects?

9. How do you personally collaborate with members of the Ministry of Agriculture on improved sanitation or any other activities?

10. What barriers do you foresee in improving collaboration between Health Ministry and Agriculture Ministry officials on sanitation projects?

11. What benefits do you foresee in improving collaboration between Health Ministry and Agriculture Ministry officials on sanitation projects?

Appendix 4: French Questionnaire for Public Health Ministry Officials

Informations générales sur les projets d'assainissement

1. Selon vous, quels sont les principaux problèmes de santé publique auxquels le pays est confronté ?
2. Quelles sont les priorités actuelles du Ministère pour les projets d'amélioration de l'assainissement ?
3. Quelles stratégies le Ministère utilise-t-il pour améliorer l'accès à l'assainissement dans les zones urbaines ? Les zones rurales ?

Assainissement écologique

4. Parlez-moi de votre compréhension de l'histoire de l'assainissement écologique au Togo : qui a initié de tels projets, quand, avec quels objectifs ?
5. Parlez-moi d'un projet d'assainissement écologique qui, selon vous, a été couronné de succès. Qu'est-ce qu'a fait son succès ?
6. Parlez-moi d'un projet d'assainissement écologique qui, selon vous, n'a pas abouti. Qu'est-ce qui l'a rendu infructueux ?
7. Quels obstacles prévoyez-vous pour accroître l'utilisation de la technologie d'assainissement écologique? En augmentant l'utilisation des excréments humains dans l'agriculture?

Collaboration entre les fonctionnaires du ministère de la Santé et de l'Agriculture

8. Connaissez-vous une collaboration actuelle ou ancienne entre des fonctionnaires du ministère de la Santé et des fonctionnaires du ministère de l'Agriculture sur des projets d'amélioration de l'assainissement ?
9. Comment collaborez-vous personnellement avec les membres du Ministère de l'agriculture sur l'amélioration de l'assainissement ou toute autre activité ?
10. Quels obstacles prévoyez-vous pour améliorer la collaboration entre les fonctionnaires du ministère de la Santé et du ministère de l'Agriculture sur les projets d'assainissement ?
11. Quels avantages prévoyez-vous pour améliorer la collaboration entre les fonctionnaires du ministère de la Santé et du ministère de l'Agriculture sur les projets d'assainissement ?

Appendix 5a: Total (Mg) amounts of carbon and major nutrients present in human excreta (combined feces and urine) by region.

Region	C	N (Low Estimate)	N (High Estimate)	P (Low Estimate)	P (High Estimate)	K (Low Estimate)	K (High Estimate)
Centrale	4,022.5	3,216.1	4,004.0	359.5	710.2	828.9	989.8
Kara	5,010.9	4,006.3	4,987.7	447.9	884.7	1,032.6	1,233.0
Maritime	17,027.9	13,614.1	16,949.3	1,521.9	3,006.3	3,508.9	4,190.0
Plateaux	8,925.7	7,136.2	8,884.4	797.8	1,575.8	1,839.3	2,196.3
Savanes	5,327.5	4,259.4	5,302.9	476.2	940.6	1,097.8	1,310.9
TOGO	**40,314.5**	**32,232.1**	**40,128.2**	**3,603.3**	**7,117.6**	**8,307.6**	**9,920.1**

Appendix 5b: Per hectare (kg ha^{-1}) amounts of carbon and major nutrients present in human excreta (combined feces and urine) by region.

Region	C	N (Low Estimate)	N (High Estimate)	P (Low Estimate)	P (High Estimate)	K (Low Estimate)	K (High Estimate)
Centrale	4.8	3.9	4.8	0.4	0.9	1.0	1.2
Kara	12.7	10.2	12.7	1.1	2.2	2.6	3.1
Maritime	65.3	52.2	65.0	5.8	11.5	13.5	16.1
Plateaux	10.1	8.1	10.0	0.9	1.8	2.1	2.5
Savanes	22.2	17.7	22.0	2.0	3.9	4.6	5.5
TOGO	**15.4**	**12.3**	**15.4**	**1.4**	**2.7**	**3.2**	**3.8**

Appendix 6a: Total (Mg) amounts of carbon and major nutrients present in urine by region.

Region	Total Population	Total Annual Urine Production (L)	N (Low Estimate)	N (High Estimate)	P (Low Estimate)	P (High Estimate)	K
Centrale	760,046	3.9E+08	2,757.5	3,545.4	118.2	275.8	748.5
Kara	946,784	4.9E+08	3,435.0	4,416.5	147.2	343.5	932.4
Maritime	3,217,371	1.7E+09	11,672.9	15,008.1	500.3	1,167.3	3,168.4
Plateaux	1,686,476	8.7E+08	6,118.7	7,866.9	262.2	611.9	1,660.8
Savanes	1,006,609	5.2E+08	3,652.1	4,695.5	156.5	365.2	991.3
TOGO	**7,617,286**	**3.9E+09**	**27,636.3**	**35,532.4**	**1,184.4**	**2,763.6**	**7,501.3**

Appendix 6b: Per hectare (kg ha^{-1}) amounts of carbon and major nutrients present in urine by region.

Region	Total Cropland (ha)	Total Annual Urine Production (L)	N (Low Estimate)	N (High Estimate)	P (Low Estimate)	P (High Estimate)	K
Centrale	834,500	3.9E+08	3.3	4.2	0.1	0.3	0.9
Kara	393,500	4.9E+08	8.7	11.2	0.4	0.9	2.4
Maritime	260,600	1.7E+09	44.8	57.6	1.9	4.5	12.2
Plateaux	884,400	8.7E+08	6.9	8.9	0.3	0.7	1.9
Savanes	240,500	5.2E+08	15.2	19.5	0.7	1.5	4.1
TOGO	**2,613,500**	**3.9E+09**	**10.6**	**13.6**	**0.5**	**1.1**	**2.9**

Appendix 7b: Total (Mg) amounts of carbon and major nutrients present in feces by region.

Region	Total Population	Total Annual Feces Production (Mg dry matter)	C	N	P (Low Estimate)	P (High Estimate)	K (Low Estimate)	K (High Estimate)
Centrale	760,046	8,045.1	4,022.5	458.6	241.4	434.4	80.5	241.4
Kara	946,784	10,021.7	5,010.9	571.2	300.7	541.2	100.2	300.7
Maritime	3,217,371	34,055.9	17,027.9	1,941.2	1,021.7	1,839.0	340.6	1,021.7
Plateaux	1,686,476	17,851.3	8,925.7	1,017.5	535.5	964.0	178.5	535.5
Savanes	1,006,609	10,655.0	5,327.5	607.3	319.6	575.4	106.5	319.6
TOGO	**7,617,286**	**80,629.0**	**40,314.5**	**4,595.9**	**2,418.9**	**4,354.0**	**806.3**	**2,418.9**

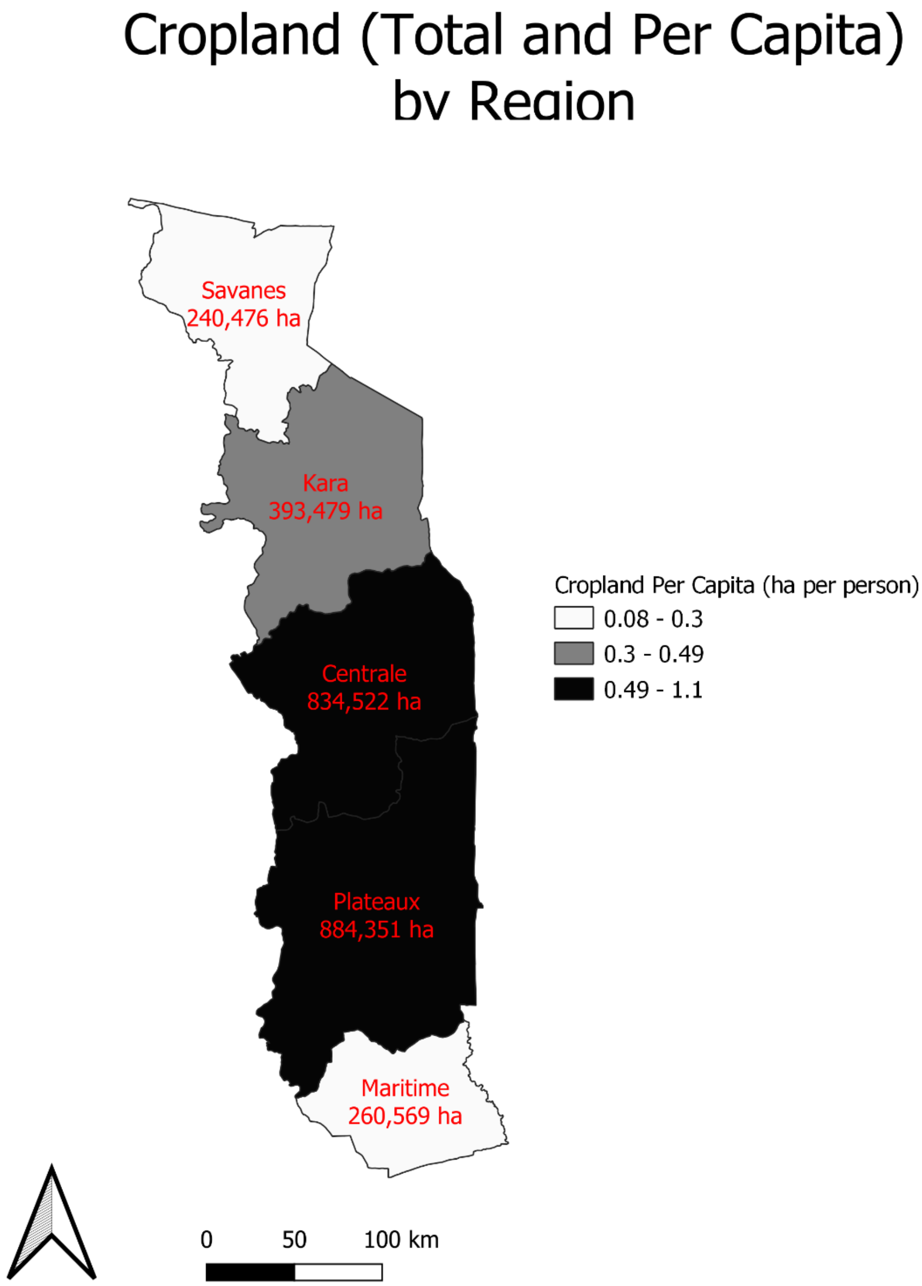
Appendix 7b: Per hectare (kg ha^{-1}) amounts of carbon and major nutrients present in feces by region.

Region	Total Cropland (ha)	Total Annual Feces Production (Mg dry matter)	C	N	P (Low Estimate)	P (High Estimate)	K (Low Estimate)	K (High Estimate)
Centrale	834,500	8,045.1	4.8	0.5	0.3	0.5	0.1	0.3
Kara	393,500	10,021.7	12.7	1.5	0.8	1.4	0.3	0.8
Maritime	260,600	34,055.9	65.3	7.4	3.9	7.1	1.3	3.9
Plateaux	884,400	17,851.3	10.1	1.2	0.6	1.1	0.2	0.6
Savanes	240,500	10,655.0	22.2	2.5	1.3	2.4	0.4	1.3
TOGO	**2,613,500**	**80,629.0**	**15.4**	**1.8**	**0.9**	**1.7**	**0.3**	**0.9**

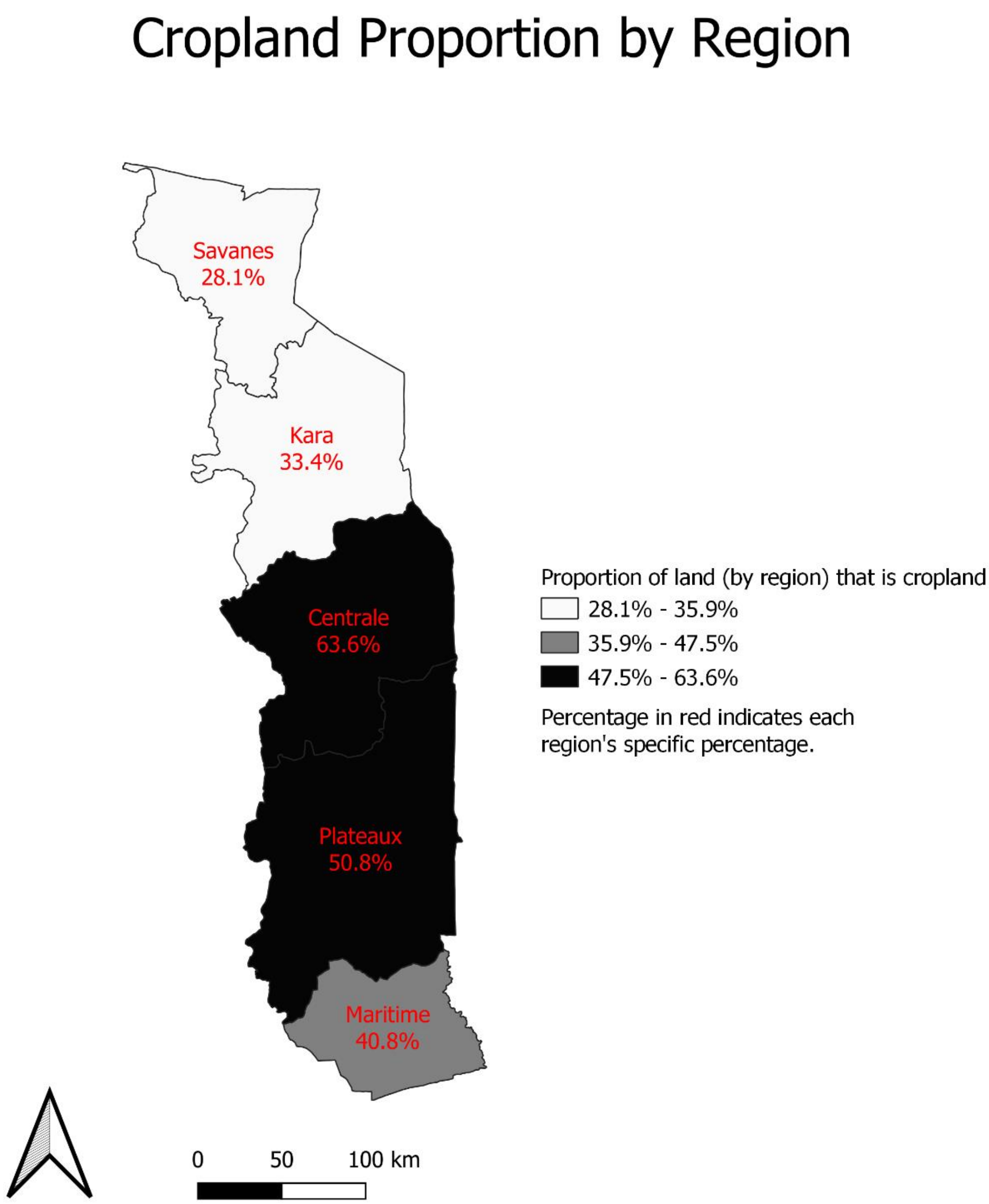
Appendix 8: Assumptions for Excreta Nutrient Content Estimations, from Harder et al. (2019), Makaya et al. (2014), Rose et al. (2015), and Winker et al. (2009).

Assumptions									
	Source								
Feces	Rose et al., 2015	Dry mass production: 29 g/capita/day							
	Harder et al., 2019	C	N (low)	N (high)	P (low)	P (high)	K (low)	K (high)	
		50.0%	5.7%	-	3.0%	5.4%	1.0%	2.5%	Note: Numbers are % of dry weight.
Urine	Makaya et al., 2014	-	7	-	0.3	-	1.9	-	Note: Numbers are grams per liter of urine (stored for 30 days).
	Winker et al., 2009	-	-	9	-	0.7	-	-	Note: Numbers are grams per liter of urine.

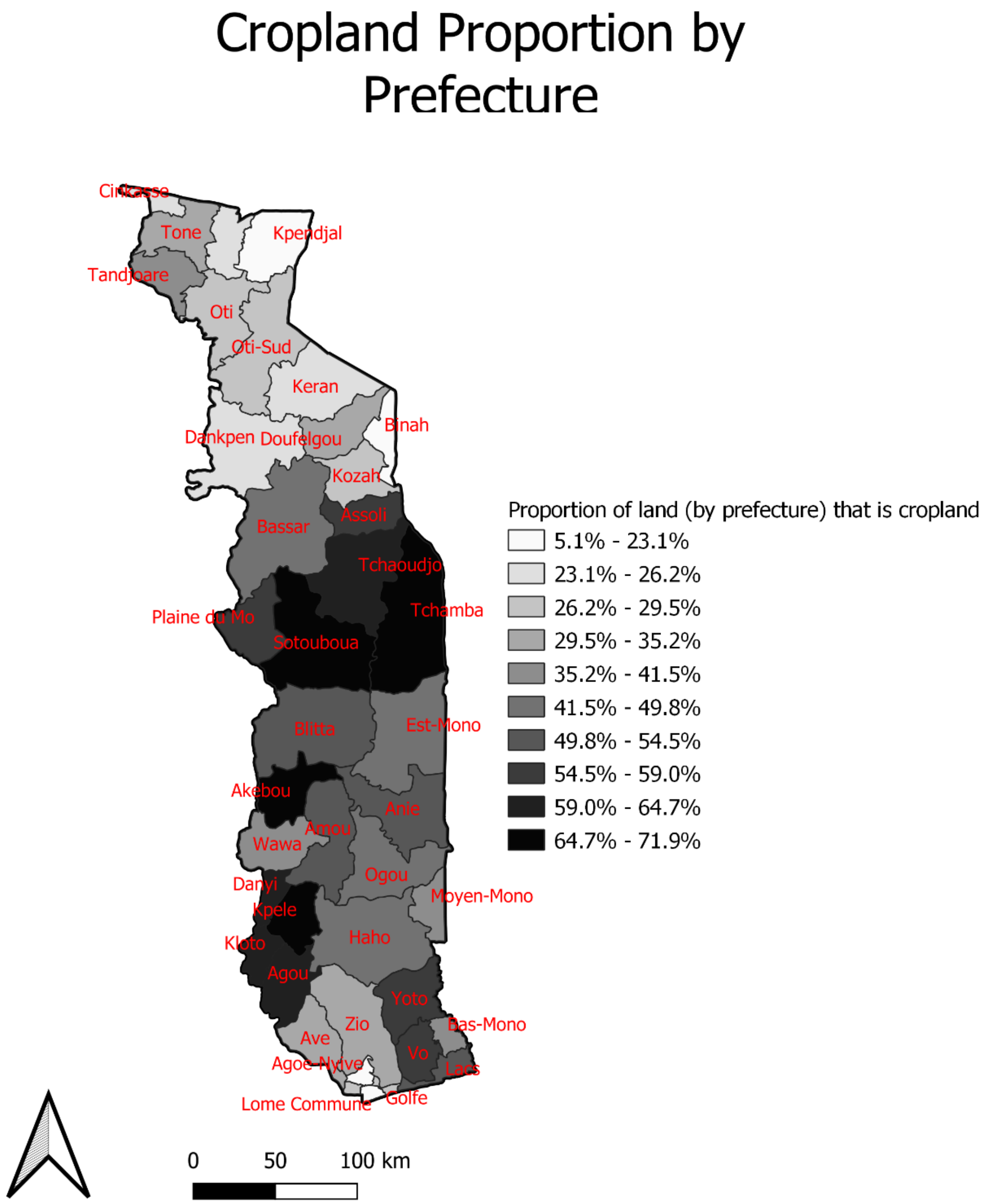
Appendix 9: Cropland (Total and Per Capita) by Region



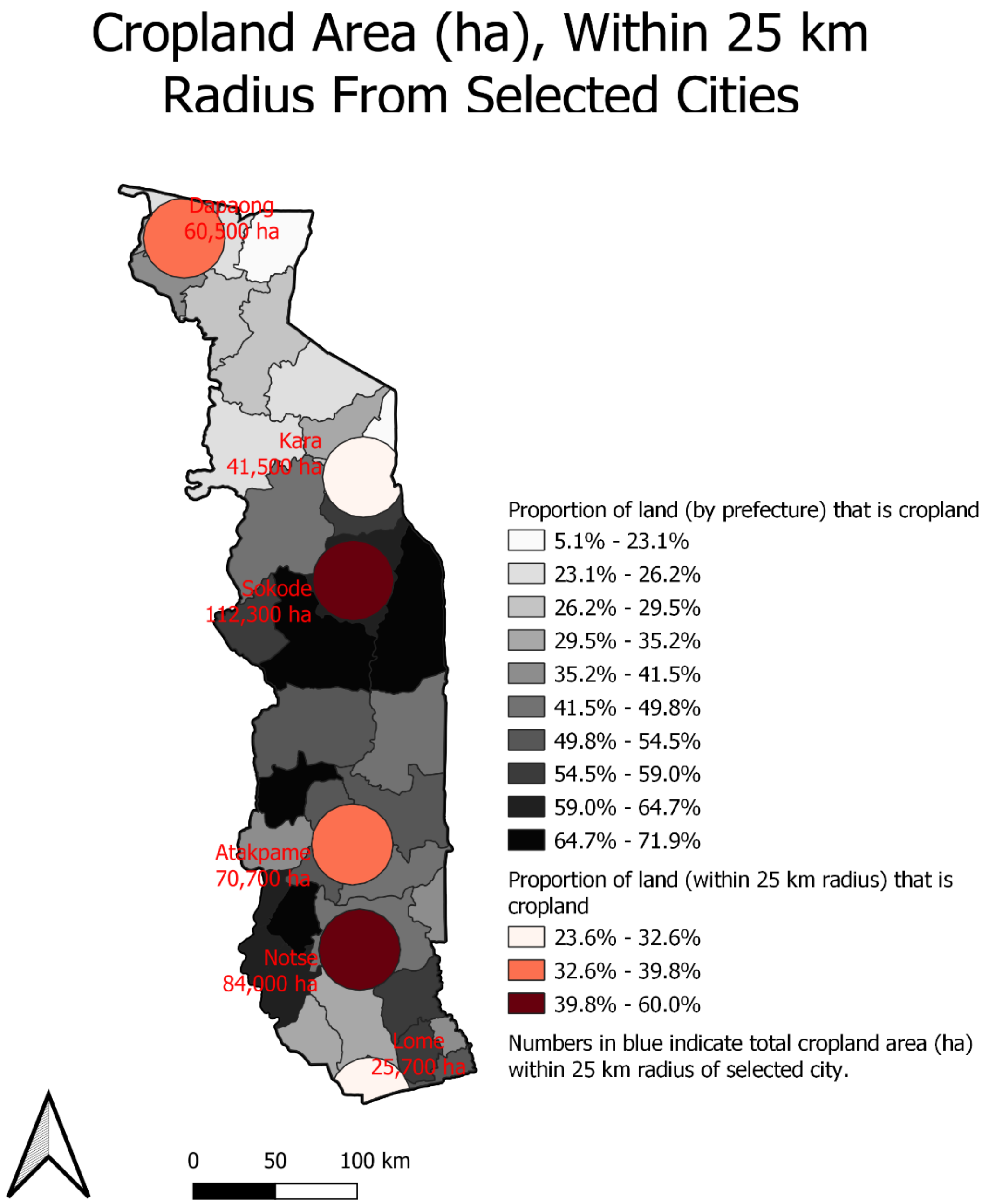
Appendix 10: Cropland Proportion by Region



Appendix 11: Cropland Proportion by Prefecture



Appendix 12: Cropland Area Within 25 km Radius from Selected Cities



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