Challenges to ecosystem services of sustainable agriculture in West Africa

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Dissertation for the acquisition of the academic degree Doktor der Agrarwissenschaften (Dr. agr.)

Presented to the Faculty of Organic Agricultural Sciences

Organic Plant Production and Agroecosystems Research in the Tropics and Subtropics (OPATS)

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Date of submission: 10.06.2020

Date of defence : 15.07.2020

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dedicated to my dear parents, and my dear Ephraim

Nil desperandum

Acknowledgement

I would like to thank my *Doktorvater*, Prof. Dr. Andreas Buerkert for giving me the opportunity to improve my knowledge in science and scientific research. It has been quite a journey, and the environment in his department toughened yet still allowed me to flourish. I would also like to thank Dr. Kathrin Stenchly, our conversations about science refined my thoughts and pushed me through my studies whenever I felt like quitting. Her steadfast support, and friendship is what I would wish for any PhD candidate. I would like to also thank Dr. Christoph Steiner, for his many ideas, and his suggestions for my research. I would like to thank Dr. Regina Roessler, for her energy, her attention, and her concentration when we worked together. I would like to thank Dr. Martin Wiehle for his friendship, for his willingness in reviewing my manuscripts with attentiveness and meticulousness no matter the stage of development it was in. I would like to thank Dr. Hanna Karg, with whom I had exciting research expeditions in West Africa.

I would also like to thank Dr. Mariko Ingold who apart from conversing with me many times about biochar, introduced me to yoga, judo, and energy dance. I would like to also thank Dr. Edmund Akoto-Danso, who listened to my complaints and made light of them, Dr. Sven Goenster for always laughing at my jokes during the 10 am coffee break, Dr. Korbinian Kaetzl for his friendship and the analysis of irrigation water. My appreciation also to Ms. Claudia Thiema-Fricke and Ms. Eva Wiegard who analysed samples for my research.

I would like to thank my dear parents, Mr. Michael Amprako, and Mrs. Christina Amprako, for offering me an education they never had and could barely afford. My love to my dear siblings, Ms. Jessica Amprako, and Mr. Peter Amprako, for their emotional support. I would also like to thank my dear friends, Ms. Helen Aron, Ms. Yuliya Golbert, Mr. Christian Boedeker (who as I type this has been on the phone with me for at least 20 hours helping me programme the dissertation line after line), Ms Elisabeth Ziegler, Mr. Gameli Adzaho, Mr. Michael Ofori-Adjei, Mr. Frank Nsafoah, Mr. Kwame Dei Dawson, Ms. Louisa Bangs, Mr. Kofi Asante, Mr. Emmanuel Darko, Dr. Emmanuel Akoto Darko, Dr. Imogen Bellwood-Howard, Dr. Erica Dickson, Ms. Merle-Marie Oelmann, Mr. Julian Plagemann, Mr. Martin Poku, and Mr. Sebastian Zublewitz for their emotional support too. I would also like to thank Mr. David Hiß who introduced me to Dr. Müller who offered me his financial support at a critical time during my education in Germany. I would also like to thank ICDD for the work and study scholarship they offered me in 2013 as master student.

I would also like to thank the friends I made on the field and in the PhD office, Mr. Budiman, Mr. Deogratias Agbotui, Mr. Alhassan Yakubu, Mr. Adam, Ms. Jennifer Provost, Mr. Arslan Nawaz, Ms. Marion Reichenbach, Dr. Annika Witte, Ms. Emily Gawum, Dr. Stefan Werner, Ms. Princess Botchway, Mr. Robin Siebert, Mr. Jan Werner, Ms. Aspasia Werner, I hope our friendship continues to thrive beyond the office door and the research fields.

Finally, I would also like to thank Witzenhausen and its lovely people for the solace I was offered.

Summary

Food security is still sub-optimal in many parts of West Africa calling for more efficient agricultural practices in mitigating food insecurity. Some of the problems faced in West African agricultural systems are bottlenecks in ruminant livestock supply, inefficiency in commercial poultry production, and loss of arthropod diversity. These issues require proper integration of farming systems, demand the closing of nutrient cycles, need diversification of production, and require enhancement of ecosystem services.

To contribute applicable data for the attainment of the aforementioned, this study investigated four topics of different contexts such as livestock and forage trade, nutrient use efficiency and detoxification of alternative feed through biochar application in poultry production, and lastly ecosystem service provision by studying arthropod diversity in cash crop fields of urban and periurban agricultural systems (UPA).

The knowledge of production and consumption regarding livestock and forage trade in West Africa is largely unknown and data are often rough estimates only. To shed light on the routes and hubs of livestock, a study was conducted in Bamako, Mali, where all major roads connecting the city were monitored for 24 hours each day for seven days, across the hot, rainy and harvest seasons. Information was collected on three ruminant livestock, goat, sheep, and cattle transported by vehicles. The origin, destination and quantity of the transported livestock were recorded. Data was also collected on the frequency of animal feed trafficked across these roads. Results showed that sheep were the most trafficked livestock of the three, due to its importance in Islamic festivals. The traffic of cattle and sheep was extensive, whereas the transport of goats was smaller and more localized. The results also showed the importance of Bamako as a hub in the livestock distribution to countries like Guinea and Senegal. Information obtained contributes significantly to the understanding of the scope of policy interventions towards further enhancing the efficiency of the livestock production and distribution sector and the enhancing of food security.

Another important component of food security is linked with nutrient use efficiency in livestock production systems, including the poultry sector. To specifically address this, two experiments about the efficacy of biochar in poultry management were conducted in Tamale, Northern Region, Ghana. In the first experiment, 24 male broiler chickens were offered commercial broiler finisher diets with 0 %, 1.5 %, 3 % and 6 % wood charcoal. The birds underwent a 14-day adaptation period and a four-day data collection period. Results showed that amendment of 6 % wood charcoal to feed stuff does not negatively affect growth performance. Although the amendment of

biochar did not significantly reduce weight gain, the 6 % biochar application slightly reduced the mean weight of those chickens. Hence more research is needed in this regard to investigate the underlying conditions that may make biochar a better poultry feed additive. Despite this, the biochar diets reduced the amount of phosphorous excreted by the chicken. It follows that at least phosphorous as a nutrient was more available to the birds. The issue of nutrient use inefficiency in West Africa poultry management is an important one as commercial feed is the most important variable of poultry production cost. Hence, this potential of biochar to accrete nutrients could be beneficial for farmers if explored more.

In the second biochar experiment, 168 female broiler chickens were offered seven diets that included different levels of biochar with different processed states of the underutilized carbohydrate rich root tuber, *Icacina oliviformis*. The root tuber is ubiquitous in the Northern Region of Ghana and has been consumed by indigenes in the past during famine periods. Despite its rich carbohydrate content, the wild crop contains antinutritive factors like terpenes, which inhibit essential amino acid receptors in poultry. Despite this, some other *Icacina* spp. also possess detoxing properties against tetrachloromethane and antimicrobial properties against *Escherichia coli*, *Staphylococcus aureus*, *Streptococcus* spp, *Candida albicans*, and *Klebsiella pneumoniae*. Results from the experiment showed that soaking the root tuber in water and feeding to poultry did not have any effect on lipophilic compounds but reduced chloroform subfractions. The addition of biochar on reducing the antinutritive effects was slight; furthermore, it resulted in low chicken body weight and blood protein. To this end, it is evident that despite the carbohydrate rich source of the root tuber, further research and breeding is needed on improving this wild plan species to make it a potential substitute for maize in poultry feeding to contribute to food security in West Africa.

As food and forage production is largely dependent on ecosystem services of arthropods (such as pollination, biological pest control, nutrient decomposition), the final study looked at the arthropod assemblage in UPA systems of Tamale. Species were sampled across lettuce, okra, and pepper fields within different management intensities. Two sampling techniques, pan trapping and pitfall trapping were used to sample the arthropods. Parameters such as wastewater irrigation, pesticide, and weedicide application, as well as manure and synthetic fertilizer usage, were assessed. From the results of 14,226 sampled arthropods, comprising 81 families, 11 orders, 211 genera, and 244 species were identified. Multivariate analyses showed that irrigation regimes had significant effect on arthropod species abundance, with *Hippeleates pusio* the most dominant, consistent with locations using wastewater as irrigation.

This vector not only transmits diseases like mastitis to livestock as well as bacterial conjunctivitis and yaws to humans. All these diseases are still prevalent in the study region. In addition, three alien ant species were recorded in the samples. The issue with ant species is that some of them form mutualistic association with deleterious aphids, which have the potential to cause serious crop damage. The other issue of concern with the ant species sampled is that they have the potential to grow into large populations, by displacing other native ant species and become invasive. Both issues may cause serious implication on food security for Tamale and beyond. Thus, future arthropod ecological research should not only evaluate the influence of wastewater application on *H. pusio* populations and related disease incidence but also the effect of alien and other arthropod species present in the area and their relationship with human food security.

Zusammenfassung

In vielen Teilen Westafrikas ist die Ernährungssicherheit immer noch suboptimal. Die Milderung dieser Ernährungsunsicherheit erfordert effizientere landwirtschaftliche Praktiken. Einige der Probleme, denen sich die westafrikanischen Agrarsysteme gegenübersehen, sind Engpässe bei der Futterversorgung von Vieh, eine ineffiziente kommerzielle Geflügelproduktion und der Verlust der Arthropodenvielfalt, die beispielsweise für die Bestäubung von Nutzpflanzen wichtig ist. Diese Probleme erfordern zielgerichtete Antworten wie beispielsweise eine angemessene Integration landwirtschaftlicher Systeme, die Schließung von Nährstoffkreisläufen, eine Diversifizierung der Produktion und die Verbesserung von Ökosystemleistungen.

Um anwendbare Daten für die Erreichung der oben genannten Ziele zu gewinnen, untersuchte diese Studie vier Themen aus verschiedenen Kontexten: (1) den Handel von Vieh und Futter, (2) die Anwendung von Biokohle für eine bessere Nährstoffnutzungseffizienz, (3) die Entgiftung von alternativen Futtermitteln in der Geflügelproduktion, und (4) die Bereitstellung von Ökosystemdienstleistungen durch Arthropoden bei Feldfrüchten in städtischen und stadtnahen landwirtschaftlichen Systemen (UPA).

Produktion und Konsum von gehandelten Futtermitteln in Westafrika ist erstaunlich wenig erforscht und die vorhandenen Daten sind oft nur Schätzwerte. Um Wege des Vieh- und Futterhandels zu untersuchen, wurde eine Studie in Bamako, Mali, durchgeführt, bei der alle in die Stadt führenden Hauptstraßen sieben Tage lang für je 24 h während der Trocken-, Regen- und Erntezeit überwacht wurden. Dabei wurden Informationen zu den drei Wiederkäuern Ziegen, Schafen und Rindern gesammelt, die mit Fahrzeugen transportiert wurden, um deren Menge, Herkunft und Bestimmungsort zu notieren. Zusätzlich wurden Daten über die Häufigkeit des Tierfuttertransports auf diesen Straßen gesammelt. Die Ergebnisse zeigen, dass Schafe aufgrund ihrer Bedeutung bei islamischen Festen das am meisten gehandelte Vieh der drei Tierarten waren. Der Handel mit Rindern und Schafen war umfangreich, während der Transport von Ziegen geringer und örtlich begrenzter war. Die Ergebnisse zeigten auch die Bedeutung von Bamako als Drehscheibe bei der Verteilung von Vieh in Länder wie Guinea und Senegal. Die gewonnenen Informationen tragen wesentlich zum Verständnis des Umfangs politischer Interventionen zur weiteren Verbesserung der Effizienz des Viehzuchtsektors und der Verteilung sowie zur Verbesserung der Nahrungsmittelsicherheit bei.

Eine weitere wichtige Komponente der Ernährungssicherheit ist die Nährstoffnutzungseffizienz in der Viehzucht, einschließlich des Geflügelsektors. Um dies zu untersuchen, wurden drei Experimente zur Effektivität von

Biokohle in der Geflügelzucht in Tamale, Nordregion von Ghana, durchgeführt. Im ersten Biokohleexperiment wurden 24 männlichen Masthähnchen „Finisher-Futter" gemischt mit 0 %, 1,5 %, 3 % und 6 % Holzkohle angeboten. Die Vögel durchliefen eine 14-tägige Anpassungszeit und danach eine viertägige Versuchsperiode. Die Ergebnisse zeigen, dass auch eine 6 %ige Beimischung von Holzkohle die Wachstumsleistung nicht negativ beeinflusst. Obwohl der Zusatz von Biokohle die Gewichtszunahme nicht signifikant verringerte, kam es zu einer leichten Reduzierung des mittleren Hähnchengewichts bei der 6 %igen Biokohlebeimischung. Es ist mehr Forschung erforderlich, um die Rahmenbedingungen zu untersuchen, die Biokohle zu einem besseren Geflügelfutterzusatzstoff machen könnten. Allerdings verringerten die Biokohlefuttermittel die Menge an Phosphor, die von den Hühnern ausgeschieden wurde. Daraus folgt, dass zumindest Phosphor als Nährstoff für die Vögel besser verfügbar war. Die Frage der Ineffizienz der Nährstoffnutzung in der westafrikanischen Geflügelwirtschaft ist ein wichtiges Thema, da kommerzielles Futter eine wichtige Kostenquelle in der Geflügelproduktion darstellt.

Im zweiten Biokohleexperiment wurden 168 Masthühner sieben Futtersorten angeboten, die unterschiedliche Mengen an Biokohle mit unterschiedlichen Verarbeitungszuständen der kohlenhydratreichen Wurzelknollen von *Icacina oliviformis* enthielten. Diese Wurzelknolle ist in der nördlichen Region Ghanas weit verbreitet und wurde in der Vergangenheit von der lokalen Bevölkerung während Hungersnöten verzehrt. Trotz ihres hohen Kohlenhydratgehalts enthält die Wildart antinutritive Inhaltsstoffe wie Terpene, die die essentiellen Aminosäurenrezeptoren des Geflügels hemmen. Andere *Icacina*-Arten besitzen entgiftende Inhaltsstoffe für Tetrachlormethan und antimikrobielle Eigenschaften gegen *Escherichia coli*, *Staphylococcus aureus*, *Streptococcus* spp., *Candida albicans* und *Klebsiella pneumoniae*. Die Ergebnisse des Versuchs zeigen, dass das Einweichen der Wurzelknolle in Wasser und die Verfütterung an Geflügel keinen Einfluss auf lipophile Verbindungen hatte, sondern die Chloroform-Subfraktionen verringerte. Die Zugabe von Biokohle zur Verringerung der antinutritiven Wirkungen war gering; darüber hinaus führte sie zu einem niedrigen Körpergewicht und Blutprotein der Hühner. Es ist daher offensichtlich, dass trotz der kohlenhydratreichen Quelle der Wurzelknolle weitere Forschung und gegebenenfalls Züchtungsmaßnahmen zur Verbesserung dieser Wildart erforderlich sind, um sie zu einem potenziellen Ersatz für Mais als Geflügelfutter zu etablieren.

Da die Nahrungs- und Futtermittelproduktion weitgehend von den Ökosystemleistungen der Arthropoden (wie Bestäubung, biologische Schädlingsbekämpfung, Nährstoffabbau) abhängt, wurde in der letzten Studie die Arthropodenvergesellschaftung in UPA-Systemen von Tamale untersucht. Die Arten wurden auf Salat (*Lactuca sativa*), Okra (*Abelmoschus esculentus*), und Chili-

feldern (*Capsicum annum*), mit unterschiedlicher Bewirtschaftungsintensität beprobt. Dazu wurden zwei Beprobungstechniken, die Bodenfalle und die Flugfalle, verwendet. Die Variablen Abwasserbewässerung, Pestizid- und Herbizidanwendung, und der Einsatz von natürlichem und künstlichem Düngers wurden ebenfalls bestimmt. Aus den Ergebnissen von 14.226 beprobten Arthropoden wurden 11 Ordnungen, 81 Familien, 211 Ordnungen, und 244 Arten identifiziert. Multivariate Analysen zeigten, dass die meisten Bewirtschaftungspraktiken, einen signifikanten Einfluss auf die Arthropoden-Artenhäufigkeit hatten. Darüber hinaus wurde festgestellt, dass eine krankheitsübertragende Art (*Hippeleates pusio*) dort dominierte, wo Abwasser zur Bewässerung verwendet wurde. Die Art überträgt nicht nur Krankheiten wie Mastitis auf das Vieh, sondern auch bakterielle Bindehautentzündung und Frambösie auf den Menschen. All diese Krankheiten sind in der Untersuchungsregion immer noch weit verbreitet. Außerdem wurde das Auftreten von drei fremden Ameisenarten in den Proben festgestellt, welche eine mutualistische Assoziation mit schädlichen Blattläusen bilden, die das Potenzial haben, schwere Ernteschäden zu verursachen. Ein weiteres Problem der untersuchten Ameisenarten ist ihr Potenzial, zu großen Populationen heranzuwachsen und andere einheimische Ameisenarten zu verdrängen und damit invasiv zu werden. Beides kann schwerwiegende Auswirkungen auf die Ernährungssicherheit in Tamale und darüber hinaus haben, weswegen zukünftige ökologische Arthropodenforschung nicht nur den Einfluss der Abwasseranwendung auf die *H. pusio*-Populationen und das damit verbundene Krankheitsgeschehen bewerten sollten. Es sollten auch verstärkt die Wechselwirkung der im Gebiet natürlich vorkommenden und eingeschleppten Arthropodenarten untersucht und die potentiell negativen Effekte auf die menschliche Nahrungssicherheit untersucht werden.

1 Chapter 1

Dissertation overview

1.1 *General introduction*

This work consists of five chapters: Chapter 1 contains a general introduction and provides an overview of agriculture in West Africa and some of its problems. In Chapter 2, the network of livestock distribution around the Mali capital of Bamako is assessed across three seasons. This chapter provides details about the important livestock demand and supply locations in Mali and how these contribute to an intraregional network of livestock. Chapter 3 and 4 comprise studies in Tamale, Ghana which provide information about the prospects of biochar in poultry production. Chapter 3 describes experiments on the potential of minute amounts of biochar as a feed additive to potentially improve nutrient assimilation of broilers. Chapter 4 contains another investigation about the potential of biochar to reduce the antinutrient properties of a root tuber in poultry while Chapter 5 examines the arthropod biodiversity in urban and peri-urban locations. Finally, Chapter 6 contains general results, final conclusions, and some recommendations. This work contains one published peer reviewed paper, and two submitted journal papers.

1.2 *Population development in West Africa*

The global population amounted to 7.7 billion in 2019 and it is estimated that by 2050 it may reach 9.7 billion, and 11 billion by 2100 (United Nations, 2019). In spite of this increase, the rate of global population increase is presently stagnating in comparison to a decade ago, partly due to progress in birth control, leading to lower fertility, improvement in healthcare, better life expectancy, a reduction in infant mortality, and the availability of formal education, which eventually may cause a decline in population (Bricker & Ibbitson, 2019). Although the latter may seem like a victory for the Anti-Malthusians, it is not necessarily valid for regions like sub-Saharan Africa which are experiencing the world's slowest population decline and highest fertility rate (United Nations, 2019). By 2050, Africa will be inhabited by 2.5 billion people, which means that Africa will have to accommodate at least 50 % of the projected additional global population (United Nations, 2019). This will also impose a further strain on the predominantly fragile food production systems of most parts of Africa (Hall et al., 2017). This will be compounded with the sporadic political and tribal conflicts (P. Williams, 2016) still present on the continent and the associated widespread corruption (Pring & Vrushi, 2019) and poor governance (Hope Sr, 2017). As African crises will spur young Africans to cross the Mediterranean in the quest for a better life (W. Williams, 2019), Europe will be closely connected to the consequences of these developments (Weber, 2019).

To mitigate negative consequences of the continent's population, critical issues threatening the sustainability of African agriculture need to be addressed. This is all the more important as for decades to come agriculture will remain a major source of employment for most of the continent's inhabitants. However, agricultural productivity is globally ranked lowest in most parts of the continent (Tadele, 2017) whereby efficient and sustainable agriculture could provide food for the continent (Adenle et al., 2019) and reduce the rates of hunger and infant mortality because of malnutrition (Kotsadam et al., 2018). Since over reliance on foreign aid retards economic growth (Yiew & Lau, 2018), efficient and sustainable African agriculture may also lead to its reduction and strengthen continental pride and belief in African human capital.

To strengthen sustainable development, more agricultural data is needed to inform decision makers, harness global technological advancement to provide tailor made solutions for the African continent and address declining productivity in many African agroecosystems.

1.3 *Agroecosystems in Africa*

To address the needs of an ever-increasing population, landscapes must house humans and produce food. However, such anthropogenic activities risk to fragment landscapes and disrupt ecosystems services, destabilizing millennia-old stable ecosystems (Amel et al., 2017). Some animals especially arthropods adjust to this disruption and continue to thrive, while many other species succumb to the pressures and decline in their abundance or richness. Arthropods are a group of animals that predate humans and thrive owing to their favourable characteristics like their exoskeleton, segmented bodies, jointed appendages, and flexible life cycle that allows them to survive even in adverse environments. These adaptations have evolved over millions of years and the current threats to their habitats due to intensification of landuse and losses of biodiversity ad different scales may have yet unknown ecological consequences. These may be resistance of potential arthropod pests to pest management, resurgence of previously controlled arthropod pests, and the replacement of arthropod pests by secondary pests (Pedigo & Rice, 2014). Biodiversity losses may occur through the introduction of alien and potentially invasive species that replace beneficial species, or through intensive agriculture which may lead to the loss of ecosystem services like pollination and herbivore antagonism. Given the value of arthropod pollination for food production, a loss in natural pollinators may reduce agricultural revenue by at least 29 % among some smallholder crop farms in Africa (Tibesigwa et al., 2019). Sometimes alien arthropod species can quickly adapt and colonise their new environment in large populations with devastating consequences. For example, in Africa the invasive Fall Army Worm *Spodoptera frugiperda* (JE SMITH) can lead to the destruction of food crop worth up to 6.2 billion USD per annum (Khan et al., 2018). Such consequences threaten food security considering that crop pests destroy staples that are a major source of food for Africans. In Europe and America crop production is more efficient so that some crops can be additionally used as animal feed and for energy production in addition to their use as staples. Not only can alien invasive arthropod species colonize rapidly their new fauna, but also introduced new or non-native crops can attract native herbivorous arthropods, nourish them, and increase their fecundity leading to the attainment of pest status of previously unknown herbivorous arthropods (Cox, 2013). Urbanisation is a global phenomenon which entails the expansion of cities spatially and numerically. Its effects on arthropods can be positive in the sense that anthropogenic activities like the construction of parks and urban gardens may improve biodiversity of beneficial animals like spiders (Lowe et al., 2014), and bees (Quistberg et al., 2016). However, urbanisation may also have negative consequences by increasing the population of invertebrates that have deleterious effects (Lindahl & Grace, 2015). Also, the synthetic use of chemicals in agroecological systems (Singh, 2017) may lead to resistance in some insects (Naqqash et al., 2016)

1.4 *The African livestock revolution: an option for enhanced sustainability?*

The ongoing population increase in Africa and changing food habits, particularly in urban population groups, will also lead to enhanced demand for meat products. This will provide opportunities for animal producers to boost their income and improve their livelihoods while satisfying meat demands especially in rapidly growing African economies (AfDB, 2019). This will further increase the demand of meat as a status symbol. The increase in the consumption of meat will in many cases be nutritionally desirable since the continent faces a deficit in the dietary protein in comparison with WHO recommendations and the rest of the world (Schonfeldt & Hall, 2013).

Commercial broiler and egg producers in Ghana for example, spend 67 % and 89 % of their respective production costs on feed (Anang et al., 2013). Since the commercial breeds of poultry are mostly exotic, poultry farmers are unable to attain the potential weight of their birds due to the unfavourable environmental conditions and relatively high feed prices (Islam & Nishibori, 2009). Moreover, the poultry industry in Africa is unable to compete with the frozen chicken market of China, Europe, and America due to Africa's current diseconomies of scale in poultry production (Banson et al., 2015).

The production of small and large ruminants is also a livelihood strategy for many Africans (Turner et al., 2014). Particularly, transhumance tribes like the Fulani of West Africa, are renowned for livestock production. For many centuries, herdsmen have used traditional migration routes to nourish and sell their livestock (Alidou, 2016). These transhumance movements are in synchrony with the changing seasons, as herdsmen seek out favourable feeding grounds for their animals (Turner et al., 2016). These traditions of transhumance are now under threat, as some of pastures have been converted into arable land with farmers objecting to transhumant landuse (Brottem, 2016). Additionally, political conflicts within and between African countries have limited the freedom of movement of African pastoralists (Walther et al., 2020). An additional threat to transhumance is climate change that puts feed and water sources under pressure (Brottem, 2016). All these circumstances have increased friction between farmers and herdsmen.

To enhance the independence of food imports and self-sufficiency, across Africa conservation of grazing areas and grazing routes for large ruminants should be taken more seriously. Meat production from monogastric animals needs to adopt improved feed mixtures possibly with additives to improve weight gains. This may include the use of underutilized crops, rich in carbohydrates, as supplementary feed resources.

1.5 *The biochar revolution: an option for agricultural efficiency and sustainability in Africa?*

In recent times, biochar, the product of pyrolysing organic material under limited oxygen conditions, has been advocated for the improved management of heavily leached tropical soils (Lehmann & Joseph, 2015). Due to biochar's ability to form long-lasting aggregates with soil minerals (Cusack et al., 2012), it has been used to slow down the emission of agriculture related greenhouse gases (Di Wu et al., 2018). Biochar application in agriculture also has the potential to improve soil faunal diversity (Steiner et al., 2016) and to improve the efficiency of composting (Steiner et al., 2015), to consequently improve crop yields in West Africa (Manka'abusi et al., 2019). Biochar as a livestock feed additive has also shown promises in the improvement of poultry (Amprako et al., 2018; Roessler et al., 2017) and small ruminant feed (Al-Kindi et al., 2017), as well as in detoxifying feed for large ruminants (Gerlach et al., 2014). The potential usage of biochar thus reaches beyond its use as a soil amendment and for animal feed improvement, it can even be used to reduce the pathogen load of waste water used for irrigation (Kaetzl et al., 2020) thereby protecting farmers and vegetable consumers from disease infection.

The production of biochar is also of potential environmental benefit as the charred material can be produced from agricultural waste materials such as corn cobs, groundnut husks, coconut husks and rice husks, and therefore does not compete with alternative uses of these substrates. Such organic waste in African countries like Ghana reach 61 % of total waste generated (Miezah et al., 2015) and its disposal may pose problems to waste management authorities (Oteng-Ababio et al., 2013).

1.6 *Study area*

The West African subregion lies within longitude 13.5317°N and latitude 2.4604°W, covering an area of about 733 million ha (FAO, 2020). Climatically the region is characterised by a dry and a wet season with uni-modally or bi-modally distributed rainfall (FAO, 1983). The dry season is characterized by high temperatures (Broecker & Putnam, 2013) and by dust related to dry trade winds (Iannicelli, 2017) blowing from November to February (FAO, 2020). The wet season is characterized by higher moisture as the equatorial air masses interact with the dry trade wind around the month of July (FAO, 2020). Agroecologically, West Africa spans vegetation zones ranging from humid tropical forests to the semi-arid Sahel and the Saharan zone, characterized by a steppe climate much drier and hotter than at the coastal West African countries (Beck et al., 2018).

Some countries of the semi-arid Sahel are especially vulnerable to food insecurity (Haggblade et al., 2017) coupled with a high frequency of violence and instability (ECC Factbook, 2020; Walther, 2017). In addition, crop production suffers from low soil fertility typical of arid and sandy Sahelian soils. This problem is exacerbated by the erratic rainfall typical for Sahelian West Africa where inhabitants largely rely on agriculture combined with animal husbandry for their livelihoods. The coastal West African countries have generally more fertile soils than in the Sahelian states, their rainfall is less erratic, and the risk of food insecurity lower.

Given the focus of this study on Ghana and Mali, their climatic and socio-economic conditions will be described in more detail as follows:

Mali a poor landlocked Sahelian country with a high risk of food insecurity compounded with political instability. Agriculture is traditionally the main livelihood for Malians and about 60 % of the population lives in rural settings. Mali's different ethnics groups can be roughly grouped into Fulbe (crop farmers) and Fulani (pastoralists) which are often in conflicts about land and water resources.

Ghana, instead, is a hot and humid coastal West African country with a recent democratic tradition and comparatively high political stability. Almost half (44 %) of the country's population belong to the middle class, whereby agriculture contributes 20 % to Ghana's GDP and employs about 45 % of its population.

1.7 *Study objectives and hypotheses*

This study analysed food networks in Mali's livestock distribution as well as the potential improvement of Ghana's poultry production by biochar feed additives and the biodiversity of arthropods in rural-urban landuse systems.

The specific aims of this doctoral research were to

1. Investigate the network distribution of livestock in Mali's capital Bamako across seasons

2. Ascertain the effectiveness of biochar as a poultry feed additive for the improvement of feed in Tamale, northern Ghana

3. Analyse the ecology of arthropod species of urban and peri-urban agricultural (UPA) systems and the relationship between management practices of farmers and arthropod abundance in Tamale, northern Ghana

Since Objective 1 was of an exploratory nature, a hypothesis could not be formulated. In contrast Objectives 2 and 3 allowed to establish the following hypotheses.

1. The addition of biochar in poultry feed enhances the performance of commercial poultry

2. Farmers' management practices affect the abundance of arthropods in UPA systems

1.8 References

References

Adenle, A. A., Wedig, K., & Azadi, H. (2019). Sustainable agriculture and food security in Africa: The role of innovative technologies and international organizations. *Technology in Society*, *58*, 101143.

AfDB. (2019). African economic outlook 2019 macroeconomic performance and prospects, jobs, growth, and firm dynamism, integration for Africa's economic prosperity. https://www.afdb.org/fileadmin/uploads/afdb/Documents/Publications/2019AEO/AEO_2019-EN.pdf accessed: 17.02.2020

Akpodiete, N. O., Diabate, A., & Tripet, F. (2019). Effect of water source and feed regime on development and phenotypic quality in *Anopheles gambiae* (sl): Prospects for improved mass-rearing techniques towards release programmes. *Parasites and Vectors*, *12*(1), 210.

Alidou, S. M. (2016). Cross-border transhumance corridors in West Africa. *CapEx in Supporting Pastoral Development*. Retrieved, from https://www.shareweb.ch/site/Agriculture-and-Food-Security/aboutus/Documents/pastoralism/pastoralism_brief_couloirs_transhumance_e.pdf

Al-Kindi, A., Schiborra, A., Buerkert, A., & Schlecht, E. (2017). Effects of quebracho tannin extract and activated charcoal on nutrient digestibility, digesta passage and faeces composition in goats. *Journal of animal physiology and animal nutrition*, *101*(3), 576–588. https://doi.org/10.1111/jpn.12461

Amel, E., Manning, C., Scott, B., & Koger, S. (2017). Beyond the roots of human inaction: Fostering collective effort toward ecosystem conservation. *Science*, *356*(6335), 275–279. https://doi.org/10.1126/science.aal1931

Amprako, L., Alhassan, M., Buerkert, A., & Roessler, R. (2018). Influence of dietary wood charcoal on growth performance, nutrient efficiency and excreta quality of male broiler chickens. *International Journal of Livestock Production*, *9*(10), 286–292. https://doi.org/10.5897/IJLP2018.0486

Banson, K. E., Gobinath Muthusamy, & Ebenezer Kondo. (2015). The import substituted poultry industry; evidence from Ghana. *International Journal of Agriculture and Forestry*. https://doi.org/10.5923/j.ijaf.20150502.11

Bricker, D., & Ibbitson, J. (2019). *Empty planet: The shock of global population decline*. Hachette UK, 2019.

Broecker, W. S., & Putnam, A. E. (2013). Hydrologic impacts of past shifts of earth's thermal equator offer insight into those to be produced by fossil fuel co2. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(42), 16710–16715. https://doi.org/10.1073/pnas.1301855110

Cox, G. W. (2013). *Alien species and evolution: The evolutionary ecology of exotic plants, animals, microbes, and interacting native species*. Island Press; [ProQuest].

Di Wu, Senbayram, M., Zang, H., Ugurlar, F., Aydemir, S., Brüggemann, N., Kuzyakov, Y., Bol, R., & Blagodatskaya, E. (2018). Effect of biochar origin and soil ph on greenhouse gas emissions from sandy and clay soils. *Applied Soil Ecology*, *129*, 121–127. https://doi.org/10.1016/j.apsoil.2018.05.009

ECC Factbook. (2020). Pastoralist and farmer-herder conflicts in the Sahel. https://factbook.ecc-platform.org/conflicts/pastoralist-and-farmer-herder-conflicts-sahel accessed: 18.02.2020

FAO. (1983). *Integrating crops and livestock in West-Africa* (Vol. 41). FAO.

FAO. (2020). West Africa. Retrieved, from http://www.fao.org/3/y1997e/y1997e0j.htm

Gerlach, H., Gerlach, A., Schrödl, W., Schottdorf, B., Haufe, S., Helm, H., Shehata, A., & Krüger, M. (2014). *Journal of Clinical Toxicology*. https://doi.org/10.4172/2161-0495.186

Haggblade, S., Me-Nsope, N. M., & Staatz, J. M. (2017). Food security implications of staple food substitution in sahelian West Africa. *Food Policy*, *71*, 27–38. https://doi.org/10.1016/j.foodpol.2017.06.003

Hall, C., Dawson, T., Macdiarmid, J., Matthews, R., & Smith, P. (2017). The impact of population growth and climate change on food security in Africa: Looking ahead to 2050. *International Journal of Agricultural Sustainability*, *15*(2), 124–135.

Hope Sr, K. R. (2017). *Corruption and governance in Africa: Swaziland, Kenya, Nigeria*. Springer.

Iannicelli, M. (2017). Accounting for hominins' fast exit from Africa ('the out of Africa event 1') due to widespread wildfires, accidentally and inevitably ignited by them, c.a. 1.8 – 1.6 mya. *Journal of Anthropology and Archaeology*, *5*(2). https://doi.org/10.15640/jaa.v5n2a4

Islam, M. A., & Nishibori, M. (2009). Indigenous naked neck chicken: A valuable genetic resource for Bangladesh. *World's Poultry Science Journal*, *65*(1), 125–138. https://doi.org/10.1017/S0043933909000105

Kaetzl, K., Lübken, M., Nettmann, E., Krimmler, S., & Wichern, M. (2020). Slow sand filtration of raw wastewater using biochar as an alternative filtration media. *Scientific Reports*, *10*(1), 1229. https://doi.org/10.1038/s41598-020-57981-0

Khan, Z. R., Pittchar, J. O., Midega, C. A. O., & Pickett, J. A. (2018). Push-pull farming system controls fall armyworm: Lessons from Africa. *Outlooks on Pest Management*, *29*(5), 220–224. https://doi.org/10.1564/v29_oct_09

Kotsadam, A., Østby, G., Rustad, S. A., Tollefsen, A. F., & Urdal, H. (2018). Development aid and infant mortality. micro-level evidence from nigeria. *World Development*, *105*, 59–69.

Lehmann, J., & Joseph, S. (Eds.). (2015). *Biochar for environmental management: Science, technology and implementation* (Second edition). Earthscan.

Lindahl, J. F., & Grace, D. (2015). The consequences of human actions on risks for infectious diseases: A review. *Infection Ecology and Epidemiology*, *5*, 30048. https://doi.org/10.3402/iee.v5.30048

Lowe, E. C., Wilder, S. M., & Hochuli, D. F. (2014). Urbanisation at multiple scales is associated with larger size and higher fecundity of an orb-weaving spider. *PloS one*, *9*(8), e105480. https://doi.org/10.1371/journal.pone.0105480

Manka'abusi, D., Steiner, C., Akoto-Danso, E. K., Lompo, D. J. P., Haering, V., Werner, S., Marschner, B., & Buerkert, A. (2019). Biochar application and wastewater irrigation in urban vegetable production of Ouagadougou, Burkina Faso. *Nutrient Cycling in Agroecosystems*, *115*(2), 263–279. https://doi.org/10.1007/s10705-019-09969-0

Miezah, K., Obiri-Danso, K., Kádár, Z., Fei-Baffoe, B., & Mensah, M. Y. (2015). Municipal solid waste characterization and quantification as a measure towards effective waste management in Ghana. *Waste management (New York, N.Y.)*, *46*, 15–27. https://doi.org/10.1016/j.wasman.2015.09.009

Naqqash, M. N., Gökçe, A., Bakhsh, A., & Salim, M. (2016). Insecticide resistance and its molecular basis in urban insect pests. *Parasitology Research*, *115*(4), 1363–1373.

Oteng-Ababio, M., Melara Arguello, J. E., & Gabbay, O. (2013). Solid waste management in African cities: Sorting the facts from the fads in Accra, Ghana. *Habitat International*, *39*, 96–104. https://doi.org/10.1016/j.habitatint.2012.10.010

Pedigo, L. P., & Rice, M. E. (2014). *Entomology and pest management*. Waveland Press.

Pring, C., & Vrushi, J. (2019). Global corruption barometer: Africa 2019. *Transparency International*.

Quistberg, R. D., Bichier, P., & Philpott, S. M. (2016). Landscape and local correlates of bee abundance and species richness in urban gardens. *Environmental Entomology*, *45*(3), 592–601. https://doi.org/10.1093/ee/nvw025

Roessler, R., Amprako, L., Sayibu, A. R., Mohammed, A., Menezes, R. C., Hölscher, D., Alenyorege, B., Dei, H. K., & Steiner, C. (2017). Effects of false yam tuber meals and charcoal on broiler chicken production and blood parameters. *South African Journal of Animal Science*, *47*(6), 843. https://doi.org/10.4314/sajas.v47i6.12

Schonfeldt, H. C., & Hall, N. (2013). Fish, chicken, lean meat and eggs can be eaten daily: A food-based dietary guideline for south africa. *South African Journal of Clinical Nutrition*, (3), S66–S76. Retrieved, from https://www.ajol.info/index.php/sajcn/article/view/97806/87111

Singh, B. (2017). Role of pesticides in management of crop pests. *Theory and Practice of Integrated Pest Management*, 76.

Steiner, C., Bayode, A. O., & Ralebitso-Senior, T. K. (2016). Feedstock and production parameters. In *Biochar application* (pp. 41–54). Elsevier. https://doi.org/10.1016/B978-0-12-803433-0.00002-3

Steiner, C., Sánchez-Monedero, M., & Kammann, C. (2015). Biochar as an additive to compost and growing media. In *Biochar for environmental management: Science, technology and implementation* (pp. 715–735). Routledge.

Tadele, Z. (2017). Raising crop productivity in Africa through intensification. *Agronomy*, *7*(1), 22.

Tibesigwa, B., Siikamäki, J., Lokina, R., & Alvsilver, J. (2019). Naturally available wild pollination services have economic value for nature dependent smallholder crop farms in Tanzania. *Scientific Reports*, *9*(1), 3434. https://doi.org/10.1038/s41598-019-39745-7

Turner, M. D., McPeak, J. G., Gillin, K., Kitchell, E., & Kimambo, N. (2016). Reconciling flexibility and tenure security for pastoral resources: The geography of transhumance networks in eastern Senegal. *Human Ecology*, *44*(2), 199–215. https://doi.org/10.1007/s10745-016-9812-2

Walther, O. J. (2017). Wars and conflicts in the Sahara-Sahel. https://doi.org/10.1787/24142026

Walther, O. J., Dambo, L., Koné, M., & van Eupen, M. (2020). Mapping travel time to assess accessibility in West Africa: The role of borders, checkpoints and road conditions. *Journal of Transport Geography*, *82*.

Weber, H. (2019). Can violent conflicts explain the recent increase in the flow of asylum seekers from Africa into Europe? *Journal of Immigrant and Refugee Studies*, *17*(4), 405–424.

Williams, P. (2016). *War and conflict in Africa*. John Wiley & Sons.

Williams, W. (2019). *Shifting borders: Africa's displacement crisis and its security implications*. Africa Center for Strategic Studies.

Yiew, T.-H., & Lau, E. (2018). Does foreign aid contribute to or impeded economic growth? *Journal of International Studies*, *11*(3).

2 Chapter 2

Vehicular livestock mobility in West Africa: Seasonal traffic flows of cattle, sheep, and goats across Bamako

Vehicular livestock mobility in West Africa: Seasonal traffic flows of cattle, sheep, and goats across Bamako

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Abstract Mali is a major livestock producing country in West Africa. However, in recent years the sector faces multiple challenges like farmer-herder conflicts, overuse of grazing and water resources, and the effects of climate change. At the same time, traditional livestock systems are evolving given increased availability of vehicular transport for regional and international animal trade as well as new opportunities for more specialised urban and periurban production systems. To assess the role of Mali's capital city, Bamako, for livestock consumption and trade, this study examined the scale of livestock movement in the city, comprising influxes, outfluxes and transits. To this end, flows of cattle and small ruminants and animal feed were recorded through road surveys covering three different seasons. The results showed that the role of Bamako as a major trade hub in the distribution of ruminants. Our results also showed that traffic of cattle and sheep were high and extensive, whereas the movements of goats were smaller and more localised. As expected, religious festivals also play a role in livestock traffic. The data and can contribute to understand the scope of policy interventions towards further enhancing the efficiency of the livestock production and distribution sector and enhance food security.

Keywords: Animal mobility, sub-Sahara Africa, truck distribution of livestock, fodder

2.1 *Introduction*

2.1.1 *Livestock production in the Sahel*

The West African Sahel is a semi-arid region located between the Sahara and the humid Savannah region. It is particularly vulnerable to food insecurity. Crop production is severely limited by low soil fertility and aridity, and therefore, pastoralism is a popular feature of the Sahelian agriculture, contributing to food supply and income generation (Waha et al., 2018). The risk of food insecurity is further exacerbated by rapid population growth (SWAC/OECD, 2018). Hence 50 % of sub Saharan Africans currently live in poverty (World Bank, 2018) and prospects are dim for this to change soon. Over millennia, Sahelian pastoralists have coevolved with their environment, migrating at the onset of the rainy season along fixed feeding corridors with their livestock to vast grasslands of the north and returning at its end to the south (Idrissa et al., 2017). Altogether, transhumance and other types of livestock production provide about 20 % of the caloric requirements of the Sahelian population (Frelat et al., 2016), contributes up to 15 % to the Gross Domestic Product (GDP), and provides income to over 40 million Sahelians (de Haan et al., 2016). Additionally, it supplies other African countries, in particular the coastal countries of West Africa (Torres et al., 2017), where a growing urban middle class demands increasingly more livestock products. Apart from its economic and nutritional contribution, livestock is also important for religious and cultural celebrations in the Sahel (van der Lee et al., 2014). To facilitate long-distance trade, livestock trade points have been established to facilitate livestock flows within the Sahel and across West Africa (Cook, 2015).

2.1.2 *Livestock production in Mali*

Mali is a major exporter of livestock throughout the Sahel region (T. O. Williams et al., 2006) and livestock trade contributes about 19 % to the country's GDP (Wane et al., 2016). However, for the last decade, livestock production and trade have been threatened by violent conflicts (Boeke & Tisseron, 2014). In 2012 an uprising involving Tuaregs, jihadists, and the government forces of Mali led to a political coup, which triggered security intervention within the country and the entire Sahel region (Boeke & Tisseron, 2014). This affected the mobility options of herders and their livestock which will likely remain as such for years to come (Moseley, 2017). There have also been simmering tensions and sporadic attacks between the Fulani livestock herders and the Bambara and Dogon crop farmers over the use of the increasingly scarce land and water resources (O. A. Diallo, 2017). There are arguments that these conflicts over resources have been fuelled by national policies favouring the development of crop farming over pastoralism since the country's independence (Benjaminsen & Ba, 2009) and the weak implementation of collective land use rights for pastoralists in the absence of land titles (Ickowicz et al., 2012).

Currently, livestock trade in Mali mostly consists of live animals that are trekked to cities or large livestock markets, either for local consumption or for further export to coastal countries (Bizimana et al., 2015). However, the limited access to grazing and water sources and the insecurity hindering livestock mobility have contributed to an expansion of vehicular long-distance transportation of live animals. Furthermore, traditional livestock farming systems are undergoing a gradual shift to more intensive sedentary livestock systems and to more specialized to milk or meat (Roessler et al., 2016), partly monetised economic systems (Rauch et al., 2016). Increasingly, such specialised livestock production systems prevail in and around larger cities and heavily rely on animal feed from from rural areas (Roessler et al., 2016). This evolution of traditional livestock production into specialised livestock systems focused on demand of urban areas stimulates livestock trading and as a result, urban centres in Africa are progressively becoming important trade hubs (Yaro, 2008) and play an important role in urban livestock rearing (Crump et al., 2019). For instance, Bamako harbours the largest livestock markets in the country and attracts increasingly large numbers of livestock for urban consumption and trade (Desiere et al., 2018). It is likely that due to the increasing demand for livestock products in urban areas across the region, the scale of livestock movements in cities of the Sahel will increase in terms of numbers as well as distance covered.

Information on the current scale of vehicular livestock movements into West African urban centres remains scarce despite its relevance towards the associated pressure on natural resources and the essential facilities that are needed to accommodate increasing numbers of animals in rapidly growing urban centres. To contribute to filling this research gap, this study examines overall vehicular livestock movements for 1) urban consumption, 2) redistribution, and 3) transits in Bamako during three different seasons. A focus was placed on the quantitative assessment of livestock flows entering, leaving, and passing through the city with an assessment of their respective origin and destination. We also assessed the origin of incoming animal feed.

2.1.3 *Site description*

Mali is one of the hottest countries in the world, with northern Mali considered a hot desert climate according to the Koeppen classification (Beck et al., 2018).Thus, northern Malian cities like Kidal, Gao and Timbuktu are hottest during the dry season and receive the least rainfall during the rainy season, whilst rainfall increases southwards in cities like Mopti, Ségou, and Bamako. The latter has a tropical savannah climate and with a mean maximum temperature of 35°C, a mean minimum temperature of 21°C, and an annual rainfall of 991 mm (World Meteorological Organization, 2019). Bamako is an African city with one of the fastest growth rates (CIA, 2020) and it currently harbours about 3 million people within its six communes (United Nations, 2019).

Due to its geographical location and its national relevance as Mali's capital, Bamako also serves as a central transportation hub for neigbouring landlocked Sahelian countries that rely on road infrastructure for the import and export of goods. This was why we chose this city as a suitable study site to gather data on vehicular livestock mobility and to analyse influxes, outfluxes, and transits within the region.

2.2 *Methods*

2.2.1 *Data collection: Primary data on flows of livestock and animal feed*

For data collection we considered the movement of cattle, sheep, and goats as well as the flows of animal feed into the city. Information was recorded on all major and minor access roads to the city of Bamako (Figure 1). Given the strong seasonality of livestock movements and animal feed transports, the surveys were carried out in three different seasons representing the hot season, the rainy season, and the harvest season.

Mali's hot season stretches from March to June, and is characterised by high temperatures (seasonal average high temperature 37°C) and negligible precipitation with 0 % chance of rainfall (Weather Spark, 2020) , making it a critical period for food security due to its associated water scarcity which severely restricts crop and animal production. The rainy season begins in June/July and lasts until October/November with an average daily high temperature of 32°C and about 26 cm of rainfall (Weather Spark, 2020). This period is suitable for the cultivation of crops for food and is characterised by the availability of grazing areas and adequate water supply for livestock. Finally, the harvest season which lasts from November to around January when the rains slowly decline then stop before the dry season commences, is characterised by widespread food availability for humans and of southern pasture and crop residues for livestock.

During data collection, incoming and outgoing livestock and feed flows were captured for seven days in a row for 24 hours (day/night on major roads) and 12 hours (daytime only on minor roads) per day in each season. Enumerators were trained to take records using a standardised survey form, including date/time, vehicle type and identification number as well as specific information on type and quantity of incoming and outgoing cattle, sheep and goats, type of incoming animal feed, geographical source and destination of livestock and animal feed. For the latter, highly processed animal feed such as concentrates, and salt licks were excluded. Livestock numbers were estimated based on the information provided by drivers and from the enumerator's visual inspection (18). Due to the size variability of units (transported mainly in bundles) used in animal feed collection, it was not possible to estimate the quantity in terms weight of animal feed flows and for this reason a measure of frequency was used. (Figure 1, p.18)

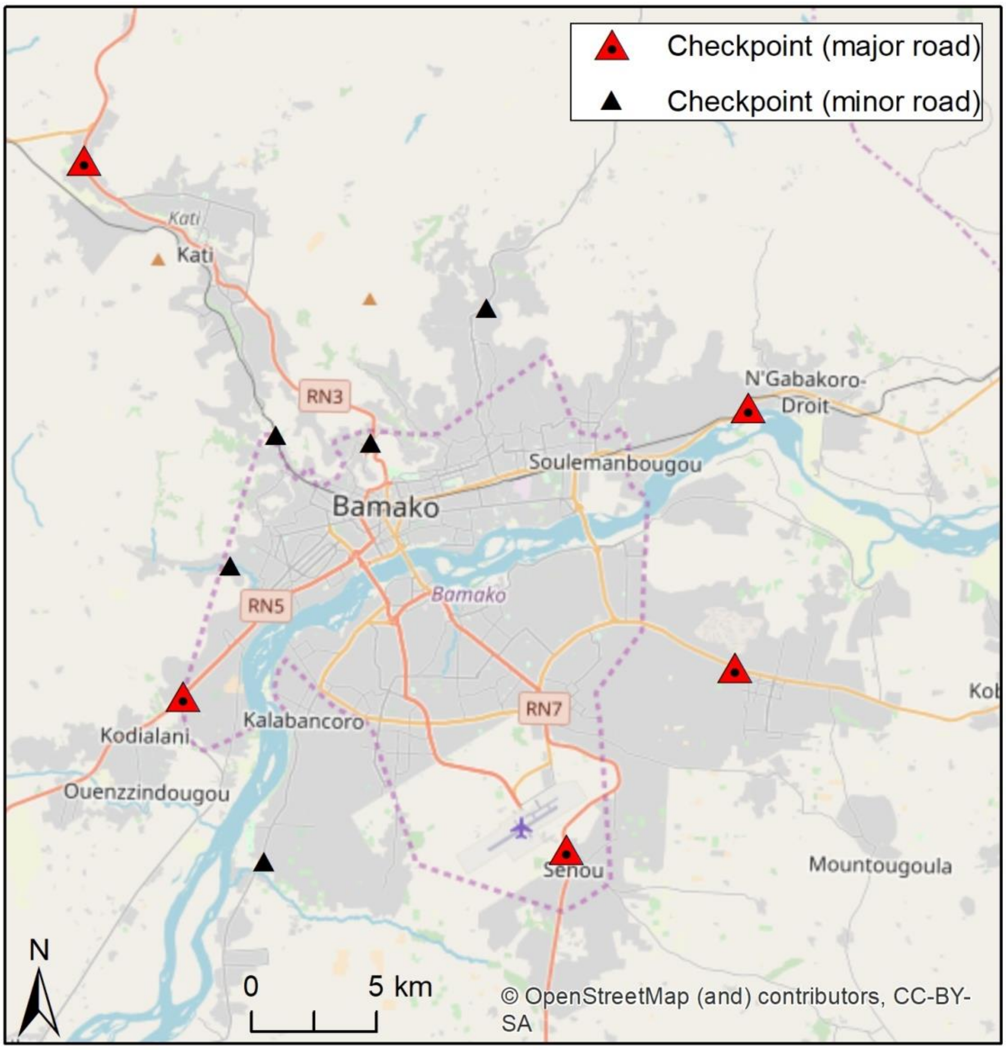

Figure 1: Data collection points on major and minor access roads leading to the city of Bamako, Mali. Note: Due to the diversion of the road leading from Kati to Bamako, data were collected at two other check points. Duplicates were removed before analysis.

Two enumerators were responsible for each road with one on either side of the road. The point of data collection was at an official checkpoint on each of the major roads and three of the minor roads; in the case of the remaining minor road the data collection was a strategically located point where vehicles would stop or slow down. At the official check points of the police, the gendarmerie, the water and forestry commission, the phytosanitary commission and the veterinary service, vehicles have to stop for document inspection

Table 1: Transportation mode, livestock type and its capacity

Transportation mode	**Livestock**	**Capacity**
Articulated truck	Cattle	40
Truck	Cattle	20
Pick-up truck	Cattle	1
Taxi	Cattle	1
Tricycle van	Cattle	1
Articulated truck	Sheep	200
Truck	Sheep/Goat	150
Pick-up truck	Sheep/Goat	10
Commercial bus	Sheep/Goat	50
Commercial bus (roof)	Sheep/Goat	15
Tricycle van	Sheep/Goat	10

or payment of fees. This short stop offered enumerators the possibility to enquire information from the drivers about their cargo. We considered bicycles, tricycles, motorbikes, private and commercial cars including trucks, tractors, (mini-)buses and articulated trucks as modes of transportation. Surveys were conducted in the harvest season from 16 – 22.11.2015, hot season from 02 - 09.05.2016 and rainy season from 25 - 31.08.2017.

2.2.2 *Data processing and analysis*

Data were entered into a PostgreSQL database, thereby linking geographical sources and destinations to georeferenced locations. When the precise number of animals was not recorded, processing included assigning a specific livestock count to each of the transportation units used based on field research and expert knowledge. After cleaning and processing the data, records were grouped into

1. Incoming flows (livestock and animal feed coming from outside the city into the city),
2. Outgoing flows (livestock moving from within the city for a destination outside the city), and
3. Transiting flows (livestock coming from outside the city, passing through the city for a destination outside the city).

Livestock flows for each season and for each livestock were calculated to determine the scale of livestock movement. The spatial analysis used the season-and livestock-specific records with georeferenced information on source and destination. First, the main geographical source areas per season were plotted for each livestock type. Second, the incoming, outgoing, and transiting livestock flows were displayed on a map with the line thickness linking source and destination proportional to the livestock numbers. Sources of animal feed were also plotted on a map. For these sources, we considered the number of records (counts) rather than overall quantities due to the aforementioned reasons.

Urban consumption was estimated as the difference of incoming livestock and outgoing livestock flows. Volumes of outgoing livestock flows indicated livestock trade between Bamako and other destinations, and thus, the city's role as a trade hub.

2.2.3 *Limitations of the study*

The study relied on information provided by the driver or his assistant. When they were reluctant to give information or when vehicles did not stop, we were unable to obtain information about their destination or source location. In these cases, the number of livestock or cargo space was estimated. Across the seasons, 27 %, 42 %, and 34 % of the recorded cattle, goats, and sheep transports, respectively, did not yield information on geographical source and destination and could therefore not be used in the spatial analysis. Additionally, we only recorded livestock movements on the road, and would have missed livestock that was trekked and thereby bypassing the road. Uncertainties regarding the local consumption of livestock arise where livestock entered Bamako for later export, or where influxes occurred before our rather short period of survey.

2.3 *Results and discussion*

2.3.1 *Scale, seasonality, and sources of livestock flows*

Throughout the three seasons, we recorded as a daily average 873 ± 131 cattle, 6,019 ± 1633 sheep and 210 ± 44 goats on Bamako's roads including those records without location data. Of all recorded livestock, vehicle transported livestock was 98 % and trekked livestock was 2 %. Most cattle recorded on the roads were transported in trucks (91 %), and only 9 % were conveyed in other transportation vehicles like tricycle vans. Sheep were also mainly transported on trucks (57 %), followed by public minibus tops (22 %), and bus tops (8 %). Goats were mainly transported by minibuses (56 %), one third transported in trucks, and the remainder by motorbikes.

For all livestock types, the number of incoming animals exceeded the number of outgoing animals by far, underlining Bamako's role as an urban consumption hub (Figures 2a-c, p.22). The difference is particularly marked in the movement of cattle, with the incoming numbers exceeding the outgoing by up to 24 times throughout the rainy season. For the hot and harvest season, they exceeded by 14 and 19 times, respectively (Figure 2a, p.22). For sheep, we recorded 7 to 11 times more incoming than outgoing numbers (Figure 2b, p.22), and 2 to 6 times more goats were entering than leaving the city (Figure 2c, p.22).

Sheep influxes were highest, with about 8,000 animals entering the city daily in the rainy season, 1,000 animals in the hot season, and 800 in the harvest season (Figure 2b, p.22). It is important to note that the actual numbers are higher, considering that 15-37 % of the records do not contain data on geographical source and destination. The higher sheep influxes during the rainy season were clearly linked to the rainy season's coincidence with the Eid al Adha celebration. This religious festivity typically requires the slaughtering and eating of livestock, typically a ram, by each Muslim household. Slaughtering of sheep and the consumption of mutton during religious and cultural festivals like Eid al Adha, baptisms, and weddings increase meat consumption (Nicolas et al., 2018), meat price and livestock price, making them lucrative for traders (Gerber et al., 2010). Like incoming sheep, the highest number of outgoing and transiting sheep was recorded during the rainy season when more than 800 sheep left the city per day, compared to about 100 sheep in the hot and harvest season. Likewise, more than 900 sheep per day were on transit in the rainy season versus 140 in the hot and 130 in the harvest season.

In the rainy season, we also recorded higher daily numbers of incoming cattle than in the other two seasons (Figure 2a, p.22). Accordingly, the cattle numbers entering the city during this season amounted to 770 animals per day, compared to 380 and 260 cattle in the hot and harvest season, respectively. Again, 3-33 % of all records do not contain spatial information, which is why actual cattle numbers are higher. Williams 2006 and Provost 2016 confirmed higher livestock numbers and market prices for livestock during the rainy season. Apart from religious festivals that stimulate livestock trade, the increased trade of cattle may also be related to the commencement of the academic year in September, when the need to pay school fees is an important factor for the sale of livestock by traders and herders in Africa (Maass et al., 2012). As already indicated, the proportion of outbound cattle was small in comparison with those incoming, and so were the absolute numbers, even when including those records without spatial information: only 13-32 cattle left the city daily, with the highest number in the rainy season.

The daily number of cattle passing through the city was highest in the hot season ($>$ 200 cattle) and lowest in the rainy season (86 cattle).

Compared to cattle and sheep, the movement of goats played a minor role, with only slightly over 100 animals entering the city per day across the seasons (17-52 % without spatial information). Possibly, goats are rather produced in private homes for consumption than imported from distant areas. The number of goats leaving the city for other destinations was similar to the number of outgoing cattle. Similar to cattle, the number of goats passing through the city was highest in the hot season and lowest in the rainy season (Figure 2, p.22).

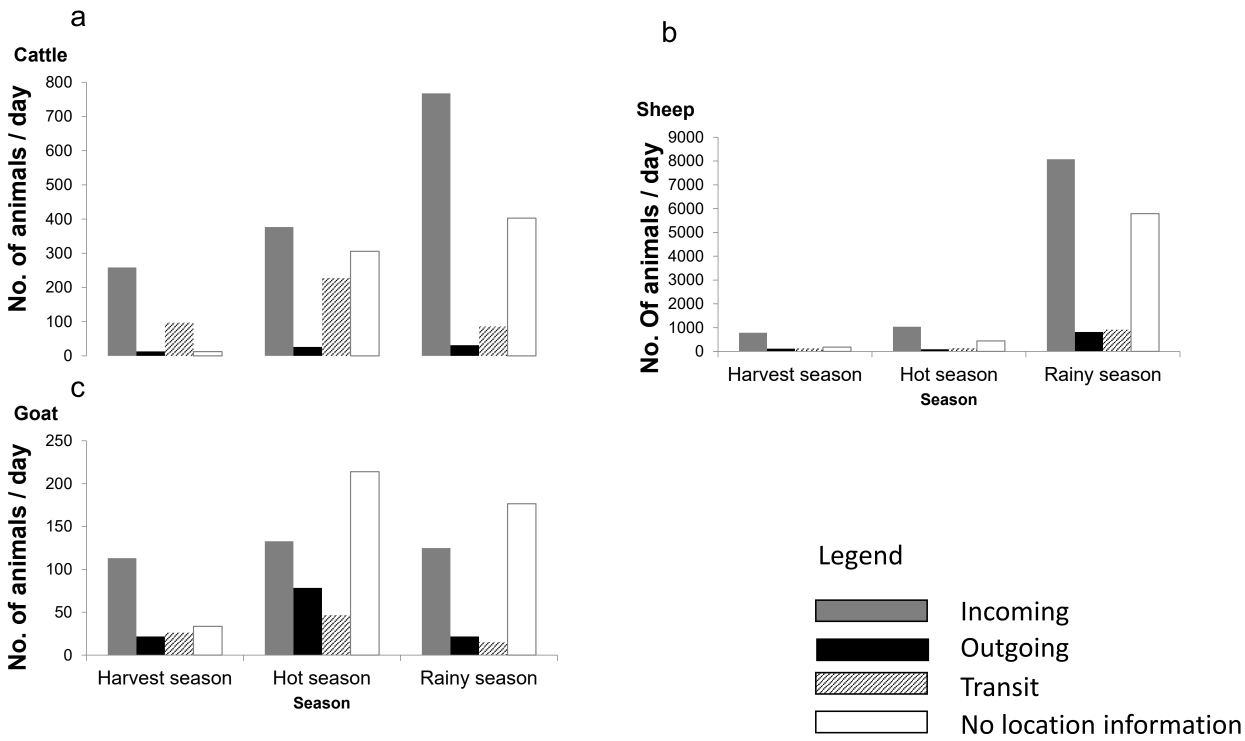

Figure 2: Daily incoming, outgoing, and transit numbers of cattle, sheep, and goat during different seasons from 2015 - 2017 in Bamako, Mali.

2.3.2 *Direction of livestock flows*

2.3.2.1 *Incoming livestock flows*

The main geographical sources for cattle entering Bamako throughout the three seasons were Ségou (21 %) and Mopti (16 %) as well as the city's surroundings within 50 km (6 %) (Figures 3 and 4). The southern part of the country around Sikasso was an additional source of cattle (3 %) which was particularly evident in the rainy season (Figure 3, p.24). Sheep were mainly from Bamako's northern surroundings up the Mauritanian border (23 %), whereas Mopti (9 %) and Ségou (4 %) were less important sources for sheep entering Bamako (Figures 3 and 4). Mauritania is an important livestock producing country in West Africa and between 2015 and 2017, a cumulative total of 81 million livestock were produced by Mali and Mauritania together with the latter contributing 40 % of the total headcount (FAOSTAT, 2019).

Irrespective of the season, goats did not cover large distances but came mainly from Bamako's surroundings (25 %) and Ségou (13 %). A plausible explanation for this could be the browsing nature of goats compared to the grazing nature of sheep (Isaakidou et al., 2019) and the suitability of rearing goats close to the homestead. This would also explain the fewer number of goats recorded on the road as compared with sheep, despite the goat population in Mali for 2017 being 24 million, that is about 28 % more than the population of sheep for that year (FAOSTAT, 2019).

The importance of Ségou, Mopti, and to a lesser extent Sikasso for livestock trade can be explained by their high number of livestock markets, allowing livestock aggregation and movement (Bizimana et al., 2015). Ségou's dominance is furthermore due to its proximity and the major road connection to Bamako, making it a reliable trade corridor. Also, the city is located in a region of Mali with large irrigation schemes making crop residues a readily available feed resource for livestock in an otherwise semi-arid region (Gautier et al., 2016). Mopti is a dominant source of cattle because of its large grazing areas which also make it a popular route for transhumance (Brottem, 2016). The large grazing areas are promoted by the hydrology of Mopti, with the presence of the Niger and the Bani rivers as well as the many connecting lakes which provide drinking water to the livestock herds during the dry season (Dayamba et al., 2018). Aside the large grazing areas, Mopti also possesses the highest number of livestock markets (113) in the country (Bizimana et al., 2015), which attract 28 % of marketed breeding cattle in Mali (DNPIA, 2016). Sikasso also is an important livestock source although not as prominent as Mopti and Ségou. It falls within a tropical wet climate according to Koeppen climate classification (Beck et al., 2018) which explains the popularity of cash crop cotton (*Gossypium hirsutum L.*) cultivation in Sikasso as an agricultural venture (Cooper & West, 2017) over livestock farming.

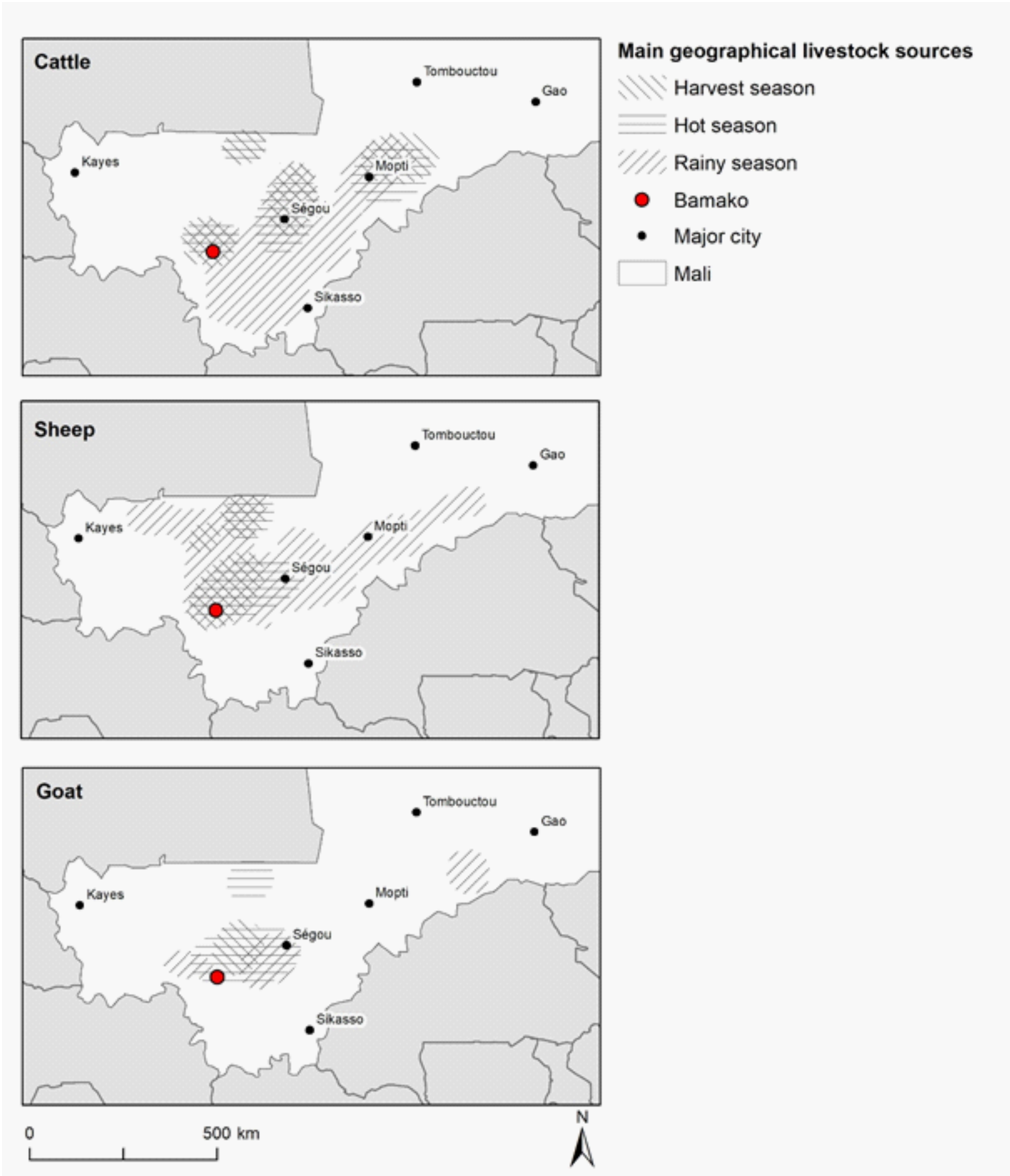

Figure 3: Geographical sources of livestock recorded in Bamako (Mali) during the hot, rainy, and harvest season of 2015 - 2017.

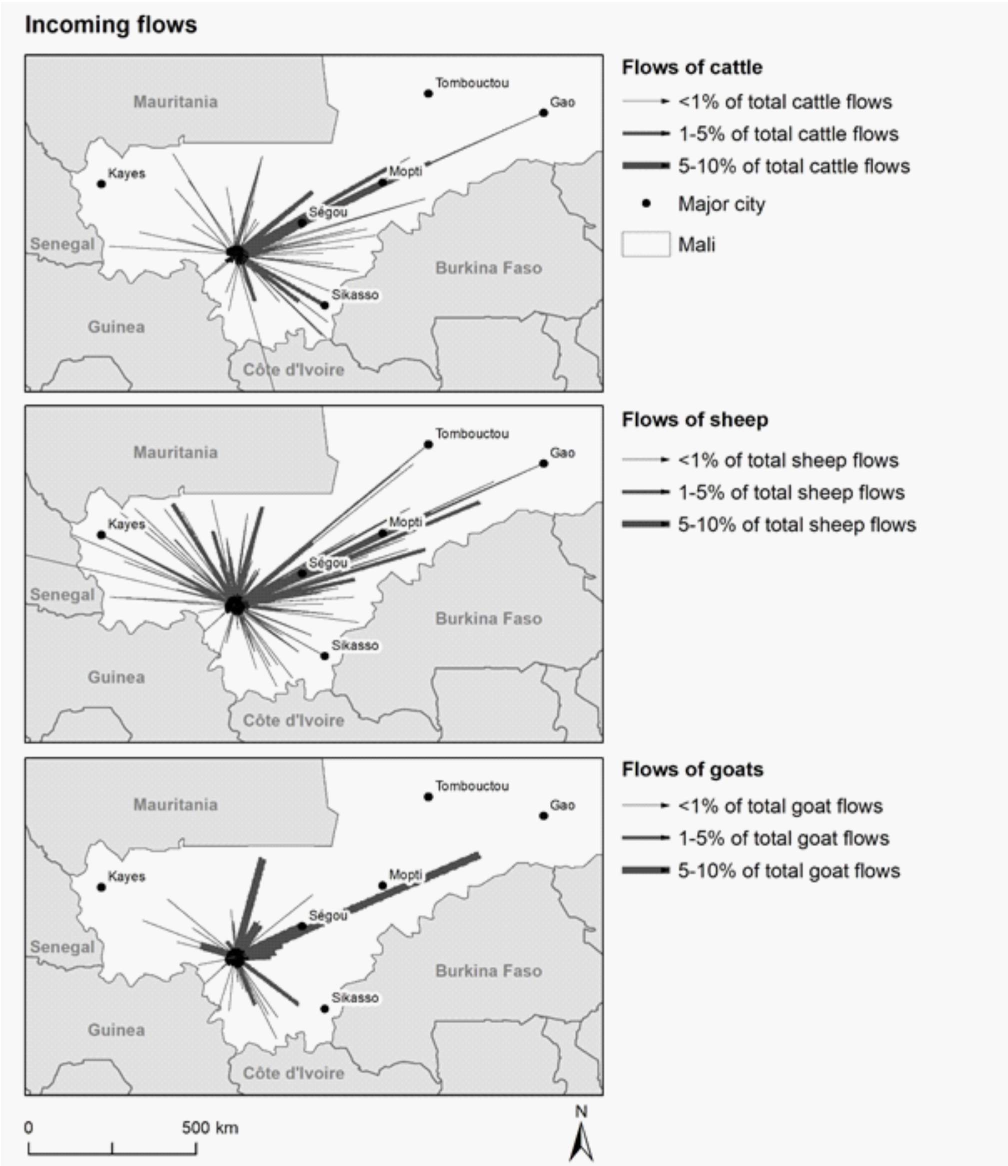

Figure 4: Map of incoming livestock flows into Bamako (Mali) for cattle, sheep and goat in the hot, rainy, and harvest season of 2015 - 2017. Line thickness is proportional to livestock volume linking sources and destinations.

2.3.2.2 *Outgoing livestock flows*

Cattle were leaving Bamako towards neighbouring Senegal (39 % of outgoing flows) and to Kourémale (19 %), one of the three livestock border markets to Guinea (Dione et al., 2017). A large proportion of outbound sheep (39 %) and goats (19 %) were directly exported to Guinea (Figure 5, p.24).

Senegal and Guinea are major importers of livestock from Mali (Figure 5, p.24). A plausible reason for this is the dominance of Islam in both countries. As already mentioned, Islamic festivals have a strong push on livestock demand in West Africa (Apolloni et al., 2018). Notwithstanding, Guinea is also transit for livestock supply to Sierra Leone and Liberia (CILSS, 2010) contributing to the large outflows from Mali. Also, Guinea's national production of livestock especially cattle is plagued by parasitic disease and Africa's highest incidence of trypanosomiasis (Kagbadouno et al., 2012).

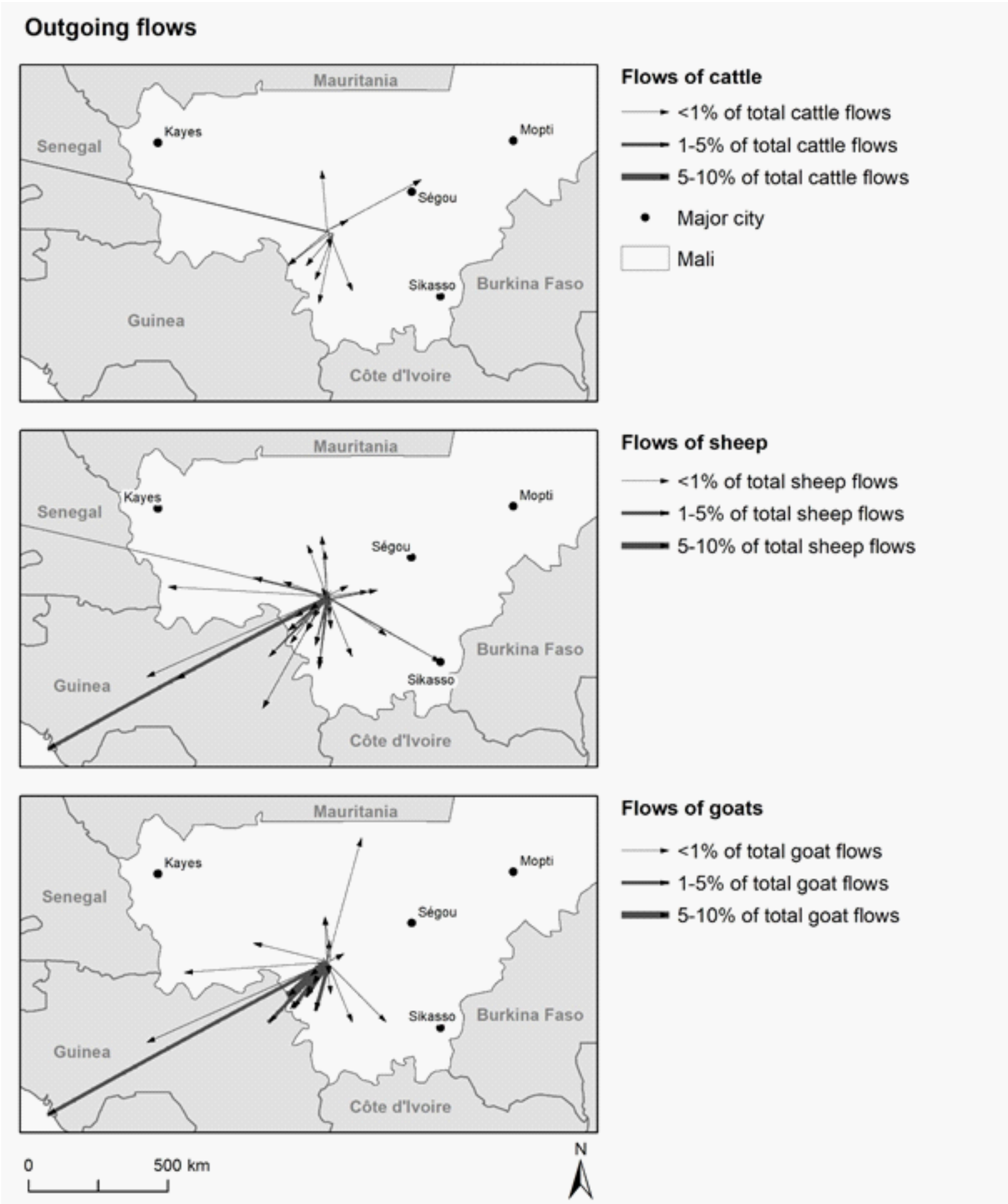

Figure 5: Map of outgoing livestock flows from Bamako (Mali) for cattle, sheep and goat in the hot, rainy, and harvest season of 2015 - 2017. Line thickness is proportional to livestock volume linking sources and destinations.

2.3.2.3 *Transits*

A hub like Bamako can be an important node in a distribution network and thus reduce costs of transportation and time for transportation (and thus livestock mortality) until destination (Elhedhli & Hu, 2005). Thus, examining livestock transits in Bamako can help to understand Bamako's capacity in routing transported livestock and livestock feed.

Transits were particularly relevant for cattle, with up to 19 % of the total cattle flows being transits (excluding flows without spatial information). Most cattle transits in Bamako were sourced from Kati Dral (43 %), 25 km from Bamako's city centre, and transported mainly to Kourémale (58 %) and to Senegal (11 %; (Figure 6, p.26). Kati Dral, a dominant livestock market, serves mainly for export and assembles cattle from other markets in the country, such as the Nioro market in the north west of the country (F. Diallo et al., 2014).

The vehicular mobility of livestock into neighbouring countries of Bamako has been facilitated by the improvement of some road infrastructure. For example, livestock distribution to Senegal has benefited from the Dakar-Bamako road and the other roads that connect to many major livestock sources within Bamako (Bizimana et al., 2015). Due to the improvement of these roads, 31 % of Mali's cattle for export, representing the highest national cattle export proportion, pass through Bamako to Senegal (DNPIA, 2016).

The proportion sheep flows excluding records without spatial information was 9-12 % and occurred both at a very small (city regional) scale (<5 %) and across West Africa (39 % to Guinea; (Figure 6, p.26). Goats accounting for 9-18 % of all flows with spatial information, moved mainly inside the national boundaries (Figure 6, p.26). Transits for the small ruminants from our survey were not of significance as it was for cattle. One plausible reason for the lower significance of transits for small livestock could be that cattle due to their larger size in comparison with sheep and goats makes them more vulnerable to heat stress (Hetem et al., 2016) especially under Mali's hot temperatures coupled with water stress. Additionally, a unit of cattle is more valuable economically than a unit of small ruminant and cattle are therefore more prized money investment as a store of wealth (Nevondo et al., 2019) in comparison to small ruminants. Another reason may be that cattle are particularly susceptible to trypanosomiasis in the more humid areas in coastal countries, therefore making keeping of cattle more difficult than of small ruminants. Hence more cattle than sheep and goats are imported in coastal countries. Lastly, small ruminants may be more easily produced on a small-scale by people, hence its lower importance for transits.

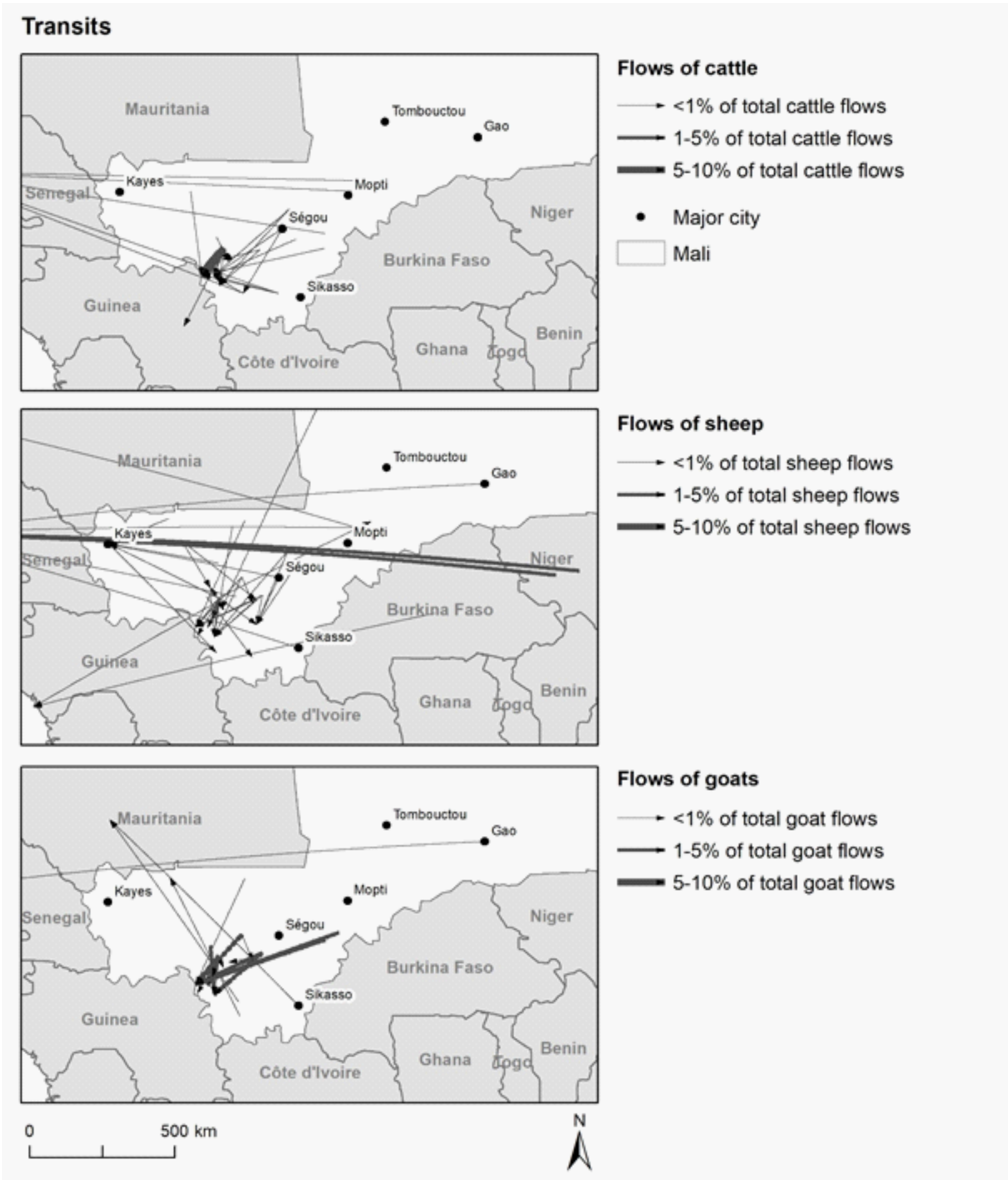

Figure 6: Map of transiting livestock flows through Bamako for cattle, sheep and goat. Line thickness is proportional to livestock volume linking sources and destinations. Data were collected in the hot, rainy, and harvest season of 2015 - 2017.

2.3.2.4 *Incoming feed flows*

In our study, we captured about 500 daily records of animal feed in the rainy season, about 200 in the harvest season, and about 124 in the hot season. Although there were a few About 43 % of the recorded animal feed flows were transported by motorbikes, followed by minibuses (15 %), motorised tricycles (14 %), hand trucks (13 %), bicycles (5 %; Figure 7a, p.27), private vehicles (4 %), pedestrians (3 %) articulated trucks and other vehicles (2 %) donkey and horse cart (1 %), indicating the small scale of the business. Also, feedstuffs are mostly transported over short distances, hence no large vehicles are required. The transported animal feed into Bamako can be found heaped or in bags by the roadside for sale (Figure 7b, p.27). Our data showed that 70 % of the feed sources were sourced from within a 25 km radius from the city centre of Bamako (Figure 8, p.28). The major areas were southwards of Bamako along the Niger river, namely Farada, Samaya, and Tourela. These areas encompass the flooded plains along the Niger river which have better access to water and are therefore favourable for crop farming and pasture (Kassambara et al., 2018) in comparison with the northern downstream section of the Niger river which is narrower, rockier and drier with less possibility for crop farming and lower availability of pasture (Ogilvie et al., 2010). The general populations of cattle, sheep, and goats in Bamako are estimated to be 35,000, 58,000 and 36,000 respectively (DNPIA, 2016). With an annual feed intake of 371 kg dry matter per animal for cattle and an annual feed intake of 366 kg dry matter per animal for sheep and goats (Schlecht et al., 2019), it can be assumed that about 47,389 tons of feed are required annually for ruminant livestock.

Currently, Bamako loses surrounding grassland at a depletion rate of about 2.6 % per year while the urban area of Bamako is expanding at an annual rate of 5.4 % (Hou et al., 2016). There has been considerable urban expansion of Bamako towards the Kabala axis, which is also one of the biggest zones for fodder sources (Figure 6, p.26). In addition, the transport of feeds into the city will lead to nutrient depletion of the feed-supplying rural hinterlands if nutrients are not returned in the form of livestock manure to the feed supplying rural hinterlands (Schlecht et al., 2019).

Figure 7: Animal feed transported by a motorised tricycle and a motorcycle in Bamako, Mali. Animal feed heap for sale by the side of the road in Bamako.

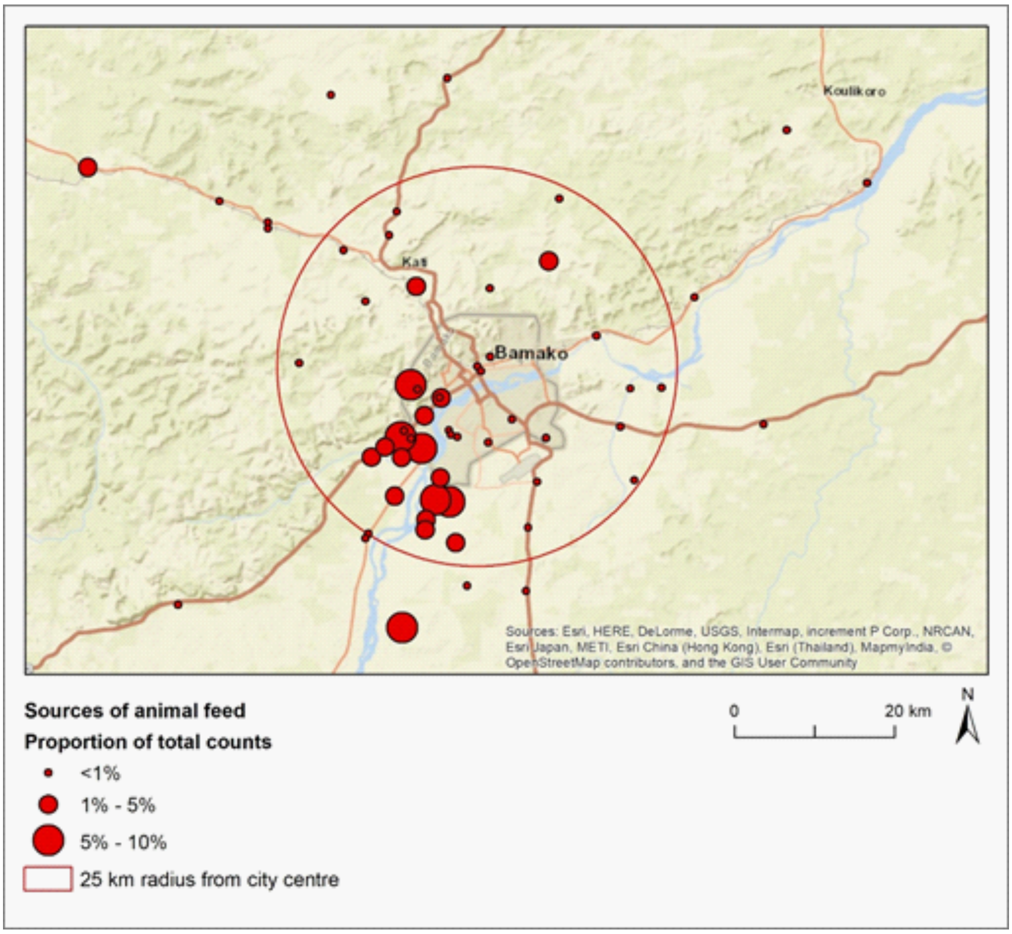

Figure 8: Locations of important sources of animal feed in Bamako. Red bubbles represent locations and their diameter proportional to the total feed count. Data were collected in the hot, rainy, and harvest season of 2015 - 2017.

2.4 *Conclusions*

Bamako drives the flow of livestock from diverse national sources to the city for local consumption and trade. Our study showed that livestock inflows exceeded the outflows by far for cattle, and to a smaller extent for small ruminants, underlining the city's role as a consumption centre. For cattle, the city of Bamako acts as a transit hub, attracting animals from the major cattle markets nationwide, and exporting large numbers to Senegal and Guinea. Sheep, on the other hand, are rather kept in urban livestock markets before being exported. The flows of goats are small scale, both in terms of quantity and distance covered, possibly due to the spatial concentration of production and consumption within Bamako and its periphery. Our study revealed the importance of religious festivals for livestock trade, reflected in the substantially higher influx of sheep compared to other seasons.

2.5 *Implications*

Considering current Bamako's population of about 3 million and a projected national population increase of 35 % by 2030 (United Nations, 2019), the city will have to keep expanding to absorb its growing urban population (Hou et al., 2016). Urban population growth will increase the demand for food and in particular livestock products (Delgado et al., 2001), given that the per capita meat consumption of dwellers in these urban areas is increasing, especially among the growing middle class in Sub-Sahara Africa (Desiere et al., 2018). This growing meat consumption in Mali reached an annual per capita consumption of 18.6 kg/capita in 2013 (FAOSTAT, 2019) which was three times as high as the per capita consumption in other parts of West Africa. However, it was still far below North America's 36.1 kg/capita for that same year (FAOSTAT, 2019). Considering that national meat consumption will continue to increase given the higher purchasing power of the middle class, Mali will have to continue intensifying its livestock industry.

Increased livestock demand also provides an economic opportunity for actors along the livestock supply chain; however, livestock infrastructure like marketing, processing, slaughtering, and veterinary services infrastructure in Bamako are inadequate (Kamuanga et al., 2008). This is partly because organization of livestock institutions has been difficult in Mali, and modern livestock infrastructure like abattoirs and milk dairies require uninterrupted electricity supply for efficient operation. Unfortunately, electricity provision in Mali is insufficient and unreliable, supplying currently <20 % of the population (Briceño-Garmendia et al., 2011).

During the past decades, donor interest in the livestock industry has been low despite its potential to reduce poverty in Mali and West Africa (Steinfeld et al., 2013). A more productive future may require increasing private investments in the sector (Steinfeld et al., 2013), including for the efficient and reliable post-processing of livestock products.

Mali's road transport of livestock is also affected by the country's poor road infrastructure and political instability. The increased number of road checkpoints in response to the threat of terrorism in Mali slows down livestock transportation, meaning that livestock will spend longer time on the road, which may affect animal welfare, animal death and finally the price of livestock. Taking into consideration that only 16 % of rural areas have access to roads (Gwilliam et al., 2019), it is obvious that this situation bottlenecks vehicular livestock transportation. Herders will have to trek their animals to the next livestock "assembly" market from where livestock can be further transported on the road. The poor road network may also affect important livestock sources in the northern areas of Mopti, Timbuktu, and Gao, which means that herders will have to trek their livestock if they want to get to Bamako for better prices (Bizimana et al., 2015). This trekking also implies that livestock herders will have more contact with farmers along the grazing corridor to Bamako which may trigger conflicts between herders and farmers (Turner et al., 2014).

Acknowledgements
This work was carried out as part of the Urban Food Plus Project, jointly funded by the German Federal Ministry of Education and Research (BMBF) and the German Federal Ministry for Economic Cooperation and Development (BMZ) under the initiative GlobE – Research for the Global Food Supply, grant number 031A242-A. Our special thanks go to Dr. Hamidou Nantoumé, Directeur Scientifique de l'Institut d'Economie Rurale (IER), Sotuba, Bamako, Mali for supporting this study.

Table 2: Livestock flows (in numbers per day) in Bamako (Mali) in the hot, rainy, and harvest season of 2015 - 2017.

		Number			**%**		
		Hot	**Harvest**	**Rainy**	**Hot**	**Harvest**	**Rainy**
Cattle	Incoming	377	259	768	40	68	60
Cattle	Outgoing	26	13	32	3	3	2
Cattle	Transits	228	97	86	24	25	7
Cattle	No location information	306	13	403	33	3	31
Cattle	**Total**	937	382	1288	100	100	100
Sheep	Incoming	1038	786	8072	61	65	52
Sheep	Outgoing	90	114	816	5	9	5
Sheep	Transits	140	130	918	8	11	6
Sheep	No location information	445	181	5785	26	15	37
Sheep	**Total**	1713	1211	15590	100	100	100
Goat	Incoming	133	113	125	28	58	37
Goat	Outgoing	78	22	22	17	11	6
Goat	Transits	47	26	15	10	13	5
Goat	No location information	214	33	177	45	17	52
Goat	**Total**	472	194	338	100	100	100

2.6 References

References

Beck, H. E., Zimmermann, N. E., McVicar, T. R., Vergopolan, N., Berg, A., & Wood, E. F. (2018). Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Scientific Data*, *5*, 180214. https://doi.org/10.1038/sdata.2018.214

Benjaminsen, T. A., & Ba, B. (2009). Farmer–herder conflicts, pastoral marginalisation and corruption: A case study from the inland Niger delta of Mali. *Geographical Journal*, *175*(1), 71–81.

Bizimana, J.-C., Angerer, J. P., Bessler, D. A., & Keita, F. (2015). Cattle markets integration and price discovery: The case of Mali. *The Journal of Development Studies*, *51*(3), 319–334.

Boeke, S., & Tisseron, A. (2014). Mali's long road ahead. *The Royal United Services Institute*, *159*(5), 32–40.

CIA. (2020). The world factbook. Retrieved, from https://www.cia.gov/library/publications/the-world-factbook/geos/ml.html

CILSS. (2010). Commerce transfrontalier et sécurité alimentaire en Afrique de l´ouest. cas du bassin ouest: Gambie, Guinée-Bissau, Guinée, Mali, Mauritanie, Sénégal. Retrieved, from https://documents.wfp.org/stellent/groups/public/documents/ena/wfp219290.pdf

Cook, R. (2015). Implementation of the trade hub livestock value chain program for the Mali-Cote d'Ivoire export corridor. Retrieved, from https://docplayer.fr/3478865-Trade-hub-and-african-partners-network-implementation-of-the-trade-hub-livestock-value-chain-program-for-the-mali-cote-d-ivoire-export-corridor.html

Cooper, M. W., & West, C. T. (2017). Unraveling the Sikasso paradox: Agricultural change and malnutrition in Sikasso, Mali. *Ecology of Food and Nutrition*, *56*(2), 101–123. https://doi.org/10.1080/03670244.2016.1263947

Crump, L., Mauti, S., Traoré, A., Shaw, A., Hattendorf, J., & Zinsstag, J. (2019). The contribution of livestock to urban resilience: The case of Bamako, Mali. *Tropical Animal Health and Production*, *51*(1), 7–16. https://doi.org/10.1007/s11250-018-1651-2

Dayamba, D. S., Ky-Dembele, C., Bayala, J., Dorward, P., Clarkson, G., Sanogo, D., Diop Mamadou, L., Traoré, I., Diakité, A., Nenkam, A., Binam, J. N., Ouedraogo, M., & Zougmore, R. (2018). Assessment of the use of participatory integrated climate services for agriculture (PICSA) approach by farmers to manage climate risk in Mali and

Senegal. *Climate Services*, *12*, 27–35. https://doi.org/10.1016/j.cliser.2018.07.003

de Haan, C., Robinson, T., Conchedda, G., Ericksen, P., Said, M., Robinson, L., Flintan, F., Shaw, A., Kifugo, S., & Wane, A. (2016). *Livestock production systems: Seizing the opportunities for pastoralists and agro-pastoralists*. https://doi.org/10.1596/978-1-4648-0817-3_ch5

Delgado, C., Rosegrant, M., Steinfeld, H., Ehui, S., & Courbois, C. (2001). Livestock to 2020: The next food revolution. *Outlook on Agriculture*, *30*(1), 27–29. https://doi.org/10.5367/000000001101293427

Diallo, F., Dembélé, M., & Gourichon, H. (2014). Analyse des incitations par les prix pour les bovins au Mali 2005-2012.

Diallo, O. A. (2017). Ethnic clashes, jihad, and insecurity in central Mali. *Peace Review*, *29*(3), 299–306. https://doi.org/10.1080/10402659.2017.1344529

Dione, M. M., Traore, I., Wieland, B., & Fall, A. (2017). *Feed the future Mali livestock technology scaling program (ftf - mltsp) - Participatory assessment of animal health service delivery systems in Mali: Constraints and opportunities*. International Livestock Research Institute. https://core.ac.uk/download/pdf/132691927.pdf

DNPIA. (2016). Direction Nationale Des Productions et des Industries Animales: Rapport Annuel 2015. Retrieved, from http://www.ofarcy.net/elevage-mali/docs/84-RAPPORT_ANNUEL_DNPIA_2015_docx.pdf

Elhedhli, S., & Hu, F. X. (2005). Hub-and-spoke network design with congestion. *Computers and Operations Research*, *32*(6), 1615–1632. https://doi.org/10.1016/j.cor.2003.11.016

FAOSTAT. (2019). http://www.fao.org/faostat/en/#search/Meat%20%2B%20Total accessed: 23.08.2019

Frelat, R., Lopez-Ridaura, S., Giller, K. E., Herrero, M., Douxchamps, S., Djurfeldt, A. A., Erenstein, O., Henderson, B., Kassie, M., & Paul, B. K. (2016). Drivers of household food availability in sub-Saharan Africa based on big data from small farms. *Proceedings of the National Academy of Sciences*, *113*(2), 458–463. https://doi.org/10.1073/pnas.1518384112

Gautier, D., Locatelli, B., Corniaux, C., & Alary, V. (2016). Global changes, livestock and vulnerability: The social construction of markets as an adaptive strategy. *Geographical Journal*, *182*(2), 153–164. https://doi.org/10.1111/geoj.12115

Gerber, P., Mooney, H. A., Dijkman, J., Tarawali, S., & de Haan, C. (2010). *Livestock in a changing landscape, volume 2: Experiences and regional perspectives*. Island Press.

Gwilliam, K., Foster, V., Archondo-Callao, R., Briceño-Garmendia, C., Nogales, A., & Sethi, K. (2019). The burden of maintenance: Roads in sub-Saharan Africa: Background paper, 14. Retrieved, from http://roadsforwater.org/wp-content/uploads/2013/10/the-burden-of-maintenance_roads-in-SSA.pdf

Hetem, R. S., Maloney, S. K., Fuller, A., & Mitchell, D. (2016). Heterothermy in large mammals: Inevitable or implemented? *Biological Reviews*, *91*(1), 187–205. https://doi.org/10.1111/brv.12166

Hou, H., Estoque, R. C., & Murayama, Y. (2016). Spatiotemporal analysis of urban growth in three African capital cities: A grid-cell-based analysis using remote sensing data. *Journal of African Earth Sciences*, *123*, 381–391. https://doi.org/10.1016/j.jafrearsci.2016.08.014

Ickowicz, A., Ancey, V., Corniaux, C., Duteurtre, G., Poccard-Chappuis, R., Touré, I., Vall, E., & Wane, A. (2012). Crop-livestock production systems in the sahel-increasing resilience for adaptation to climate change and preserving food security. In Centre de coopération internationale en recherche agronomique pour le (Ed.), *Building resilience for adaptation to climate change in the agriculture sector* (pp. 261–294). Retrieved, from http://www.fao.org/3/i3084e/i3084e.pdf#page=268. accessed: 20.08.20

Idrissa, S., M Moussa, B., Issiaka, Y., Mahamane, A., JM Karimou, A., & Saadou, M. (2017). Ecological drivers of ecosystem diversity in Sahelian rangeland of Niger. *Journal of Rangeland Science*, *7*(3), 265–288.

Isaakidou, V., Styring, A., Halstead, P., Nitsch, E., Stroud, E., Le Roux, P., Lee-Thorp, J., & Bogaard, A. (2019). From texts to teeth: A multi-isotope study of sheep and goat herding practices in the late bronze age ('Mycenaean') polity of Knossos, Crete. *Journal of Archaeological Science: Reports*, *23*, 36–56. https://doi.org/10.1016/j.jasrep.2018.09.019

Kagbadouno, M. S., Camara, M., Rouamba, J., Rayaisse, J.-B., Traoré, I. S., Camara, O., Onikoyamou, M. F., Courtin, F., Ravel, S., de Meeûs, T., Bucheton, B., Jamonneau, V., & Solano, P. (2012). Epidemiology of sleeping sickness in Boffa (Guinea): Where are the trypanosomes? *PLoS Neglected Tropical Diseases*, *6*(12), e1949. https://doi.org/10.1371/journal.pntd.0001949

Kassambara, B., Ganji, H., & Kajisa, T. (2018). Impact of agricultural water allocation on the ecosystems in the inner Niger river delta. *International Journal*, *14*(42), 164–170. https://doi.org/10.21660/2018.42.7252

Maass, B. L., Musale, D. K., Chiuri, W. L., Gassner, A., & Peters, M. (2012). Challenges and opportunities for smallholder livestock production in post-conflict South Kivu, eastern DR Congo. *Tropical Animal Health and Production*, *44*(6), 1221–1232. https://doi.org/10.1007/s11250-011-0061-5

Moseley, W. G. (2017). The minimalist state and donor landscapes: Livelihood security in Mali during and after the 2012–2013 coup and rebellion. *African Studies Review*, *60*(1), 37–51. https://doi.org/10.1017/asr.2017.11

Nevondo, T. T., Chaminuka, P., Nhundu, K., & Liebenberg, F. (2019). Economic returns from investment in beef cattle improvement research in South Africa. *Agrekon*, *58*(1), 113–124. https://doi.org/10.1080/03031853.2019.1566080

Ogilvie, A., Mahé, G., Ward, J., Serpantié, G., Lemoalle, J., Morand, P., Barbier, B., Tamsir Diop, A., Caron, A., Namarra, R., Kaczan, D., Lukasiewicz, A., Paturel, J.-E., Liénou, G., & Charles Clanet, J. (2010). Water, agriculture and poverty in the niger river basin. *Water International*, *35*(5), 594–622. https://doi.org/10.1080/02508060.2010.515545

Provost, J. (2016). *Market participation of livestock owners in Bamako, Mali* (Master's thesis). Georg-August-University. Göttingen, Faculty of Agricultural Sciences. Retrieved, from https://www.researchgate.net/publication/330448760_Market_Participation_of_Livestock_Owners_in_Bamako_Mali

Rauch, T., Beckmann, G., Neubert, S., & Rettberg, S. (2016). Rural transformation in Sub-Saharan Africa: Conceptual study. https://doi.org/10.18452/18002

Roessler, R., Mpouam, S., Muchemwa, T., & Schlecht, E. (2016). Emerging development pathways of urban livestock production in rapidly growing West Africa cities. *Sustainability*, *8*(11), 1199.

Schlecht, E., Plagemann, J., Mpouam, S. E., Sanon, H. O., Sangaré, M., & Roessler, R. (2019). Input and output of nutrients and energy in urban and peri-urban livestock holdings of Ouagadougou, Burkina Faso. *Nutrient Cycling in Agroecosystems*, *115*(2), 201–230. https://doi.org/10.1007/s10705-019-09996-x

SWAC/OECD. (2018). https://www.africapolis.org accessed: 21.07.2020

Torres, C., van Seters, J., Karaki, K., & Kpadonou, R. (2017). An exploratory analysis of measures to make trade facilitation work for inclusive regional agro-food value chains in West Africa.

United Nations. (2019). *Department of Economic and Social Affairs (DESA), Population Division: World Population Prospects 2019: Data Booklet (ST/ESA/SER.A/424)*. United Nations New York, NY.

van der Lee, J., Schiere, J. B., Bosma, R. H., de Olde, E., Bol, S., & Cornelissen, J. M. (2014). Aid and trade for livestock development and food security in West Africa.

Waha, K., van Wijk, M. T., Fritz, S., See, L., Thornton, P. K., Wichern, J., & Herrero, M. (2018). Agricultural diversification as an important strategy for achieving food security in Africa. *Global Change Biology*, *24*(8), 3390–3400.

Wane, A., Fall, A., & Keïta, F. (2016). Situation analysis of the national livestock market information system (LMIS) for Mali.

Weather Spark. (2020). Average weather in Bamako Mali. Retrieved, from https://weatherspark.com/y/32134/Average-Weather-in-Bamako-Mali-Year-Round

Williams, T. O., Spycher, B., & Okike, I. (2006). *Improving livestock marketing and intra-regional trade in West Africa: Determining appropriate economic incentives and policy framework: ILRI (International Livestock Research Institute), Nairobi, Kenya.*

World Meteorological Organization. (2019). https://worldweather.wmo.int/en/city.html?cityId=129 accessed: 21.07.2020

Yaro, J. A. (2008). Migration in west africa: Patterns, issues and challenges. Retrieved, from https://www.researchgate.net/profile/Joseph_Yaro/publication/242096940_Migration_in_West_Africa_Patterns_Issues_and_Challenges/links/5568a1fb08aefcb861d5c3b4.pdf

3 Chapter 3

Influence of dietary wood charcoal on growth performance, nutrient efficiency and excreta quality of male broiler chickens

This chapter has been published in International Journal of Livestock Production

Influence of dietary wood charcoal on growth performance, nutrient efficiency, and excreta quality of male broiler chickens

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Abstract Dietary wood charcoal can be a potential low-cost feed supplement for the improvement of performance in broiler chicken production, while reducing loss of nutrients through birds' excreta. An experiment was conducted with a total of 28 day-old male broiler chickens which were subjected to commercial broiler finisher diets with 0 %, 1.5 %, 3 %, and 6 % wood charcoal (on a dry matter basis). This was to ascertain the potential of dietary wood charcoal to increase production performance of broiler chickens by improved nutrient utilization and reduction of nutrient losses through birds' excreta under adverse climatic conditions in Northern Ghana. Birds' feed consumption, body weight gain, as well as excreta quality were assessed for four days. Results showed that dietary wood charcoal can replace up to 6 % of a commercial broiler chicken feed without negative effects on growth performance, nutrient utilization, and excreta consistency. Future research should analyze the long-term effect of feeding charcoal on performance and health of laying hens.

Keywords:Broiler chickens, dietary wood charcoal, nutrient utilization, production performance, excreta quality

3.1 *Introduction*

Poultry production is the fastest growing livestock sector in Ghana (FAO, 2005). However, high feed costs increase the overall cost of production for poultry keepers which could negatively affect its economic sustainability (Sumberg et al., 2017). One of the means of reducing feed cost is to increase the efficiency of feed nutrient utilization. However, increase in temperature reduces the efficient utilization of feed required for optimum body weight of birds (de Moura et al., 2015). The reported body weights of broiler chickens in Ghana typically are 2.6-2.7 kg after nine weeks with a feed conversion rate of 3.3-3.6 at the finisher phase (Oppong-Sekyere et al., 2012). Charcoal has been proposed as feed additive to stimulate feed intake and digestion, thereby enhancing growth performance of broiler chickens in Turkey, Cameroon, and Poland (Kana et al., 2011; Khadem et al., 2012; Kutlu et al., 2001; Majewska et al., 2011). In pigs, it has been demonstrated that charcoal reduced faecal gas emissions (Chu et al., 2013), and hence might be an option to reduce negative environmental effects of pig production. Finally, charcoal has a good adsorption capability of toxins and therefore has the potential to improve birds' health (Khadem et al., 2012; Rafiu et al., 2014).

Notwithstanding the potential positive effects, feeding charcoal to poultry might also have negative consequences for animals' health and feeding behaviour, growth performance and nutrient availability in manure. Charcoal has no nutritive value and may cause constipation if fed in excess.Quaranta et al. 2013 demonstrated that the faecal consistency of goats changed from normal to hard when they consumed diets with over 5 % activated charcoal. Similarly, the faecal N content decreased, while its carbon content increased with higher levels of supplemented activated charcoal (Quaranta et al., 2013). There is a lack of research that systematically evaluated the effect of dietary wood charcoal on the accretion and utilization of feed nutrients by broiler chickens, and on the quality of birds' excreta. Therefore, this study evaluated the potential of dietary wood charcoal to (1) improve feed use efficiency of broiler chickens in unfavourable climatic conditions of Northern Ghana without causing constipation and (2) ensure environmental sustainability through reduction of nitrogen (N) and phosphorus (P) losses through excreta by improving nutrient availability and utilization.

3.2 *Material and methods*

An experiment was conducted in March 2016 at the Poultry Unit of the University for Development Studies (UDS) in Tamale, Northern Region, Ghana. The study was closely supervised by a Veterinarian and followed the regulations for Animal experiments of UDS. Ethical clearance was obtained on 14 January 2016 from UDS (code number ANS/FOA/02/14012016).

3.2.1 Experimental birds

Twenty-four healthy male Cobb 500 strain broiler chickens of similar body weight were randomly selected from a flock of 500 mixed sex 28-day old chickens. They were vaccinated against Newcastle disease, bronchitis, and coccidiosis. The chickens were transferred to individual cages with a wire floor (1.6 x 1.4 x 1.6 m^3) in a separate house which allowed for ventilation. Artificial source of light (10 lx) was provided in the pen at night from 18:00 - 7:00 hours to encourage feeding. An adaptation period of 14 days allowed the birds to adjust to the new surroundings and diet. The experimental period with data collection lasted four days beginning when birds were 42 days old.

3.2.2 Dietary treatments

Each experimental bird was randomly assigned to one of four experimental diets, each replicated six times. The dietary treatments were based on a commercial finisher feed with vitamin premix and added phytase. The analysed chemical composition of the commercial broiler feed was 907 g organic matter (OM)/kg, 192 g CP/kg, 397 g carbon (C)/kg and 8 g P/kg, on a dry matter (DM) basis (Table 3, p.38). Wood charcoal was purchased from Tamale market, ground and sieve with 1 mm sieve. The ground charcoal contained 880 g dry matter (DM), 874 g OM/kg DM, 721 g C/kg DM, 43 g CP/kg DM and 1 g P/kg DM (Table 3, p.38). It was thoroughly mixed with the feed, replacing 0 % (T-0 %), 1.5 % (T-1.5 %), 3 % (T-3 %) and 6 % (T-6 %) of of the commercial broiler feed, on a DM basis. All dietary treatments covered 1.2 times the N-corrected metabolisable energy (AMEn) requirements of the experimental birds (National Research Council, 1994). For the wood charcoal, we assumed energy content of 0 kcal. Feed was supplied daily at 07:00 h and clean water was provided *ad libitum*.

Table 3: Analysed chemical composition (g/kg DM) of experimental diets and dietary wood charcoal used fed to male broiler chickens

		Dietary treatments[1]			
Composition	**Wood charcoal**	**T-0%**	**T-1.5%**	**T-3%**	**T-6%**
Dry matter [g DM/kg fresh matter]	880	881	893	899	913
Organic matter	874	907	925	921	922
Crude protein[2]	43	192	203	202	188
Carbon	721	397	437	442	447
Phosphorus	1	8	7	8	7

3.2.3 Growth performance, excreta colour and consistency

Birds were weighed before feeding on day 42 (initial body weight) and day 46 (final body weight) to calculate the total weight gain (g/bird). Daily feed consumption (g/bird) was calculated as the difference of daily feed offered and daily feed leftover from day 42 - 45. Feed leftovers included all remaining feed in the feeders and on the plastic sheets below the cages after 24 hours. The total feed consumption and total weight gain were used to calculate the overall feed conversion rate. Mortality of birds was recorded as it occurred. Birds' excreta were collected daily from the plastic sheets placed under the wire mesh floor of the cages using the total excreta collection method before feeding. For each cage, five fresh dropping samples were assessed for color and consistency daily. Colour assessment was based on a grey scale and value finder (Colour Wheel), with graduation 1 for 100 % black up to 10 for white. The dropping consistency was determined by feeling fresh dropping samples in between the index finger and the thumb wearing latex gloves. It was given a value from 1 - 4, with 1 being very soft (very watery, dropping flows very easily), 2 as soft (watery yet slightly more viscous than consistency 1), 3 as medium (firm yet does not maintain shape very well after it drops, also shape collapses easily when held with little pressure in between thumb and index finger) and 4 as hard (very firm, maintains perfect conical shape after it drops, sticks together when held between thumb and index finger). A composite score was calculated as mean from color and consistency values of each cage.

3.2.4 Nutrient accretion and utilisation

Excreta, feed, and charcoal samples were oven dried (80°C until constant weight), weighed, pooled, and sub-sampled for each cage. For two cages, sub-samples of excreta were missing, resulting in a total of 20 sub-samples (replicates), five for each dietary treatment. Sub-samples of feed, charcoal, and excreta were ground to pass a 1 mm sieve (Cyclotec, FOSS GmbH, Hamburg, Germany) and analysed in duplicate in the laboratory of Universität Kassel in Witzenhausen, Germany. The dry matter (DM) and organic matter (OM) concentrations were determined following the standard procedures of the Association of German Agricultural Analytic and Research Institutes (Verband Deutscher Landwirtschafts und Forschungsanstalten (VDLUFA), 2006). OM was calculated as the difference between DM and crude ash. The vanadate-molybdate-method was used to determine the P content (Hitachi U-2000 photometer, Hitachi Co. Ltd., Tokyo, Japan), and the C and N concentrations were analysed with a C/N-TCD analyser using DUMAS combustion (Elementar Analysensysteme GmbH, Hanau, Germany). The N concentration was multiplied by the factor 6.25 to obtain CP concentrations (AOAC (Association of Official Analytical Chemists), 1990). The values obtained were used to compute accretion and utilization of DM, C, N and P by broiler chickens. Accretion (g/day) was calculated as difference between consumption (g/day) and output in total excreta (g/day), while utilization represented accretion as a percentage of consumption.

3.2.5 Statistical analyses

Data were analysed with R version 3.3.0 (Team, 2013). Data was assessed for conformity to normal distribution using Shapiro-Wilk tests and homogeneity of variances was tested with the Bartlett's test. Residuals of data that were not normally distributed and or data with non-homogeneous variances were analysed using Kruskal Wallis tests. Other data were analysed using a one-way analysis of variance (ANOVA). Differences were considered significant if $p \leq 0.05$. All graphs were created by the software package.

3.3 *Results and discussion*

3.3.1 Effects of dietary wood charcoal on growth performance of male broiler chickens

The initial and final body weight of experimental birds and hence the average daily body weight gain were similar, indicating that feeding wood charcoal had no effect on broiler chicken' growth rate ($P > 0.05$). Similarly, the total feed consumption did not differ across dietary treatments ($P > 0.05$), resulting in comparable feed conversion rates across dietary treatments ($P > 0.05$; Table 4, p.41). Also Kutlu et al. 2001, Kana et al. 2011 and Majewska et al. 2011 showed no improvement of feed efficiency in broiler chickens when charcoal was included in the diet, but recorded an increase in body weight gain with the inclusion of charcoal of up to 0.4 and 0.3 %, respectively. In contrast, Bakr 2008 demonstrated that wood charcoal increased the feed conversion efficiency and other growth performance parameters in broiler chickens if the inclusion rate does not exceed 2 %. However, this effect was age-dependent, limited to birds younger than 29 days, which might explain the missing effect in this study. Finally, Odunsi et al. 2007 observed a negative impact of feeding wood charcoal on growth performance of broilers and did not recommend dietary inclusion of wood charcoal.

Table 4: Growth performance of male broiler chickens fed different substitution levels of charcoal in commercial broiler feed (day 42 - 45)

		Dietary treatments[1] (mean)					Overall			Kruskal Wallis
Parameters	**Unit**	**T-0%**	**T-1.5%**	**T-3%**	**T-6%**	**SEM[3]**	**Median**	**Min.**	**Max.**	**p-value[4]**
Replicates[5]	N	5	6	6	5					
Initial body weight	G	1645	1631	1598	1762	44.4	1611	1396	2096	n.s.
Final body weight	G	1998	1936	1931	2082	56.8	1929	1577	2594	n.s.
Weight gain	g/bird	353	305	333	319	20	321	181	498	n.s.
Feed consumption	g FM[2] /bird	499	537	535	573	22.6	502	385	765	n.s.
Feed conversion rate	g/g	1.5	1.8	1.6	1.9	0.08	1.7	1.2	2.8	n.s.

T-0 %: Commercial broiler feed with 0 % charcoal, **T-1.5** %: Commercial broiler feed with 1.5 % charcoal, **T-3** %: Commercial broiler feed with 3 % charcoal, **T-6** %: Commercial broiler feed with 6 % charcoal, **FM**: Fresh matter, **SEM**: Standard error of the mean, Probability values are indicated as $^{*}P \leq 0.05$, $^{**} \leq 0.01$, $^{***} \leq 0.001$. n.s. not significant $P > 0.05$.

3.3.2 Effects of dietary wood charcoal on nutrient accretion and utilization in male broiler chickens

The addition of dietary wood charcoal to broiler chicken finisher feed did not show any effect on the accretion and utilization of dry matter (DM), carbon (C), nitrogen (N), and phosphorous (P) of the birds ($P > 0.05$; Figure 9, p.42 and Figure 10, p.43). Still, the dry matter, carbon and nitrogen accretion slightly increased with increasing level of dietary wood charcoal in the diet (DM: 69.2 g/day in T-0 %, 86.6 g/day in T-6 %; C: 28.3 g/day in T-0 %, 39.2 g/day in T-6 %; N: 1.2 g/day in T-0 %, 1.9 g/day in T-6 %),while the phosphorus accretion remained constant at 0.25, 0.13, 0.24 and 0.24 g/day in T-0 %, T-1.5 %, T-3 % and T-6 %, respectively (SEM: 0.03 g/day). Accordingly, no effect on the nutrient utilization was observed ($P > 0.05$; Figure 2). The mean utilization of nutrients by broiler chickens fed T-0 %, T-1.5 %, T-3 % and T-6 %, respectively, was 64.7, 62.2, 64.4, and 66.4 %, SEM: 1.24 % (dry matter); 66.7, 65.9, 67.5, and 67.3 %, SEM: 1.10 % (carbon); 35.6, 41.9, 42.7, and 48.3 %, SEM: 2.72 % (nitrogen); and 28.0, 15.0, 27.9, and 27.9 %, SEM: 3.31 % (phosphorus). This is in accordance with a previous study of Oso et al. 2014 who concluded that the inclusion of dietary wood charcoal did not influence the apparent DM and crude protein digestibility of broilers. In the same study, however, the inclusion of charcoal into unpeeled cassava root meals could counterbalance the negative effect of dietary cyanide on the crude protein utilization. Similarly, the crude protein digestibility of broilers fed Aflatoxin infested diets was improved using charcoal as toxin binder Rafiu et al. 2014 (Figure 9, p.42 and Figure 10, p.43).

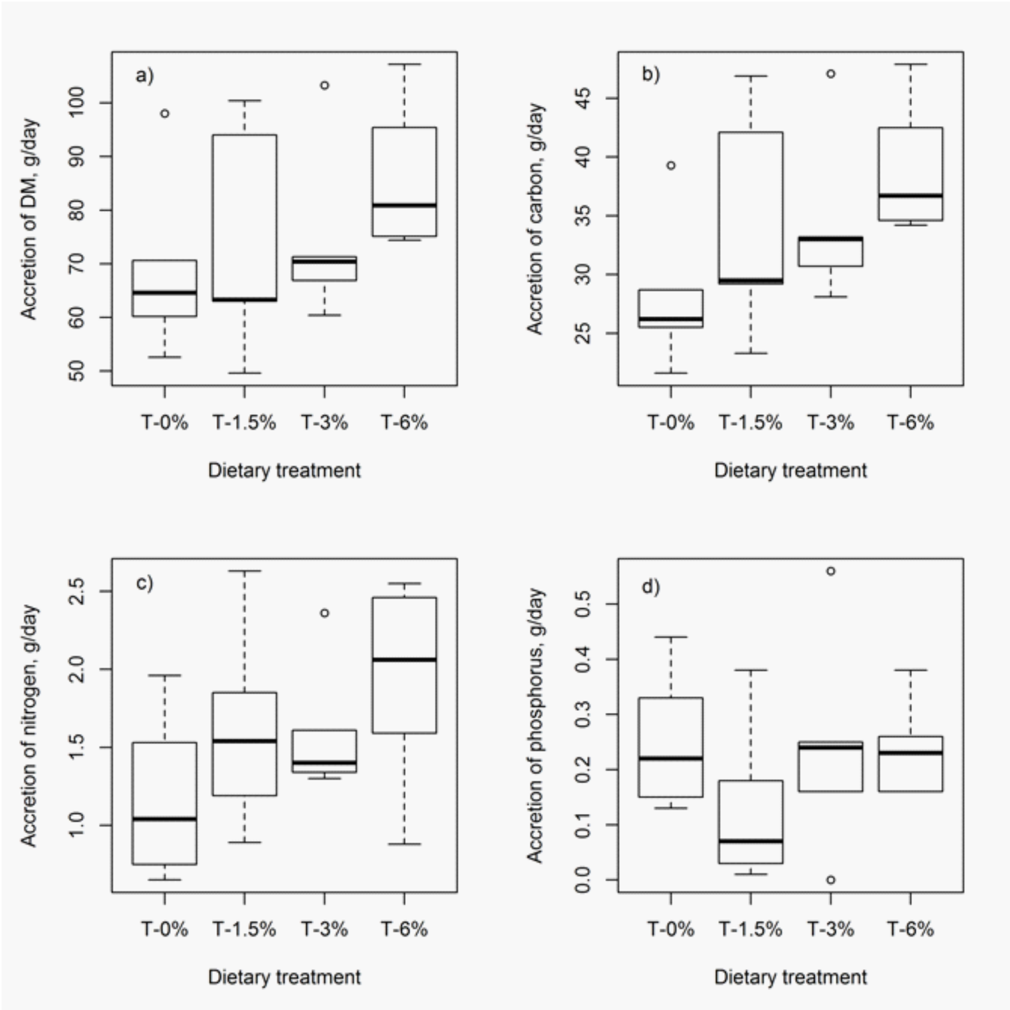

Figure 9: Accretion of a) dry matter b) carbon, c) nitrogen and d) phosphorous (all in g/day; P > 0.05, ANOVA) by broiler chickens fed with different substitution level of charcoal using total excreta collection. T-0 %: Commercial broiler feed with 0 % charcoal, T-1.5 %: Commercial broiler feed with 1.5 % charcoal, T-3 %: Commercial broiler feed with 3 % charcoal, T-6 %: Commercial broiler feed with 6 % charcoal. n = 5 replicates for each dietary treatment.

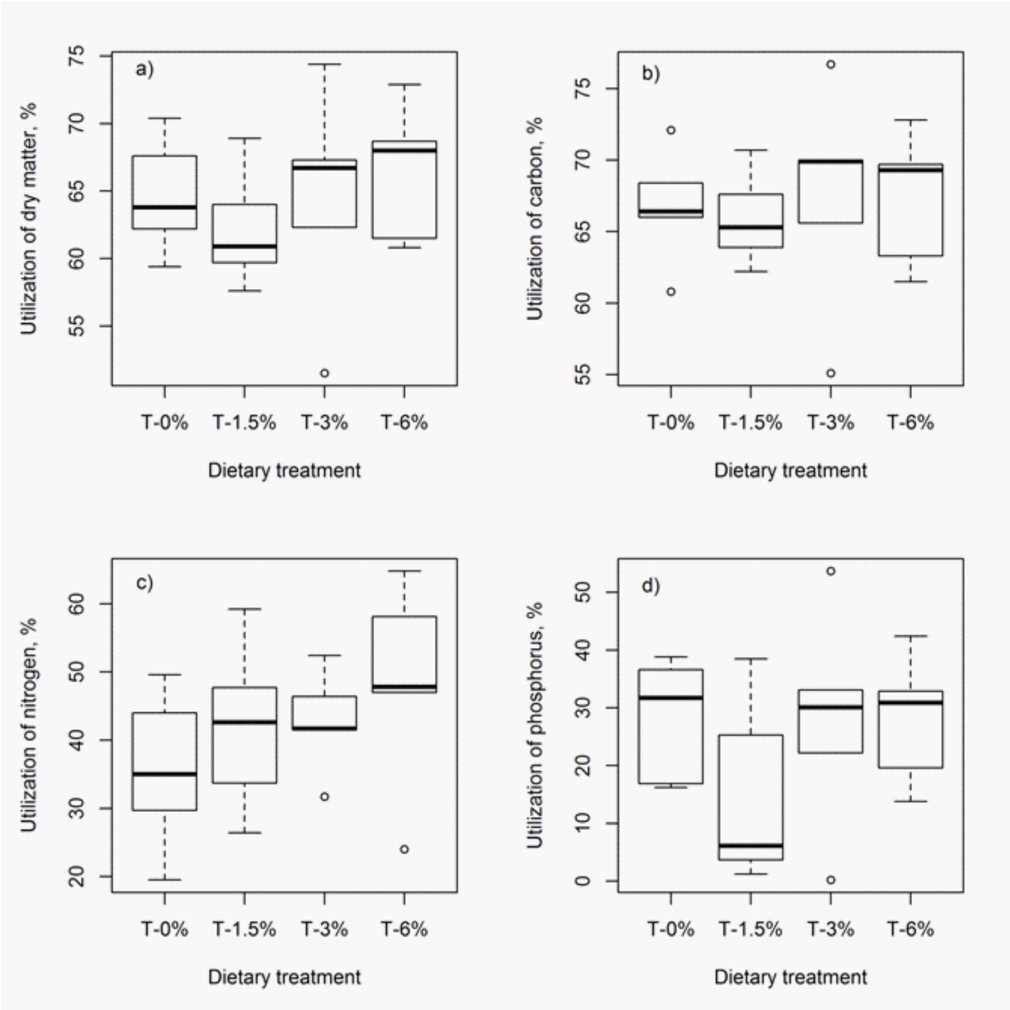

Figure 10: Utilization of a) dry matter b) carbon, c) nitrogen and d) phosphorous (all in %; P > 0.05, ANOVA) by broiler chickens fed with different substitution level of charcoal using total excreta collection. T-0 %: Commercial broiler feed with 0 % charcoal, T-1.5 %: Commercial broiler feed with 1.5 % charcoal, T-3 %: Commercial broiler feed with 3 % charcoal, T-6 %: Commercial broiler feed with 6 % charcoal. n = 5 replicates for each dietary treatment.

3.3.3 Effects of dietary wood charcoal on excreta quality of male broiler chickens

As could be expected, feeding charcoal increased the C concentration in total excreta by 5.3 % (T-1.5 %), 8.0 % (T-3 %) and 16.3 % (T-6 %), respectively, compared with excreta of birds fed the dietary treatment without wood charcoal (T-0 %) (P 0.05). Charcoal is inert and indigestible and therefore is excreted together with the undigested feed residues, as already argued by Al-Kindi et al. 2016. In contrast to the C concentration, the P concentration of the excreta decreased by 5.9 % (T-1.5 %), 11.2 % (T-3 %) and 14.2 % (T-6 %) in our study (P 0.05), while the OM and N concentrations of total excreta were not altered by substituting part of the commercial broiler feed by dietary wood charcoal (P 0.05) as shown in Table 5, p.44. This agrees with Kutlu et al. 2001, who also detected a linear effect of dietary charcoal on the composition of excreta of broiler chickens, with the exception of the N concentration. It is also plausible that the reduction in Phosphorous concentration in excreta was as a result of the improvement of intestinal absorption properties as evidenced by Prasai et al. 2016 in their broiler charcoal diet study. Although the addition of charcoal had no additional influence on the utilization of P by broiler chickens in the present study, the lower P concentration in excreta of birds fed high levels of dietary wood charcoal demonstrates the potential of dietary wood charcoal to increase the bioavailability of P bound in the phytin of poultry diets that is generally limited due to an insufficient production of endogenous phytase in poultry (Maenz & Classen, 1998). Lowering the P concentration in poultry manure that is usually high (up to 2.4 %) (Bolan et al., 2010), might also reduce the risk of surface water contamination.

Table 5: Chemical composition (g/kg DM; mg/kg DM for P) of total excreta of male broiler chickens fed with different substitution level of charcoal

	Dietary treatments[1] (mean)					**ANOVA**
	T-0%	**T-1.5%**	**T-3%**	**T-6%**	**SEM[2]**	**p-value[3]**
Replicates (n)	5	5	5	5	-	-
Organic matter	797	810	813	810	3.35	n.s.
Carbon	374^{b}	394^{ab}	404^{a}	435^{a}	5.54	***
Nitrogen	55.7	49.8	53.2	45.6	1.61	n.s.
Phosphorus	17.0^{a}	16.0^{ab}	15.1^{b}	14.6^{b}	0.3	**

T-0 %: Commercial broiler feed with 0 % charcoal, **T-1.5** %: Commercial broiler feed with 1.5 % charcoal, **T-3** %: Commercial broiler feed with 3 % charcoal, **T-6** %: Commercial broiler feed with 6 % charcoal, **SEM**: Standard error of the mean. Probability values are indicated as $^{*}P \leq 0.05$, $^{**} \leq 0.01$, $^{***} \leq 0.001$. n.s. not significant $P > 0.05$ (Table 5, p.44).

As could be expected there was a clear color change of birds' fresh excreta from light grey for birds fed with no wood charcoal, i.e. T-0 %, to very dark grey for birds fed the dietary treatment with the highest level of charcoal (T-6 %) (P 0.01); however, the consistency of excreta was not influenced by the addition of charcoal and no signs of constipation were observed in broiler chickens fed dietary treatments with wood charcoal (Table 6, p.45).

Table 6: Consistency and color of total excreta of male broiler chickens fed with different substitution level of charcoal

	Dietary treatments[1] (median)						**Kruskal Wallis**
	T-0%	**T-1.5%**	**T-3%**	**T-6%**	**Min**	**Max**	**p-value[2]**
Replicates (n)	5	6	6	5	-	-	-
Color	7.4	5.7	4.4	2.2	1.2	8	**
Consistency	2.3	2.4	2.4	2.5	1.6	3.4	n.s.

T-0 %: Commercial broiler feed with 0 % charcoal, **T-1.5** %: Commercial broiler feed with 1.5 % charcoal, **T-3** %: Commercial broiler feed with 3 % charcoal, **T-6** %: Commercial broiler feed with 6 % charcoal. Probability values are indicated as $^{*}P \leq 0.05$, $^{**} \leq 0.01$, $^{***} \leq 0.001$, n.s. not significant, $P > 0.05$.

3.4 *Conclusions*

Dietary wood charcoal could replace up to 6 % of commercial broiler finisher feeding broiler without negative effect on production performance, nutrient accretion, and utilization of male broiler chickens, as well as excreta consistency. The use of wood charcoal as a broiler feed additive, particularly at 6 % substitution level, reduced P in total excreta Increased C excretion through feeding wood charcoal could potentially improve the poor soil quality in northern Ghana. Future research should analyse the long-term effect of feeding wood charcoal on performances and health of laying hens.

Acknowledgements
This work was carried out as part of the Urban Food Plus Project, jointly funded by the German Federal Ministry of Education and Research (BMBF) and the German Federal Ministry for Economic Cooperation and Development (BMZ) under the initiative GlobE – Research for the Global Food Supply, grant number 031A242-A. Our special thanks go to Prof. George

Nyarko, dean of the Faculty of Agricultural Sciences of the University for Development Studies in Tamale, Ghana, for supporting this study.

3.5 References

References

Al-Kindi, A., Dickhoefer, U., Schlecht, E., Sundrum, A., & Schiborra, A. (2016). Effects of quebracho tannin extract (*Schinopsis balansae* Engl.) and activated charcoal on nitrogen balance, rumen microbial protein synthesis and faecal composition of growing Boer goats. *Archives of Animal Nutrition*, *70*(4), 307–321. https://doi.org/10.1080/1745039X.2016.1175807

AOAC (Association of Official Analytical Chemists). (1990). Official methods of analysis.

Bakr, B. (2008). The effect of using citrus wood charcoal in broiler rations on the performance of broilers. *An-Najah University Journal for Research – Natural Sciences*, *22*, 17–24.

Bolan, N., Szogi, A., Seshadri, B., & Chuasavathi, T. (2010). The management of phosphorus in poultry litter. *Natural Resources*, 7.

Chu, G. M., Kim, J. H., Kim, H. Y., Ha, J. H., Jung, M. S., Song, Y., Cho, J. H., Lee, S. J., Ibrahim, R. I. H., & Lee, S. S. (2013). Effects of bamboo charcoal on the growth performance, blood characteristics and noxious gas emission in fattening pigs. *Journal of Applied Animal Research*, *41*(1), 48–55. https://doi.org/10.1080/09712119.2012.738219

de Moura, D. J., Vercellino, R. D. A., Santos, J. P. A., & do Vale, M. M. (Eds.). (2015). Heat stress impact on weight gain in broiler chickens: A meta-analytical study of environmental factor that impact production losses. In *ASABE 1st climate change symposium: Adaptation and mitigation conference proceedings*.

FAO. (2005). Ghana livestock sector brief. Retrieved, from http://www.fao.org/ag/againfo/resources/en/publications/sector_briefs/lsb_GHA.pdf

Kana, J. R., Teguia, A., Mungfu, B. M., & Tchoumboue, J. (2011). Growth performance and carcass characteristics of broiler chickens fed diets supplemented with graded levels of charcoal from maize cob or seed of *Canarium schweinfurthii* engl. *Tropical Animal Health and Production*, *43*(1), 51–56. https://doi.org/10.1007/s11250-010-9653-8

Khadem, A. A., Sharifi, S, D, Barati, M., & Borji, M. (2012). Evaluation of the effectiveness of yeast, zeolite and active charcoal as aflatoxin absorbents in broiler diets. *Global Veterinaria*, *8*(4), 426–432.

Kutlu, H. R., Ünsal, I., & Görgülü, M. (2001). Effects of providing dietary wood (oak) charcoal to broiler chicks and laying hens. *Animal Feed*

Science and Technology, *90*(3-4), 213–226. https://doi.org/10.1016/S0377-8401(01)00205-X

Maenz, D. D., & Classen, H. L. (1998). Phytase activity in the small intestinal brush border membrane of the chicken. *Poultry Science*, *77*(4), 557–563. https://doi.org/10.1093/ps/77.4.557

Majewska, T., Pudyszak, K., & Kozłowski, K. (2011). The effect of charcoal addition to diets for broilers on performance and carcass parameters. *Veterinarija ir Zootechnika*, *55*, 10–12.

Odunsi, A. A., Oladele, T. O., Olaiya, A. O., & Onifade, O. S. (2007). Response of broiler chickens to wood charcoal and vegetable oil based diets. *World Journal of Agricultural Sciences*, *3*(5), 572–575.

Oppong-Sekyere, D., Donkoh, A., & Addo, A. (2012). Effect of feed particle size on growth performance of broiler chickens in Ghana. *International Journal of Plant and Animal Science*, *2*, 241–247.

Oso, A., Akapo, O., Sanwo, K., & Bamgbose, A. (2014). Utilization of unpeeled cassava (*Manihot esculenta* c rantz) root meal supplemented with or without charcoal by broiler chickens. *Journal of Animal Physiology and Animal Nutrition*, *98*(3), 431–438.

Prasai, T. P., Walsh, K. B., Bhattarai, S. P., Midmore, D. J., Van, T. T. H., Moore, R. J., & Stanley, D. (2016). Biochar, bentonite and zeolite supplemented feeding of layer chickens alters intestinal microbiota and reduces campylobacter load. *PloS one*, *11*(4). https://doi.org/10.1371/journal.pone.0154061

Quaranta, L., Schlecht, E., & Schiborra, A. (2013). Supplementing goats with charcoal: Effects on feeding behaviour and faecal nutrient output. *Proceedings of Tropentag*, 17–19.

Rafiu, T. A., Babatunde, G. M., Akinwumi, A. O., Akinboro, A., Adegoke, Z. A., & Oyelola, O. B. (2014). Assessment of activated charcoal vs synthetic toxin-binders on performance, nutrient utilization and meat-quality of broilers fed infected diets. *International Journal of Agriculture and Biosciences*, *3*(5), 219–224.

Sumberg, J., Awo, M., & Kwadzo, G. T.-M. (2017). Poultry and policy in Ghana: Lessons from the periphery of an agricultural policy system. *Development Policy Review*, *35*(3), 419–438. https://doi.org/10.1111/dpr.12223

Team, R. C. (2013). R: A language and environment for statistical computing.

Verband Deutscher Landwirtschafts und Forschungsanstalten (VDLUFA). (2006). Chemical analysis of animal feed [Die chemische Untersuchung von Futtermitteln], Methodenbuch, Band III-Futtermittel.

4 Chapter 4

Effects of false yam tuber meals and charcoal on broiler chicken production and blood parameters

This chapter has been published in the South African Journal of Animal Sciences

Effects of false yam tuber meals and charcoal on broiler chicken production and blood parameters

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Abstract The authors investigated the effect of substituting part of commercial broiler feed with false yam tuber meals on broilers' growth performance, feed conversion rate and blood parameters. Furthermore, wood charcoal was added at different levels to the false yam tuber meals to explore its potential to attenuate toxic effects. One hundred and sixty-eight 28-day old healthy female broiler chickens (average initial body weight 1081.1 ± 66.20 g) were randomly assigned to 28 experimental groups (7 dietary treatments, 4 replicates) of six birds each, using a randomized complete block design. Dietary treatments included: the control diet (commercial broiler feed), raw false yam tuber meal (RFY) replacing 50 g/kg of the commercial broiler feed, and false yam tuber meal soaked in water (SFY) replacing 150 g/kg of the commercial broiler feed, RFY with 30 g/kg and 60 g/kg wood charcoal, and SFY with 30 g/kg and 60 g/kg wood charcoal. Growth performance, feed intake and feed conversion rate (FCR) were assessed over four weeks. At the end of the experiment, blood samples were collected from 21 birds (3 of each dietary treatment) to analyse haematological and serum biochemical parameters. Analysis of variance, Kruskal-Wallis tests, and simple regressions were used to evaluate effects of false yam tuber meals and charcoal. Results indicated that broilers fed 150 g/kg SFY had a significantly lower growth rate and poorest FCR. Consequently, highest body weights were observed for the control and RFY diets. Also, blood serum proteins were below references ranges for birds fed SFY, particularly with additional charcoal. In contrast, RFY could be included at 50 g/kg in broiler chickens' diets without any adverse effects on birds' performances and blood (serum) parameters. Anti-nutritional substances contained in SFY at this substitution level are harmful to the birds, irrespective of whether charcoal is added or not. In contrast, RFY could replace commercial feed at the studied level (50 g/kg).

Keywords: Feed efficiency, growth performance, haematology, serum biochemistry, terpenes

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4.1 *Introduction*

False yam (*Icacina oliviformis (Poiret)* J. Raynal, synonym *I. senegalensis* A. Juss, family Icacinaceae) is a drought-resistant shrub native to West and Central Africa (National Research Council, 1996). It belongs to the family of the *Icacinaceae* which phylogenetic relationships are still under discussion (Byng et al., 2014). It provides three edible products that are appreciated for human consumption: Fruits, seeds, and a large starch-rich tuber (National Research Council, 1996). Sun-dried false yam tuber meals contain 486.3 g/kg starch, high levels of neutral detergent fibre (286.1 g/kg DM), but low levels of crude protein (54.1 g/kg DM) (Dei et al., 2011). Umoh and Iwe 2014 additionally reported that false yam is a good source of micro-nutrients necessary for human nutrition such as potassium, sodium, calcium, and zinc. Recently, extensive research focused on the phytochemical profile of *Icacina trichantha* Oliv. It revealed pimarane-type diterpenoid compounds belonging to the small subclasses of 17-norpimarane, (9β H)-pimarane, (9β H)-17-norpimarane, 16,17-di-nor- and 17,19-di-nor-pimarane, a rare compound class in nature (Guo et al., 2016; Onakpa, Michael and Zhao, Ming and Gödecke, Tanja and Chen, Wei-Lun and Che, Chun-Tao and Santarsiero, Bernard D. and Swanson, Steven M. and Uzoma Asuzu, Isaac, 2014; Zhao et al., 2015). Pimarane-type momilactones were also found in rice plants *Oryza sativa* and mosses (*Hypnum plumaeforme* and *Pseudoleskeella papillosa*). These secondary metabolites are known for their cytotoxic and antitumor activities (S.-J. Kim et al., 2007; Onakpa, Michael and Zhao, Ming and Gödecke, Tanja and Chen, Wei-Lun and Che, Chun-Tao and Santarsiero, Bernard D. and Swanson, Steven M. and Uzoma Asuzu, Isaac, 2014) and are reported to function as phytoalexins and allelochemicals (Kato-Noguchi & Peters, 2013; Liu et al., 2012; Nozaki et al., 2007). Hence, several *Icacina* species are used in popular herbal medicine to treat food poisoning, constipation, and malaria or as a starch source during periods of famine for the people of tropical West Africa (Asuzu & Abubakar, 1995; Sarr et al., 2011).

Seeds, leaves and tubers of false yam have been also described as low-cost alternative feed for poultry or rabbit production in Ghana (Alhassan, 2015; Ansah et al., 2011; Dei et al., 2015a). However, despite its abundance in the northern part of the country, its use as alternative poultry feed is rather limited so far. This is probably due to anti-nutritional factors in raw false yam meals (Dei et al., 2011) which affect final bodyweights and carcass characteristics of broiler chickens negatively (Teye et al., 2011).

Traditional food processing methods such as soaking have been suggested to wash toxic substances out of false yam tubers. For instance, Dei et al. 2015a and Dei et al. 2015b proved that broiler chickens fed tubers that were soaked in water or saltpetre solution had similar performances to broiler chickens fed a normal diet. Adding dietary wood charcoal to false yam meals might help further reduce negative effects of toxic substances (Gerlach & Schmidt, 2012). Although charcoal as general feed additive received much interest in recent years, scientific studies addressing this topic in broiler chickens are scarce (Kana et al., 2011; Kutlu et al., 2001). The objectives of the present experiment were therefore to i) compare growth performance, feed intake and feed conversion rate, ii) as well as haematological and serological profiles of female broiler chickens fed raw and soaked false yam tuber meals, and to iii) evaluate if wood charcoal can attenuate toxic effects of the two false yam tuber meals.

4.2 *Materials and methods*

The study was conducted in February/March 2016 at the University for Development Studies (UDS), Tamale, in northern Ghana. The outdoor temperature during the experiment averaged 32.1 ± 1.4 °C, with a minimum of 28.8 °C and maximum of 34.8 °C. The average relative humidity was 31.0 ± 18.1 %, ranging between 7.3 % and 69.1 %. The poultry house was open sided to allow for natural ventilation. Light was provided 24 h d^{-1}, as is common practice in northern Ghana to stimulate feed intake during cooler night temperatures (Dei et al., 2011). The intensity of light was 10 lx. Ethical clearance was obtained on 14 January 2016 from UDS (code number ANS/FOA/02/14012016). The experiment was conducted in compliance with regulations for animal experiments of UDS, and was closely supervised by a veterinarian.

At 28 days of age, 168 healthy female broiler chickens (Cobb 500 strain) were selected on weight equalization basis and randomly assigned to 28 experimental groups with 6 birds each, using a randomized complete block design. Two blocks consisted of 14 floor pens with deep litter (1.65×0.84 m^2) and the other two blocks of 14 pens with wire mesh floor (1.8×0.9 m^2). Each dietary treatment was replicated four times. The seven dietary treatments included i) C: commercial broiler finisher diet (control), ii) RFY-0: raw false yam tuber meal, replacing 50 g/kg of the commercial broiler feed, iii) SFY-0: false yam tuber meal soaked in water, replacing 150 g/kg of the commercial broiler feed, iv) RFY-30: RFY with 30 g/kg wood charcoal (WC), V) SFY-30: SFY with 30 g/kg WC, vi) RFY-60: RFY with 60 g/kg WC, vii) SFY-60: SFY with 60 g/kg WC. The birds were adapted to the respective diet for one week. Feed and water were provided *ad libitum*.

All dietary treatments were based on a commercial finisher feed with added vitamin premix and phytase. It was purchased from Agricare Ltd. in Kumasi (Ghana) and contained 11.7 MJ metabolizable energy/kg according to the manufacturer's declaration (Agricare Ltd., Kumasi, Ghana). False yam tubers were harvested at the UDS Nyankpala campus. They were washed with water, peeled and sliced into chips. Part of the false yam chips was sun-dried and milled into gritty flour. The other part of the false yam chips was soaked in water (1 part of fresh false yam tuber chips to 2 parts of water) for 12 days. Water was changed every 3 days. Finally, the soaked false yam tuber chips were washed, sun-dried and milled into gritty flour. Wood charcoal was purchased from the Tamale wood and charcoal market, crushed, and milled into gritty powder to pass a 1 mm sieve and included in the false yam diets.

Representative samples of each dietary treatment and the pure wood charcoal and false yam tuber meals were collected, weighed using an electronic precision balance (3,500 g weighing capacity, 0.01 g resolution; Kern PCB, Kern und Sohn GmbH, Balingen, Germany) and dried in a hot-air drying oven (80 °C) to constant weight, weighed again and ground to pass a 1 mm sieve (Cyclotec, FOSS, Hamburg, Germany) before analysis. Following standard procedures of the Association of German Agricultural Analytic and Research Institutes (Verband Deutscher Landwirtschafts und Forschungsanstalten (VDLUFA), 2006), the dry matter (DM) and organic matter (OM) concentration of the feedstuffs were determined in two replicates per sample by consecutively drying the materials at 105 °C overnight, weighing the residual and incinerating it at 550 °C for 3 h. Based on the resulting ash weight, the OM concentration was calculated. A semi-automated Ankom 220 Fibre Analyser (ANKOM Technology, Macedon, NY, USA) served to determine, in two independent steps, the concentrations of ash-free neutral detergent fiber and acid detergent fiber (ADFom). Whereas heat-stable amylase was used for NDF determination (aNDFom), decalin and sodium sulphite were not added to the detergent solutions (van Soest et al., 1991).

DUMAS combustion was used to analyse the samples for their carbon (C) and nitrogen (N) concentration (C/N–TCD analyser, Elementar Analysensysteme GmbH, Hanau, Germany); the latter was multiplied by the factor 6.25 to obtain the concentration of crude protein (CP). Phosphorus (P) content in samples was determined by the Vanadate Molybdate method (Hitachi U-2000 photometer, Hitachi Co. Ltd., Tokyo, Japan) (Table 7, p.53).

Table 7: Analysed chemical composition of feed components and dietary treatments used in the broiler chicken experiment (g/kg DM)

	Composition [g/kg DM]					
Item	**OM**	**aNDFom**	**ADFom**	**CP**	**C**	**P**
WC	875	nd	nd	43	726	1.6
RFY	973	191	102	36	432	0.4
SFY	974	210	134	35	431	0.5
C	898	163	65	201	416	8.1
RFY-0	902	167	80	197	414	8
SFY-0	917	168	76	171	423	7.4
RFY-30	908	167	88	190	430	7.6
SFY-30	918	177	90	172	439	7
RFY-60	912	195	100	176	437	7.4
SFY-60	917	211	111	168	441	6.7

WC: wood charcoal, **RFY**: pure raw false yam tuber meal, **SFY**: pure soaked false yam tuber meal, **C**: commercial broiler finisher feed (control), **RFY-0**: **RFY** without WC, **SFY-0**: SFY without WC, **RFY**-30: RFY with 30 g/kg WC, **SFY-30**: SFY with 30 g/kg WC, **RFY-60**: RFY with 60 g/kg WC, **SFY-60**: SFY with 60 g/kg WC. **DM**: dry matter, **OM**: organic matter, **aNDF-NDFom**: neutral detergent fibre assayed with heat-stable amylase and exclusive of residual ash, **ADF-ADFom**: acid detergent fiber exclusive of residual ash, **CP**: crude protein, calculated as nitrogen × 6.25, **C**: total carbon, **P**: phosphorus. **nd**: not determined.

To determine essential amino acids (except tryptophan), ion chromatographic methods were used that conformed with the German Food and Feed Code (§64 LFGB L 49.07-2). Tryptophan was in accordance with procedures specified by the Association of German Agricultural Analytic and Research Institutes using HPLC methods (tryptophan; (Verband Deutscher Landwirtschafts und Forschungsanstalten (VDLUFA), 2006)). Amino acid concentrations were determined for dietary treatments without wood charcoal

(C, RFY-0 and SFY-0) and extrapolated for treatments with wood charcoal (RFY-30, RFY-60, SFY-30 and SFY-60) (Table 8, p.55).

Table 8: Amino acid profile of dietary treatments used in the broiler experiment

	Dietary treatment						
Amino acid* [g/kg DM]	**C**	**RFY-0**	**SFY-0**	**RFY-30**	**SFY-30**	**RFY-60**	**SFY-60**
Arginine	12.2	12.2	10.8	11.8	10.5	11.5	10.2
Histidine	6.1	6.1	5.8	5.9	5.6	5.7	5.5
Isoleucine	8.6	8.2	7.5	8	7.3	7.7	7.1
Leucine	19.7	18.3	16.9	17.8	16.4	17.2	15.9
Lysine	12.1	12.2	11.3	11.8	11	11.5	10.6
Methionine	3.9	3.7	3.4	3.6	3.3	3.5	3.2
Phenylalanine	10.5	10.1	9.1	9.8	8.8	9.5	8.6
Threonine	7.6	7.2	6.7	7	6.5	6.8	6.3
Valine	10	9.3	8.7	9	8.4	8.7	8.2
Tryptophan	1.9	1.9	1.7	1.8	1.6	1.8	1.6

*Calculated for RFY-30, RFY-60, SFY-30 and SFY-60, **C**: commercial broiler finisher feed (control), **RFY-0**: raw false yam tuber meal (50 g/kg; RFY) without wood charcoal (WC), **SFY-0**: false yam tuber meal soaked in water (150 g/kg, SFY) without WC, **RFY-30**: RFY and 30 g/kg WC, **SFY-30**: SFY and 30 g/kg WC, **RFY-60**: RFY and 60 g/kg WC, **SFY-60**: SFY and 60 g/kg WC. **DM**: dry matter.

To determine terpenic constituents, 10 g of each pure tuber meal (RFY and SFY) was exhaustively extracted with ethanol three times for 30 minutes in a shaking water bath at 30°C. The ethanol extract was evaporated (< 40 °C) and partitioned between *n*-hexane–H_2O, CHCl3–H_2O, EtOAc–H_2O and *n*-butanol–H_2O. The sub-fractions were evaporated (< 40 °C) and their amounts were as following for the RFY meal: 204.0 mg (n-hexane-sub-fraction), 27.8 mg (CHCl3-sub-fraction), 6.8 mg (EtOAc-sub-fraction), 3.6 mg (*n*-butanol-sub-fraction), 6.0 mg (H_2O-sub-fraction); and for the SFY meal: 202.2 mg (n-hexane-sub-fraction), 21.2 mg (CHC_{l3}-sub-fraction), 6.5 mg (EtOAc-sub-fraction), 1.4 mg (n-butanol-subfraction), 4.5 mg (H_2O-sub-fraction). Ultra-performance liquid chromatography-mass spectrometry (UPLC-MS) analyses of *Icacina* extracts were performed on a Q-Exactive Plus Hybrid Quadrupole-Orbitrap Mass Spectrometer (Thermo Fisher Scientific, Bremen, Germany) equipped with an Ultimate 3000 series RSLC (Dionex, Sunnyvale, CA, USA) chromatograph. An Acclaim C18 column (150 × 2.1 mm, 2.2 μ m particles with 120 Å pore diameter, Dionex, Sunnyvale, CA, USA) with a flow rate of 300 μL min^{-1} in a binary solvent system of water (Solvent A) and acetonitrile (Solvent B), both containing 0.1 % (v/v) formic acid was used to chromatographically separate the extracts. Fifteen μL of each extract, diluted 1:100, were loaded onto the column and eluted using the following gradient: linear increase from 0 % B to 100 % B within 15 minutes – 100 % B constant for 5 minutes – equilibration time at 0 % B for 5 minutes. The mass spectrometer was operated in positive and negative ionization modes using Heated-Electrospray Ionization (H-ESI) in the mass range of m/z 100 to 1,000 using 70,000 m/Δm resolving power in the Orbitrap mass analyser. H-ESI source parameters were set to 4 kV for spray voltage, 35 V for transfer capillary voltage at a capillary temperature of 300 °C. Data was evaluated and interpreted using Xcalibur v.3.0.63 software (Thermo Fisher Scientific, Waltham, MA, USA) (Hölscher et al., 2017).

For the evaluation of the UPLC-MS-data, a database of 25 reported pimarane-type diterpenoids identified from *Icacina* species producing such compounds was created. These secondary metabolites were listed according to their exact mass, with isomers grouped together. The evaluation of sub-fractions of raw and soaked FY tuber material revealed the exact mass of all listed isomer groups of pimarane-type candidate structures. (Table 9, p.58). Due to lack of reference compounds a differentiation between candidates with an identical molecular formula was not possible. Considering reported isomers, two of them (No. 4 and 11 Table 9, p.58) have been identified in *I. oliviformis* (Vanhaelen et al., 1987). The exact mass of *m/z* 391.17622 can be assigned to $[M+H]^+$ of icacinol and the *m/z* 359.11371 is attributable to icacenone, two pimarane diterpenoid isolated from *I. oliviformis*. The method used provides rapid information about the phytochemical constituents of biological samples.

Table 9: Pimarane-type diterpenoid compound candidates detected in false yam tubers (UPLC-MS)

No.	**Name**	**Molecular formula**	**Measured [M-H]⁻/[M+H]⁺ monoisotopic mass (u); MS (ppm) in brackets**
1	Icacine	$C_{22}H_{30}O_6N$	404.20810 (0.592)
2	17-Hydroxyicacinol*	$C_20H_{26}O_8$	395.17029 (0.622)
3	14α-Methoxyhumirianthol	$C_{21}H_{28}O_7$	391.17622 (-0.016)
4	Icacinol*	$C_20H_{26}O_7$	379.17535 (0.581)
5	7α-Hydroxyicacenone	$C_{19}H_{20}O_8$	375.10840 (-0.375)
6	Icaceine	$C_{22}H_{32}O_4N$	374.23340 (2.178)
7	Icacinlactone C*	$C_20H_{20}O_7$	373.12853 (0.940)
	Icacinlactone D*		
	7β-Hydroxyicacinlactone B*		
8	Icacinlactone L	$C_20H_{18}O_7$	369.09727 (-1.859)
	Icacintrichantholide		
9	Humirianthol	$C_20H_{26}O_6$	361.16536 (-0.005)
10	2β-Hydroxyhumirianthenolide C	$C_{19}H_{22}O_7$	361.12958 (0.841)
11	Icacenone	$C_{19}H_{20}O_7$	359.11371 (0.233)
	Icacinlactone F		
	Icacinlactone K		
12	Icacinlactone B	$C_20H_{20}O6$	355.11856 (-0.427)
13	Humirianthenolide C	$C_{19}H_{22}O_6$	345.13434 (-0.063)
	Icacinlactone G		
	Icacinlactone I		
	Icacinlactone J		
14	Icacinlactone E	$C_{19}H_{20}O6$	343.11856 (-0.442)
	Icacintrichanone		
15	12-Hydroxyicacinlactone A	$C_{19}H_{18}O_6$	341.10260 (-1.353)
16	Icacinlactone A	$C_{19}H_{18}O_5$	325.10746 (-2.113)

UPLC-MS: Ultra-performance liquid chromatography-mass spectrometry. * detected as [M+H] ⁺

Broiler chickens were weighed individually on a weekly basis using an electronic precision balance (3,500 g weighing capacity, 0.01 g resolution: Kern PCB, Kern und Sohn GmbH, Balingen, Germany). The average weight gain (ADG; g/d) was calculated by deducting the individual bird weight at the end of previous week from the weight at the end of the respective experimental week, divided by seven days. The average weighted body weight was calculated per treatment, corrected for mortalities. Feed intake was assessed for each replicate on a weekly basis and calculated as the difference between the amount of feed offered during the week and feed refused at the end of the week. This was further divided by the number of days (7). The average daily feed intake (DFI) was obtained (g/bird and day). Feed conversion rate (FCR) was calculated per replicate as unit of feed consumed daily (FM) per unit of daily body weight gain (g/g).

At the end of the experimental period (at 63 days of age), one bird from three replicates of each treatment was randomly selected for blood sampling. The selected birds were restrained, and 2 mL of blood were drawn from their wing veins with a syringe and needle. Blood samples for haematological evaluation were collected into EDTA tubes, while blood samples for blood chemistry evaluation were collected without anticoagulant. Samples were kept in cooled condition prior to analysis. These haematological parameters were assessed: Packed cell volume (PCV, %) following Mukherjee 2005, red blood cell count (RBC, $\times$ 106/μL) following Lewis et al. 2000, white blood cell count (WBC, $\times$ 103/μL) following Hoffbrand et al. 2006, haemoglobin (Hb, g/dL) following Cheesbrough 2006, white blood cell differentials (heterophils, lymphocytes, eosinophils, monocytes, basophils; all %), mean corpuscular haemoglobin concentration (MCHC, g/dL), mean corpuscular haemoglobin (MCH, pg), mean corpuscular volume (MCV, μm^3) and platelets (PLAT, $\times$ 103/μL) using a haemo-analyser (Sysmex Hematology Analyser, XS-500i, Sysmex Europe GmbH, Norderstedt, Germany). The serum biochemical assay was carried out by spectrophotometry. The parameters included total serum proteins (g/L), albumin (g/L), globulins (g/L), alkaline phosphate (units (U)/L), aspartate transferase (U/L) and alanine transferase (U/L).

Data were assessed for normality by Shapiro-Wilk test and for constant variance by Bartlett test. Normally distributed data with homogeneous variance were subjected to one-way analysis of variance (ANOVA) and Post-hoc Tukey's honest significant difference (HSD) test with 95 % family-wise confidence level. All other data were subjected to Kruskal-Wallis rank sum test, followed by Wilcoxon rank sum test for pairwise comparison of treatments. No block effect was observed and therefore not further considered in the models. First step analyses included the control and the false yam tuber meals without additional wood charcoal (treatments C, RFY-0, SFY-0), next step analyses compared the false yam tuber meals without (RFY-0, SFY-0) and with additional wood charcoal (RFY-30, SFY-30, RFY-60, SFY-60). Finally, MCV values were fitted into a simple linear regression model to predict relationship with increasing inclusion level of charcoal to the false yam meals (RFY, SFY). All statistical analyses were performed in R version 3.3.0 (The R Foundation for Statistical Computing). The same software was used to created graphs.

4.3 *Results*

Substituting part of the commercial broiler feed with SFY tuber meal reduced bird' weight gain (P <0.001) (Table 10, p.60), while RFY tuber meal at the studied inclusion level had no effect on birds' weight gain. The addition of wood charcoal to false yam tuber meals did not show any effect (P >0.05), positive or negative, on bird' weight gain (Table 11, p.61) and hence final body weight.

Table 10: Mean performances of experimental broiler chickens fed a control diet and different false yam tuber meals without wood charcoal

	Control (C)	**RFY-0**	**SFY-0**	**SEM**	***P-value***
Weight gain (g/d)	39.7	41.4	31	1.16	0.001
Feed intake (g/d)	129.7	137.6	143.9	6.05	0.472
Feed:gain ratio	3.3	3.5	4.7	0.29	0.093
Mortality rate	0.13	0.21	0.04	0.05	0.352

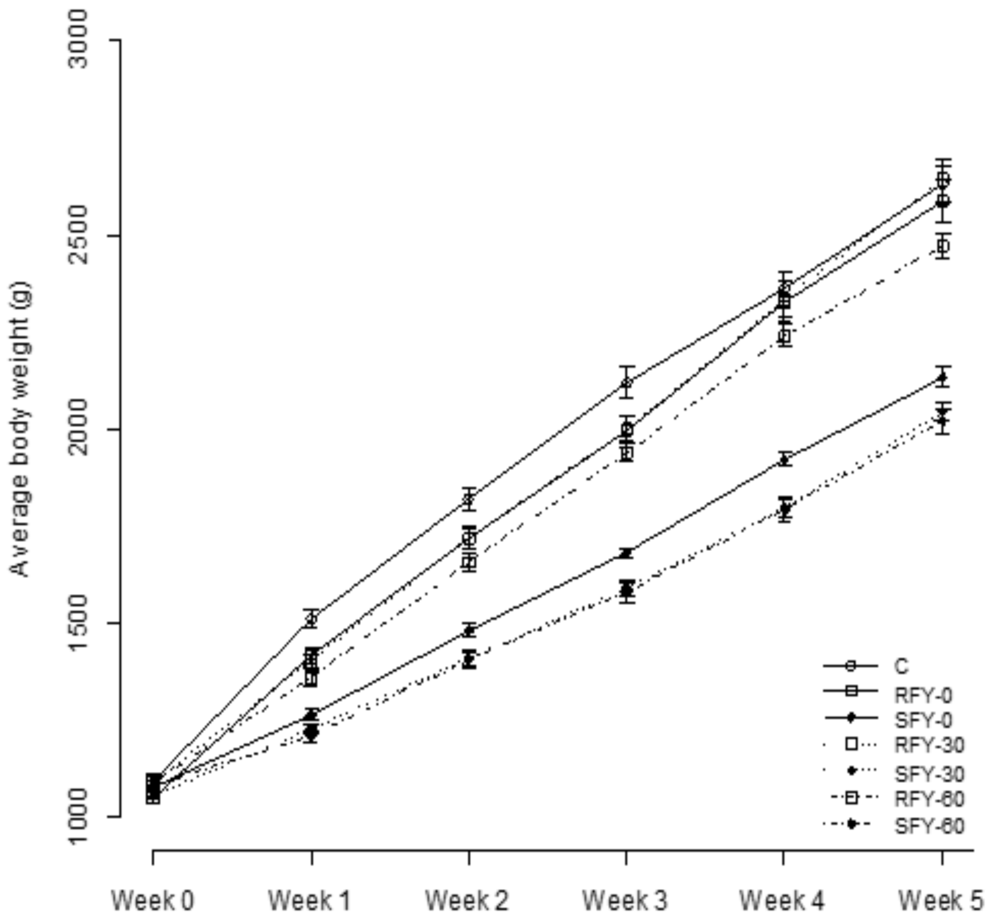
Control: commercial broiler finisher diet, **RFY-0**: raw false yam tuber meal (50 g/kg; RFY) without wood charcoal (WC), **SFY-0**: false yam tuber meal soaked in water (150 g/kg; SFY) without WC. Kruskal-Wallis test and Post-hoc Wilcoxon rank sum test. **SEM**: Standard error of mean.

Table 11: Effect of varying inclusion levels of wood charcoal to false yam tuber meals on daily weight gain, daily feed intake, feed conversion rate and mortality rate of experimental broiler chickens

	RFY-0	**RFY-30**	**RFY-60**	**SEM**	***P-value***	**SFY-0**	**SFY-30**	**SFY-60**	**SEM**	***P-value***
Weight gain [g/d]	41.4	43.9	39.7	1.06	0.252	31	29	28.9	0.72	0.387
Feed intake [g/d]	137.6	141.4	143.6	4.99	0.368	143.9	150.2	129.3	4.99	0.118
Feed:gain ratio	3.5	3.3	3.6	0.21	0.309	4.7	5.2	4.5	0.2	0.309
Mortality rate	0.21	0.17	0	0.046	0.085	0.04	0.04	0	0.019	0.577

RFY-0: raw false yam tuber meal (50 g/kg; RFY) without wood charcoal (WC), **RFY-30 & RFY-60**: raw false yam tuber meal with 30 g/kg and 60 g/kg wood charcoal, **SFY-0**: false yam tuber meal soaked in water (150 g/kg; SFY) without WC, **SFY-30 SFY-60**: soaked false yam tuber meal with 30 g/kg and 60 g/kg wood charcoal. Kruskal-Wallis test and Post-hoc Wilcoxon rank sum test. **SEM**: Standard error of mean.

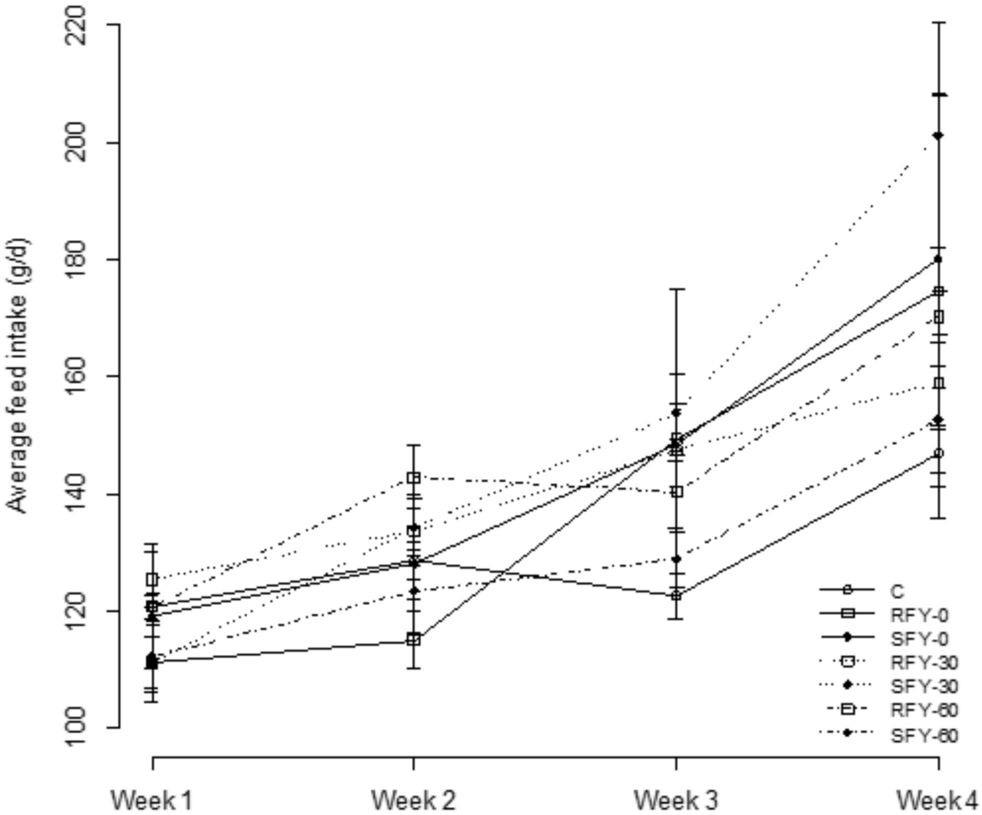
After the adaptation week, the birds' body weights varied depending on the diet (Figure 11, p.63). Comparing the diets without wood charcoal, the highest body weights at the start of the first experimental week (week 1) were found for birds fed the control diet (C). Birds fed RFY-0 diets had lower body weights ($P < 0.01$) as compared to the control diet, and lowest body weights were observed for birds fed the SFY diet (SFY-0) ($P < 0.001$). For the latter the mean body weight remained lowest over the four experimental weeks, resulting in 19 % lower final body weight compared to birds fed the control diet ($P < 0.05$). In contrast, the final body weights of birds fed the RFY diet (RFY-0) were similar to those of the control diet ($P > 0.05$). As could be expected from the aforementioned results, no effect of wood charcoal on birds' weights were obtained ($P > 0.05$).



C: commercial broiler finisher diet (control), **RFY-0**: raw false yam tuber meal (50 g/kg; RFY) without wood charcoal (WC), **SFY-0**: false yam tuber meal soaked in water (150 g/kg; SFY) without WC, RFY-30: RFY with 30 g/kg WC, **SFY-30**: SFY with 30 g/kg WC, **RFY-60**: RFY with 60 g/kg WC, **SFY-60**: SFY with 60 g/kg WC.

Figure 11: Average body weight of broiler chickens at the start of each week

The average DFI, FCR and mortalities did not differ between dietary treatments without wood charcoal ($P > 0.05$) (Table 10, p.60), and as for ADG and the body weight no effect of wood charcoal at the studied inclusion levels on these variables was observed ($P > 0.05$) (Table 11, p.61). However, DFI increased more sharply for false yam tuber meals as compared to the control diet in experimental weeks 2 to 4, for SFY-0 and SFY-30 (Figure 12, p.65). Consequently, FCR was poorest in broiler chickens fed SFY, particularly SFY-30.



C: commercial broiler finisher diet (control), **RFY-0**: raw false yam tuber meal (50 g/kg; RFY) without wood charcoal (WC), **SFY-0**: false yam tuber meal soaked in water (150 g/kg; SFY) without WC, **RFY-30**: RFY with 30 g/kg WC, **SFY-30**: SFY with 30 g/kg WC, **RFY-60**: RFY with 60 g/kg WC, SFY-60: SFY with 60 g/kg WC.

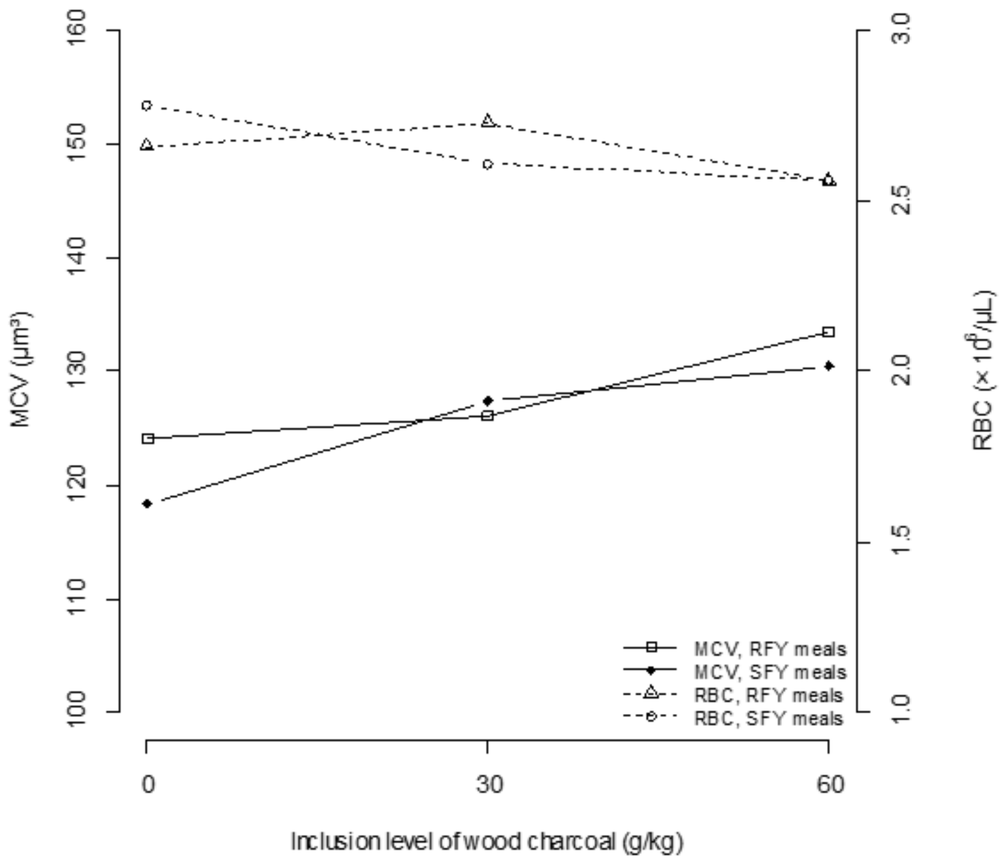
Figure 12: Average daily feed intake of broiler chickens for each experimental week

With regard to haematological parameters, we observed no effect of false yam tuber meals, except a decrease in the MCV and an increase in RBC of birds fed SFY-0 as compared to birds fed the control and RFY-0 diet (P <0.05). Furthermore, basophils were detected in the blood of birds fed SFY-0 (Table 12, p.66). The inclusion of wood charcoal to false yam tuber meals could counterbalance the negative effect in MCV and MCV values for birds fed RFY-30, RFY-60, SFY-30 and SFY-60 were not different to the control diet. A linear increase in MCV was realized with increasing level of wood charcoal. In contrast, no effect of varying levels of wood charcoal was observed for RBC values of birds fed the SFY meal (Figure 13, p.67).

Table 12: Haematology of experimental broiler chickens fed a control diet and different false yam tuber meals without wood charcoal

Variable	**Unit**	**C**	**RFY-0**	**SFY-0**	**SEM**	***P-value***
PCV[a]	%	32.77	32.93	32.87	0.229	0.334
RBC[a]	× 106/µL	2.37[c]	2.66[c]	2.78[d]	0.071	0.023
Hb[a]	g/dL	7.73	7.93	8.23	0.156	0.482
MCHC[a]	g/dL	23.67	24.1	25.03	0.453	0.484
MCH[a]	pg	32.67	29.93	29.7	0.605	0.068
MCV[b]	µm³	138.63[c]	124.10[c]	118.37[d]	3.469	0.032
Platelets[a]	× 103/µL	11.33	10.33	11.33	1.691	0.971
WBC[a]	× 103/µL	8.11	13.29	11.02	1.567	0.46
Heterophils[b]	%	51	50.67	50	0.747	0.888
Lymphocytes[a]	%	48.67	48.67	48	0.747	0.935
Eosinophils[b]	%	0	0	0.33	0.111	0.368
Monocyte[b]	%	0.33	0.67	1	0.289	0.656
Basophils[b]	%	0	0	0.67	0.147	0.102

C: commercial broiler finisher diet (control), **RFY-0**: raw false yam tuber meal (50 g/kg; RFY) without wood charcoal (WC), **SFY-0**: false yam tuber meal soaked in water (150 g/kg; SFY) without WC. **PCV**: packed cell count, **RBC**: red blood cell count, **Hb**: hemoglobin, **MCHC**: mean corpuscular hemoglobin concentration, **MCH**: mean corpuscular hemoglobin, **MCV**: mean corpuscular volume, **WBC**: white blood cell count. **SEM**: standard error of the mean. **a** ANOVA and post-hoc Tukey HSD test. **b** Kruskal-Wallis test.



RFY: raw false yam tuber meal at 50 g/kg substitution level, **SFY**: soaked false yam tuber meal at 150 g/kg substitution level) in relation to increasing level of included wood charcoal (0 g/kg, 30 g/kg, 60 g/kg).

Figure 13: Mean corpuscular volume (MCV) and red blood cell count (RBC) of broiler chickens fed false yam tuber meals

Similar to haematological variables, the type of false yam tuber meal did not affect blood serum proteins, globulin, alkaline phosphate, aspartate transferase and alanine transferase levels of broiler chickens (P >0.05) (Table 13, p.68). Furthermore, no effect of increasing level of wood charcoal to false yam tuber meals was observed for serological parameters (P >0.05).

Table 13: Serology of experimental broiler chickens fed a control diet and different false yam tuber meals without wood charcoal

	Unit	**C**	**RFY-0**	**SFY-0**	**SEM**	***P-value***
Total protein	g/L	35.4	32.8	31.57	1.286	0.526
Albumin	g/L	16.17	13.77	13.4	0.563	0.067
Globulin	g/L	19.2	19.07	18.2	1.008	0.929
ALK	U/L	155.1	154.27	168.27	7.73	0.764
ASP	U/L	126.5	91.53	142.5	18.699	0.589
ALA	U/L	10.97	7.87	8.4	1.287	0.64

C: commercial broiler finisher diet (control), **RFY-0**: raw false yam tuber meal (50 g/kg; RFY) without wood charcoal (WC), **SFY-0**: false yam tuber meal soaked in water (150 g/kg; SFY) without WC. **ALK**: alkaline phosphate, **ASP**: aspartate transferase, **ALA**: alanine transferase. **U**: unit. **SEM**: standard error of the mean. ANOVA test.

4.4 *Discussion*

The RFY at 50 g/kg inclusion level might be an option to substitute part of commercial broiler feed in northern Ghana as well as in other countries where *Icacina oliviformis* is native. No effect of RFY on birds' production performances was observed. A higher inclusion of RFY would however lead to a reduction in broilers' production performances (Teye et al., 2011). In contrast, MCV in the blood of experimental birds was reduced if no additional charcoal was added, but values were still within the reference range of 100-139 μ m^3 (Greenacre & Morishita, 2014). MCV defines the size of RBC and is used to morphologically classify anaemias. Reduced MCV might be an indicator of microcytic anaemia (Sarma, 1990). Nevertheless, experimental birds fed the RFY diet did not show any signs of anaemia. Finally, toxic substances in RFY might lead to slightly higher mortality rates.

In contrast to the results obtained for RFY, the inclusion of SFY in commercial broiler feed at the investigated level of 150 g/kg is not recommended due to negative effects on bird' production performances. Limiting the inclusion level to 120 g/kg as suggested by (Dei et al., 2015b) might be an option to avoid negative effects on performance characteristics. In our study, the decrease in growth performance of birds fed SFY could not be compensated by a comparably higher DFI that was particularly observed at the end of the finisher phase. This can be explained by the relatively low CP concentrations of SFY tuber meals which were below the recommended values of 200 g/kg (4-6 weeks of age) and 180 g/kg (above 6 weeks of age) for broiler chickens (Aiello et al., 2016; National Research Council, 1994). Also, Bregendahl et al. 2002, among others, revealed a lower growth performance, higher feed intake and thus poorer feed conversion rate of broiler chickens fed low-protein diets. Hence, more feed and feed additives might be needed to compensate the low energy and protein content of false yam meals (Dei et al., 2015b) and to allow birds to counterbalance the toxic effect of terpenic constituents in false yam tubers (Nersesian et al., 2012). In addition to the time needed to soak false yam tubers, this will increase costs and thereby potentially limit the benefits of false yam in poultry production.

Despite their low CP concentrations, the false yam tuber meals met the requirements for most limiting amino acids as shown by the amino acid profiles of the diets, with the exception of the calculated threonine concentrations of SFY-30 and SFY-60 that were below the recommendations set by (National Research Council, 1994). This lack might explain the negative effect on total serum protein, albumin and globulin concentrations that were below the reference ranges (Greenacre & Morishita, 2014). A decrease in blood proteins reflect decreased protein synthesis due to malnutrition or lack of essential amino acids that are required for protein synthesis (Shikora et al., 2002). Despite we observed such a decrease for both types of false yam tuber meals, differences were insignificant to the control diet.

Furthermore, terpenes could be an antagonist of essential amino acid receptors in poultry. However, the mechanisms of interaction and effects of terpenes in *Icacina oliviformis* on birds' physiology are still largely unknown and additional studies are needed to clearly confirm negative effects of false yam tuber meals on birds' performances, serological parameters and consequently health status. In general, studies revealed a large variety of different properties of extracts of *Icacina* species. Ethanol extracts of *Icacina trichantha* were reported to protect the kidneys and the liver of tetrachloromethane-poisoned rats (Asuzu & Abubakar, 1995). Hydroalcoholic extracts of *Icacina trichantha* tubers showed an edema inhibition of the croton oil-induced ear oedema in mice (Asuzu & Abubakar, 1995). Some sub-fractions of methanol extracts of leaves of *Icacina oliviformis* inhibited the growth of chloroquine resistant strains of *Plasmodium falciparum*, which cause malaria in humans (Sarr et al., 2011). Ethanol and water extracts of leaves *Icacina oliviformis* showed antimicrobial activities against *Escherichia coli*, *Staphylococcus aureus*, *Streptococcus* spp, *Candida albicans* and *Klebsiella pneumonia* (Shagal

& Kubmarawa, 2013). Unfortunately, all these results were and are preliminary as secondary metabolites have not yet been identified nor have their properties been tested and proven in *in vivo* studies. In contrast, (Zhao et al., 2015) reported cytotoxic activities of isolated, purified and identified pimarane-type diterpenoids from tubers of *Icacina trichantha*. Especially the diterpene humirianthenolide C showed activity against the human melanoma cancer (MDA-MB-435) and human breast cancer cells (MDA-MB-231, (Zhao et al., 2015).

Soaking of the false yam tubers in water to remove terpenes before feeding as suggested by Dei et al. 2015bhad almost no effect on the amount of the lipophilic n-hexane subfractions, but starting with the CHCl3-subfraction all other sub-fractions showed smaller mass data for the soaked than for the raw biological material. This demonstrates that water removes more easily hydrophilic compounds from the false yam tubers than lipophilic ones. Including wood charcoal along with false yam tuber meals partially attenuated anti-nutritive effects of *Icacina oliviformis*, particularly for raw tubers. However, it has to be considered that adding charcoal along with false yam tuber meals further reduces the energy and nutrient density per unit feed, which is reflected in lowest final body weights and blood protein of birds fed SFY with 30 g/kg and 60 g/kg added charcoal. Although the inclusion of WC to FY diets did not further increase the feed intake of birds of these groups in our study, higher feed intakes and lower feed conversion rates obtained in other studies clearly do not justify the inclusion of WC to broiler diets (Odunsi et al., 2007). A study by (Chu et al., 2013) also revealed a negative effect of bamboo charcoal on total blood protein in fattening pigs, while contrary to our results, a positive effect on pigs' growth performance was observed. Finally, the inclusion of charcoal into livestock feed is only sustainable if sustainable sources of biomass have been used as feedstock for its production and if there are no alternative uses of this material. A review by (Duku et al., 2011) showed that Ghana owns a large variety of potential feedstock for the production of charcoal, including agricultural (for example rise husks and maize cobs) and forestry residues, as well as wood processing wastes such as saw dust.

4.5 *Conclusions*

Anti-nutritional substances contained in SFY at the studied substitution level are harmful to the birds, irrespective of adding charcoal or not. In contrast, including 50 g/kg RFY had no effect on the studied parameters, except for mortality that tended to be slightly higher. There seems to be a potential of charcoal to reduce mortality in birds fed RFY, but only at inclusion levels higher than 30 g/kg. It would be of interest to verify the effect of false yam tuber meals and charcoal on performances and blood parameters of local avian genetic resources due to their adaptation to adverse climatic conditions and husbandry practices and their role for food security of urban and rural households in northern Ghana.

Acknowledgement
This work was carried out as part of the UrbanFoodPlus Project, jointly funded by the German Federal Ministry of Education and Research (BMBF) and the German Federal Ministry for Economic Cooperation and Development (BMZ) under the initiative GlobE – Research for the Global Food Supply, grant number 031A242-A. The sponsor had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results. Our special thanks go to George Nyarko, dean of the Faculty of Agricultural Sciences of the University for Development Studies in Tamale, Ghana, for supporting this study.

4.6 References

References

Aiello, S. E., Moses, M. A., & Allen, D. G. (2016). *The Merck veterinary manual 11th ed., Merck and Co.*

Alhassan, M. (2015). Effect of soaked false yam (*Icacina oliviformis*) seed meal on laying performance of chicken. *Global Journal of Animal Scientific Research*, *3*(3).

Ansah, T., Emelia, A. A., Deku, G., & Karikari, P. K. (2011). Evaluation of false yam (*Icacina oliviformis*) leaves on the growth performance of weaner rabbits (*Oryctolagus cuniculus*). *Online Journal of Animal and Feed Research.*

Asuzu, I. U., & Abubakar. (1995). The effects of *Icacina trichantha* tuber extract on the nervous system. *Phytotherapy Research*, *9*(1), 21–25.

Bregendahl, K., Sell, J. L., & Zimmerman. (2002). Effect of low-protein diets on growth performance and body composition of broiler chicks. *Poultry Science*, *81*(8), 1156–1167.

Byng, J. W., Bernardini, B., Joseph, J. A., Chase, M. W., & Utteridge, T. M. A. (2014). Phylogenetic relationships of Icacinaceae focusing on the vining genera. *Botanical Journal of the Linnean Society*, *176*(3), 277–294.

Cheesbrough, M. (2006). *District laboratory practice in tropical countries, part 2.* Cambridge university press.

Chu, G. M., Kim, J. H., Kim, H. Y., Ha, J. H., Jung, M. S., Song, Y., Cho, J. H., Lee, S. J., Ibrahim, R. I. H., & Lee, S. S. (2013). Effects of bamboo charcoal on the growth performance, blood characteristics and noxious gas emission in fattening pigs. *Journal of Applied Animal Research*, *41*(1), 48–55. https://doi.org/10.1080/09712119.2012.738219

Dei, H. K., Ajigepungu, W. T., & Mohammed, A. (2015b). Growth performance of broilers fed varying levels of soaked false yam (*Icacina oliviformis*) tuber meal. *Ghana Journal of Science, Technology and Development*, *3*(1).

Dei, H. K., Asare, A. I., & Mohammed, A. (2015a). Growth response of broiler chickens fed false yam (*Icacina oliviformis*) tuber soaked in saltpetre solution. *Ghana Journal of Science, Technology and Development*, *3*(1).

Duku, M. H., Gu, S., & Hagan, E. B. (2011). Biochar production potential in Ghana — a review. *Renewable and Sustainable Energy Reviews*, *15*(8), 3539–3551.

Gerlach, H., & Schmidt, H.-P. (2012). Biochar in poultry farming. *Ithaka Journal*, *2012*(1), 262–4p.

Greenacre, C. B., & Morishita, T. Y. (2014). *Backyard poultry medicine and surgery*. Wiley Online Library.

Guo, B., Onakpa, M. M., Huang, X.-J., Santarsiero, B. D., Chen, W.-L., Zhao, M., Zhang, X.-Q., Swanson, S. M., Burdette, J. E., & Che, C.-T. (2016). Di-nor-and 17-nor-pimaranes from *Icacina trichantha*. *Journal of Natural Products*, *79*(7), 1815–1821.

Hoffbrand, A., Moss, P., & Pettit, J. (2006). *Essential haematology, 2006* (Vol. 5).

Hölscher, D., Vollrath, A., Kai, M., Dhakshinamoorthy, S., Menezes, R. C., Svatoš, A., Schubert, U. S., Buerkert, A., & Schneider, B. (2017). Local phytochemical response of *Musa acuminata*× *balbisiana* colla cv.'bluggoe'(abb) to colonization by Sternorrhyncha. *Phytochemistry*, *133*, 26–32.

Kana, J. R., Teguia, A., Mungfu, B. M., & Tchoumboue, J. (2011). Growth performance and carcass characteristics of broiler chickens fed diets supplemented with graded levels of charcoal from maize cob or seed of *Canarium schweinfurthii* engl. *Tropical Animal Health and Production*, *43*(1), 51–56. https://doi.org/10.1007/s11250-010-9653-8

Kato-Noguchi, H., & Peters, R. J. (2013). The role of momilactones in rice allelopathy. *Journal of Chemical Ecology*, *39*(2), 175–185.

Kim, S.-J., Park, H.-R., Park, E., & Lee, S.-C. (2007). Cytotoxic and antitumor activity of momilactone b from rice hulls. *Journal of Agricultural and Food Chemistry*, *55*(5), 1702–1706.

Kutlu, H. R., Ünsal, I., & Görgülü, M. (2001). Effects of providing dietary wood (oak) charcoal to broiler chicks and laying hens. *Animal Feed Science and Technology*, *90*(3-4), 213–226. https://doi.org/10.1016/S0377-8401(01)00205-X

Lewis, S., Bain, B., & Bates, I. (2000). Dacie and Lewis practical haematology ed. *Churchill Livingston, Edinburg*.

Liu, N., Wang, S., & Lou, H. (2012). A new pimarane-type diterpenoid from moss *Pseudoleskeella papillosa* (lindb.) kindb. *Acta Pharmaceutica Sinica B*, *2*(3), 256–259.

Mukherjee, K. (2005). *Manual for routine diagnostic tests. vol. 1*. Tata McGraw-Hill, New Delhi, India.

National Research Council (Ed.). (1994). *Nutrient requirements of poultry*. National Research Council. National Academies Press.

National Research Council (Ed.). (1996). *Lost crops of Africa: Volume i: Grains*. National Research Council. National Academies Press.

Nersesian, C. L., Banks, P. B., Simpson, S. J., & McArthur, C. (2012). Mixing nutrients mitigates the intake constraints of a plant toxin in a generalist herbivore. *Behavioral Ecology*, *23*(4), 879–888.

Nozaki, H., Hayashi, K.-i., Nishimura, N., Kawaide, H., Matsuo, A., & Takaoka, D. (2007). Momilactone a and b as allelochemicals from moss *Hypnum plumaeforme*: First occurrence in bryophytes. *Bioscience, biotechnology, and biochemistry*, *71*(12), 3127–3130. https://doi.org/10.1271/bbb.70625.

Odunsi, A. A., Oladele, T. O., Olaiya, A. O., & Onifade, O. S. (2007). Response of broiler chickens to wood charcoal and vegetable oil based diets. *World Journal of Agricultural Sciences*, *3*(5), 572–575.

Onakpa, Michael and Zhao, Ming and Gödecke, Tanja and Chen, Wei-Lun and Che, Chun-Tao and Santarsiero, Bernard D. and Swanson, Steven M. and Uzoma Asuzu, Isaac. (2014). Cytotoxic (9bh)-pimarane and (9bh)-17-norpimarane diterpenes from the tuber of *Icacina trichantha*. *Chemistry and Biodiversity*, *11*(12), 1914–1922. https://doi.org/10.1002/cbdv.201400151.

Sarma, P. R. (1990). Red cell indices. In *Clinical methods: The history, physical, and laboratory examinations. 3rd edition*. Butterworths.

Sarr, S. O., Perrotey, S., Fall, I., Ennahar, S., Zhao, M., Diop, Y. M., Candolfi, E., & Marchioni, E. (2011). *Icacina senegalensis* (Icacinaceae), traditionally used for the treatment of malaria, inhibits in vitro *Plasmodium falciparum* growth without host cell toxicity. *Malaria Journal*, *10*, 85. https://doi.org/10.1186/1475-2875-10-85.

Shagal, M. H., & Kubmarawa, D. (2013). Antimicrobial and phytochemical screening of *Icacina trichantha*. *American Journal of Biomedical and Life Sciences*, *1*(2), 37–40.

Shikora, S., Martindale, R., & Schwaitzberg, S. (2002). *Nutritional considerations in the intensive care unit. iowa: Kendall*. Hunt Publishing Co.

Teye, G. A., Coffie, M., & Teye, M. (2011). Effects of raw false yam (*Icacina oliviformis*) seed meal in broiler rations, on carcass yield and eating qualities of the meat. *Journal of Animal Science Advances*.

Umoh, E. O., & Iwe, M. O. (2014). Effects of processing on the nutrient composition of false yam (*Icacina trichantha*) flour. *Nigerian Food Journal*, *32*(2), 1–7.

van Soest, P. J., Robertson, J. B., & Lewis, B. A. (1991). Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. *Journal of Dairy Science*, *74*(10), 3583–3597. https://doi.org/10.3168/jds.S0022-0302(91)78551-2

Vanhaelen, M., Planchon, C., Vanhaelen-Fastré, R., & On'Okoko, P. (1987). Terpenic constituents from *Icacina senegalensis*. *Journal of Natural Products*, *50*(2), 312–312.

Verband Deutscher Landwirtschafts und Forschungsanstalten (VDLUFA). (2006). Chemical analysis of animal feed [Die chemische Untersuchung von Futtermitteln], Methodenbuch, Band III-Futtermittel.

Zhao, M., Onakpa, M. M., Santarsiero, B. D., Chen, W.-L., Szymulanska-Ramamurthy, K. M., Swanson, S. M., Burdette, J. E., & Che, C.-T. (2015). (9bh)-pimaranes and derivatives from the tuber of *Icacina trichantha*. *Journal of Natural Products*, *78*(11), 2731–2737. https://doi.org/10.1021/acs.jnatprod.5b00688.

5 Chapter 5

Arthropod communities in urban agricultural production systems under different irrigation regimes in the Northern Region, Ghana

This chapter has been published as Amprako, L. K., Stenchly, K., Wiehle, M., Nyarko, G. and Buerkert, A. 2020. Arthropod communities in urban agricultural production systems under different irrigation regimes in the Northern Region of Ghana. Insects 11(8), E488. DOI: 10.3390/insects11080488.

Arthropod communities in urban agricultural production systems under different irrigation regimes in the Northern Region, Ghana.

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Abstract Urban and peri-urban agricultural (UPA) production systems in West African countries do not only mitigate food and financial insecurity, they may also foster biodiversity of arthropods and partly compensate for structural losses of natural environments. However, management practices in UPA systems like irrigation may also contribute to further disturbances in arthropod ecology. To fill knowledge gaps in the relationships between UPA management and arthropod populations, we compared arthropods species across different irrigation regimes in Tamale. During a 72-hour sampling period 14,226 arthropods were caught with pitfall traps and pan traps from 36 fields. These specimens comprised 13 orders, 103 families, 264 genera, and 329 taxa (243 identified species, 86 unidentified species) and categorized into five feeding guilds (carnivores, decomposers, herbivores, omnivores, and pollinators). Species richness, species accumulation curves, and diversity functions (richness, evenness, and dispersion) were calculated to characterize the arthropod community. Non-metric multidimensional scaling was applied to examine structural similarity of arthropod communities among sites. To account for the effects of soil-related data, we furthermore applied a redundancy analysis. Arthropods grouped according to the irrigation water source, whereby the dipterans were most dominant under wastewater conditions.

Here, particularly the eye gnat fly *Hippelates pusio* a disease causing vector for humans, accounted for the dipterans. The occurrence of three alien ant species suggests shifts in community assemblages through invasive species, while the occurrence of seven ant species that form mutualistic relationships with aphids, highlights future risk of aphid pest outbreak. Future studies on these taxa could specifically target their ecological and economic effects and potential countermeasures.

Keywords: Agrobiodiversity, Ecosystem service, Feeding guild, Insects, NMDS, RDA, species function, Sub-Sahara Africa, Urban agriculture

5.1 *Introduction*

Agriculture practiced within and around human agglomerations known as urban and peri-urban agriculture (UPA) has been a source of food for humans for centuries (Watts, 2016). Its role during the last two decades has grown due to its contribution to food security and the improvement of livelihoods.

Food and financial security have been a global concern for many decades, especially in the developing world where food insecurity risk is high and cascading effects like mass migration and conflicts within affected areas prevail. Africa is a region where one-fifth of the population experience hunger (World Health Organization, 2018) and in Sub.Saharan Africa, almost half of the people live below the poverty line (World Bank, 2018). Under these conditions, UPA helps to mitigate hunger and poverty in the urban population and thus contributes to the resilience of African cities (Bellwood-Howard et al., 2018).

Since UPA systems are productive vegetative features they may also increase the arthropod biodiversity of urban landscapes and improve ecosystem services, ameliorate urban-heat-island, and serve as habitats for wildlife (Lin et al., 2015). Moreover, these typically small-scale land use systems not only support urban biodiversity, their productivity in turn also heavily depends on the biodiversity of diverse pollinating insects and pest regulating agents (Lowe et al., 2019). It is in this context that it becomes interesting for ecologists to collect data from the field to gain a better understanding about the diversity of arthropod communities and how these are determined by agricultural intensification as well as the relationship with other environmental conditions.

Agricultural intensification has been shown to influence the species composition of communities and negatively affect their functional trait diversity and thus contributes to the attenuation of ecosystem functioning and ecosystem services (Emmerson et al., 2016). In and around West African cities, agricultural intensification leads to nutrient applications far beyond optimum (Lompo et al., 2012). High fertilization rates are often combined with high doses of pesticides. Additionally, because of the long lean season, West African UPA farmers mostly rely on external water sources other than rainfall to irrigate their crops whereby some farmers resort to the usage of untreated municipal wastewater from open channels. Such water sources often run through cities and carry a mixture of natural dilutes and human waste, laden with chemicals and pathogens. Irrigation water may also be a medium for the pupation of insect pests (Z. Li et al., 2019) and disease vectors such as mosquitoes of the genus *Anopheles* and *Culex* (Akpodiete et al., 2019). As such, the usage of inadequately processed wastewater for irrigation that in turn can pose major threats to soil properties (Okorogbona et al., 2018) as well as below and above-ground biodiversity (Githongo, 2010) may negatively affect farmers' and consumers' livelihoods in West Africa. In addition, the shift in agricultural land use from wind pollinated crops such as sorghum (*Sorghum bicolor* MOENCH), millet (*Pennisetum glaucum* (L.) R.BR.), and maize (*Zea mays* L.) to crops that rely on insect pollination for seed and fruit development such as okra (*Abelmoschus esculentus* (L.) MOENCH), pepper (*Capsicum annum* L.) and garden eggs (*Solanum aethiopicum* L.) (Stenchly et al., 2017), has led to an increased dependence of West African farmers' livelihoods and food security on the existing biodiversity (Tilman et al., 2017).

Cities are hotspots of biological invasions. Particularly semi-natural urban ecosystems, as such as UPA systems, can assist in the invasion of non-native species which negatively affect ecosystem services upon which human societies depend (Gaertner et al., 2017). They may further affect human health by acting as vectors of human and animal diseases, causing allergic reactions (Rabitsch et al., 2017) and displace native species, thereby contributing to the homogenization or even to the loss of species within cities (McKinney, 2006; Sánchez-Bayo & Wyckhuys, 2019)

Despite these contributions, little is known about species composition of arthropod communities and their ecological role in West African urban agroecosystems and how these arthropod communities are affected by farmer' management practices such as irrigation sources.

This study therefore aimed at conducting a baseline species inventory of arthropods inhabiting West African urban production systems and assessing how arthropod communities are shaped by farmers' practices, considering the use of different sources of irrigation water.

5.2 *Materials and methods*

5.2.1 Study area

The Northern Region of Ghana, with its capital Tamale, is a rapidly developing provinc. It has a tradition of UPA with a positive impact on household food security as it provides access to food and generates income. In Tamale, UPA activities are the third most important source of earnings, after informal business and wage income, and contribute nearly a fifth to a household's earning (Ayerakwa, 2017). UPA in and around Tamale takes many forms, with various crop farm types characterised by different spatial and tenure arrangements, and different sources of irrigation (Bellwood-Howard et al., 2018). Irrigation water is a limiting factor in this Sudanian region. Notwithstanding, it has the least available source of groundwater in the entire country, due to its highly weathered soils that have a high water permeability of water which reduces the storage capacity of aquifers in the region (Carrier et al., 2011). The region is the poorest in Ghana (Abdulai et al., 2018) and tap water is available to just about 50 % of the urban dwellers (Boateng et al., 2013). In this context, UPA farmers resort to rainwater, tap water, well water, dam water, and municipal wastewater to irrigate crops depending on its proximity or availability. The UPA systems constitute a mosaic of small fields in which vegetables like cabbage (*Brassica* spp. L.), lettuce (*Lactuca sativa* L.), amaranth (*Amaranthus* spp. L.), okra (*Abelmoschus esculentus* (L.) MOENCH), sweet pepper (*Capsicum annum* L.), spring onion (*Allium* spp. L.), garden eggs *Solanum aethiopicum* L.), tomatoes (*Solanum lycopersicum* L.), carrots (*Daucus carota* (HOFFM.) SCHÜBL. & G. MARTENS), and jute mallow (*Corchorus* spp. L.) are grown in polycropping systems.

The study was conducted in and around Tamale. The local climate is classified as semi-arid with annual mean minimum and maximum temperature of 22 °C and 34 °C, respectively, and a uni-modally distributed monthly precipitation of 1111 mm per year peaking between June and October (Climate-data.org, 2020). Data were collected in the suburbs (locations) of Nyanshegu (9°25'22.8"N, 0°50'6"W), Gumbehene New Dam (9°14'52.8"N, 0°10'19.2"W), Sangaani (9°25'8.4"N, 0°50'20.4"W), and Youngi Duuni (9°14'52.8"N, 0°42'43.2"W). Between seven to eight vegetable (pepper *Capsicum annum* L., okra (*Abelmoschus esculentus* (L.) MOENCH, and lettuce *Lactuca sativa* L.) fields were distributed across locations, comprising a total of 36 vegetable fields (Figure 14, p.81) with an average size of 300 m^2.

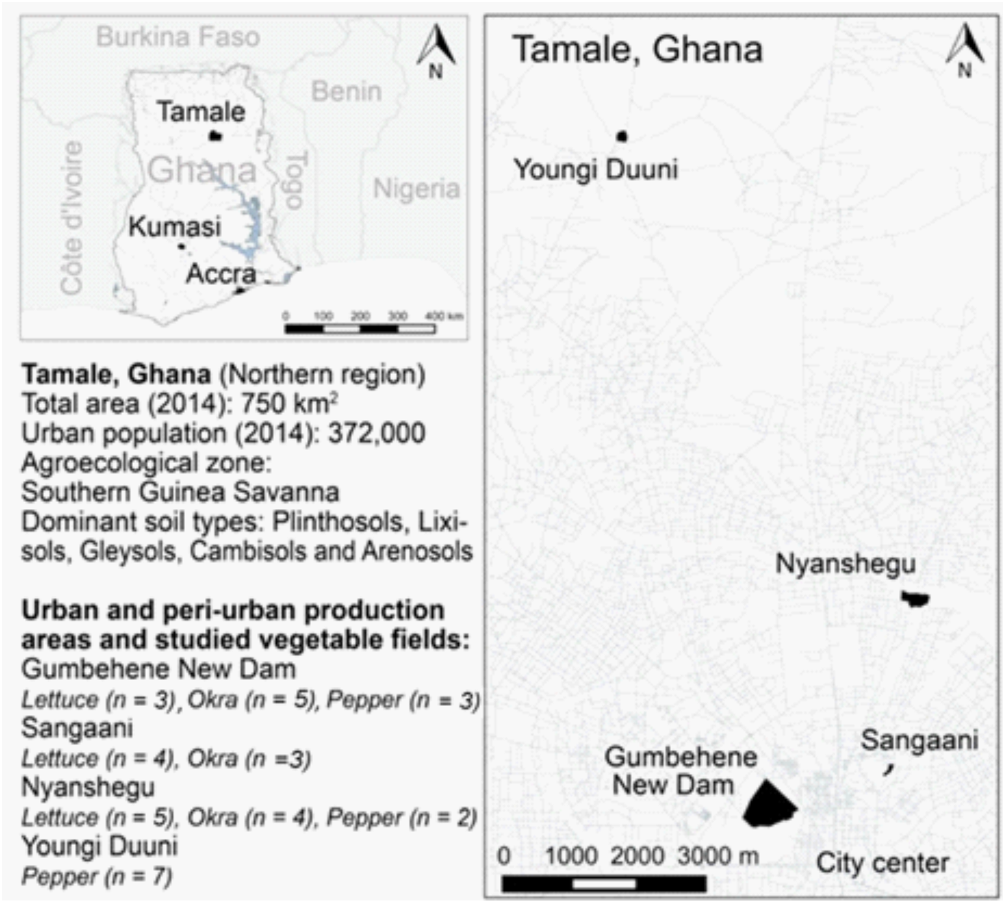

Figure 14: Map of Ghana with major cities (left) and Tamale in the Northern Region of Ghana (right) showing the location of the studied urban and peri-urban production systems. Data retrieved from www.openstreetmap.org (OpenStreetMap contributors 2019). Figure produced in R version 3.6.0 (R Development Core Team 2018)

5.2.2 Site description

Across the 36 fields, a set of parameters related to farmer's management were recorded such as type of amendments and irrigation water, age of farm as well as pesticide and weedicide usage. Also determined were the topsoils' (0- 20 cm) electrical conductivity (EC), carbon-to-nitrogen ratio (C/N), total phosphorous (P), and pH. To further characterize location-specific differences the most probable number (MPN) of faecal indicator bacteria *Escherichia coli* and *Enterococccus* spp. per 100 ml of each irrigation source was sampled once in August 2016 and analyzed using standard protocols. In addition, in the centre of each of the four locations, a 200 m long transect (north-south direction) was established to count all perennial species with > 5 cm diameter at breast height 10 m left and right each of the transect and identified to the species level. richness and diversity indices (Exponential Shannon index, Inverse Simpson´s index, Inverse Berger-Parker index) based on Hill's numbers (Chao et al., 2014) were calculated with the 'hillR' and 'divers' packages (Guevara et al., 2016; D. Li, 2020) in R version 3.6.2 "Dark and Stormy Night" (R Development Core Team, 2019).

The sources of irrigation water differed markedly per location (Table 14, p.83). in Youngi Duuni, the least urbanised location, agriculture was purely rainfed, while crop cultivation in Gumbehene New Dam a farming area located on the periphery of a protected forest, relied on tap water irrigation. Irrigation with tap is made possible due to the proximity of this farming location (less than 200 m away) to the Ghana Water Company Limited, which provides water to the region. The Sangaani fields are irrigated with water from a well, whilst the farming location of Nyanshegu relies on water from an open (wastewater) channel.

Most of the fields were amended with mineral fertilisers: comprising all rainfed fields (n = 7), 82 % of wastewater (n = 12) and 82 % of tap water irrigated (n = 10) fields, and 50 % of well water regime fields (n = 7). In contrast, manure fertilisation was uncommon (28 % of fields) and applied by 50 % of the well water fields, by 20 % of the rainfed and wastewater fields each, and by 10 % of the tap water fields. All types of irrigation water were contaminated with the faecal indicator bacteria *Escherichia coli* and *Enterococcus* spp., with high loads in wastewater. Wastewater usage significantly increased soil EC, Bray-P, C/N ratio (Table 14., p.83).

Table 14: Mean standard deviation of soils' electrical conductivity (EC), carbon-to-nitrogen ratio (C/N), total phosphorous (P), pH, and counts of *Escherichia coli* and *Enterococccus* spp. (in most probable count number (MPN) 100 ml $^{-1}$) within the irrigation water source measured in vegetable fields under different irrigation sources in four UPA locations in Tamale, Ghana in August 2016. Different letters indicate significant differences between groups using p 0.05 as threshold for significance. NB faecal bacteria loads were only sampled once per location, hence no standard deviations were calculated.

Irrigation	**EC**	**C/N**	**P**	**pH**	***E. coli***	***Enterococcus spp.***
	(µS cm^{-1})		**(g kg^{-1})**		**(MPN 100 ml^{-1})**	
Rainfed	68.84 ± 33.75^{a}	10.14 ± 1.50^{a}	75.38 ± 77.98^{a}	6.37 ± 0.70^{ab}	-	-
Tap	129.01 ± 135.69^{ab}	11.94 ± 2.80^{ab}	73.25 ± 43.69^{a}	5.92 ± 0.81^{a}	4.23	3.71
Well	225.95 ± 98.52^{ab}	12.73 ± 2.97^{ab}	210.82 ± 101.90^{ab}	6.67 ± 0.13^{ab}	3.63	3.04
WW	280.83 ± 187.20^{b}	13.71 ± 2.75^{b}	94.64 ± 36.90^{b}	6.70 ± 0.99^{b}	6.57	5.83

For the four sampled UPA locations tree abundance ranged between 73 and 125 individuals (Table 19, p.106). The rainfed location of Youngi Duuni, approximately 15 km from the city centre (linear distance), had highest tree species richness, whereas richness was lowest for the tap irrigated fields of Gumbehene New Dam, located next to a forest reserve in Tamale's city centre (Table 15, p.84). The well water irrigated fields of Sangaani and wastewater irrigated fields of Nyanshegu instead exhibited 11 and 13 species, respectively. At all four locations, mango (*Magnifera indica* L.), neem (*Azadirachta indica* A.JUSS), and lebbeck (*Albizia lebbeck* (L.) BENTH) were the most common tree species (Table 19, p.106). The tree exponential Shannon index among locations was more balanced (5.2 – 6.9) than the Inverse Simpson's and the Inverse Berger-Parker index (3.3 – 5.7 and 1.9 - 3.2 respectively) (Table 15, p.84).

Table 15: Total abundance, total species richness, and diversity indices of tree communities found on vegetable farms in four UPA locations under different irrigation regimes, namely rainfed (RF), tap water (Tap), well water (Well), and wastewater (WW) in Tamale, Ghana in August 2016. NB that tree species abundance and richness were only sampled once per location; hence, no standard deviations were calculated.

Location	**Abundance**	**Species richness**	**Exponential Shannon index**	**Inverse Simpsons's index**	**Berger Parker index**
Rainfed	101	15	5.6	3.3	1.9
Tap	125	11	5.2	4.1	2.7
Well	78	13	6.9	5.7	3.3
WW	73	9	5.8	5.2	3.2

5.2.3 Arthropod collection and species functions

For arthropod sampling, two types of traps (pitfall and pan trap) were used in August 2016 (rainy season). Ground active arthropods were sampled with a set of five roofed pitfall traps per plot on a 5 × 5 m grid (one trap in the centre; diameter top opening = 12 cm, depth = 11 cm; n = 180), while flying arthropods were sampled using a line of four pan traps (n = 144) along a 5 m tran-sect within a field. Each pan trap consisted of three plastic soup bowls attached to a stake at one-meter height above ground. Each bowl had a depth of 3 cm and was sprayed with white, yellow, and blue UV-reflecting colours, respectively, to catch Diptera, Hymenoptera, and Hemiptera, which are particularly attracted by the UV spectrum. Salt-saturated water with a drop of detergent soap was poured into the trap liquid. Pitfall and pan traps were exposed for 72 hours each, after which all arthropods were deposited in 70 % alcohol and determined to the species level. Arthropod species sampled were determined with arthropod taxa-specific literature and later cross-checked against the GBIF data base (Global Biodiversity Information Facility, 2020) for recent taxonomic changes. All verified entries were classified into one of five feeding guilds, namely carnivores, decomposers, herbivores, omnivores, or pollinators based on intensive online literature and data base searches. Carnivores comprised arthropods that relied primarily on other arthropods for food during their adult stage (or during their larval stage if they do not feed as adults). Decomposers comprised arthropods that obtained their diet from decaying organic matter, while herbivores obtained their diet by feeding on any part of a plant (including seeds). Omnivores referred to those arthropods that fed on other animal species, organic matter, and plants, whilst pollinators were those that fed on pollen and or nectar and pollinated flowers as a result.

5.2.4 Species indices and multivariate statistics

To evaluate the reliability of the sampling procedure, rarefaction curves by means of the Mao Tao estimator (Chao et al., 2013) were generated with EstimateS (Colwell, 2006). All further calculations and visualizations were done with R version 3.6.2 "Dark and Stormy Night" (R Development Core Team, 2019). The overall share of arthropod orders were displayed using the 'treemap' (Tennekes & Ellis, 2017). As for tree abundance, arthropod richness and diversity indices (Exponential Shannon index, Inverse Simpson´s index, Inverse Berger-Parker index) based on Hill numbers (Chao et al., 2014) were calculated with the 'hillR' package. Arthropod abundance data were analysed with the 'vegan' package (Oksanen et al., 2013). To describe arthropod communities' function (evenness and dispersion, the 'functional diversity' (FD) package (Laliberté et al., 2014) was used in R by linking a species-abundance matrix with a species-function (feeding guild) matrix giving equal weight to all functions. The community-weighted mean of a trait (CWM hereafter) defined as the, field-level trait presence weighted by species abundances was calculated to characterize arthropod communities (Lavorel et al., 2008). Since data were not normally distributed, Kruskal-Wallis followed by posthoc Conover Imam tests (where necessary) were performed to assess the difference between the mean FD indices and CWMs for each irrigation source.

Thereafter, all arthropods with a frequency of at least 0.1 % and an occurrence in at least three of four types of irrigation sources were selected, resulting in a total of 24 species (64 % of the total abundance of species studied). The analyses of only a fraction of sampled species is not untypical in ecological studies as it reduces noise and allows the drawing of more meaningful relationships (Gamito & Furtado, 2009; Lavorel et al., 2008). Boeckel and Baumann 2008 for instance, selected only the most abundant species in their study of phytoplankton in the South Atlantic Ocean. Also Morales and Aizen 2006 and Gamito 2009 reduced species communities when analysing plant-pollinator interactions and benthic communities, respectively, to improve ordination display. To reduce the effect of largely differing abundances of the 24 species involved, abundance data were Hellinger-transformed. Afterwards the 'arthropod species – irrigation regime – crop type' matrix was subjected to Non-Metric Dimensional Scaling (NMDS) of unconstrained orientation (Dube et al., 2017). The stress (Kruskal's goodness-of-fit index) value was used to evaluate the goodness of the NMDS and a non-parametric permutational Multivariate Analysis of Variance (bootstrapped perMANOVA test) based on 999 permutations permutations accompanied by the Levene's variance homogeneity test were performed to compare the arthropods sampled under the different irrigation sources. The arthropod species-irrigation matrix (response data) was also subjected to a redundancy analysis (RDA), using the soil parameters, C/, N, EC, P, and pH as explanatory variables. The amount of variance explained by the explanatory variables was evaluated based on adjusted R^2 statistics

5.3 ***Results***

5.3.1 Arthropod communities' structure

A total of 14,226 arthropod individuals (13 orders, 103 families, 264 genera, and 329 taxa) were sampled, from which 12,089 (85 % of the total arthropods) comprising 243 species (12 orders, 88 families, 205 genera) were successfully determined, while 86 taxa (15 % of the total arthropods, 10 orders, 55 families) could only be determined to the genus level (Table 20, p.107). The most abundant orders were the Diptera, the Hymenoptera, and the Coleoptera (Fig. 2). Individuals belonging to the orders Dermaptera, Dictyoptera, Glomerida, Isopoda, Lepidoptera, and Orthoptera, accounted for about 2.4 % of the sampled arthropod community and were grouped as 'Others' (Fig. 2). The most abundant families were the Chloropidae (Diptera; n = 6123, 43 %), Formicidae (Hymenoptera; n = 3698, 26 %), Thripidae (Thysanoptera; n = 674, 5 %).

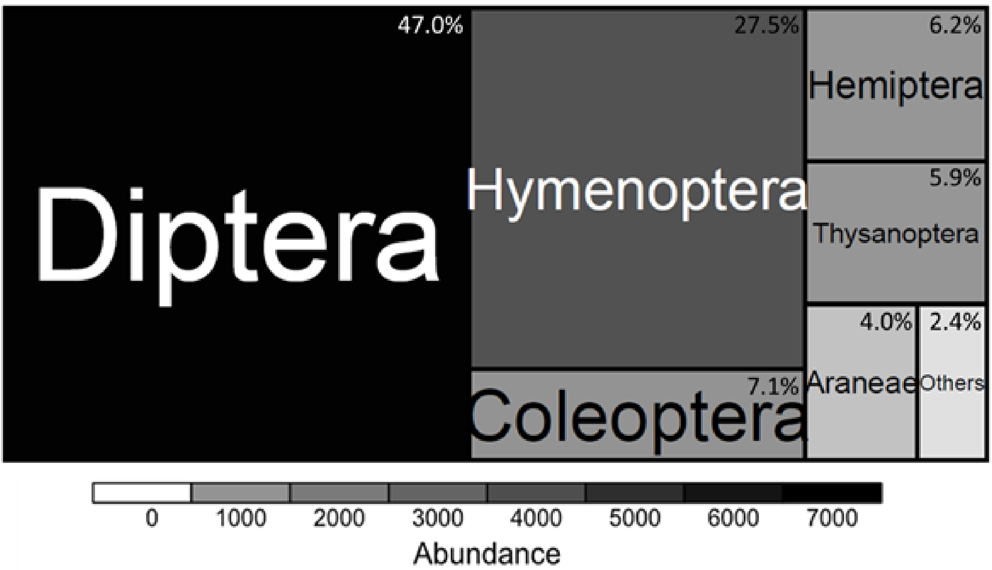

Figure 15: Abundance of arthropod orders caught with pitfall and pan traps during a 72-hour sampling in 36 vegetable fields of Tamale, Northern Region, Ghana in August 2016.

The most abundant species was the eye gnat (*Hippelates pusio* Chloropidae, Diptera; n = 5011, 35 % of all arthropods). Apart from the arthropods, two Haplotaxida species were caught (*Eisenia fetida* SAVIGNY, 1826, n = 4, 0.03 % and *Eudrilus eugeniae* KINBERG, 1876, n = 3, 0.02 %).

Overall, arthropod species accumulation curves for the different irrigation water sources differed significantly for the tap and the wastewater sources but none of the curves plateaued (Figure 16, p.87).

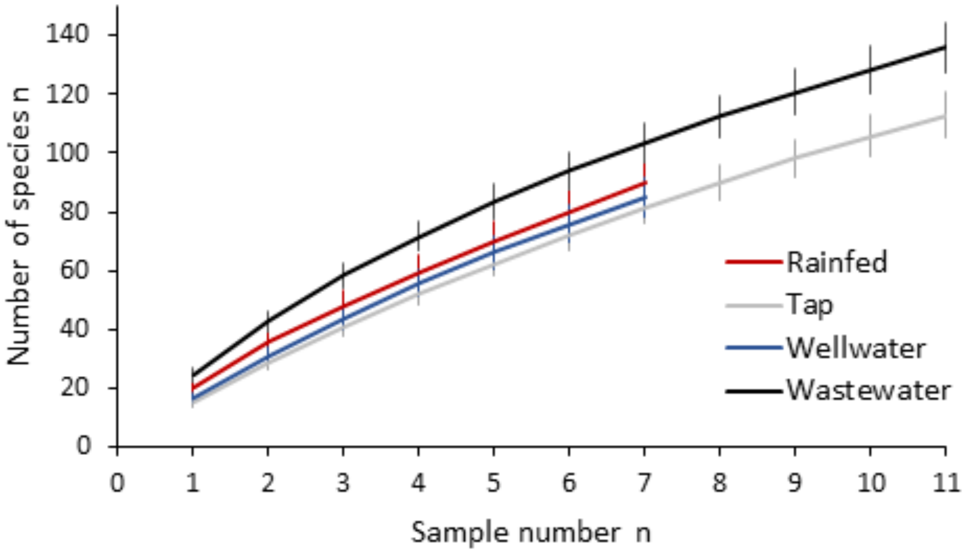

Figure 16: Arthropod species accumulation curves (Mao Tao estimator stan- dard deviation) of vegetable fields under different irrigation sources (four UPA locations) of Tamale, Northern Region, Ghana in August 2016.

The wastewater irrigated fields captured the highest abundance and richness, while the rainfed and well water irrigated fields had the highest diversity indices (Table 16, p.88). Functional richness and diversity (evenness and dispersion) in all four locations were low and rather homogeneously distributed (Table 17, p.89). Although statistically also non-significant, CWM of the different guilds indicated that carnivores and decomposers tended to be absent, while omnivores were present under rainfed conditions (Table 17, p.89). Herbivores and pollinators were unaffected by irrigation type.

Table 16: Total abundance, total species richness, and diversity indices based on Hill numbers of arthropod communities found on vegetable fields in four UPA locations and with different irrigation water sources, namely, rainfed (RF), tap water (Tap), well water (Well), and wastewater (WW), in Tamale, Ghana in August 2016.

Location	**Total abundance**	**Species richness**	**Exponential Shannon index**	**Inverse Simpson's index**	**Inverse Berger Parker index**
Rainfed	2105	90	19	9.36	3.89
Tap	3888	113	12	5.65	2.16
Well	2131	85	18	6.11	2.38
WW	6102	136	11	4.11	2.00

Table 17: Mean functional richness, evenness and dispersion of arthropod communities as well as community-weighted mean (standard deviation) of the five arthropod guilds recorded during a 72-hour sampling using pan and pitfall traps in different vegetable fields in four UPA locations with different irrigation regimes, namely, rainfed (RF), tap water (Tap), well water (Well), and wastewater (WW) in Tamale, Ghana in August 2016.

Locations	**Functional richness**	**Functional evenness**	**Functional dispersion**	**CWM Carnivore**	**CWM Decomposer**	**CWM Herbivore**	**CWM Omnivore**	**CWM Pollinator**
Rain-fed	4.71 ± 0.50	0.13 ± 0.02	0.27 ± 0.09	0.04 ± 0.03	0.11 ± 0.14	0.25 ± 0.18	0.58 ± 0.21	0.01 ± 0.01
Tap	3.90 ± 1.04	0.13± 0.06	0.23 ± 0.08	0.14 ± 0.21	0.24 ± 0.36	0.19 ± 0.24	0.41 ± 0.31	0.01 ± 0.02
Well	4.43 ± 0.53	0.14 ± 0.06	0.34 ± 0.05	0.13 ± 0.12	0.42 ± 0.20	0.26 ± 0.12	0.17 ± 0.17	0.01 ± 0.01
WW	4.55 ± 0.69	0.14 ± 0.06	0.31 ± 0.05	0.20 ± 0.22	0.40 ± 0.21	0.23 ± 0.19	0.16 ± 0.19	0.01 ± 0.01

Table 18: Ecological relevance and abundance of the 24 most abundant and equally distributed arthro-pod species found on vegetable farms under different irrigation regimes, namely rainfed (RF), tap water (Tap), well water (Well), and wastewater (WW) in Tamale, Ghana in August 2016.

Order	**Family**	**Genus**	**Species**	**Distribution/ Origin**	**Relevance**	**Rainfed**	**Tap**	**Well**	**WW**	**Total abundance**
Araneae	Agelenidae	*Agelenopsis*	*aperta*	Dry regions	Carnivore/ Pest regulator	12	24	29	442	507
Coleoptera	Chrysomelidae	*Ootheca*	*mutabilis*	Afrotropic	Herbivore	10	17	4	66	97
Coleoptera	Chrysomelidae	*Podagrica*	*sjostedti*	n.a.	Herbivore	15	8	90	50	163
Coleoptera	Scarabaeidae	*Sarcophaga*	carnaria	Worldwide	Decomposer	0	32	1	7	40
Diptera	Calliphoridae	*Calliphora*	sp.	n.a.	Decomposer	1	0	5	1	7
Diptera	Chironomidae	*Chironomus*	*plumosus*	Northern hemisphere	Decomposer	0	5	56	33	94
Diptera	Chloropidae	*Hippelates*	*pusio*	Nearctic, Neotropic	Decomposer/ Vector	191	1120	817	2883	5011
Diptera	Muscidae	*Musca*	*domestica*	Worldwide	Decomposer	11	15	0	22	48
Diptera	Stratiomyidae	*Hermetia*	*illucens*	Worldwide	Decomposer	1	50	0	1	52
Hemiptera	Cicadellidae	*Empoasca*	*facialis*	Neotropic	Herbivore	36	41	60	105	242
Hemiptera	Delphacidae	*Javesella*	*pellucida*	Worldwide	Herbivore/ Vector	29	0	10	14	53
Hemiptera	Miridae	*Lygus*	sp.	n.a.	Herbivore	0	6	9	3	18
Hemiptera	Pentatomidae	*Aspavia*	*armigera*	Neotropic	Herbivore	0	1	5	2	8
Hymenoptera	Apidae	*Apis*	*mellifera*	Worldwide	Herbivore	10	6	9	6	31
Hymenoptera	Formicidae	*Camponotus*	sp.	n.a.	Omnivore	22	237	0	60	319
Hymenoptera	Formicidae	*Monomorium*	*pharaonis*	Neotropic, Palaearctic	Omnivore	320	72	0	205	597
Hymenoptera	Formicidae	*Solenopsis*	*xyloni*	USA	Omnivore	501	256	60	146	963
Hymenoptera	Formicidae	*Tetramorium*	*caespitum*	Europe	Omnivore	169	0	121	392	682
Hymenoptera	Megachilidae	*Megachile*	*latimanus*	Worldwide	Pollinator	0	5	2	1	8
Hymenoptera	Scelionidae	*Eumicrosoma*	*beneficum*	Worldwide	Carnivore/ Pest regulator	2	4	0	5	11
Lepidoptera	Crambidae	*Hellula*	*undalis*	Worldwide	Herbivore	15	17	16	8	56
Lepidoptera	Hesperiidae	*Zophopetes*	*dysmephila*	Afrotropic	Herbivore	8	2	0	3	13
Orthoptera	Gryllidae	*Gryllus*	sp.	n.a.	Herbivore	5	4	27	44	80
Orthoptera	Tetrigidae	*Tetrix*	*subulata*	Worldwide	Herbivore	0	4	3	13	20

5.3.2 Effect of farmers' management on arthropod species

Out of the short-listed 24 taxa, a strong association (higher than 60 % occurrence per taxa) to wastewater were found for: *Agelenopsis aperta*, *Ootheca mutabilis*, and *Tetrix subulata* (Table 18, p.90). Dominant in well water irrigated fields were *Calliphora* sp., *Aspavia armigera*, and *Chironomus plumosus*, while for tap water *Hermetia illucens*, *Sarcophaga carnaria*, *Camponotus* sp., and *Megachile latimanus* prevailed. *Zophopetes dysmephila* dominated rainfed fields.

The NMDS biplot (stress = 0.15, k = 3; Figure 17, p.91) shows that irrigation affected arthropod species more than crop type; however, both parameters were statistically significant ($p = 0.001$ and $p = 0.029$ respectively). Particularly rainfed and wastewater clustered with almost no overlap (p = 0.003 perMANOVA). The test of homogeneity of variance was equal for crops ($p = 0.182$, homogeneity given), but unequal for water sources ($p = 0.001$, homogeneity not given). Other assessed management related parameters had no influence on the arthropod community.

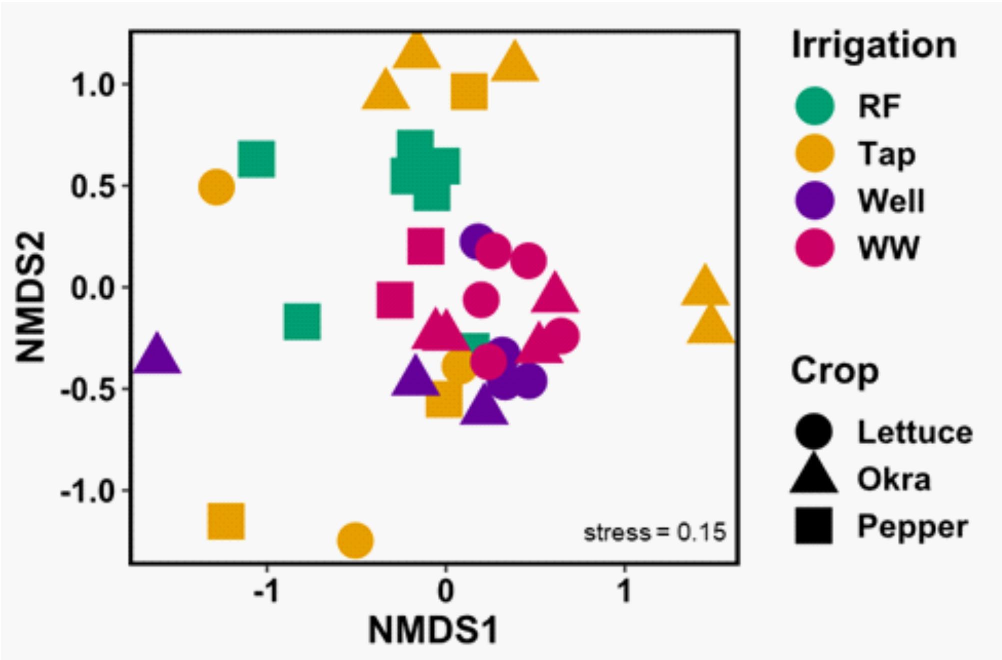

Figure 17: Non-metric multidimensional scaling (NMDS) biplot based on Bray-Curtis dissimilarity of all 36 arthropod communities caught on vegetable fields considering irrigation regime, namely rainfed (RF; green), tap water (Tap; yellow), well water (Well; purple), wastewater (WW; magenta) and crop type by using the 24 most abundant and equally distributed species sampled in UPA systems in Tamale, Northern Region, Ghana in August 2016.

Some of the 24 shortlisted species showed some dependence on the soil-related parameters visualized by the RDA (Figure 18, p.92). Occurrence of *Agelenopsis aperta* reflected an increase in P and EC, whilst number of *Hermeticia illucens*, *Sarcophagia carnaria*, and *Solenopsis xyloni* correlated with an increase in pH. *Gryllus* sp., *Hippelates pusio*, and *Ootheca mutabilis* seemed to be intermediately dependent on all three soil parameters, but in general related to higher nutrient loads (opposed to C/N, which indicates excess of nitrogen). Presence of *Tetramorium caespitum* and *Zophopetes dysmephilia* were moderately corresponded to an increase of C/N. Species like *Apis mellifera*, *Chironomus plumosus*, *Megachile latiamanus*, and *Tetrix subulata* appeared to be less affected by soil C/N, EC, P, and responded to rather low pH values. However, the model (R^2 adjusted) explained only 2.3% of the variation and was non-significant ($p = 0.25$).

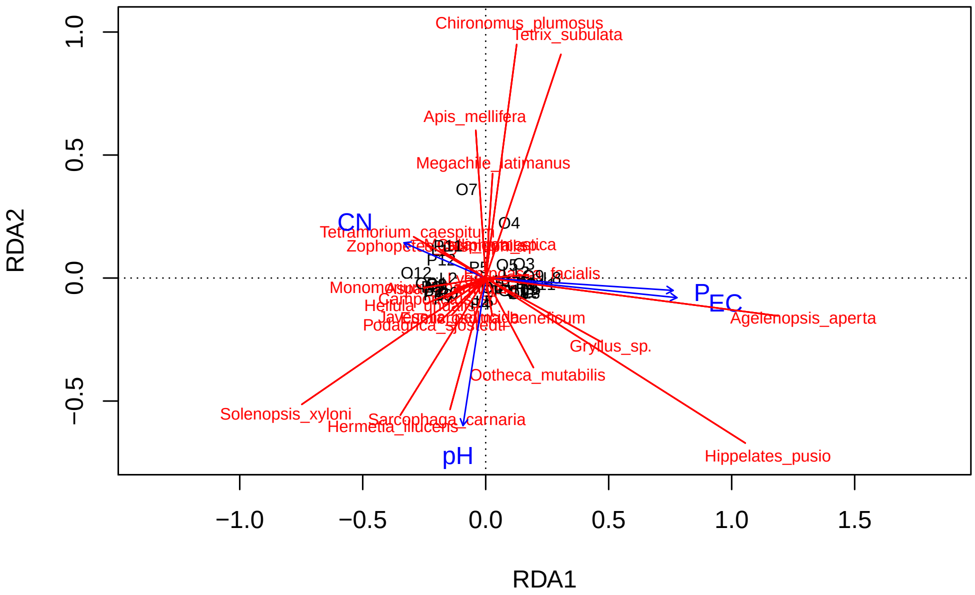

Figure 18: RDA (redundancy analysis) triplot (scaling 1) showing the relationship between soil carbon-to-nitrogen ratio (C/N), soil electric conductivity (EC), soil phosphorous content (P), and soil pH to the shortlisted 24 arthropod species sampled for 72 h in UPA systems of Tamale, Northern Region, Ghana, in August 2016

5.4 *Discussion*

5.4.1 Richness and function of arthropod species in the context of UPA-systems

Studies on arthropods' functional role within UPA systems, as for instance their contribution to improving and stabilizing crop-pollination services, are still rare (Wood et al., 2015). Particularly in West Africa where UPA systems play a key role in improving the nutritional security of vulnerable populations (Hallett et al., 2016), knowledge on crops-associated species communities and their functional (beneficial) role is limited. Given the growing economic importance of West African UPA activities which comprises the cultivation of more and more crops which require animal-mediated services such as pollination and predation (Stenchly et al., 2018), a better understanding of the effects of land use intensity and irrigation water quality on biodiversity-based ecosystem services is needed. Filling this knowledge gap is urgent as West African systems are increasingly exploited by the excessive and uncontrolled application of potentially harmful pesticides. Thus, studies on the functional community ecology of crop-associated insects should comprise a more comprehensive biodiversity monitoring (i.a. pollinator efficiency, predators' prey spectrum) while ensuring that different life stages of all taxa are taken into consideration (Rader et al., 2016). This knowledge may allow the implementation of more sustainable management practices in UPA systems.

Among the few available studies on arthropods in Northern Ghana Agyen-Sampong 1978 described 25 families and 46 genera of arthropod pests of sorghum in Nyankpala. N'Djolossè et al. 2012 recorded 8 orders, 36 families, and 56 genera of arthropods associated with shea trees (*Vitellaria paradoxa* C.F.GAERTN.) in Northern Ghana, while a study in the Kogyae Strict Nature Reserve (Forest Savanna Transition zone) recorded 21 orders, 135 families, including 107 butterfly species (Kyerematen et al., 2014). These values are in agreement with our data even if one would have expected that overall species richness was lower in our region than in the more humid zones studied in the aforementioned regions. The species accumulation curves suggest that even more species could be caught with an intensified sampling approach.

5.4.2 Effects of water irrigation sources on arthropod community structure

Almost a quarter of the UPA farmers in the Northern Region strongly relied on the usage of municipal untreated wastewater as the only source for irrigation, particularly for lettuce and okra production. From a farmer's perspective, the use of municipal wastewater in UPA is highly advantageous as its content of inorganic and organic dissolved substances makes wastewater a free fertilizer source (Vergine et al., 2017). Depending on its quality and origin, regular wastewater irrigation may retard plant growth (Pennington et al., 2018) and change soil properties (Abd-Elwahed, 2018; Dao et al., 2019). Furthermore, the usage of wastewater in agricultural production can directly and indirectly affect arthropod communities, below and aboveground. Aboveground effects can be related to changing plant chemical compositions, irregular flower formation, or changed nectar composition repelling pollinating insects (Knight et al., 2018). In our study, soils that received high doses of wastewater had a significantly higher EC, C/N ratio, and P-Bray content, and the highest soil pH (Table 14, p.83), therefore likely also influencing below-ground arthropod communities.

Arthropod abundance was highest in wastewater irrigated fields and lowest under rainfed and well water conditions. A possible explanation for this may be the higher quantity and quality of the foliage stimulated by nutrient rich wastewater thereby attracting herbivorous insects as observed in Ouagadougou, Burkina Faso by Stenchly et al. 2017, who recorded high abundances of orthopterans and hymenopterans in spinach fields (*Spinacia oleracea* L.) irrigated with wastewater. Another explanation could be the well-developed olfactory system of insects (Evershed, 2018), which allows a rapid detection of carbohydrates in irrigation wastewater (Body et al., 2018). A further explanation might be related to the low tree abundance recorded, which is known to decrease micro-habitat conditions for arthropod predators such as bats and birds, but also arthropods such as spiders which potentially regulate arthropod communities (Blaum et al., 2009). In spite of the high arthropod abundance and richness in wastewater irrigated fields, arthropod communities under these conditions are dominated by a few species only, as reveales by the low values of the exponential Shannon index, the Inverse Simpson's and Inverse Berger-Parker. Silva et al. 2020 found that amending fields with mineral fertilizers increased the abundance of arthropod predators, while other feeding guilds declined. Despite the plausibility of this explanation, none of our results on functional richness, and CWM indicated that this could have been valid for our study. Instead, the guild of decomposers had lowest CWM under rainfed and the highest one under well water conditions. The decomposer species *Chironomus plumosus* (Dipterans, Chironomidae) was found especially under well and wastewater conditions. Chironomidae are known to prefer decaying organic amendments (Menta & Remelli, 2020). Considering only the CWM values for decom-posers may indicate the usefulness of this guild as indicator group for non-contaminated soil and water conditions and therefore ecosystem health in UPA systems. Bundschuh et al. 2009 showed a reduced invertebrate decomposer activity in the presence of chemicals in wastewater irrigation.

5.4.3 Ecology of the dominant arthropod species

The alien eye gnat (*Hippelates pusio*, Diptera), which is a vector for bovine mastitis (Gerhardt & Axtell, 1973), anaplasmosis (Dantas-Torres & Otranto, 2017), bacterial conjunctivitis (Machtinger & Kaufman, 2011), and yaws (Mitjà et al., 2013), dominated our samples to almost 50 %. To our knowledge, this is the first time a study highlights the association between wastewater irrigation and the occurrence of eye gnats in Tamale, and further studies should investigate how this may be related to the incidence of this vector transmitted diseases. From our data, *Hippelates pusio* was strongly correlated with the use of wastewater amounting to 58% occurrence in wastewater irrigated fields of Nyanshegu (Table 18, p.90). Yaws is a skin and bone disease caused by the spirochete bacterium *Treponem pallidum pertenu* SCHAUDINN & HOFFMAN. The disease was controlled in the late 1960s in Ghana, but it resurged in the early 1980s (Agadzi et al., 1983). It is still prevalent in Ghana and is even believed to have developed resistance to antibacterial drugs (Ghinai et al., 2015). Anaplosmosis, a disease caused by the bacteria genus *Anaplasma*, causes leukopenia, thrombocytopenia, and anaemia in livestock and fevers in humans (Dantas-Torres & Otranto, 2017). It was found to have an incidence of 60 % in livestock in Ghana's capital Accra (Bell-Sakyi et al., 2004). Given that livestock production is more common in the north of Ghana (Ghana Statistical Service, 2020), it is plausible that anaplasmosis incidence will be higher also in our study region than in the more developed southern capital area.

While the eye gnat dominated in fields with problematic hygiene, two out of three alien ant species (Formicidae, Hymenoptera) dominated in rainfed fields. Among those was the most abundant species – the fire ant *Solenopsis xyloni* – belonging to the *Solenopsis geminate* species group (Trager, 1991) and a native to the USA. Due to the species' highly carnivorous feeding behaviour that may cause a destabilisation in community patterns of important predatory arthropods on agricultural fields, this species has a great potential to become a serious pest (Wetterer, 2010) and as such it poses a great risk of becoming invasive in West African UPA systems. Furthermore, *Solenopsis xyloni* attends not only to aphids and leaf hoppers for their honeydew (Wheeler, 1914), it also causes considerable damage to seed banks, attacks newly hatched birds, girdles agricultural plants, and affects agricultural produce (MacKay & Mackay, 2002). The origin of the second most dominant ant – the Pharaoh ant *Monomorium pharaonis* – is uncertain and was ascribed to South East Asia (Wetterer, 2010) as well as to tropical Africa (Leong et al., 2017). Although its influence on agriculture is yet to be determined, its abundance is associated with urbanisation (Leong et al., 2017) and it is believed to spread diseases in hospitals (van den Noortgate et al., 2018). Although only 12 % of the Pharoah ants were sampled in the tap irrigated fields of Gumbehene New Dam which are among the most urbanised areas of Tamale, the species' potential to cause problems as just about four kilometres from these fields is the third largest teaching hospital of Ghana. The third most dominant species – the sugar ant *Tetramoroum caespitum* is native to Europe (Wagner et al., 2017). It is known to avoid urban areas, however the exact reason for this non-synanthrope behaviour is unknown (Cordonnier et al., 2019). *Tetramoroum caespitum* may thus still be of concern for farmers in less urbanized suburbs of Tamale since it is also known to protect aphids from biological predators (Katayama & Suzuki, 2003). All three highly aggressive ant species of exotic origin, which were found to dominate arthropods' composition within UPA fields, may have negative effects on native arthropod communities and their functions and they become invasive in the future. The three alien ant species accounted alone for nearly 16%.

Apart from the dominance of some invasive species, one pest regulatory species, the desert spider *Agelenopsis aperta*, occurred up to 87 % in wastewater-irrigated fields. A plausible explanation could be the lush growth of crops through nutrient rich wastewaters which attracted abundant prey for this species. Pommeresche et al. 2017 and Utami et al. 2017 reported a high correlation between soil amendments with the abundance and diversity of soil fauna while Akamatsu et al. found that insects attracted to wastewater discharge are potential feed sources for spiders.

The occurrence of ants and lepidopterans are also of agricultural concern. At least seven ant species which were found within the studied UPA systems (*Camponotus atriceps* and *C. chrysurus* only in tap water irrigated fields, *C. importunes* dominated in rainfed fields (73%), *Monomorium bicolor* only in well irrigated fields, *M. pharaonis* dominated in rainfed (53%) and well irrigated fields (34%), *Odontomachus brunneus* dominated in well water irrigated fields (95%) and, *Tetramorium caespitum* dominated in well water irrigated fields (58%) and rainfed fields (24%)) that form mutualistic relationships with aphids. Aphid-ant mutualism has serious consequences for food security as they reduce crop yield while depleting pest regulator populations by up to 50 % (Ortega-Ramos et al., 2020). This mutualistic relationship is further strengthened by urbanisation (Rocha & de Fellowes, 2020) as prevalent in the Northern Region of Ghana. Lepidopterans like *Colotis* sp., *Dyptergia* sp., and coleoptearans like *Podagrica sjostedti* and *P. uniformis* are herbivores that may be of further of concern to farmers although their sampled abundances were low in this study.

5.5 *Evaluation and reliability of the data*

Lepidopterans have different feeding strategies and intensities at different life stages. While the juvenile larva feeds on plants for a couple of weeks, the adult may only feed on nectar for a few days, while moderately pollinating flowers. Ant species instead, have very flexible feeding behaviours, which largely depend on the available feed sources around a nest. They can be purely carnivorous or omnivorous, even indirectly herbivorous when attending aphids. Although the present study may contain this bias, the most abundant species used for our calculations are comparatively well known and their feeding behaviour is well characterized.

The methodological decision to reduce our overall sample set to 24 species is critical, demands a careful trade-off, and justification, but allowed for a reliable ordination (NMDS, RDA). The analyses of only a fraction of the sampled species is, however, typical in ecological studies dealing with multivariate data analyses as it reduces noise and allows the drawing of more meaningful relationships (Boeckel & Baumann, 2008; Gamito, 2006; Gamito & Furtado, 2009; Morales & Aizen, 2006).

In our study, we applied a quite rigorous reduction because we found only a few species that were heterogeneously distributed across the sampling locations but were still abundant. To our knowledge there are only rules of thumb on how many species should be considered for a NMDS ordination and how their results are interpreted: i) species used should not exceed the number of plots sampled, which was true for our case (24 species vs. 36 fields); ii) abundances should be more or less equally distributed across groupings, which was achieved by choosing only taxa that were present in at least three of the four irrigation water sources; iii) rare species should be excluded, which was done by applying the 0.1 % frequency criteria; lastly iv) only stress values below 0.2 are considered acceptable for NMDS outputs. However, we also tested the most dominant 9 (all those with a frequency >1.5 %), 15 (>1 %), 20 (>0.5 %), 29 (>0.4 %), and found stress values of 0.15, 0.11, 0.12, and 0.17, respectively, where certain distortions were observed (except for n = 9), although the overall tendency of similarly behaving well- and wastewater (strong clustering and almost no overlap) locations were both confirmed.

The RDA analysis showed that our explanatory parameters, C/N, EC, P, and pH explained only a very small part of the variation of the arthropod species data and this was not statistically significant. Borcard et al. 2018 recommend that such a result should not be interpreted nor plotted at all. However, since p values are not measures of evidence, we showed the plots to allow the display of trends in an otherwise very noisy data. A plausible explanation of low explanatory power could be that presence of arthropods is rather induced by volatile chemical components of the irrigation water, than by the soil parameters we measured.

In general our data indicated local effects of the irrigation source but we may have missed to find any relationship of the cultivated vegetable species on arthropod richness, diversity and feeding guilds. Instead, several factors may have led to these rather heterogeneous outcomes:

First, we studied a highly mosaic-like small-scale vegetable farming system characterized by a high spatial concentration of multiple crops with dozens of niches. This rather favours a homogeneous distribution of most species in space and time, although changes in the dominance of specific feeding guild with crop type can be expected even in small-scale systems (Fok et al., 2014). Plant species and their density affect arthropod communities significantly due to their variable plant architectures, specific traits, alternate micro-climatic conditions, pest attractiveness, and nectar provision potential (Koricheva & Hayes, 2018).

Second, most of the species observed are highly mobile and live under continuously changing agro-ecosystem conditions such as planting and harvesting activities, different farmers' practices, comparatively rapid crop cycles (lettuce), different life stages (all crops), variable fertilizer applications, and varying irrigation sources. All these lead to high turnovers and highly flexible habitat dwelling times. Hence, the timing and the extent of the sampling approach including the length of monitoring and the choice of the season has major effects on the catch and therefore the data. Jung et al. 2019 for instance suggested > 28 days for sampling and assessing arthropod communities. Although we covered this time period (August), the actual sample time per field was limited to three days. The choice of the season on the other hand may have affected feeding guilds like the pollinators who are particularly abundant when crops are in bloom (Shaw et al., 2020). In our study, the main flowering period had happened already, which likely resulted in a comparatively low number of caught pollinator species. However, considering the comparatively high number of 36 fields (and more trap repetitions within), the chosen sampling intensity seems still reliable and technically feasible.

Third, also the sizes of the sampled vegetable fields and the sample area per location largely differed. The tap irrigated location, Gumbehene New Dam, was the largest sampling area providing certainly also a wide range of niches. This effect appears evident when considering the second largest count of species richness as well as the most spread NMDS coordinates for Gumbehene New Dam.

Lastly, our experimental setup did not allow for random distribution of the test fields and the water source that farmers used to irrigate their fields. Thus, our data was affected by spatial autocorrelation, preventing us from elucidating the relationship between wastewater irrigation and the prevalence of disease-transmitting insects, which may pose a risk to farmers' health.

5.6 *Conclusions*

To our knowledge, this study is the first attempt to characterize the composition and functional partitioning of arthropod species communities sampled in West African UPA systems, in which farmers' management strategies vary widely regarding irrigation water quality. Despite the sampling's short duration, our results showed an effect of wastewater use for irrigation on arthropod species and abundance with particular focus on the presence of critical species (invaders and disease vectors). To predict how the aforementioned and highly dynamic species communities will affect vegetable production and human livelihoods in urban areas of the Northern Region of Ghana, a heavily understudied area so far, biodiversity monitoring schemes must be implemented at regional scales. These allow to deliver long-term data and to monitor biodiversity change associated with land use, population pressure and agricultural intensification.

Acknowledgement
We would like to thank the UPA farmers of Tamale, for their cooperation, our field assistant Alhassan Yakubu for his tireless support, Henry Davis for arthropod species identification, Korbinian Kaetzl for the analysis of irrigation water, and Stefan Werner for soil analyses. The support of the University for Development Studies (UDS) in Tamale, Ghana, is greatly appreciated.

5.7 References

References

Abd-Elwahed, M. S. (2018). Influence of long-term wastewater irrigation on soil quality and its spatial distribution. *Annals of Agricultural Sciences*, *63*(2), 191–199. https://doi.org/10.1016/j.aoas.2018.11.004

Abdulai, A.-G., Bawole, J. N., & Kojo Sakyi, E. (2018). Rethinking persistent poverty in northern ghana: The primacy of policy and politics over geography. *Politics and Policy*, *46*(2), 233–262. https://doi.org/10.1111/polp.12250

Agadzi, V. K., Aboagye-Atta, Y., Nelson, J. W., Perine, P. L., & Hopkins. (1983). Resurgence of yaws in Ghana. *The Lancet*, *322*(8346), 389–390.

Agyen-Sampong, M. (1978). Insect pests of sorghum heads and assessment of crop loss by the major pests. *Ghana Journal of Agricultural Science*, *11*(1.2.3), 109–115.

Akamatsu, F., Hideshige, T., & Okino, T. (2004). Food source of riparian spiders analyzed by using stable isotope ratios. *Ecological Research*, *19*(6), 655–662. https://doi.org/10.1111/j.1440-1703.2004.00680.x

Ayerakwa, H. M. (2017). Urban households' engagement in agriculture: Implications for household food security in ghana's medium sized cities. *Geographical Research*, *55*(2), 217–230. https://doi.org/10.1111/1745-5871.12205

Bell-Sakyi, L., Koney, E. B., Dogbey, O., & Walker, A. R. (2004). Incidence and prevalence of tick-borne haemoparasites in domestic ruminants in Ghana. *Veterinary Parasitology*, *124*(1-2), 25–42. https://doi.org/10.1016/j.vetpar.2004.05.027

Bellwood-Howard, I., Shakya, M., Korbeogo, G., & Schlesinger, J. (2018). The role of backyard farms in two West African urban landscapes. *Landscape and Urban Planning*, *170*, 34–47. https://doi.org/10.1016/j.landurbplan.2017.09.026

Blaum, N., Seymour, C., Rossmanith, E., Schwager, M., & Jeltsch, F. (2009). Changes in arthropod diversity along a land use driven gradient of shrub cover in savanna rangelands: Identification of suitable indicators. *Biodiversity and Conservation*, *18*(5), 1187–1199. https://doi.org/10.1007/s10531-008-9498-x

Boateng, D., Tia-Adjei, M., & Adams, E. A. (2013). Determinants of household water quality in the Tamale metropolis, Ghana. *Journal of Environment and Earth Science*, *3*(7), 70–77.

Body, M. J. A., Casas, J., Christidès, J.-P., & Giron, D. (2018). Underestimation of carbohydrates by sugar alcohols in classical anthrone-based colorimetric techniques compromises insect metabolic and energetic studies. *Journal of Insects as Food and Feed*, 322123. https://doi.org/10.1101/322123

Boeckel, B., & Baumann, K.-H. (2008). Vertical and lateral variations in coccolithophore community structure across the subtropical frontal zone in the South Atlantic Ocean. *Marine Micropaleontology*, *67*(3-4), 255–273. https://doi.org/10.1016/j.marmicro.2008.01.014

Borcard, D., Gillet, F., & Legendre, P. (2018). Canonical ordination. In *Numerical ecology with r* (pp. 203–297). Springer. https://doi.org/10.1007/978-3-319-71404-2_6

Bundschuh, M., Hahn, T., Gessner, M. O., & Schulz, R. (2009). Antibiotics as a chemical stressor affecting an aquatic decomposer–detritivore system. *Environmental Toxicology and Chemistry*, *28*(1), 197–203. https://doi.org/10.1897/08-075.1

Carrier, M.-A., Boyaud, C., Lefebvre, R., & Asare, E. (2011). Final technical report: Hydrogeological assessment project of the northern regions of Ghana (hap). http://espace.inrs.ca/id/eprint/1647/1/R001326.pdf accessed: 23.08.20

Chao, A., Wang, Y. T., & Jost, L. (2013). Entropy and the species accumulation curve: A novel entropy estimator via discovery rates of new species. *Methods in Ecology and Evolution*, *4*(11), 1091–1100. https://doi.org/10.1111/2041-210X.12108

Colwell, R. K. (2006). Estimates, version 9.1: Statistical estimation of species richness and shared species from samples: Software and user's guide. http://viceroy.%20eeb.%20uconn.%20edu/estimates.

Cordonnier, M., Gibert, C., Bellec, A., Kaufmann, B., & Escarguel, G. (2019). Multi-scale impacts of urbanization on species distribution within the genus *Tetramorium*. *Landscape Ecology*, *34*(8), 1937–1948. https://doi.org/10.5281/zenodo.3229214

Dantas-Torres, F., & Otranto, D. (2017). Anaplasmosis. In C. B. Marcondes (Ed.), *Arthropod borne diseases* (pp. 215–222). Springer International Publishing. https://doi.org/10.1007/978-3-319-13884-8_15

Dao, J., Lompo, D. J.-P., Stenchly, K., Haering, V., Marschner, B., & Buerkert, A. (2019). Gypsum amendment to soil and plants affected by sodic alkaline industrial wastewater irrigation in urban agriculture of Ouagadougou, Burkina Faso. *Water, Air, and Soil Pollution*, *230*(12). https://doi.org/10.1007/s11270-019-4311-x

Dube, T., DeNecker, L., van Vuren, J. H. J., Wepener, V., Smit, N. J., & Brendonck, L. (2017). Spatial and temporal variation of invertebrate community structure in flood-controlled tropical floodplain wetlands. *Journal of Freshwater Ecology*, *32*(1), 1–15. https://doi.org/10.1080/02705060.2016.1230562

Emmerson, M., Morales, M. B., Oñate, J. J., Batary, P., Berendse, F., Liira, J., Aavik, T., Guerrero, I., Bommarco, R., & Eggers, S. (2016). How agricultural intensification affects biodiversity and ecosystem services. *Advances in Ecological Research*, *55*, 43–97. https://doi.org/10.1016/bs.aecr.2016.08.005

Evershed, R. P. (2018). Insect olfaction and molecular structure. In B. N. Mandava (Ed.), *Handbook of natural pesticides* (pp. 1–33). CRC Press.

Fok, E. J., Petersen, J. D., & Nault, B. A. (2014). Relationships between insect predator populations and their prey, *Thrips tabaci*, in onion fields grown in large-scale and small-scale cropping systems. *Biocontrol Science*, *59*(6), 739–748. https://doi.org/10.1007/s10526-014-9612-9

Gaertner, M., Wilson, J. R., Cadotte, M. W., MacIvor, J. S., Zenni, R. D., & Richardson, D. M. (2017). Non-native species in urban environments: Patterns, processes, impacts and challenges. *Springer*. https://doi.org/10.1007/s10530-017-1598-7

Gamito, S. (2006). Benthic ecology of semi-natural coastal lagoons, in the Ria Formosa (Southern Portugal), exposed to different water renewal regimes. In K. Martens, H. Queiroga, M. R. Cunha, A. Cunha, M. H. Moreira, V. Quintino, A. M. Rodrigues, J. Seroôdio, & R. M. Warwick (Eds.), *Marine biodiversity* (pp. 75–87). Springer. https://doi.org/10.1007/1-4020-4697-9_7

Gamito, S., & Furtado, R. (2009). Feeding diversity in macroinvertebrate communities: A contribution to estimate the ecological status in shallow waters. *Ecological Indicators*, *9*(5), 1009–1019. https://doi.org/10.1016/j.ecolind.2008.11.012

Gerhardt, R. R., & Axtell, R. C. (1973). Flight of the Eye Gnat, *Hippelates pallipes* (Diptera: Chloropidae): Correlation with temperature, light, moisture and wind velocity. *Journal of Medical Entomology*, *10*(3), 290–294. https://doi.org/10.1093/jmedent/10.3.290

Githongo, M. (2010). Effect of sewage wastewater irrigation on soil biodiversity and heavy metals accumulation in soils and selected crops. *Journal of Tropical and Subtropical Agrosystems*, *12*, 1–63. https://doi.org/10.1016/j.agwat.2011.10.022

Global Biodiversity Information Facility. (2020). Retrieved, from Available%20from%20www.gbif.org/what-is-gbif

Hallett, S., Hoagland, L., Toner, E., Gradziel, T. M., Mitchell, C. A., & Whipkey, A. L. (2016). Urban agriculture: Environmental, economic, and social perspectives. *Horticultural Reviews*, *44*, 65–120.

Jung, J.-.-K., Jeong, J.-.-C., & Lee, J.-.-H. (2019). Effects of pitfall trap size and sampling duration on collection of ground beetles (Coleoptera: Carabidae) in temperate forests. *Entomological Research*, *49*(5), 229–236. https://doi.org/10.1111/1748-5967.12358

Katayama, N., & Suzuki, N. (2003). Bodyguard effects for aphids of *Aphis craccivora* koch (Homoptera: Aphididae) as related to the activity of two ant species, *Tetramorium caespitum* linnaeus (Hymenoptera: Formicidae) and *Lasius niger* l. (Hymenoptera: Formicidae). *Applied Entomology and Zoology*, *38*(3), 427–433. https://doi.org/10.1303/aez.2003.427

Knight, E. R., Carter, L. J., & McLaughlin, M. J. (2018). Bioaccumulation, uptake, and toxicity of carbamazepine in soil–plant systems. *Environmental Toxicology and Chemistry*, *37*(4), 1122–1130. https://doi.org/10.1002/etc.4053

Koricheva, J., & Hayes, D. (2018). The relative importance of plant intraspecific diversity in structuring arthropod communities: A meta–analysis. *Functional Ecology*, *32*(7), 1704–1717. https://doi.org/10.1111/1365-2435.13062

Kyerematen, R., Owusu, E. H., Acquah-Lamptey, D., Anderson, R. S., & Ntiamoa-Baidu, Y. (2014). Species composition and diversity of insects of the Kogyae Strict Nature Reserve in Ghana. *Open Journal of Ecology*, *4*, 1061–1079. https://doi.org/10.4236/oje.2014.417087

Laliberté, E., Legendre, P., Shipley, B., & Laliberté, M. E. (2014). Package 'FD' - measuring functional diversity (FD) from multiple traits, and other tools for functional ecology.

Lavorel, S., Grigulis, K., McIntyre, S., Williams, N. S. G., Garden, D., Dorrough, J., Berman, S., Quétier, F., Thébault, A., & Bonis, A. (2008). Assessing functional diversity in the field–methodology matters! *Functional Ecology*, *22*(1), 134–147. https://doi.org/10.1111/j.1365-2435.2007.01339.x

Leong, C.-M., Shiao, S.-F., & Guenard, B. S. (2017). Ants in the city, a preliminary checklist of Formicidae (Hymenoptera) in Macau, one of the most heavily urbanized regions of the world. *Asian Myrmecology*, *9*, e009014, 1–20. https://doi.org/10.20362/am.009014

Li, Z., Chambi, C., Du, T., Huang, C., Wang, F., Zhang, G., Li, C., & Juma Kayeke, M. (2019). Effects of water immersion and soil moisture content on larval and pupal survival of *Bactrocera minax* (diptera: Tephritidae). *Insects*, *10*(5), 138. https://doi.org/10.3390/insects10050138

Lin, Brenda, P., Stacy M, J., & Shalene. (2015). The future of urban agriculture and biodiversity-ecosystem services: Challenges and next steps.

Basic and Applied Ecology, *16*(3), 189–201. https://doi.org/10.1016/j.baae.2015.01.005

Lompo, D. J.-P., Sangaré, S. A. K., Compaoré, E., Papoada Sedogo, M., Predotova, M., Schlecht, E., & Buerkert, A. (2012). Gaseous emissions of nitrogen and carbon from urban vegetable gardens in Bobo-Dioulasso, Burkina Faso. *Journal of Plant Nutrition and Soil Science*, *175*(6), 846–853. https://doi.org/10.1002/jpln.201200012

Lowe, E. C., Latty, T., Webb, C. E., Whitehouse, M. E. A., & Saunders, M. E. (2019). Engaging urban stakeholders in the sustainable management of arthropod pests. *Journal of Pest Science*, 1–16. https://doi.org/10.1007/s10340-019-01087-8

Machtinger, E., & Kaufman, P. E. (2011). Eye gnats, grass flies, eye flies, fruit flies liohippelates spp. (insecta: Diptera: Chloropidae). *Electronic Data Information Source of University of Florida IFAS Extension*, *2011*(4).

MacKay, W. P., & Mackay, E. (2002). *The ants of New Mexico (hymenoptera: Formicidae)*. Edwin Mellen Press Lewiston, NY.

Menta, C., & Remelli, S. (2020). Soil health and arthropods: From complex system to worthwhile investigation. *Insects*, *11*(1). https://doi.org/10.3390/insects11010054

Morales, C. L., & Aizen, M. A. (2006). Invasive mutualisms and the structure of plant–pollinator interactions in the temperate forests of north–west Patagonia, Argentina. *Journal of Ecology*, *94*(1), 171–180. https://doi.org/10.1111/j.1365-2745.2005.01069.x

N'Djolossè, K., Atachi, P., & Gnanglè, C. P. (2012). Inventory of insects associated with shea trees (*Vitellaria paradoxa*) (sapotaceae) in central and northern Benin. *International Journal of Tropical Insect Science*, *32*(3), 158–165. https://doi.org/10.1017/S1742758412000240

Okorogbona, A. O. M., Denner, F. D. N., Managa, L. R., Khosa, T. B., Maduwa, K., Adebola, P. O., Amoo, S. O., Ngobeni, H. M., & Macevele, S. (2018). Water quality impacts on agricultural productivity and environment. In *Sustainable agriculture reviews 27* (pp. 1–35). Springer. https://doi.org/10.1007/978-3-319-75190-0_1

Oksanen, J., Blanchet, F. G., Kindt, R., Legendre, P., Minchin, P. R., O'hara, R. B., Simpson, G. L., Solymos, P., Stevens, M. H., & Wagner, H. (2013). Community ecology package, 2.0–2.

Pennington, M. J., Rothman, J. A., Jones, M. B., McFrederick, Q. S., Gan, J., & Trumble, J. T. (2018). Effects of contaminants of emerging concern on *Myzus persicae* (sulzer, hemiptera: Aphididae) biology and on their host plant, *Capsicum annuum*. *Environmental Monitoring and Assessment*, *190*(3), 125. https://doi.org/10.1007/s10661-018-6503-z

Pommeresche, R., Løes, A.-K., & Torp, T. (2017). Effects of animal manure application on springtails (collembola) in perennial ley. *Applied Soil Ecology*, *110*, 137–145. https://doi.org/10.1016/j.apsoil.2016.10.004

Rader, R., Bartomeus, I., Garibaldi, L. A., Garratt, M. P. D., Howlett, B. G., Winfree, R., Cunningham, S. A., Mayfield, M. M., Arthur, A. D., & Andersson, G. K. S. (2016). Non-bee insects are important contributors to global crop pollination. *Proceedings of the National Academy of Sciences*, *113*(1), 146–151. https://doi.org/10.1073/pnas.1517092112

Rocha, E. A., & de Fellowes, M. (2020). Urbanisation alters ecological interactions: Ant mutualists increase and specialist insect predators decrease on an urban gradient. *Scientific Reports*, *10*(1), 1–8. https://doi.org/10.1038/s41598-020-62422-z

Shaw, R. F., Phillips, B. B., Doyle, T., Pell, J. K., Redhead, J. W., Savage, J., Woodcock, B. A., Bullock, J. M., & Osborne, J. L. (2020). Mass-flowering crops have a greater impact than semi-natural habitat on crop pollinators and pollen deposition. *Landscape Ecology*, *35*(2), 513–527. https://doi.org/10.1007/s10980-019-00962-0

Silva, J. L., Demolin Leite, G. L., de Souza Tavares, W., Souza Silva, F. W., Sampaio, R. A., Azevedo, A. M., Serrão, J. E., & Zanuncio, J. C. (2020). Diversity of arthropods on *Acacia mangium* (fabaceae) and production of this plant with dehydrated sewage sludge in degraded area. *Royal Society Open Science*, *7*(2), 191196. https://doi.org/10.1098/rsos.191196

Stenchly, K., Dao, J., Lompo, D. J.-P., & Buerkert, A. (2017). Effects of waste water irrigation on soil properties and soil fauna of spinach fields in a West African urban vegetable production system. *Environmental Pollution*, *222*, 58–63. https://doi.org/10.1016/j.envpol.2017.01.006

Stenchly, K., Hansen, M. V., Stein, K., Buerkert, A., & Loewenstein, W. (2018). Income vulnerability of West African farming households to losses in pollination services: A case study from Ouagadougou, Burkina Faso. https://doi.org/10.17170/kobra-20190204144

Tennekes, M., & Ellis, P. (2017). Package 'treemap'.

Tilman, D., Clark, M., Williams, D. R., Kimmel, K., Polasky, S., & Packer, C. (2017). Future threats to biodiversity and pathways to their prevention. *Nature*, *546*, 73–81. https://doi.org/10.1038/nature22900

Trager, J. C. (1991). A revision of the fire ants, *Solenopsis geminata* group (hymenoptera: Formicidae: Myrmicinae). *Journal of the New York Entomological Society*, 141–198.

Utami, A. I., Utami, S. N. H., & Indarti, S. (2017). Influence of cow and chicken manure on soil fauna abundance and N uptake by rice in conversion from conventional to organic farming system. In A. Isnansetyo & T. R. Nuringtyas (Eds.), *Proceeding of the 1st international conference on tropical agriculture* (pp. 23–39). Springer International Publishing. https://doi.org/10.1007/978-3-319-60363-6_3

van den Noortgate, H., Lagrain, B., Wenseleers, T., & Martens, J. A. (2018). Analysis of cuticular lipids of the pharaoh ant (*Monomorium pharaonis*) and their selective adsorption on insecticidal zeolite powders. *International Journal of Molecular Sciences*, *19*(9), 2797. https://doi.org/10.3390/ijms19092797

Vergine, P., Salerno, C., Libutti, A., Beneduce, L., Gatta, G., Berardi, G., & Pollice, A. (2017). Closing the water cycle in the agro-industrial sector by reusing treated wastewater for irrigation. *Journal of Cleaner Production*, *164*, 587–596. https://doi.org/10.1016/j.jclepro.2017.06.239

Wagner, H. C., Arthofer, W., Seifert, B., Muster, C., Steiner, F. M., & Schlick-Steiner, B. C. (2017). Light at the end of the tunnel: Integrative taxonomy delimits cryptic species in the *Tetramorium caespitum* complex (hymenoptera: Formicidae). *Myrmecological News*, *25*, 95–129.

Watts, T. E. (2016). *Beyond the pleasure garden: Urban agriculture in ancient rome*. University of California, Santa Barbara.

Wetterer, J. K. (2010). Worldwide spread of the pharaoh ant, *Monomorium pharaonis* (hymenoptera: Formicidae). *Myrmecological News*, *13*, 115–129.

Wheeler, W. M. (1914). *The ants of the baltic amber*. BG Teubner.

Wood, S. A., Karp, D. S., DeClerck, F., Kremen, C., Naeem, S., & Palm, C. A. (2015). Functional traits in agriculture: Agrobiodiversity and ecosystem services. *Trends in Ecology and Evolution*, *30*(9), 531–539. https://doi.org/10.1016/j.tree.2015.06.013

World Bank. (2018). Poverty and shared prosperity 2018: Piecing together the poverty puzzle. http://www.fao.org/3/i9553en/i9553en.pdf

World Health Organization. (2018). *The state of food security and nutrition in the world 2018: Building climate resilience for food security and nutrition*. Food & Agriculture Organisation (FAO). http://www.fao.org/3/i9553en/i9553en.pdf

Table 19: List of tree species found on urban and peri-urban vegetable farms under different irrigation regimes in Tamale, Northern Region, Ghana in August 2016.

Tree species	**Rainfed (Youngi-duuni)**	**Tap water (Gumbehene New Dam)**	**Well water (Sangaani)**	**Wastewater (Nyanshegu)**
Anogeissus leiocarpus	3	0	0	0
Acacia versillatum	0	2	0	0
Adansonia digitata	3	0	0	0
Albizia lebbeck	12	36	3	16
Anarcardium occidentale	1	0	0	0
Annona muricata	0	0	1	0
Azadirachta indica	53	46	15	11
Ceiba petandra	5	9	4	8
Citrus sinensis	2	0	1	0
Cocos nucifera	1	0	3	0
Delonix regia	0	1	1	0
Diospyros mespiliformis	2	0	0	0
Elaeis guineensis	0	0	5	0
Faidherbia albida	2	0	0	0
Ficus benjamina	4	0	0	0
Ficus glumosa	0	0	0	1
Ficus gnaphalorcarpa	0	0	0	2
Ficus sp.	0	0	13	0
Khaya senegalensis	7	2	0	0
Lagenaria siceraria	0	0	2	0
Lannea acida	2	0	0	0
Mangifera indica	3	13	24	23
Milletia thonningia	0	2	0	0
Moringa oleifera	0	10	0	3
Parkia biglobosa	0	2	0	0
Polyalthia longifolia	0	0	5	0
Tectona grandis	0	2	0	0
Terminalia catappa	0	0	1	4
Vitellaria paradoxa	1	0	0	5

Table 20: List of arthropod species found in urban- and peri-urban vegetable farms under different irrigation regimes in Tamale, Northern Region, Ghana in August 2016.

Order	Family	Genus	Species	Author	Rainfed	Tap water	Well water	Waste water	Total abundance
Araneae	Agelenidae	*Agelenopsis*	*aperta*	Gertsch, 1934	012	024	029	442	507
Araneae	Desidae	*Badumna*	*insignia*	L. Koch, 1872			090	011	011
Araneae	Desidae	*Badumna*	sp.	Thorell, 1890		041	004		041
Araneae	Sparassidae	*Isopedella*	sp.	Hirst, 1990		002	001		002
Araneae	Sparassidae	*Palystes*	*superciliosus*	L. Koch, 1875		001	817		001
Coleoptera	Anthicidae	*Anthelephila*	*pedestris*	Rossi, 1790	001		005	003	004
Coleoptera	Aphididae	*Aphis*	*gossypii*	Glover, 1877	002		056		002
Coleoptera	Buprestidae	*Agrilus*	*derasofasciatus*	Boisduval & Lacordaire, 1835			000		001
Coleoptera	Buprestidae	*Sternocera*	*interrupta*	Olivier, 1790	001		000		001
Coleoptera	Buprestidae	*Sternoceras*	sp.	Eschscholtz, 1829			005		001
Coleoptera	Carabidae	*Agonum*	sp.	Linne, 1758		006	060		006
Coleoptera	Carabidae	*Agonum*	*viduum*	Panzer, 1796			010	015	015
Coleoptera	Carabidae	*Amara*	*plebeja*	Gyllenhal, 1810		002	009		002
Coleoptera	Carabidae	*Bembidion*	*articulatum*	Panzer, 1796		001	060		001
Coleoptera	Carabidae	*Bembidion*	sp.	Latreille, 1802			000	001	005
Coleoptera	Carabidae	*Brachypeplus*	*pilosellus*	Murray, 1864			000		016
Coleoptera	Carabidae	*Bradycellus*	*ruficollis*	Stephens, 1828		003	009		006
Coleoptera	Carabidae	*Bradycellus*	sp.	Erichson, 1837		001	002		001
Coleoptera	Carabidae	*Calathus*	*rotundicollis*	Dejean, 1828			000	001	001
Coleoptera	Carabidae	*Calathus*	*rotundicollis*	Dejean, 1829			121	001	001
Coleoptera	Carabidae	*Calathus*	*rotundicollis*	Dejean, 1830			016	001	001
Coleoptera	Carabidae	*Calathus*	*rotundicollis*	Dejean, 1831			000	001	001
Coleoptera	Carabidae	*Catascopus*	sp.	Kirby, 1825			027	001	001
Coleoptera	Carabidae	*Cicindela*	*nigrior*	Linnaeus, 1758			003	013	013
Coleoptera	Carabidae	*Colliuris*	sp.	De Geer, 1774	001				001
Coleoptera	Carabidae	*Galerita*	sp.	Fabricius, 1801	007				007
Coleoptera	Carabidae	*Hybothecus*	*flohri*	Bates, 1882				005	005
Coleoptera	Carabidae	*Panagaeus*	*bipustulatus*	Fabricius, 1775		002			002
Coleoptera	Carabidae	*Tachyta*	sp.	Kirby, 1837					001
Coleoptera	Carabidae	*Tachyta*	sp.	Meigen, 1803					001
Coleoptera	Certonidae	*Diplognatha*	*gagates*	Forster, 1771		001			001
Coleoptera	Chrysomelidae	*Acanthoscelides*	*obtectus*	Say, 1831		002			002
Coleoptera	Chrysomelidae	*Altica*	*oleracea*	Scott, 1876	004				004
Coleoptera	Chrysomelidae	*Calomela*	*eyrei*	Blackburn, 1890		001			001
Coleoptera	Chrysomelidae	*Cryptocephalus*	*sericeus*	Franz, 1938		001			001
Coleoptera	Chrysomelidae	*Lema*	*daturaphila*	Kogan & Goeden, 1970		002			002
Coleoptera	Chrysomelidae	*Lema*	sp.	Fabricius, 1798	004				004
Coleoptera	Chrysomelidae	*Ootheca*	*mutabilis*	Sahlberg, 1829	010	017		066	097
Coleoptera	Chrysomelidae	*Phyllotreta*	*undulata*	Kutschera, 1860	001				001
Coleoptera	Chrysomelidae	*Podagrica*	*sjostedti*	Fabricius, 1794	015	008		050	163
Coleoptera	Chrysomelidae	*Podagrica*	*uniformis*	Jacoby				122	122
Coleoptera	Ciidae	*Cis*	*fuscipes*	Fabricius, 1794	001				001
Coleoptera	Coccinellidae	*Aphidecta*	sp.	Linnaeus, 1758	001				001
Coleoptera	Coccinellidae	*Cheilomenes*	*lunata*	Fabricius, 1775	002	001			003
Coleoptera	Coccinellidae	*Chilocorus*	*circumdatus*	Gyllenhall in Schönherr, 1808				001	001
Coleoptera	Coccinellidae	*Scymnus*	sp.	Kugelann 1794					001

Order	**Family**	**Genus**	**Species**	**Author**	**Rainfed**	**Tap water**	**Well water**	**Waste water**	**Total abundance**
Coleoptera	Corylophidae	*Orthoperus*	*atomus*	Gyllenhal, 1808		002			002
Coleoptera	Curculionidae	*Archarias*	*salicivorus*	Paykull, 1792				001	001
Coleoptera	Curculionidae	*Bryochaeta*	*pusillus*	Pascoe, 1871					004
Coleoptera	Curculionidae	*Curculio*	*glandium*	Marsham, 1802	002				002
Coleoptera	Curculionidae	*Neomycta*	sp.	Pascoe, 1877					002
Coleoptera	Curculionidae	*Xyleborus*	*nitidipennis*	Roubal, 1937					007
Coleoptera	Cyrambicidae	*Exocentrus*	sp.	Dejean, 1835				001	001
Coleoptera	Dermastidae	*Trogoderma*	*glabrum*	Herbst, 1783				002	002
Coleoptera	Elateridae	*Adrastus*	*pallens*	Fabricius, 1792	001				001
Coleoptera	Elateridae	*Athous*	*niger*	Linnaeus, 1758		001			001
Coleoptera	Elateridae	*Athous*	*vittatus*	Fabricius, 1793					001
Coleoptera	Elateridae	*Conoderus*	*lividus*	De Geer, 1774		001			001
Coleoptera	Elateridae	*Dalopius*	*marginatus*	Linnaeus, 1758		003			003
Coleoptera	Geotrupidae	*Geotrupes*	sp.	Latreille, 1797				001	001
Coleoptera	Geotrupidae	*Geotrupes*	*splendidus*	Fabricius, 1775		001			001
Coleoptera	Histeridae	*Asolenus*	*julietteae*	Gomy, 2014	003				003
Coleoptera	Histeridae	*Hister*	*quadrimaculatus*	Linnaeus, 1758					002
Coleoptera	Histeridae	*Margarinotus*	*niponicus*	Lewis, 1895				001	001
Coleoptera	Histeridae	*Margarinotus*	sp.	Marseul, 1853				002	002
Coleoptera	Histeridae	*Platylomalus*	sp.	Jacoby				001	001
Coleoptera	Lamproblattidae	*Dictyoptera*	sp.	Gistel, 1857		002			002
Coleoptera	Meliodae	*Mylabris*	*variabilis*	Pallas, 1782	004			003	007
Coleoptera	Nitidulidae	*Epuraea*	*aestiva*	Linnaeus, 1758	051				051
Coleoptera	Nitidulidae	*Epuraea*	*alternans*	Grouvelle, 1912		058			075
Coleoptera	Nitidulidae	*Epuraea*	*luteola*	Erichson, 1843				147	212
Coleoptera	Rhagionidae	*Rhagio*	*aterrimus*	Fabricius, 1775	004				004
Coleoptera	Scarabaeidae	*Chiron*	sp.	Macleay, 1819				003	003
Coleoptera	Scarabaeidae	*Cyclocephala*	*lurida*	Bland, 1863		001			001
Coleoptera	Scarabaeidae	*Diplotaxis*	sp.	Kirby, 1837				001	001
Coleoptera	Scarabaeidae	*Omaloplia*	sp.	Schönherr, 1817					002
Coleoptera	Scarabaeidae	*Onthophagus*	*coenobita*	Herbst, 1783					
Coleoptera	Scarabaeidae	*Phyllophaga*	sp.	Harris, 1827	001				001
Coleoptera	Scarabaeidae	*Rhizotrogus*	sp.	Lepeletier & Serville, 1825				002	002
Coleoptera	Scarabaeidae	*Sarcophaga*	*carnaria*	Linnaeus, 1758		032		007	040
Coleoptera	Scarabaeidae	*Sarcophaga*	sp.	Meigen, 1826				002	002
Coleoptera	Scarabaeidae	*Serica*	sp.	Macleay, 1819		002			002
Coleoptera	Silvanidae	*Oryzaephilus*	*surinamensis*	Linnaeus, 1758				002	002
Coleoptera	Staphylinidae	*Batrisodes*	*venustus*	Reichenbach, 1816		005			005
Coleoptera	Staphylinidae	*Dacnochilus*	*compactus*	Casey, 1905		001			001
Coleoptera	Staphylinidae	*Gabrius*	*nigritulus*	Gravenhorst, 1802					005
Coleoptera	Staphylinidae	*Leptacinus*	*intermedius*	Donisthorpe, 1935				015	030
Coleoptera	Staphylinidae	*Othius*	*punctulatus*	Goeze, 1777		001			001
Coleoptera	Staphylinidae	*Paederus*	*riparius*	Fabricius, 1775					004
Coleoptera	Staphylinidae	*Scopaeus*	*sulcicollis*	Stephens, 1833)					001
Coleoptera	Staphylinidae	*Xantholinus*	*bicolor*	Sharp, 1876					002
Coleoptera	Staphylinidae	*Xantholinus*	*decorus*	Erichson, 1839				001	001
Coleoptera	Staphylinidae	*Xantholinus*	*elegans*	Olivier, 1795				003	003
Coleoptera	Staphylinidae	*Xantholinus*	*tricolor*	Fabricius, 1787		001			001
Coleoptera	Tenebrionidae	*Gonocephalum*	*simplex*	Fabricius, 1801				005	005
Coleoptera	Tenebrionidae	*Selinus*	sp.	Mulsant & Rey, 1853					001

Order	**Family**	**Genus**	**Species**	**Author**	**Rainfed**	**Tap water**	**Well water**	**Waste water**	**Total abundance**
Coleoptera	Tenebrionidae	*Tenebrio*	*molitor*	Linnaeus, 1758	001	003			004
Coleoptera	Tenebrionidae	*Tenebrio*	*obscurus*	Fabricius, 1792					003
Coleoptera	Tenebrionidae	*Tenibrio*	sp.	Linnaeus, 1758	002				002
Dermaptera	Forficulidae	*Forficula*	*auricularia*	Linnaeus, 1758	001			001	002
Dictyoptera	Ectobiidae	*Blattella*	*germanica*	Linnaeus, 1767		001		010	011
Dictyoptera	Ectobiidae	*Deropeltis*	sp.	Burmeister, 1838				001	001
Dictyoptera	Ectobiidae	*Periplaneta*	*americana*	Linnaeus, 1758				004	004
Diplopoda	Glomeridae	*Glomeris*	*marginata*	Villers, 1789				001	022
Diptera	Acroceridae	*Ogcodes*	*pallipes*	Latreille in Olivier, 1812				005	005
Diptera	Agromyzidae	*Agromyza*	*lambi*	Hendel, 1923				002	002
Diptera	Agromyzidae	*Ophiomyia*	*simplex*	Loew, 1869	003				003
Diptera	Asilidae	*Efferia*	*pogonias*	Walker, 1866	004				004
Diptera	Calliphoridae	*Calliphora*	sp.	Brauer & Bergenstamm, 1889	001			001	002
Diptera	Calliphoridae	*Calliphora*	sp.	Linnaeus, 1758					002
Diptera	Calliphoridae	*Calliphora*	sp.	Nixon, 1931					003
Diptera	Calliphoridae	*Calliphora*	*vomitoria*	Linnaeus, 1758					055
Diptera	Calliphoridae	*Lucilia*	*sericata*	Meigen, 1826		018		009	027
Diptera	Chironomidae	*Chironomus*	*plumosus*	Linnaeus, 1758		005		033	094
Diptera	Chironomidae	*Chlorops*	*pumilionis*	Bjerkander, 1778		155			155
Diptera	Chloropidae	*Hippelates*	*pusio*	Loew	191	1120		2883	5011
Diptera	Chloropidae	*Hippelates*	sp.	Lioy, 1864		1112			1112
Diptera	Dolichopodidae	*Condylostylus*	sp.	Bigot, 1859		003			003
Diptera	Dolichopodidae	*Sciapus*	sp.	Zeller, 1842				008	008
Diptera	Drosophilidae	*Drosophila*	*melanogaster*	Meigen, 1830					002
Diptera	Ephydridae	*Paralimna*	*nubifer*	Cresson, 1929		002			002
Diptera	Luxanidae	*Minettia*	*lupulina*	Linnaeus, 1758				005	005
Diptera	Muscidae	*Atherigona*	sp.	Rondani, 1856				001	002
Diptera	Muscidae	*Fannia*	*canicularis*	Linnaeus, 1761		008			008
Diptera	Muscidae	*Musca*	*domestica*	Linnaeus, 1758	011	015		022	048
Diptera	Muscidae	*Stomoxys*	*calcitrans*	Linnaeus, 1758					002
Diptera	Mycetophilidae	*Mycetophila*	sp.	Meigen, 1803		008			008
Diptera	Stratiomyidae	*Hermetia*	*illucens*	Linnaeus, 1758	001	050		001	052
Diptera	Syrphidae	*Episyrphus*	*balteatus*	De Geer, 1776				004	004
Diptera	Syrphidae	*Syrphus*	*ribesii*	Linnaeus, 1758					002
Diptera	Tachinidae	*Phryxe*	*vulgaris*	Fallén, 1810		003			009
Diptera	Tachinidae	*Spoggosia*	*claripennis*	Macquart	007				007
Diptera	Tachinidae	*Tachina*	*grossa*	Linnaeus, 1758					004
Diptera	Tachinidae	*Tachina*	sp.	Meigen, 1803				017	029
Diptera	Tephritidae	*Ceratitis*	*capitata*	Wiedemann, 1824	002				002
Diptera	Tephritidae	*Ceratitis*	*inscripta*	Wiedemann, 1824					002
Diptera	Tephritidae	*Rhagoletis*	sp.	Loew, 1862				003	003
Diptera	Tephritidae	*Rhynencina*	sp.	Johnson, 1922		002			002
Diptera	Tephritidae	*Trypeta*	sp.	Meigen, 1803	001				001
Glomerida	Glomeridae	*Glomeris*	*marginata*	Villers, 1789				002	003
Hemiptera	Alydidae	*Alydus*	*eurinus*	Linnaeus, 1758		001			001
Hemiptera	Alydidae	*Alydus*	sp.	Fabricius, 1803	012			009	021
Hemiptera	Alydidae	*Riptortus*	*serripes*	Fabricius, 1775				001	001
Hemiptera	Alydidae	*Stenocoris*	*americana*	Ahmad, 1965				001	003
Hemiptera	Anthocoridae	*Orius*	*tantillus*	Motschulsky				059	059
Hemiptera	Aphididae	*Brevicoryne*	*brassicae*	Linnaeus, 1758		003			003

Order	Family	Genus	Species	Author	Rainfed	Tap water	Well water	Waste water	Total abundance
Hemiptera	Aphrophoridae	*Aphrophora*	*salicina*	Goeze, 1778				002	002
Hemiptera	Aphrophoridae	*Lepyronia*	*quadrangularis*	Say, 1825		026			041
Hemiptera	Aradidae	*Aradus*	sp.	Fabricius, 1803		002			002
Hemiptera	Anthocoridae	*Poophilus*	sp.	Stål, 1866		015		013	028
Hemiptera	Anthocoridae	*Ptyelus*	*flavescens*	Fabricius, 1794				015	042
Hemiptera	Anthocoridae	*Ptyelus*	*flavescens*	Fabricius, 1794					012
Hemiptera	Anthocoridae	*Ptyelus*	*grossus*	Fabricius, 1781				012	012
Hemiptera	Cicadellidae	*Allygus*	*modestus*	Scott, 1876	007				007
Hemiptera	Cicadellidae	*Amrasca*	*biguttula*	Ishida, 1912	007			045	052
Hemiptera	Cicadellidae	*Cicadella*	*viridis*	Franz, 1938		003			003
Hemiptera	Cicadellidae	*Cicadula*	*quadrinotata*	Franz, 1938	005				005
Hemiptera	Cicadellidae	*Empoasca*	*facialis*	Jacobi 1912	036	041		105	242
Hemiptera	Cicadellidae	*Erythroneura*	sp.	Fitch, 1851					004
Hemiptera	Cicadellidae	*Streptanus*	*sordidus*	Zetterstedt, 1828	015				015
Hemiptera	Cicadellidae	*Xerophloea*	*viridis*	Fabricius, 1794	007				007
Hemiptera	Cicadellidae	*Zyginidia*	*scutellaris*	Herrich-Schaeffer, 1838	020				020
Hemiptera	Cixiidae	*Oliarus*	*humilis*	Say, 1830					002
Hemiptera	Coreidae	*Anoplocnemis*	*fuscus*	Westwood, 1842				001	001
Hemiptera	Coreidae	*Cletus*	sp.	Mellié, 1848				002	002
Hemiptera	Coreidae	*Cletus*	sp.	Schaupp, 1884				003	003
Hemiptera	Coreidae	*Cletus*	sp.	Stål, 1860	002			002	004
Hemiptera	Coreidae	*Cletus*	*trigonus*	Thunberg, 1783				002	002
Hemiptera	Coreidae	*Coreus*	*marginatus*	Linnaeus, 1758		002			002
Hemiptera	Cydnidae	*Pangaeus*	*bilineatus*	Say, 1825		002			002
Hemiptera	Delphacidae	*Javesella*	*pellucida*	Fabricius, 1794	029			014	053
Hemiptera	Delphacidae	*Kamendaka*	sp.	Distant, 1906				017	017
Hemiptera	Delphacidae	*Sogatella*	sp.	Fennah, 1956	003				003
Hemiptera	Delphacidae	*Stobaera*	*tricarinata*	Say, 1825				017	017
Hemiptera	Elateridae	*Aspavia*	*armigera*	Fabricius, 1775				003	003
Hemiptera	Fulgoridae	*Fulgora*	sp.	Linnaeus, 1767					*
Hemiptera	Lygaeidae	*Lygaeus*	*rivularis*	Germar, 1837		009		006	015
Hemiptera	Lygaeidae	*Lygaeus*	sp.	Fabricius, 1794				001	001
Hemiptera	Lygaeidae	*Pseudolasius*	sp.	Brailovsky, 1982					025
Hemiptera	Lygaeidae	*Pseudopamera*	*aurivilliana*	Distant, 1892	011				011
Hemiptera	Lygaeidae	*Spilostethus*	*hospes*	Fabricius & J.C., 1794				007	007
Hemiptera	Lygaeidae	*Spilostethus*	*saxatilis*	Scopoli, 1763		001			001
Hemiptera	Miridae	*Boxia*	*khayae*	China, 1943					008
Hemiptera	Miridae	*Capsus*	*ater*	Linnaeus, 1758	003				003
Hemiptera	Miridae	*Chamus*	*boxi*	China					020
Hemiptera	Miridae	*Chamus*	sp.	Distant, 1904					009
Hemiptera	Miridae	*Liocoris*	*tripustulatus*	Fieber, 1858				008	008
Hemiptera	Miridae	*Lygus*	*lineolaris*	Palisot de Beauvois, 1818		002			002
Hemiptera	Miridae	*Lygus*	*neavei*	Poppius, 1914		005			005
Hemiptera	Miridae	*Lygus*	sp.	Hahn, 1833		006		003	018
Hemiptera	Mordellidae	*Glipa*	*oculata*	Linnaeus, 1758	001				001
Hemiptera	Pentatomidae	*Aspavia*	*armigera*	Fabricius, 1775		001		002	008
Hemiptera	Pentatomidae	*Nezara*	*viridula*	Linnaeus, 1758				001	001
Hemiptera	Pentatomidae	*Oebalus*	*pugnax*	Fabricius, 1775				005	005
Hemiptera	Pentatomidae	*Oebalus*	*pugnax*	Sahlberg, 1829					002
Hemiptera	Pentatomidae	*Pentatoma*	*rufipes*	Cresson, 1929		001			001

Order	Family	Genus	Species	Author	Rainfed	Tap water	Well water	Waste water	Total abundance
Hemiptera	Pentatomidae	*Podisus*	*brevispinus*	Phillips, 1982	005				005
Hemiptera	Pyrrhocoridae	*Dysdercus*	sp.	Meigen, 1830		010			010
Hemiptera	Pyrrhocoridae	*Dysdercus*	*superstitiosus*	Fabricius		010		001	011
Hemiptera	Pyrrhocoridae	*Dysdercus*	*suturellus*	Herrich-Schaeffer, 1842		001			001
Hemiptera	Reduviidae	*Empicoris*	*vagabundus*	Linnaeus, 1758					001
Hemiptera	Reduviidae	*Ricania*	*cervina*	Melichar, 1898		001			001
Hemiptera	Reduviidae	*Triatoma*	*rubida*	Uhler, 1894				004	004
Hemiptera	Scutelleridae	*Sphaerocoris*	*annulus*	Fabricius, 1775				001	001
Hemiptera	Tingidae	*Tingidae*	sp.	Laporte, 1807				001	001
Hymenoptera	Sphecidae	*Chalybion*	sp.	Dahlbom, 1843				001	001
Hymenoptera	Sphecidae	*Liris*	*beatus*	Cameron, 1889				020	020
Hymenoptera	Sphecidae	*Podalonia*	*hirsuta*	Scopoli, 1763		002			002
Hymenoptera	Sphecidae	*Sceliphron*	*caementarium*	Drury, 1773		002			002
Hymenoptera	Sphecidae	*Sceliphron*	*curvatum*	Westwood, 1833	001				001
Hymenoptera	Andrenidae	*Andrena*	sp.	Fabricius, 1775		002			002
Hymenoptera	Andrenidae	*Perdita*	sp.	Smith, 1853		001			001
Hymenoptera	Apidae	*Apis*	*mellifera*	Linnaeus, 1758	010	006		006	031
Hymenoptera	Apidae	*Melipona*	sp.	Illiger, 1806	003				003
Hymenoptera	Apidae	*Meliponula*	*ferruginea*	Cockerell, 1934	001				001
Hymenoptera	Apidae	*Meliponula*	sp.	Cockerell, 1934	002			006	008
Hymenoptera	Apidae	*Nomada*	*maculata*	Cresson, 1863					001
Hymenoptera	Apidae	*Xylocopa*	*violacea*	Linnaeus, 1758		001			001
Hymenoptera	Bethylidae	*Cephalonomia*	sp.	Wiedemann, 1824				003	003
Hymenoptera	Cabronidae	*Tachytes*	*panzeri*	Dufour, 1841	001				001
Hymenoptera	Chalcididae	*Brachymeria*	sp.	Westwood, 1829	001				001
Hymenoptera	Chrysididae	*Trichrysis*	*cyanea*	Franz, 1938		001			001
Hymenoptera	Colletidae	*Hylaeus*	*brevicornis*	Nylander, 1852	002				002
Hymenoptera	Colletidae	*Hylaeus*	*modestus*	Say, 1837		001			001
Hymenoptera	Crabronidae	*Tachytes*	*panzeri*	Dufour, 1841	001				001
Hymenoptera	Evaniidae	*Hyptia*	sp.	Illiger, 1807				002	002
Hymenoptera	Formicidae	*Acanthomyrmex*	*volcanus*	Wheeler, W.M., 1937		007			007
Hymenoptera	Formicidae	*Camponotus*	*atriceps*	Smith, 1858		075			075
Hymenoptera	Formicidae	*Camponotus*	*auriventris*	Emery, 1889		016			016
Hymenoptera	Formicidae	*Camponotus*	*chrysurus*	Gerstäcker, 1870					015
Hymenoptera	Formicidae	*Camponotus*	*chrysurus*	Gerstäcker, 1871		123			123
Hymenoptera	Formicidae	*Camponotus*	*importunus*	Forel, 1911	143			057	200
Hymenoptera	Formicidae	*Camponotus*	*ligniperda*	Forel, 1911		018			018
Hymenoptera	Formicidae	*Camponotus*	*pennsylvanicus*	De Geer, 1773	008				008
Hymenoptera	Formicidae	*Camponotus*	sp.	Mayr, 1861	022	237		060	319
Hymenoptera	Formicidae	*Cataulacus*	*erinaceus*	Stitz, 1910	001				001
Hymenoptera	Formicidae	*Dorylus*	sp.	Fabricius, 1793		007			024
Hymenoptera	Formicidae	*Formica*	*rufa*	Linnaeus, 1761		044			044
Hymenoptera	Formicidae	*Hypoponera*	*monticola*	Mann, 1921				008	008
Hymenoptera	Formicidae	*Lasius*	*claviger*	Roger, 1862		007			007
Hymenoptera	Formicidae	*Lasius*	*fuliginosus*	Latreille, 1798		012			012
Hymenoptera	Formicidae	*Linepithema*	*humile*	Fabricius, 1794	047				047
Hymenoptera	Formicidae	*Manica*	*rubida*	Latreille, 1802		005			005
Hymenoptera	Formicidae	*Monomorium*	*biocolor*	Emery, 1877		001			147
Hymenoptera	Formicidae	*Monomorium*	*pharaonis*	Linnaeus, 1758	283	072		135	490
Hymenoptera	Formicidae	*Monomorium*	*pharaonis*	Linnaeus, 1758	037			070	107

Order	Family	Genus	Species	Author	Rainfed	Tap water	Well water	Waste water	Total abundance
Hymenoptera	Formicidae	*Odontomachus*	*brunneus*	Patton, 1894		003		060	063
Hymenoptera	Formicidae	*Odontomachus*	sp.	Latreille, 1804				003	003
Hymenoptera	Formicidae	*Pachycondyla*	*commutata*	Roger					055
Hymenoptera	Formicidae	*Pachycondyla*	*rufipes*	Jerdon, 1851	003			003	006
Hymenoptera	Formicidae	*Pachycondyla*	sp.	Smith, F., 1858				044	044
Hymenoptera	Formicidae	*Pheidole*	*megacephala*	Fabricius, 1793					036
Hymenoptera	Formicidae	*Pogonomyrmex*	*barbatus*	Smith, 1858		010			010
Hymenoptera	Formicidae	*Pogonomyrmex*	*occidentalis*	Cresson, 1865	015				015
Hymenoptera	Formicidae	*Pogonomyrmex*	sp.	Mayr, 1868				002	002
Hymenoptera	Formicidae	*Polyrhachis*	*decemdentata*	André, 1889					027
Hymenoptera	Formicidae	*Solenopsis*	sp.	McCook, 1879					057
Hymenoptera	Formicidae	*Solenopsis*	*xyloni*	McCook, 1879	501	256		146	963
Hymenoptera	Formicidae	*Sphinctomyrmex*	sp.	Mayr, 1866				002	002
Hymenoptera	Formicidae	*Tetramorium*	*caespitum*	Linnaeus, 1758	169			392	682
Hymenoptera	Formicidae	*Tetramorium*	sp.	Mayr, 1855	018			042	060
Hymenoptera	Halictidae	*Agapostemon*	*virescens*	Fabricius, 1775		002			002
Hymenoptera	Halictidae	*Lasioglossum*	*sordidum*	Smith, 1853				003	003
Hymenoptera	Halictidae	*Lasioglossum*	sp.	Curtis, 1833	001				001
Hymenoptera	Lygaeidae	*Taphropeltus*	*contractus*	Herrich-Schaeffer & G.H.W., 1835				007	007
Hymenoptera	Megachilidae	*Anthidium*	*manicatum*	Linnaeus, 1758	001				002
Hymenoptera	Megachilidae	*Anthidium*	*punctatum*	Latreille, 1809				001	001
Hymenoptera	Megachilidae	*Anthocoris*	*confusus*	Reuter, 1884	002			029	031
Hymenoptera	Megachilidae	*Anthocoris*	sp.	Fallen, 1814	006				006
Hymenoptera	Megachilidae	*Megachile*	*latimanus*	Say, 1823		005		001	008
Hymenoptera	Megachilidae	*Megachile*	sp.	Latreille, 1802	001			005	006
Hymenoptera	Megachilidae	*Osmia*	*lignaria*	Say, 1837				003	003
Hymenoptera	Pompilidae	*Anoplius*	*americanus*	Beauvois, 1811		014			014
Hymenoptera	Pompilidae	*Entypus*	sp.	Dahlbom, 1843				001	001
Hymenoptera	Pompilidae	*Entypus*	*unifasciatus*	Say, 1828				009	009
Hymenoptera	Scelionidae	*Aradophagus*	*fasciatus*	Ashmead, 1893				002	002
Hymenoptera	Scelionidae	*Calliscelio*	*gracilis*	Nixon, 1931		007			007
Hymenoptera	Scelionidae	*Eumicrosoma*	*beneficum*	Gahan, 1913	002	004		005	011
Hymenoptera	Scelionidae	*Scelio*	sp.	Latreille, 1805	002				002
Hymenoptera	Sphecidae	*Sphex*	*maximiliani*	Kohl, 1890		003			003
Hymenoptera	Sphecidae	*Sphex*	sp.	Christ, 1791				001	001
Hymenoptera	Trichogrammatidae	*Megaphragma*	sp.	Timberlake, 1924	001				001
Hymenoptera	Vespidae	*Polistes*	*exclamans*	Viereck, 1906	002				002
Hymenoptera	Vespidae	*Polistes*	*instabilis*	Saussure, 1853	001				001
Hymenoptera	Vespidae	*Polistes*	*parametricus*	Matthias Buck et al., 2012				001	001
Hymenoptera	Vespidae	*Polistes*	*rubiginosus*	Lepeletier, 1836				003	003
Hymenoptera	Vespidae	*Polistes*	sp.	Latreille, 1802				001	001
Hymenoptera	Vespidae	*Ropalidia*	*cincta*	Lepeletier, 1836					001
Hymenoptera	Vespidae	*Vespa*	*crabro*	Linnaeus, 1758					001
Isopoda	Oniscidae	*Oniscus*	*asellus*	Linnaeus, 1758					*
Lepidoptera	Arctiinae	*Arctiinae*	sp.	Leach, 1815					001
Lepidoptera	Crambidae	*Crocidolomia*	*binotalis*	Zeller, 1852				004	004
Lepidoptera	Crambidae	*Hellula*	*undalis*	Fabricius, 1794	015	017		008	056
Lepidoptera	Crambidae	*Sylepta*	*derogata*	Fabricius, 1775		022			022
Lepidoptera	Depressariidae	*Ptilobola*	*inornatella*	Walsingham, 1891					005
Lepidoptera	Erebidae	*Melipotis*	*gubernata*	Walker, 1857					002

Order	Family	Genus	Species	Author	Rainfed	Tap water	Well water	Waste water	Total abundance
Lepidoptera	Geometridae	*Scopula*	*calothysanis*	Herbulot, 1965		001			001
Lepidoptera	Hesperiidae	*Fresna*	*nyassae*	Hewitson, 1878				002	002
Lepidoptera	Hesperiidae	*Pyrgus*	*malvae*	Linnaeus, 1758		003			003
Lepidoptera	Hesperiidae	*Zophopetes*	*dysmephila*	Trimen, 1868	008	002		003	013
Lepidoptera	Noctuidae	*Dypterygia*	sp.	Gay				001	001
Lepidoptera	Noctuidae	*Ericeia*	*sobria*	Walker, 1857		001			001
Lepidoptera	Noctuidae	*Prodenia*	*litura*	Fabricius, 1775		001			001
Lepidoptera	Noctuidae	*Sesamia*	*calamistis*	Guenée, 1852				001	001
Lepidoptera	Nolidae	*Earias*	*biplaga*	Walker, 1866	001				001
Lepidoptera	Nymphalidae	*Acraea*	*eponina*	Cramer, 1780				001	001
Lepidoptera	Nymphalidae	*Amauris*	*psyttalae*	Strand, 1913		001			001
Lepidoptera	Nymphalidae	*Aterica*	*galene*	Brown, 1776					001
Lepidoptera	Nymphalidae	*Acraea*	*eponina*	Cramer, 1780	001				001
Lepidoptera	Pieridae	*Appias*	*epaphia*	Cramer, 1779				001	001
Lepidoptera	Pieridae	*Colotis*	sp.	Hübner, 1819		001			001
Lepidoptera	Pieridae	*Nepheronia*	*thalassina*	Boisduval, 1836	001			001	002
Lepidoptera	Sphingidae	*Daphnis*	*nerii*	Linnaeus, 1758				001	001
Lepidoptera	Sphingidae	*Sphinx*	*chersis*	Hübner, 1823	001				001
Lepidoptera	Sphingidae	*Tinostoma*	sp.	Rothschild & Jordan, 1903	001				001
Orthoptera	Acrididae	*Acrida*	*conica*	Fabricius, 1781	001				001
Orthoptera	Acrididae	*Chorthippus*	*dorsatus*	Zetterstedt, 1821				001	001
Orthoptera	Acrididae	*Orchelimum*	*gladiator*	Gyllenhal, 1808					001
Orthoptera	Acrididae	*Pholidoptera*	sp.	Wesmael, 1838					007
Orthoptera	Acrididae	*Phymateus*	*viridipes*	Stål, 1873		001			001
Orthoptera	Acrididae	*Ruspolia*	*indica*	Redtenbacher, 1891					008
Orthoptera	Acrididae	*Schistocerca*	*nitens*	Thunberg, 1815		003			003
Orthoptera	Gryllidae	*Acheta*	*domesticus*	Linnaeus, 1758	002				002
Orthoptera	Gryllidae	*Brachytrupes*	*membranaceus*	Drury, 1770				003	003
Orthoptera	Gryllidae	*Gryllus*	*lucens*	Walker, 1869				009	012
Orthoptera	Gryllidae	*Gryllus*	sp.	Linnaeus, 1758	005	004		044	080
Orthoptera	Gryllidae	*Teleogryllus*	*marini*	Otte, D. & R.D. Alexander, 1983				001	001
Orthoptera	Tetrigidae	*Tetrix*	*arenosa*	Burmeister, 1838					002
Orthoptera	Tetrigidae	*Tetrix*	*arenosa*	Linnaeus, 1758				005	005
Orthoptera	Tetrigidae	*Tetrix*	sp.	Latreille, 1802		002		011	013
Orthoptera	Tetrigidae	*Tetrix*	*subulata*	Linnaeus, 1761		004		013	020
Orthoptera	Tettigoniidae	*Neoconocephalus*	*ensiger*	Harris, 1841				006	006
Orthoptera	Tettigoniidae	*Neoconocephalus*	*triops*	Linnaeus, 1758				001	001
Orthoptera	Tettigoniidae	*Scudderia*	*furcata*	Brunner von Wattenwyl, 1878		001			001
Phasmatodea	Phasmatidae	*Phobaeticus*	sp.	Brunner von Wattenwyl, 1907				002	002
Thysanoptera	Thripidae	*Frankliniella*	*occidentalis*	Pergande, 1895				035	035
Thysanoptera	Thripidae	*Frankliniella*	*schultzei*	Trybom, 1910	122				122
Thysanoptera	Thripidae	*Frankliniella*	sp.	Fitch, 1855	058				058
Thysanoptera	Thripidae	*Frankliniella*	*tritici*	Fitch, 1855		006			021
Thysanoptera	Thripidae	*Megalurothrips*	*sjostedti*	Trybom, 1908	085			342	427
Thysanoptera	Thripidae	*Selenothrips*	*rubrocinctus*	Giard, 1901					010
Thysanoptera	Thripidae	*Thrips*	*tabaci*	Lindeman, 1889					001
Thysanoptera	Trichogrammatidae	*Megalurothrips*	*sjostedti*	Trybom, 1908				162	162
Grand Total					**2105**	**3888**		**6102**	**14226**

6 Chapter 6

General discussion and conclusions

6.1 *Food security and Africa*

Although over the last two decades there has been a general improvement in the global standard of living (Pinker, 2018), Africa remains as one of the regions with serious food insecurity (Peng & Berry, 2019). Livestock production and crop farming are practised by many inhabitants to mitigate this food insecurity and to improve their livelihoods. In livestock production, small and large ruminants are predominantly herded by transhumant Fulanis from the Sahel to the coastal West African countries (Adum et al., 2019; Idehen & Ikuru, 2019). Other pastoralists rear livestock on fixed farms whilst others resort to commercial production of monogastric animals such as chicken. Apart from these groups of livestock, another group of animals that - although indirectly - provide food for most Africans are arthropods (van Huis, 2020), through the pollination of food crops, the regulation of insect pests, and the decomposition of organic matter (Pappas et al., 2019).

Despite the importance of these animals towards securing food security, there are issues that affect their potential in the mitigation of the effects of food insecurity. Some of these issues are the threats from the increase in global temperatures on livestock (Ayantunde et al., 2020), the shift of the seasons (Ayantunde et al., 2019), and the political conflicts within the region (Brottem, 2016). There are also inefficiencies in the production of monogastric (Herrero et al., 2016) and ruminant animal production (Henderson et al., 2018). In chicken for example, heat stress reduces feed intake and feed conversion, leading to lower final weight of exotic breeds of chicken used in the tropics (Pawar et al., 2016). Also arthropods despite their importance face a decline in their abundance and in their diversity (Whitener et al., 2019), face fragmentations of their populations, and face shifts in their assemblies (Benitez-Malvido et al., 2016), which may potentially lead to an increase in the economic damage on crops.

6.2 *Review of livestock traffic*

African pastoralism has been echoed as a major contributor to food security (Krätli et al., 2013). This is especially true since the African middle class is larger than ever before (Kharas, 2017), offering livestock producers markets to improve their livelihoods. In this regard, more extensive and faster means of ruminant livestock distribution may contribute to the satisfaction of the increasing meat and dairy demand.

At the same time climate change creates higher competition for land resources which exacerbate poor herder-farmer relationships resulting in rising tensions between ruminant livestock herders and farmers (Brottem, 2016).

Even worse is the creeping terrorism which has led to the rustling of livestock herds and the widespread displacement and murder of livestock herders in the Sahel (UNOWAS, 2018).

Apart from conflicts which threaten livestock distribution, pasture availability and productivity may also be threatened by climate change effects (Snorek, 2016) and pasture mismanagement due to overstocking (Turner, 2018) which further worsens the plight of traditional pastoralists. These livestock herders heavily rely on pasture resources and crop residues as animal feed (Amole & Ayantunde, 2016), while using little processed feed. As livestock traders and herders get more closely connected to city markets, they increasingly maintain their animals with feed bought from traders who harvest pasture vegetation in the city's periphery. Although this supply of pasture is necessary, its sustainability is threatened by the rapid spatial and numerical growth of Sahelian cities (B. A. Diallo & Zhengyu, 2010).

There is not much information about the network of vehicle transported livestock or livestock feed in any parts of Africa, although there are many herd movements (Apolloni et al., 2019; Jahel et al.,). Trekking of livestock still remains popular because they decrease transportation costs (Apolloni et al., 2018), which grow with limited road conditions (Whitelegg, 2017), endless security checkpoints with frequent bribes (Clack & Johnson, 2019), and red tape at the borders (Corniaux et al., 2018).

Seasonal effects are very important for livestock distribution particularly due to the Islamic religious festival of sacrifice, Eid Al Adha (Nicolas et al., 2018), as observed in this study. Over the decades, this festival has gained popularity across the Sahel due to the growing role of Islam and it offers pastoralists the opportunity to improve their economic livelihoods. During the duration of this study in 2015 - 2019, this festival was celebrated during the rainy season, however, since the religious celebration is based on the lunar calendar, future celebrations will coincide with the hot dry season (March-June) of the Sahel when feed resources are even scarcer. In addition to the threat of insufficient feed affecting livestock production, the current increase in meat consumption throughout Sub-Saharan Africa (Desiere et al., 2018) will put more demand on pastoralists to supply livestock to consumers. However, often Sahelian cities that are important for livestock distribution like Bamako, are not sufficiently equipped with livestock marketing chains, livestock processing units, abattoirs, and veterinary services (Kamuanga et al., 2008) to adequately handle current and future demands. Additionally, Mali like other countries in the Sahel does not produce enough electric power required to run modern livestock infrastructure required to harness the economic opportunity that the increase in meat consumption presents (Briceño-Garmendia et al., 2011). There also has been too little donor focus on the potential of livestock production in poverty alleviation (Steinfeld et al., 2013) which requires more information for effective planning and action. To this end our study provides information about vehicular transported livestock and livestock feed.

6.3 *Review of the potential of biochar as a poultry feed additive*

The commercial production of monogastric animals such as poultry is a popular venture across Africa. However, the exotic breeds used are not well adapted to the harsh West African environment (Bekele et al., 2010). Recent data show that West African commercial poultry farmers invest more than half of total production costs in feed provision (Anang et al., 2013; Hagan, 2020) which is often inefficiently converted by poultry because of high temperatures (Sugito et al., 2020). Hence, large amounts of nutrients are lost in faecal droppings, necessitating an increased attention by West African poultry farmers to nutrient accretion. Meanwhile, pyrolysing of waste organic substances for the improvement of agriculture leading to the provision of so-called 'biochar' has gained wide use since the discovery that the Amazon Dark Earth soils derived from the use of charred materials as soil amendment by generations of ancient Amazonian Indians (Lehmann & Joseph, 2015).

Experiments have shown that the use of biochar in agricultural soils may lead to complex aggregate formation with nutrients extending their residence time (Cusack et al., 2012) and ensuring a slow release of soil nutrients to plants. In view of this, this study assessed the potential of biochar addition to chicken feed to increase 'the residence time' of nutrients in the chicken for better assimilation and higher nutrient efficiency. Our data show that biochar reduced the amount of phosphorous excreted by chickens. This is a desirable result as phosphorous is important for metabolism, the development of bone tissue, the boosting of the immune system and improvement of energy utilisation (Oster et al., 2016). Monogastrics lack phytases needed to hydrolyse phytate, the chief store of phosphorous in seed-based animal feed (Bai, 2019), hence the need to improve phosphorous efficiency. Not only is phosphorous efficiency important for animal health, inefficient phosphorous utilisation contributes to an increase in phosphorous excretion leading to algae bloom of water ecosystems, raising environmental issues (Ngatia et al., 2019). In spite of the prospects biochar apparently has for phosphorous accretion, this study found no effect of biochar on the improvement of final weight of poultry, feed intake and feed conversion. These results are confirmed by recent work of Hinz et al. 2019. In contrast Khadem et al. 2012 reported a positive effect of charcoal on weight gain and feed conversion.

Majewska et al. 2011 also found an increase in the weight gain of broiler chicken at the end of their six-week experiment while Kana et al. 2011 also discovered improved growth with the inclusion of 0.2 % of pyrolysed corn cob in the diet of broiler chicken which was supported by data of Kutlu and Unsal 1998. Not only did charcoal improve broiler performance, Kutlu et al. 2001 also found that it reduced the number of cracked eggs from layer hens.

Apart from the improvement of feed, charred substances are traditionally used in livestock production as first aid for poisoning and even sometimes by humans for the treatment of diarrhoea. Our study showed that the inclusion of charcoal in poultry slightly reduced the effects of anti-nutritional factors of underutilized West African tubers such as of *Icacina oliviformis* an underutilized root tuber rich in carbohydrates (Oladokun & Johnson, 2012). However, this semi-domesticated tuber also contains anti-nutritive substances like terpenes which increases the negative effects of other toxic substances on cell membranes (Rossi et al., 2020). Therefore, the potential of charcoal in reducing toxicity levels of secondary plant metabolites is of interest to West African poultry production. This potential will help mitigate food insecurity as it may contribute to reducing the dependence on maize as an animal feed. Rafiu et al. 2014 also found that the inclusion of charcoal in broiler diets significantly reduced the effect of feed toxins and contributed to an improved feed efficiency ratio, whilst Pfab et al. 2017 also discovered that it reduced toxin absorption in the gut soon after charcoal ingestion. In pig, Kim et al. 2017 found that charcoal feed additives promoted an improvement in feed digestibility and toxin reduction, whilst van Chao et al. 2016 investigated that it reduced the incidence of diarrhoea in pigs. The potential of charcoal as a detoxifier has also been demonstrated in human health as a treatment against kidney disease (Cupisti et al., 2020; Lin et al., 2020).

The evidence from this study thus reinforces the evidence in literature about the prospects of biochar in animal health improvement and animal feed utilisation.

6.4 *Effects of agricultural management practices on arthropod ecology*

Finally, this thesis also focused on a small but very important part of West African agroecology, the soil arthropods. These animals are not only providers of ecosystem services (Stenchly et al., 2019), but can also damage (Diatte et al., 2018) and transmit crop diseases (Mayer et al., 2017), hence decrease food security. Anthropogenic disruptions in the ecology of arthropods may erode biodiversity (Fletcher et al., 2018) and increase the risk of ecological backlashes (Pedigo & Rice, 2015). Therefore, information about the effects of agricultural activities on the structure of arthropod communities is important to mitigate negative effects on arthropod disruption. In this study, wastewater irrigation was found to be consistent with the occurrence of *Hippaletes pusio* a vector for conjunctivitis and yaws, a tropical infection of the skin, bones and joints caused by the spirochete bacterium *Treponema pallidum pertenue* (Mitjà et al., 2013), still prevalent in Tamale (Ghinai et al., 2015). Arthropod vector-borne diseases also continue to ravage the health of humans, especially those living in the tropics, and their pathogenicity apparently increases with the current population increase and urbanisation rate (Ramalho-Ortigao & Gubler, 2020). In Africa arthropods are reported to cause at least 13 % of all fevers and many other human illnesses (Ehounoud et al., 2017).

The arthropod study of this doctoral thesis also found the occurrence of three alien ant species, and seven other indigenous ant species that form mutualistic relationships with aphids. Alien ants have the potential to overwhelm native ant species (Pyšek et al., 2017), while ant-aphid mutualistic relationships, protect these deleterious aphids from potential pest regulators, which may eventually promote these aphids until they reach pest status (Ortega-Ramos et al., 2020). Aphids at sufficient populations may cause serious economic damage to farmers (van Emden & Harrington, 2017). Bearing in mind that areas in West Africa such as Tamale (Ghana) already have a high risk of food insecurity (Batinge & Jenkins, 2018; Kleemann et al., 2017), more knowledge is necessary to mitigate such risks and ultimately contribute to increasing farmers' income. Unfortunately, information about such relationships in West Africa is rare in the literature. This study thus provides an overview of the community assemblage of arthropods in Tamale's UPA systems. Such information is valuable for the extension officers to educate farmers, for the Ministry of Agriculture in Ghana to share it with agricultural stakeholders, and for West African ecologists to continue with the study of current transformation processes and their effect on biodiversity as it benefits agriculture.

6.5 *Conclusions*

The study on vehicular livestock traffic in Bamako provides vital information on current constraints and prospects of livestock movements in West Africa. It will be imperative for the Economic Community of West African States (ECOWAS) to implement / enforce existing agreements on transborder trade and develop policies for pasture conservation and improvement of road conditions. The latter will reduce the cost of vehicular transportation of livestock for herdsmen and thus ultimately contribute to the improvement of livelihoods.

Our data provide evidence that biochar could reduce the toxicity of feedstocks. This is particularly useful since underutilized tuber crops rich in carbohydrates are ubiquitous in many parts of West Africa and could reduce the region's dependence on maize which is a staple. Biochar also showed potential in the reduction of excreted phosphorous of poultry pointing to its usage as an additive for the improvement of feed digestibility.

The study on arthropod ecology provides information about arthropods which merit further investigation. There were at least three invasive ant species and seven indigenous ant species notorious for symbiotic relationships with other arthropods which have the potential to cause considerable crop damage. Bearing in mind the vulnerability of West Africa in terms of food security, results obtained, contributes to the body of knowledge necessary for improved UPA systems in West Africa. Not only were invasive species ubiquitous in the agroecosystem's studies, there was also a dominance of an arthropod vector, *H. pusio* in the samples collected in the Northern Region of Ghana. The yaws disease transmitted by this arthropod is still prevalent in the region, yet no study has been undertaken to ascertain the relationship of *H. pusio* and the incidence of this disease.

6.6 References

References

Adum, A. N., Okafor, G. O., Ekwenchi, O., & Nnatu, S. (2019). Addressing the emerging security challenges from transhumance in west africa: The ecowas perspective. *International Journal of Social Sciences and Management Research*, *5*(2), 71–79.

Amole, T. A., & Ayantunde, A. A. (2016). Assessment of existing and potential feed resources for improving livestock productivity in niger. *International Journal of Agric Research*, *11*(2), 40–55.

Anang, B. T., Yeboah, C., & Amison Agbolosu, A. (2013). Profitability of broiler and layer production in the brong ahafo region of ghana. *ARPN Journal of Agricultural and Biological Science*, *8*(5).

Apolloni, A., Corniaux, C., Coste, C., Lancelot, R., & Touré, I. (2019). Livestock mobility in west africa and sahel and transboundary animal diseases (M. Kardjadj, A. Diallo, & R. Lancelot, Eds.). *9*, 31–52. https://doi.org/10.1007/978-3-030-25385-1_3

Apolloni, A., Nicolas, G., Coste, C., El Mamy, A. B., Yahya, B., El Arbi, A. S., Gueya, M. B., Baba, D., Gilbert, M., & Lancelot, R. (2018). Towards the description of livestock mobility in sahelian africa: Some results from a survey in mauritania. *PloS one*, *13*(1), e0191565. https://doi.org/10.1371/journal.pone.0191565

Ayantunde, A. A., Boubacar, H. A., Adamou, K., Moumini, O., & Umutoni, C. (2019). Evaluation of feed resources in the mixed crop-livestock systems of the sahelian zone in burkina faso and niger.

Ayantunde, A. A., Oluwatosin, B. O., Yameogo, V., & van Wijk, M. (2020). Perceived benefits, constraints and determinants of sustainable intensification of mixed crop and livestock systems in the sahelian zone of burkina faso. *International Journal of Agricultural Sustainability*, *18*(1), 84–98.

Bai, Y. (2019). *Elevated phosphorus retention after facilitating phytase efficacy via intermittent feeding and acidification* (Doctoral dissertation). Norwegian University of Life Sciences, Ås.

Batinge, B. K., & Jenkins, H. (2018). Assessing the factors militating against microfinance in alleviating chronic poverty and food insecurity in rural northern ghana. In N. Ozatac & K. K. Gökmenoglu (Eds.), *Emerging trends in banking and finance* (pp. 181–198). Springer International Publishing. https://doi.org/10.1007/978-3-030-01784-2_11

Bekele, F., Adnoy, T., Gjoen, H. M., Kathle, J., & Abebe, G. (2010). Production performance of dual purpose crosses of two indigenous with two exotic chicken breeds in sub-tropical environment. *International Journal of Poultry Science*, *9*(7), 702–710. https://doi.org/10.3923/ijps.2010.702.710

Benitez-Malvido, J., Dattilo, W., Martinez-Falcon, A. P., Duran-Barron, C., Valenzuela, J., Lopez, S., & Lombera, R. (2016). The multiple impacts of tropical forest fragmentation on arthropod biodiversity and on their patterns of interactions with host plants. *PloS one*, *11*(1). https://doi.org/10.1371/journal.pone.0146461

Briceño-Garmendia, C. M., Dominguez, C., & Pushak, N. (2011). *Mali's infrastructure: A continental perspective*. The World Bank.

Brottem, L. V. (2016). Environmental change and farmer-herder conflict in agro-pastoral west africa. *Human Ecology*, *44*(5), 547–563. https://doi.org/10.1007/s10745-016-9846-5

Clack, T., & Johnson, R. (Eds.). (2019). *Before military intervention*. Springer International Publishing. https://doi.org/10.1007/978-3-319-98437-7

Corniaux, C., Thébaud, B., Powell, A., Apolloni, A., & Touré I. (2018). Cross-border livestock mobility: Challenges for wet africa. Retrieved, from https://agritrop.cirad.fr/588455/1/FAO-Betail_Corniaux%20ANGLAIS%20HD.pdf

Cupisti, A., Piccoli, G. B., & Gallieni, M. (2020). Charcoal for the management of pruritus and uremic toxins in patients with chronic kidney disease. *Current Opinion in Nephrology and Hypertension*, *29*(1), 71–79. https://doi.org/10.1097/MNH.0000000000000567

Cusack, D. F., Chadwick, O. A., Hockaday, W. C., & Vitousek, P. M. (2012). Mineralogical controls on soil black carbon preservation. *Global Biogeochemical Cycles*, *26*(2). https://doi.org/10.1029/2011GB004109

Dei, H. K., Bacho, A., Adeti, J., & Rose, S. P. (2011). Nutritive value of false yam (*Icacina oliviformis*) tuber meal for broiler chickens. *Poultry Science*, *90*(6), 1239–1244.

Desiere, S., Hung, Y., Verbeke, W., & D'Haese, M. (2018). Assessing current and future meat and fish consumption in Sub-Sahara Africa: Learnings from FAO food balance sheets and LSMS household survey data. *Global Food Security*, *16*, 116–126. https://doi.org/10.1016/j.gfs.2017.12.004

Diallo, B. A., & Zhengyu, B. (2010). Land cover change assessment using remote sensing: Case study of Bamako, Mali. *Researcher*, *2*(4), 7–14.

Diatte, M., Brévault, T., Sylla, S., Tendeng, E., Sall-Sy, D., & Diarra, K. (2018). Arthropod pest complex and associated damage in field-grown tomato in Senegal. *International Journal of Tropical Insect Science*, *38*(03), 243–253. https://doi.org/10.1017/S1742758418000061

Ehounoud, C. B., Fenollar, F., Dahmani, M., N'Guessan, J. D., Raoult, D., & Mediannikov, O. (2017). Bacterial arthropod-borne diseases in West Africa. *Acta Tropica*, *171*, 124–137. https://doi.org/10.1016/j.actatropica.2017.03.029

Fletcher, R. J., Didham, R. K., Banks-Leite, C., Barlow, J., Ewers, R. M., Rosindell, J., Holt, R. D., Gonzalez, A., Pardini, R., Damschen, E. I., Melo, F. P., Ries, L., Prevedello, J. A., Tscharntke, T., Laurance, W. F., Lovejoy, T., & Haddad, N. M. (2018). Is habitat fragmentation good for biodiversity? *Biological Conservation*, *226*, 9–15. https://doi.org/10.1016/j.biocon.2018.07.022

Ghinai, R., El-Duah, P., Chi, K.-H., Pillay, A., Solomon, A. W., Bailey, R. L., Agana, N., Mabey, D. C. W., Chen, C.-Y., Adu-Sarkodie, Y., & Marks, M. (2015). A cross-sectional study of 'yaws' in districts of Ghana which have previously undertaken azithromycin mass drug administration for trachoma control. *PLoS Neglected Tropical Diseases*, *9*(1), e0003496. https://doi.org/10.1371/journal.pntd.0003496

Hagan, M. A. S. (2020). Challenges of poultry farmers at Ejisu municipality, Ghana. *Asian Journal of Agricultural Extension, Economics and Sociology*, 63–77. https://doi.org/10.9734/ajaees/2020/v38i130299

Henderson, B., Golub, A., Pambudi, D., Hertel, T., Godde, C., Herrero, M., Cacho, O., & Gerber, P. (2018). The power and pain of market-based carbon policies: A global application to greenhouse gases from ruminant livestock production. *Mitigation and Adaptation Strategies for Global Change*, *23*(3), 349–369. https://doi.org/10.1007/s11027-017-9737-0

Herrero, M., Henderson, B., Havlík, P., Thornton, P. K., Conant, R. T., Smith, P., Wirsenius, S., Hristov, A. N., Gerber, P., & Gill, M. (2016). Greenhouse gas mitigation potentials in the livestock sector. *Nature Climate Change*, *6*(5), 452–461. https://doi.org/10.1038/nclimate2925

Hinz, K., Stracke, J., Schättler, J. K., Kemper, N., & Spindler, B. (2019). Effects of enriched charcoal as permanent 0.2% feed-additive in standard and low-protein diets of male fattening turkeys: An on-farm study. *Animals : an open access journal from MDPI*, *9*(8). https://doi.org/10.3390/ani9080541

Idehen, R. O., & Ikuru, U. R. (2019). Migration and the emerging security challenges in West Africa: Case of Fulani herders/sedentary farmers conflicts in Nigeria. *AFRREV IJAH: An International Journal of Arts and Humanities*, *8*(4), 128–137. https://doi.org/10.4314/ijah.v8i4.12

Jahel, C., Lenormand, M., Seck, I., Apolloni, A., Toure, I., Faye, C., Sall, B., Lo Mbargou, Diaw, C. S., Lancelot, R., & Coste, C. (). Mapping livestock movements in Sahelian Africa. http://arxiv.org/pdf/1910.10476v1

Kamuanga, M. J. B., Somda, J., Sanon, Y., & Kagoné, H. (2008). Livestock and regional market in the Sahel and West Africa: Potentials and Challenges.

Kana, J. R., Teguia, A., Mungfu, B. M., & Tchoumboue, J. (2011). Growth performance and carcass characteristics of broiler chickens fed diets supplemented with graded levels of charcoal from maize cob or seed of *Canarium schweinfurthii* engl. *Tropical Animal Health and Production*, *43*(1), 51–56. https://doi.org/10.1007/s11250-010-9653-8

Khadem, A. A., Sharifi, S, D, Barati, M., & Borji, M. (2012). Evaluation of the effectiveness of yeast, zeolite and active charcoal as aflatoxin absorbents in broiler diets. *Global Veterinaria*, *8*(4), 426–432.

Kharas, H. (2017). The unprecedented expansion of the global middle class: An update: Global economy & development working paper 100 — february 2017. https://think-asia.org/bitstream/handle/11540/7251/global_20170228_global-middle-class.pdf?sequence=1

Kim, Kim, Y.-H., Park, J.-C., Yun, W., Jang, K.-I., Yoo, D.-I., Lee, D.-H., Kim, B.-G., & Cho, J.-H. (2017). Effect of organic medicinal charcoal supplementation in finishing pig diets. *Korean Journal of Agricultural Science*, *44*(1). https://doi.org/10.7744/kjoas.20170006

Kleemann, J., Celio, E., Nyarko, B. K., Jimenez-Martinez, M., & Fürst, C. (2017). Assessing the risk of seasonal food insecurity with an expert-based bayesian belief network approach in northern ghana, west africa. *Ecological Complexity*, *32*, 53–73. https://doi.org/10.1016/j.ecocom.2017.09.002

Krätli, S., Huelsebusch, C., Brooks, S., & Kaufmann, B. (2013). Pastoralism: A critical asset for food security under global climate change. *Animal Frontiers*, *3*(1), 42–50. https://doi.org/10.2527/af.2013-0007

Kutlu, H. R., & Unsal, I. (1998). Effects of dietary wood charcoal on performance and fatness of broiler chicks. *British Poultry Science*, *39 Suppl*, S31–2. https://doi.org/10.1080/00071669888214

Kutlu, H. R., Ünsal, I., & Görgülü, M. (2001). Effects of providing dietary wood (oak) charcoal to broiler chicks and laying hens. *Animal Feed Science and Technology*, *90*(3-4), 213–226. https://doi.org/10.1016/S0377-8401(01)00205-X

Lin, Sun, C.-Y., Wu, C.-J., Wu, C.-C., Wu, V., & Lin, F.-H. (2020). Charxgen-activated bamboo charcoal encapsulated in sodium alginate microsphere as the absorbent of uremic toxins to retard kidney function deterioration. *International Journal of Molecular Sciences*, *21*(4), 1257. https://doi.org/10.3390/ijms21041257

Mayer, S. V., Tesh, R. B., & Vasilakis, N. (2017). The emergence of arthropod-borne viral diseases: A global prospective on dengue, chikungunya and zika fevers. *Acta Tropica*, *166*, 155–163. https://doi.org/10.1016/j.actatropica.2016.11.020

Mitjà, O., Asiedu, K., & Mabey, D. (2013). Yaws. *The Lancet*, *381*(9868), 763–773. https://doi.org/10.1016/S0140-6736(12)62130-8

Ngatia, L. M., M. Grace III, J., Moriasi, D., Bolques, A., K. Osei, G., & W. Taylor, R. (2019). Biochar phosphorus sorption-desorption: Potential phosphorus eutrophication mitigation strategy. In V. Abrol & P. Sharma (Eds.), *Biochar - an imperative amendment for soil and the environment*. IntechOpen. https://doi.org/10.5772/intechopen.82092

Nicolas, G., Apolloni, A., Coste, C., Wint, G. R. W., Lancelot, R., & Gilbert, M. (2018). Predictive gravity models of livestock mobility in mauritania: The effects of supply, demand and cultural factors. *PloS one*, *13*(7), e0199547. https://doi.org/10.1371/journal.pone.0199547

Oladokun, V. O., & Johnson, A. (2012). Feed formulation problem in nigerian poultry farms: A mathematical programming approach. *American Journal of Scientific and Industrial Research*, *3*(1), 14–20. https://doi.org/10.5251/ajsir.2012.3.1.14.20

Ortega-Ramos, P. A., Mezquida, E. T., & Acebes, P. (2020). Ants indirectly reduce the reproductive performance of a leafless shrub by benefiting aphids through predator deterrence. *Plant Ecology*, *221*(2), 91–101. https://doi.org/10.1007/s11258-019-00995-0

Oster, M., Just, F., Büsing, K., Wolf, P., Polley, C., Vollmar, B., Muráni, E., Ponsuksili, S., & Wimmers, K. (2016). Toward improved phosphorus efficiency in monogastrics-interplay of serum, minerals, bone, and immune system after divergent dietary phosphorus supply in swine. *American Journal of Physiology - Regulatory, Integrative and Comparative Physiology*, *310*(10), R917–25. https://doi.org/10.1152/ajpregu.00215.2015

Pappas, M. L., Broufas, G. D., Pozzebon, A., Duso, C., & Wackers, F. (2019). Ecosystem services and disservices provided by plant-feeding predatory arthropods. *Frontiers in Ecology and Evolution*, *7*, 425. https://doi.org/10.3389/fevo.2019.00425

Pawar, S. S., Sajjanar, B., Lonkar, V. D., Kurade, N. P., Kadam, A. S., Nirmal, A. V., Brahmane, M. P., & Bal, S. K. (2016). Assessing and mitigating the impact of heat stress on poultry. *Advances in Animal and Veterinary Sciences*, *4*(6), 332–341.

Pedigo, L. P., & Rice, M. E. (2015). *Entomology and pest management* (Sixth edition). Waveland Press, Inc.

Peng, W., & Berry, E. M. (2019). The concept of food security. *Encyclopedia of Food Security and Sustainability*, *2*, 1–7. https://doi.org/10.1016/B978-0-08-100596-5.22314-7

Pfab, R., Schmoll, S., Dostal, G., Stenzel, J., Hapfelmeier, A., & Eyer, F. (2017). Single dose activated charcoal for gut decontamination: Application by medical non-professionals -a prospective study on availability and practicability. *Toxicology Reports*, *4*, 49–54. https://doi.org/10.1016/j.toxrep.2016.12.007

Pinker, S. (2018). Cheer up: The optimism of neuroscientist steven pinker runs counter to widespread gloom about humanity's future. *The Australian Rationalist*, *111*, 16.

Pyšek, P., Blackburn, T. M., García-Berthou, E., Perglová, I., & Rabitsch, W. (2017). Displacement and local extinction of native and endemic species. In M. Vilà & P. E. Hulme (Eds.), *Impact of biological invasions on ecosystem services* (pp. 157–175). Springer International Publishing. https://doi.org/10.1007/978-3-319-45121-3_10

Ramalho-Ortigao, M., & Gubler, D. J. (2020). 147 - human diseases associated with vectors (arthropods in disease transmission). *Elsevier*. https://doi.org/10.1016/B978-0-323-55512-8.00147-2

Rossi, B., Toschi, A., Piva, A., & Grilli, E. (2020). Single components of botanicals and nature-identical compounds as a non-antibiotic strategy to ameliorate health status and improve performance in poultry and pigs. *Nutrition Research Reviews*, 1–17. https://doi.org/10.1017/S0954422420000013

Snorek, j. (2016). *Shrinking pasture, burgeoning herds: Divergent adaptation to climate change in tahoua, niger* (Dissertation). Universitat Autonoma de Barcelona. Spain, Universitat Autonoma de Barcelona. Retrieved, from https://ddd.uab.cat/pub/tesis/2016/hdl_10803_400717/jusn1de1.pdf

Steinfeld, H., Mooney, H. A., Schneider, F., & Neville, L. E. (2013). *Livestock in a changing landscape, volume 1: Drivers, consequences, and responses*. Island Press.

Stenchly, K., Waongo, A., Schaeper, W., Nyarko, G., & Buerkert, A. (2019). Structural landscape changes in urban and peri-urban agricultural systems of two west african cities and their relations to ecosystem services provided by woody plant communities. *Urban Ecosystems*, *22*(2), 397–408. https://doi.org/10.1007/s11252-018-0811-5

Sugito, S., Rahmi, E., Delima, M., Nurliana, N., Rusli, R., & Isa, M. (2020). Effect of salix tetrasperma roxb. extract on the value of feed conversion ratio, carcass weight, and abdominal fat content of broiler chicken with heat stress condition. *Edition Diffusion Presse Sciences*, *151*(10), 01034. https://doi.org/10.1051/e3sconf/202015101034

Turner, M. D. (2018). Assessment through socioecological abstraction: The case of nutrient management models in Sudano-Sahelian west Africa. *Land Use Policy*. https://doi.org/10.1016/j.landusepol.2018.09.034

Turner, M. D., McPeak, J. G., & Ayantunde, A. (2014). The role of livestock mobility in the livelihood strategies of rural peoples in semi-arid west africa. *Human Ecology*, *42*(2), 231–247. https://doi.org/10.1007/s10745-013-9636-2

UNOWAS. (2018). Pastoralism and security in west africa and the sahel: Towards peaceful coexistence. https://pdfs.semanticscholar.org/f7a7/02119674607ca39ba12085add81378005a5f.pdf

van Chao, N., Thong, H. T., Le QuynhChau, H., Tam, V. T., & Rui, Z. (2016). Effects of charcoal and wood vinegar dietary supplementation to diarrhea incidence and faecal hydrogen sulfide emissions in pigs.

van Emden, H. F., & Harrington, R. (2017). *Aphids as crop pests* (Second edition). CAB International.

van Huis, A. (2020). Importance of insects as food in africa. In *African edible insects as alternative source of food, oil, protein and bioactive components* (pp. 1–17). Springer.

Whitelegg, J. (2017). *The earthscan reader on world transport policy and practice*. Routledge. https://doi.org/10.4324/9781315782898

Whitener, A., Parker, C., Holt, J., Esquivel-Palma, C., Gantz, J. D., & Justus, E. (2019). 2017 student debates: The anthropocene: Implications for arthropods and biodiversity. *American Entomologist*, *65*(1), 50–60. https://doi.org/10.1093/ae/tmz001