Grain legume fodders as ruminant feed in mixed crop-livestock systems in northern Ghana

Daniel Brain Akakpo

Grain legume fodders as ruminant feed in mixed crop-livestock systems in northern Ghana

Daniel Brain Akakpo

Thesis committee

Promotors

Prof. Dr I.J.M. de Boer
Professor of Animal Production Systems
Wageningen University & Research

Prof. Dr K.E. Giller
Professor of Plant Production Systems
Wageningen University & Research

Co-promotors

Dr S.J. Oosting
Associate professor, Animal Production Systems Group
Wageningen University & Research

Dr A.J. Duncan
Principal Livestock Scientist
International Livestock Research Institute, Nairobi, Ethiopia
Visiting Professor of Livestock & Development
University of Edinburgh, Scotland

Other members

Prof. Dr P.C. Struik, Wageningen University & Research
Dr W.F. Pellikaan, Wageningen University & Research
Prof. B.O. Bebe, Egerton University, Kenya
Dr A.A. Ayantunde, International Livestock Research Institute, Ouagadougou, Burkina Faso

This research was conducted under the auspices of the Graduate School
Wageningen Institute of Animal Sciences (WIAS)

Grain legume fodders as ruminant feed

in mixed crop-livestock systems in northern Ghana

Daniel Brain Akakpo

Thesis

submitted in fulfilment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus,
Prof. Dr A.P.J. Mol,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Wednesday 11 March 2020
at 1:30 p.m. in the Aula.

Daniel Brain Akakpo
Grain legume fodders as ruminant feed in mixed crop-livestock systems in northern Ghana
136 pages.

PhD thesis, Wageningen University, Wageningen, the Netherlands (2020)
With references, with summary in English

ISBN: 978-94-6395-237-8
DOI: https://doi.org/10.18174/508346

This thesis is dedicated to:

*My family, especially **Philicia,** my wife, **Selikem,** my daughter and **Harrison**, my brother.*

Abstract

Grain legumes are important crops in the mixed crop-livestock (MCL) systems in Africa because they provide food and cash for humans, fodder for animals and they improve soil fertility through biological nitrogen fixation. The residues of grain legumes, also known as grain legume fodders (GLFs), have better nutritional quality than cereal residues, such as maize and rice straw. Besides their function as livestock feed, GLFs supply fuel, construction material and mulch for soil improvement. However, knowledge about factors that drive the diversity of use of GLFs in different farming systems is limited. Therefore, the objective of this thesis was to understand the roles of grain legume fodders in mixed crop-livestock systems and identify options to improve their quality and utilisation by smallholders in northern Ghana. To achieve this objective, we conducted four multi-disciplinary studies. First, we assessed and described the variation in the use of GLFs to understand their impacts on MCL systems. Second, we evaluated and compared the effects of rhizobium inoculation and phosphorus fertilization on grain and fodder yield and fodder quality of the major grain legumes in two agro-ecological zones. Third, we evaluated the effects of storage conditions and duration on dry matter loss and nutritional quality of GLFs and to risk of aflatoxin formation in stored fodder. Lastly, we assessed the nutritional quality of stored GLFs using different quality assessment methods. Results show there is variation in the use of GLFs in the study regions in northern Ghana. For example, in Upper East region, most of the GLFs (87%) was stall-fed, whereas in Upper West region GLFs were for a considerable extent (61%), left on the field and used for mulching. In Northern region, both stall-feeding and grazing of GLFs was important. In our agronomic studies we found that rhizobium inoculation of cowpea seed, for example, increased grain yield by 44%, P-fertilization increased grain yield by 102% while the combination of P and inoculation increased grain yield by 123% compared to the control treatment where no input was applied. In the storage experiment, we found that dry matter loss during storage for 120 days was on average 24% across all storage conditions, 35% for the worst condition (tied in bundles and stored on roofs or tree-forks) and 14% for the best condition (sacks and in rooms). During storage, the CP content and OMD decreased, and the content of cell wall components increased. Aflatoxins were not detected in stored GLFs. Finally, in fodder quality assessment studies, all the four methods used (farmers' perception, sheep preference, leaf-to-stem ratio and laboratory analyses) successfully discriminated GLF quality between crops. Only farmers and sheep could distinguish quality differences among storage conditions, whereas laboratory assessment methods

could not. In general we concluded that with increasing importance of livestock in intensified MCL systems, GLFs become more important and more valuable for feeding, especially in the dry season. For this reason smallholder farmers can increased both grain and fodder yield of grain legumes concurrently through the use of rhizobium inoculation and P-fertilization. They can also reduce GLF nutritional quality and dry matter quantity loss by adopting appropriate fodder storage methods. The absence of aflatoxin in the groundnut fodder samples indicated that there is minimal risk of aflatoxin development when stored under dry conditions as in our study. Finally, farmers' experience and local knowledge in feeding GLFs to livestock is valuable in determining the quality of GLFs and preference of their animals.

Table of contents

General introduction

1.0 Introduction

In Ghana, agriculture is one of the pillars of the economy. In 2016, it contributed about 22% to the gross domestic product (MoFA, 2016). The agricultural sector is dominated by smallholder farms. Most of these smallholder farms are mixed crop-livestock (MCL) systems, which combine crop production with livestock rearing. Smallholder MCL systems in Ghana produce most of the food crops and meat. Major food crops are cereals (e.g. maize, rice, sorghum and millet) and legumes (e.g. cowpea, groundnut, soybean and bambara groundnut). Cattle, sheep, goats, pigs and poultry are the major livestock species kept by smallholders. Livestock rearing is an important component of MCL systems because livestock not only can convert crop residues into valuable food and manure, but they also provide cash income and insurance against crop failure. In most MCL systems in Ghana, however, livestock are kept to support crop production and not the other way around (Savadogo et al., 1999; Schiere et al., 2004). Livestock, moreover, are kept for transportation and traction power, for religious purposes and for the farmer's prestige (Oosting et al., 2014; Thornton, 2010).

According to the Ministry of Food and Agriculture of Ghana, domestic production of animal-source food does not meet the national demand, resulting in an annual import of, for example, 48,000 metric tonnes of meat, which is 25% of the national demand. Northern Ghana is producing about 40% of the country's needs for animal-source food, due to its availability of natural grasslands, which provide the basal feed for ruminants, i.e. cattle, sheep and goats. With the increasing demand for animal-source food, especially in the south of the country, there is scope for increased ruminant production in northern Ghana (Amankwah et al., 2012; Konlan et al., 2016). Ruminant production in northern Ghana, however, faces several major challenges. One important challenge is feed shortages during the dry season, both in terms of quantity and quality (Ayantunde et al., 2007; Konlan et al., 2016). This lack of enough nutritious ruminant feed results in low productivity (Addah and Yakubu 2008; Konlan et al., 2014). Another challenge for ruminant production is the increasing population pressure, leading to expansion of croplands at the expense of grazing lands. Population pressure moreover results in the intensification of cropping land and reduces the accessibility of livestock to graze crop residues after crop harvests. Wet season accessibility to rangelands in regions with cropping is another limitation in northern Ghana. Crop farmers in such regions fear destruction of their crops and therefore they ban livestock in their area. To overcome the above described feed challenges, smallholders in Ghana search for alternative feed sources. Potential alternative feed sources are: crop residues, tree fodders and agro-industrial by-products (Ayantunde et al., 2007; Duncan et al., 2016; Savadogo et al., 1999).

1.1 The potential of grain-legumes in the farming system

In Ghana, crop residues are the second largest source of livestock feed after grazing, and residues from grain legumes, also known as grain legume fodders (GLFs), are particularly important (Ayantunde et al. 2014; Konlan et al. 2014). Smallholder farmers generate extra household income through the sale of GLFs to livestock fatteners and traders. Studies by Ayantunde et al. (2014) and Konlan et al. (2018) revealed that the economic value of GLFs is rising and that these residues have become tradable feed resources in West Africa.

Traditionally, livestock had access to crop residues, by grazing cropland after harvest. Livestock consumed crop residues and left manure in exchange, which contributed to soil fertility. Since all livestock had access to such cropland, crop residues were regarded as a communal feed resource. Due to the reduction of grazing lands and feed shortages, however, crop residues in general and GLFs in particular, have become private goods instead of communal resources, with a market value.

Policymakers and development projects advocate increased use of grain legumes, such as groundnut, cowpea, pigeon pea and soybean for the following reasons. First, grain legumes fix atmospheric dinitrogen (N_2) in symbiosis with rhizobium bacteria and, therefore, contribute to enhanced soil fertility. Second, grain legumes are highly suitable for intercropping, such as relay cropping, or can easily be grown in rotation with cereal crops, without compromising the yield of the main crop (Kermah et al., 2017). Moreover, including grain legumes in crop rotation reduces risks for pests, diseases and weeds (Liebman and Dyck, 1993; Trenbath, 1993). Third, when the fodders of grain legumes are compared to cereal residues, such as straws and stovers, GLFs are more palatable, have a better digestibility and have higher energy and protein contents (Ayantunde et al., 2014; López et al., 2005; Schiere et al., 2004).

The role of GLFs as livestock feed, however, is currently limited by the low yields of grain legumes and their fodders, among others due to poor soil conditions and lack of improved crop varieties. To improve the soil fertility and enhance crop yields, a project called "N2Africa" (Textbox 1) was implemented in Africa. With funding from the Bill & Melinda Gates Foundation, N2Africa has been active since 2013 in Ethiopia, Tanzania and Uganda, and since 2009 in DR Congo,

Textbox 1. "N2Africa" Project: putting nitrogen fixation to work for smallholder farmers in Africa

N2AFRICA is a large scale, science-based "research-in-development" project focused on putting N_2-fixation to work for smallholder farmers growing legume crops in Africa.

With funding from the Bill & Melinda Gates Foundation, N2Africa has been active since 2013 in Ethiopia, Tanzania and Uganda, and since 2009 in DRCongo, Ghana, Kenya, Malawi, Mozambique, Nigeria, Rwanda and Zimbabwe. Focal legume crops are common bean, chickpea, cowpea, faba bean, groundnut and soybean.

Legumes bring atmospheric N_2 into the crops and the soil through a symbiosis with Rhizobium bacteria, and they are an important source of protein in a healthy diet. Enhanced productivity of legumes thereby contributes to improvements in soil fertility, household nutrition and income. N2Africa enables African smallholder farmers to reap these benefits through the implementation of effective production technologies including inoculants and fertilizers.

Direct beneficiaries of N2Africa are the farming households with increased benefits from biological N fixation – such as greater food and nutrition security or increased incomes. These households benefit from the network that was built to improve access to information, agricultural inputs and markets. By 2018, N2Africa had already reached more than 660,000 smallholder farmers with improved technologies for grain legume production.

N2Africa links scientific research with capacity building (from farmers to traders, development workers in extension and non-governmental organisations), educating MSc and PhD candidates, women's empowerment, and access to input-output markets through public-private partnerships

This PhD thesis project is a sub-project with the aim of intensification of smallholder farming systems by integrating crops (legumes) and livestock through the use of grain legume fodders as livestock feed. This project is a collaboration between Animal Production Systems and Plant Production Systems groups of Wageningen University & Research, International Institute of Tropical Agriculture (IITA) in Ghana, and the International Livestock Research Institute (ILRI) in Ethiopia.

Source: www.n2africa.org

Ghana, Kenya, Malawi, Mozambique, Nigeria, Rwanda and Zimbabwe. The focal legume crops of this project are: common bean, chickpea, cowpea, faba bean, groundnut and soybean. This project is promoting the use of improved grain legumes to bring the benefits of biological N_2-fixation such as: increased food security, improved soil fertility and improved livestock feeds to households in Africa.

1.2 Knowledge gap

Besides the function as feed, GLFs may have a function as fuel, construction material and mulch for soil improvement. To get insights into the scope for further development of the use of GLFs for livestock feed in northern Ghana, knowledge is required about the use of GLFs in the MCL systems and about the factors that drive the use of GLFs for different functions. So far, such knowledge has not been published. Currently, research and development activities are being implemented by governmental and non-governmental organizations to learn about and expand the use of grain legumes for smallholder farmers in northernGhana. More so, agronomic practices such as the use of rhizobium inoculants (Giller 2001; Rurangwa et al. 2017) and phosphorus (P) fertilizers (Ronner et al. 2016; Kyei-Boahen et al. 2017) have proven to enhance the yield of grain legume. However, these studies did not consider the value of GLFs as animal feed. Most previous studies so far have focused on varieties of a single crop species (Anele et al., 2010; Larbi et al., 1999). Best to our knowledge, there is no study which compares grain yields, fodder yields and fodder quality traits among grain legumes grown under similar conditions in a single experiment. Moreover, in most previous studies, the nutritional qualities of fodders as affected by agro-ecological conditions and agronomic inputs used have not been evaluated (Kyei-Boahen et al., 2017; van Heerwaarden et al., 2017). This showed that most of the previous research and development activities focus on the development of crop varieties and agronomic practices to increase grain yield and quality for food, without considering the uses of GLFs in the MCL systems in northern Ghana.

To ensure feed supply in the dry season, farmers and middlemen store GLFs until the late dry season from January to April. During the storage of GLFs, the nutritional quality is not checked before use or before marketing to other buyers. Even though storage aims to preserve the quality and quantity of fodders for later use, losses of nutrients during the storage process have been reported, particularly in crude protein content of hays (Lemus, 2009; Guerrero et al., 2010). However, there is no information about nutrient losses in stored GLFs. According to Guerrero et al. (2010) and Fekede et al. (2014), factors such as sunlight, heat, and precipitation, affect the quality of forages during storage. Another quality factor of concern is the development of mould during storage, which may lead to aflatoxin contamination. Aflatoxin contamination can compromise the health of livestock and consumers of animal source foods. Considerable variability in aflatoxin prevalence and concentration levels has been reported in forages, which were attributed to environmental and forage management-related factors (Gallo et al., 2015). It is not known, however, how storage conditions affect nutritional quality and development of aflatoxin in GLFs during storage.

To evaluate the nutritional quality of livestock feed and GLFs, laboratory analyses are required. However, such formal laboratory analyses are time-consuming and expensive to conduct and are also not widely available in low-income countries. For the above reasons, smallholder farmers in West Africa continue to rely on local knowledge to evaluate the nutritional quality of livestock feed. This local knowledge of farmers is based on the physical characteristics of the fodder, such as colour, leafiness, maturity stage, softness and smell. Currently, there is no effort to harness and integrate scientific methods of fodder nutritional quality evaluation with local knowledge of farmers. It would be important to explore the relationships between these fodder nutritional evaluation methods to reduce the time and cost of fodder nutritional quality evaluation for the smallholders in Africa.

1.3 Objectives of the study

The main aim of this PhD thesis is to understand the roles of grain legume fodders in mixed crop-livestock systems and identify options to improve their quality and utilisation by smallholders in northern Ghana. To address this generic aim, I needed to:

1. assess and describe the variation in the use of GLFs and understand their impacts on MCL systems in northern Ghana,
2. evaluate and compare the effects of rhizobium inoculation and phosphorus fertilization on grain and fodder yield and fodder quality of the major grain legumes in two agro-ecological zones of northern Ghana,

3. evaluate the effects of storage conditions and duration on dry matter and nutritional quality of GLFs and to assess the risk of aflatoxin in stored fodder,
4. assess the nutritional quality of stored GLFs using different quality assessment methods.

1.4 Summary of research approach

To address these four specific research objectives, I adapted and followed the Describe-Explain-Explore-Design (DEED) cycle (Descheemaeker et al., 2016; Giller et al., 2011). The DEED cycle is used to systematically **d**escribe the current systems, **e**xplain the phenomena of the systems, i.e. analyse reasons and mechanisms underlying the phenomena of systems, **e**xplore the implications of options to overcome constraints faced by systems (e.g. by modelling or on-farm trials) and **d**esign suitable options to overcome constraints and integrate them in crop and animal production systems.

To **describe** and **explain** the challenges faced by farmers in feeding their livestock and possible options for improvement, we first conducted focus group discussions (FGDs) in selected communities, including farmers, agriculture researchers and extension workers. After the FGDs, regions and districts were selected for further investigations. A total of 150 households were surveyed from 15 villages, five from one district each in each region. We subsequently **explored** the option of increasing grain and fodder yield and fodder quality of major grain legumes (cowpea, groundnut and soybean) through P-fertilization and rhizobium inoculation. To this aim, a multi-locational on-farm agronomic trials in eight communities were established. To make GLFs available to the farmers in the dry season, we **explored** different storage options to evaluate the fodder quantity and quality loss as affected by storage conditions. We finally **explored** various approaches to evaluate fodder quality i.e. farmer perception, sheep preference, leaf-stem ratio and laboratory analyses.

The interdisciplinary and participatory approach (involving focus group discussions, surveys, on-farm agronomic and storage experiments, laboratory analyses in combination with assessment of farmers perceptions and animal preferences) allowed us to explore the value of GLFs from production to usage. The combinations of these approaches and specifically the involvement of farmers and other stakeholders in the research process were important to conclude about and propose sustainable improvement options for adoption by farmers. I consider this "recommending of sustainable improvement options" as the **design** stage of the DEED cycle.

1.5 Description of the study area

The study was carried out in northern Ghana, including the northern region (NR), the Upper East region (UER) and Upper West region (UWR) (Fig. 1). These three regions are located in the agro-ecological zones referred to as southern Guinea Savanna (SGS) and northern Guinea Savanna (NGS). The mean annual rainfall is about 1200 mm for NR, 900 mm for UER and 1000 mm for UWR. The rainfall pattern in the regions is unimodal and begins in May and ends in October, with a long dry season from November to April. Due to the unimodal rainfall pattern and harsh climatic conditions in northern Ghana, traditional farming systems, which are mainly rain-fed, low input smallholder MCL systems, have developed over time as a way to adapt to these different agro-ecological conditions. These regions differed in many ways, including human population and livestock density, land availability, and farming systems (GSS, 2012; Kuivanen et al., 2016; Timler et al., 2014).

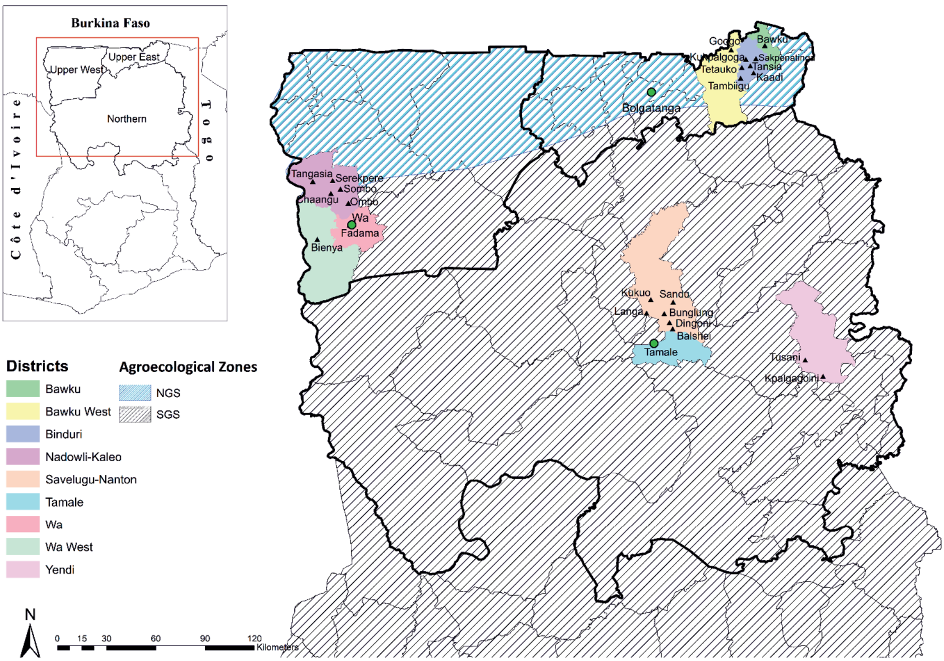


Fig. 1. Map of northern Ghana showing the study areas

1.6 Outline of the thesis

Fig. 2 presents the outline of the thesis. In **Chapter 2,** we assess and describe the variation in the use of GLFs and seek to understand the drivers for their use in MCL systems in northern Ghana. The variation between MCL systems is studied by comparing three regions with different population pressure and agro-ecological conditions, and consequently different farming systems. Through focus group discussions and household interviews, we describe and explain the use of GLFs in the farming systems of northern Ghana. **Chapter 3** focuses on the effects of rhizobium inoculation, phosphorus fertilizer and agro-ecology on grain and fodder yields of major grain legumes. To assess grain and fodder yields across two agro-ecological zones, we designed and applied multi-locational on-farm agronomic trials. In these trials, we additionally evaluate the influence of rhizobia inoculation and P-fertilizer on the nutritional quality of fodder of the grain legume species. In **Chapter 4,** we evaluate the effects of storage conditions on dry matter loss and change of nutritional quality of GLFs during storage. In the same **Chapter 4**, we evaluate the development of aflatoxins in groundnut fodder during and after storage. **Chapter 5** focuses on the nutritional quality of GLFs using four different methods including farmer perception, sheep

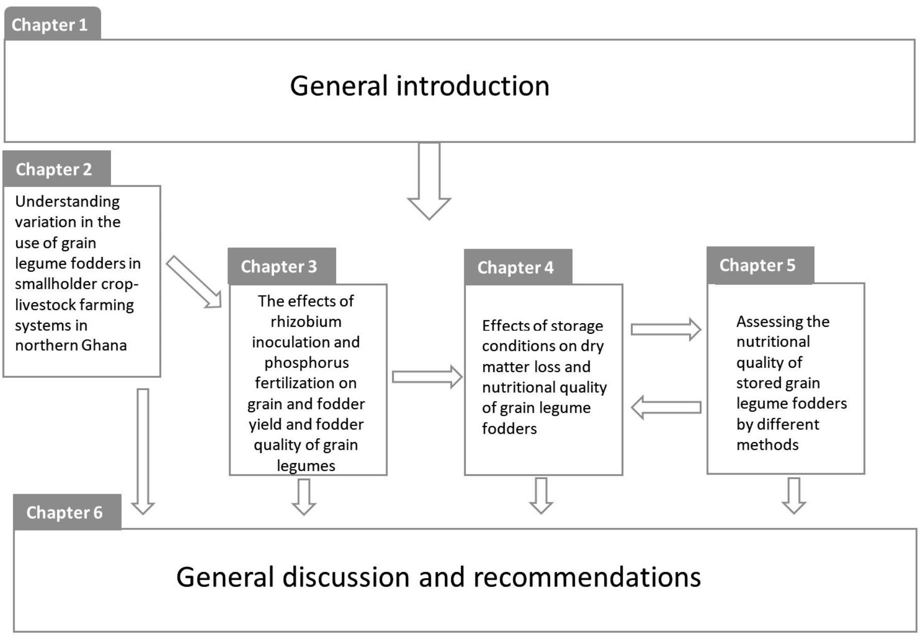


Fig. 2. Thesis outline adapting the DEED research cycle with collaborations between researchers, farmers and other stakeholders.

preference, leaf-stem ratio and laboratory analyses. These fodder nutritional quality assessment methods are then compared. Finally, in **Chapter 6,** I integrate and discuss the findings from Chapter 2 to 5 to recommend possible sustainable options to enhance the productivity of MCL systems through the use of GLFs.

Chapter 2

Understanding variation in the use of grain legume fodders in smallholder mixed crop-livestock systems in northern Ghana*

*This chapter will be published as:

Daniel Brain Akakpo, Imke J.M. de Boer, Ken E. Giller, Fokje A. Steenstra, Samuel Adjei-Nsiah, Alan Duncan and Simon J. Oosting. Understanding variation in the use of grain legume fodders in smallholder mixed crop-livestock systems in northern Ghana.

Abstract
Crop residues are a major feed resource in smallholder mixed crop-livestock (MCL) systems in West Africa. Grain legume residues, also known as grain legume fodders (GLFs) are considered more valuable livestock feed than cereal residues since they have higher digestibility and protein content. Besides the function as feed, GLFs may be used as fuel, in construction and as mulch for soil improvement. However, information is lacking about the variation in the use of GLFs and potential drivers for their use. The objective of the present study is, therefore, to assess and describe the variation in the use of GLFs and understand the potential drivers for their use in MCL systems in northern Ghana. A total of 150 households were surveyed in Northern (NR), Upper East (UER) and Upper West (UWR) regions in northern Ghana during the 2016 off-season In UER, the majority of the GLF (87%) was brought home and stall-fed, whereas in UWR GLF was mainly used for mulching (61%). In NR, both stall feeding and grazing of GLF was important. Compared to UWR and NR, UER had a high population density, low potential for crop production and low level of mechanisation of crop production, which all explanations for the relatively high importance of livestock in the farming systems. UWR and NR had a lower population density, higher crop production potential and more crop mechanisation and livestock was less important here than in UER. Use of GLFs followed the importance of livestock in the farming systems across the three study regions. We conclude that with increasing importance of livestock in intensified systems, GLFs become more important and more valuable for feeding especially in the dry season. The consequence of increased use of GLFs in intensifying MCL systems is that GLFs turn from being a communal resource that can be freely grazed during the dry season into a private resource with restrictions on use.

Keywords: crop residues, intensification, ruminants diet, farming systems

1.0 Introduction

Mixed crop-livestock (MCL) farming is common in West Africa: it is practised by about two-thirds of the farmers and produces about 70% of the food (Herrero et al., 2010; Livingston et al., 2011; Wiggins, 2009). In MCL systems, livestock support crop production through the supply of manure and draught power, whereas crops supply crop residues as a major feed for livestock. Livestock in MCL systems also has a financial function, as a store of wealth and insurance, besides the function in food supply (Oosting et al., 2014). The diversification of farm activities is an important contributor to the resilience of the MCL systems and livestock are important in this regard (Herrero et al., 2010; Rusinamhodzi et al., 2016; Thornton, 2010).

As in other West African countries, population pressure and urbanization are affecting the development of farming systems in northern Ghana. The pressure on land calls for the intensification of farming systems as a way of enhancing productivity. Grain legume crops are often introduced into the farming system as a route to intensification. Grain legumes have the capacity to fix atmospheric di-nitrogen (N_2) in symbiosis with rhizobium bacteria and can contribute to enhancing soil fertility and increasing grain and fodder yields in the cereal-dominated systems of West Africa. Grain legumes can be intercropped as a relay, or grown in rotation with cereal crops without compromising the yield of the main crop (Kermah et al., 2019). Including grain legumes in the farming system breaks the cycle and build-up of pests and diseases and reduces infestation by weeds (Liebman and Dyck, 1993; Trenbath, 1993). In addition, the residues of grain legumes, also known as grain legume fodders (GLFs), are considered a more valuable livestock feed than cereal residues since they have higher digestibility and higher protein contents (López et al., 2005; Schiere et al., 2004).

Besides their function as livestock feed, GLFs supply fuel, construction material and mulch for soil improvement (Akinola et al., 2016; Duncan et al., 2016; Valbuena et al., 2012). Such functions of GLFs may differ across MCL farming systems. Differences between MCL farming systems may include differences in population density, market opportunities and agro-ecology. For example, it is likely that high population density leads to land scarcity and good market opportunities and results in intensified land use if agro-ecological conditions allow (Migose et al., 2018; Oosting et al., 2014). Marketable crops and livestock production are important components of farming systems with intensified land use. It could be assumed that grain legumes fit in such intensified systems since the grain has a high market value and the crop residue supports improvement in livestock production. In regions with less population pressure, grain legumes and their residues may have different functions in the farming system since farming systems will be more extensive and more subsistence-oriented. However, knowledge about factors that drive the diversity of use of GLFs in different farming systems in Sub-Saharan Africa (SSA) is lacking. Having such knowledge could contribute to further development of production of grain legumes and use of GLFs for livestock production in MCL systems in northern Ghana and in SSA more generally. Therefore, the objective of the present study is to assess and describe the variation in the use of GLFs and understand the potential drivers for their use in MCL systems in northern Ghana. The variation between MCL systems is studied by comparing three regions with different population pressure and agro-ecological conditions, and consequently different farming systems.

2.0 Materials and methods

2.1 Study area

We selected three regions in northern Ghana, i.e. the Northern Region (NR), the Upper East Region (UER) and the Upper West Region (UWR). According to Ghana Statistical Service (2012), these regions differ regarding human population density, land size, livestock densities and agro-ecological conditions (Table 1). NR and UWR are located in the agro-ecological zones referred to as southern Guinea Savanna (SGS) while UER is located in the northern Guinea Savanna (NGS). The mean annual rainfall is about 1200 mm for NR, 900 mm for UER and 1000 mm for UWR (Table 1). The rainfall pattern in the regions is unimodal and begins in May and ends in October, with a long dry season from November to April.

Table 1. Characteristics of the study sites in the three case regions in northern Ghana

Regional characteristics	Regions		
	Northern	Upper East	Upper West
Land area (in 1000 km^2)	70	9	19
Population density (n/km^2)	35	118	38
Livestock owning households (%)	61	83	64
Average rainfall (mm/y)	1155	912	1022
Agro-ecological zone	Southern Guinea savanna	Southern/Northern Guinea savanna	Southern/Northern Guinea savanna

Source: Ghana Statistical Service (2012).

The farming systems, which are mainly rain-fed, low-input smallholder MCL systems, have developed over time as a way to adapt to the agro-ecological conditions and market situation. We presumed differences among the three regions regarding agro-ecological conditions and market situation and consequently expected different farming system development.

Crop production in northern Ghana is focused on staple crops (for food and cash), such as maize, millet, and sorghum. Rice, cassava, yam, and legumes are also grown. Among the legumes, cowpea, soybean and groundnut (mainly as cash crops) are cultivated (Konlan et al., 2016; Kuivanen et al., 2016; Timler et al., 2014). Common livestock species reared in northern Ghana are cattle, sheep, goats, and poultry. Donkeys, horses and pigs are kept to a lesser extent.

2.2 Study design and data collection

To make a quick appraisal of the study site, we first conducted two focus group discussions (FGD) per region using the Feed Assessment Tool (FEAST) developed by the International Livestock Research Institute (Duncan et al., 2012). FEAST was chosen because it offers the opportunity for broad-based analyses of the livestock production systems, identification of site-specific feeds and other related production constraints and opportunities. Second, we conducted interviews for which we selected one district from each of the three regions where the N2Africa Project (www.n2africa.org) was being implemented. These districts were Savelugu in NR, Binduri in UER and Nadowli in UWR. In each district, five villages were selected in consultation with agricultural extension agents (AEAs). A multistage approach within each village was adopted in selecting the households (HH) to be interviewed. First, the AEAs in charge of the villages listed 30 HH which grew grain legumes and used GLFs. Second, 10 out of these 30 HH were selected randomly for the interview. Third, when the farmer of a selected HH was not available at the time of the interview, the farmer of the next HH on the list was interviewed. A total of 150 farmers from 15 villages were interviewed after the farming season (i.e. from November 2016 to January 2017). Interviews were conducted at the homestead of the farmers by trained enumerators in the regions who spoke the language of the farmers. As part of the household survey, we collected information about household characteristics, including age and sex of the household head, family size and income sources. We also asked farmers about the total size of arable land owned, crops grown and harvested per area of land, and management of crop residues. Finally, we collected information about livestock production and the reasons for keeping livestock.

2.3 Data analyses

Means, standard errors and percentages were used to describe farming system characteristics observed for each region. A one-way analysis of variance (ANOVA) was used to compare values between regions. The one-way ANOVA model (equation 1) is:

$$Y_{ij} = \mu + R_i + \varepsilon_{ij} \quad [1]$$

where, Y_{ij} is the j^{th} observation in the i^{th} region, μ is the mean, R_i is the effect of the i^{th} region, relative to the mean, and ε_{ij} is the random error associated with the j^{th} observation in the i^{th} region. The tests were done at a 95% level of confidence ($\alpha = 0.05$). To identify differences in means between regions, we performed the post hoc Turkey's tests and a non-parametric Kruskal Wallis test where our data did not conform to the assumptions analysis of variance. All statistical analyses were carried out using IBM SPSS version 25.0 statistical software (IBM, 2017)

3.0 Results

3.1 Farm household characteristics

Table 2 summarises the farm household characteristics in each region. About 90% of the respondents were male in each region. The average age of a household

Table 2. Farm household characteristics (standard error) of the mixed crop-livestock systems in the three case regions in northern Ghana.

Households characteristics	Regions		
	Northern (n=50)	Upper East (n=49)	Upper West (n=50)
Male headed HH* (% of farms)	92	92	88
Educated** HH head (% of farms)	16^{a}	55^{c}	33^{b}
Age of HH head (y)	48 (1.84)	52 (2.44)	40 (2.16)
Years in farming (y)	23 (1.37)	27 (2.39)	24 (2.13)
Size of HH (n)	18^{b} (1.06)	15^{b} (1.37)	9^{a} (0.86)
Arable land holding (ha HH^{-1})	5.5^{b} (0.53)	3.8^{a} (0.34)	4.3^{ab} (0.43)
HH land tenure schemes (% of total)			
1. Own land	86^{a}	79^{a}	60^{b}
2. Family land	7^{a}	6^{a}	37^{b}
3. Others	7	15	3
Average one-way walking time to the crop fields (min)	29^{b} (1.51)	15^{a} (1.51)	25^{b} (1.37)

*HH refers to households;

**Educated refers to the percentage of HH heads who had some level of formal education

a,b,c Means in a row with different superscripts differ significantly ($p < 0.05$) between regions.

head was about 50 years, with about 25 years of farming experience. In UER, 55% of the respondents had at least education at the primary level, whereas the figure was 33% in UWR and 16% in NR. Household (HH) sizes in NR and UER were comparable and larger than in UWR. Average arable land size per HH was 5.5 ha in NR, which was higher than that in UER (3.8 ha) but comparable to that in UWR (4.3 ha). The majority of the land owned in each region was inherited from parents. In UWR, however, 37% of the respondents used family land. Such family land belongs to extended families consisting of many members. Allocation of family land is managed by a recognized extended family head. To a lesser extent, we also found other land tenure schemes, such as renting of land and shared-cropping (sharing crops harvested with the landowner). One way walking time to the plots was shorter (16 min) in UER than NR (29 min) and UWR (26 min) (Table 2).

3.2 Livestock holdings

Table 3 summarizes the herd size per HH and the proportion of HH owning different livestock species in northern Ghana. We found no differences in total herd size and cattle herd across HHs in all regions. Sheep flock size, however, was higher in NR than in UER and UWR. Also, HHs in UER owned more horses and donkeys than HHs in NR, while HHs in UWR owned no horses and donkeys. NR had a lower livestock density than UR and UWR. In UER, a higher proportion of the HHs owned cattle than in NR and UWR. Poultry was owned by almost all HHs in the study sample.

3.3 Reasons for keeping livestock

Table 4 summarizes the major reasons for keeping livestock by smallholders in our study regions. Overall, cash was the main reason for keeping cattle followed by manure being important in UER and NR. Meat for own consumption was a more important reason for keeping cattle in UWR than in NR and UER, whereas provision of draught power by cattle was considered more important in UER than in NR and UWR. Besides providing cash, small ruminants (i.e. sheep and goats) were especially important as a source of household food and manure, especially in the NR. Farmers from the UER and UWR considered wealth status an important reason for keeping livestock, particularly for sheep and cattle, whereas this was not the case in the NR. Furthermore, another important reason for keeping cattle in the UER was for cultural and religious events, such as dowry and sacrifices. Also, sheep and goats were important for dowry and sacrifice in UER, and for gifts in NR and UWR.

Table 3. Average herd size (standard errors) and percentage of households owning major livestock species in smallholder MCL systems in the three case regions in northern Ghana.

Livestock species	Regions		
	Northern (n=50)	Upper East (n=49)	Upper West (n=50)
Herd size (TLU HH^{-1}**)*			
Total herd size	4.9 (0.68)	5.7 (1.02)	6.1 (1.32)
Cattle	2.4 (0.54)	3.4 (0.83)	4.1 (1.27)
Sheep	1.1^{b} (0.12)	0.6^{a} (0.12)	0.5^{a} (0.09)
Goat	0.7 (0.09)	0.7 (0.06)	0.7 (0.11)
Donkey/Horse	0.0^{a} (0.01)	0.3^{b} (0.09)	0.0^{a} (0.00)
Pigs	0.5 (0.36)	0.4 (0.10)	0.4 (0.13)
Poultry	0.4 (0.05)	0.4 (0.05)	0.3 (0.05)
Livestock density (TLU ha^{-1})	1.0^{a} (0.16)	1.7^{b} (0.25)	1.6^{b} (0.36)
Percentage (%) of households owning livestock			
Cattle	40^{a}	76^{b}	36^{a}
Sheep	94^{b}	98^{b}	62^{a}
Goats	82	67	84
Donkey/Horse	2^{a}	22^{b}	0^{a}
Pigs	6^{a}	41^{b}	46^{b}
Poultry	98	96	98

*TLU is Tropical Livestock Unit which equals animal of 250 kg live weight

**HH refers to a household

[a,b,c] Means in a row with different superscripts differ significantly ($p < 0.05$) between regions.

Table 4. Major reasons for keeping livestock by smallholders in the three case regions in northern Ghana (scale varies from 1-3, where 1 is not important, 2 is neutral and 3 is important).

Livestock species	Regions	Cash	Meat	Milk	Draught power	Manure	Store of wealth	Other(s)**
Cattle	NR*	3.0	1.5^a	1.3	2.0^a	2.6^{ab}	1.8^a	-
	UER	2.9	2.0^a	1.6	2.9^b	2.9^b	2.5^b	2.6
	UWR	2.7	2.5^b	1.6	2.3^a	2.3^a	2.2^{ab}	-
	p-value	ns	0.001	ns	<0.001	0.013	0.01	
Sheep	NR	3.0	2.7^b	1.0	1.0	2.6	1.9^a	3.0
	UER	2.9	2.3^a	1.0	1.0	2.6	2.8^b	2.8
	UW	2.9	2.0^a	1.0	1.0	2.4	2.0^a	-
	p-value	ns	<0.001	ns	ns	ns	<0.001	ns
Goat	NR	3.0	2.9^c	1.0	1.0	2.5	1.8^a	3.0
	UER	2.9	2.5^b	1.0	1.0	2.5	2.5^b	2.6
	UWR	3.0	2.1^a	1.0	1.0	2.4	1.9^a	2.0
	p-value	ns	<0.001	ns	ns	ns	<0.001	ns

*NR=Northern region, UER=Upper East region, UWR=Upper West region
**Other(s) = dowry and sacrifice in Upper East region, gifts in Northern and Upper West regions

a,b,c Means in a column with different superscripts differ significantly ($P < 0.05$) between regions within an animal species. P-values were based on a non-parametric Kruskal Wallis test. ns = not significant. - = not mentioned

3.4 Crop production

Information regarding the cultivation of staple crops, which are major sources of crop residues, is presented in Table 5 and the size of land allocated to the production of each crop in Table 5. We corrected for intercropping by assuming a 50% share of land for each intercrop (Waldman et al., 2016). Maize was a major cereal crop across regions, and it was grown by almost all farmers. The second most important cereal crop differed across regions. In NR, about half of the farmers cultivated rice as a second crop, whereas in UER, the second crop was millet. In UWR, millet, sorghum and rice were about equally important, after maize. Maize grain and fodder yields were higher in NR and UER than in UWR, whereas rice yields were higher in NR than UER and UWR. The major grain legumes across regions were cowpea, groundnut and soybean. In NR and UWR, groundnut was the major grain legume, followed by cowpea, while in UER cowpea was the major grain legume, followed by soybean. Only in NR, pigeon

Table 5. Average grain and fodder yields and allocation of arable land to crops grown in smallholder mixed-crop systems in the three study regions in northern Ghana

Crops	Grain yield (kg ha^{-1})			Fodder** yield (kg ha^{-1})		
	NR*	UER	UWR	NR	UER	UWR
Cereals						
Maize	1133^{b}	1105^{b}	729^{a}	1046^{b}	1020^{b}	673^{a}
Millet	400	508	558	-	-	-
Sorghum	273	608	399	410	497	326
Rice	1258^{b}	695^{a}	711^{a}	1029^{b}	569^{a}	582^{a}
Legumes						
Cowpea	463	363	408	431	338	380
Groundnut	709^{b}	153^{a}	504^{b}	1446^{b}	312^{a}	1028^{b}
Soybean	912^{c}	617^{b}	351^{a}	1854^{c}	1255^{b}	714^{a}
Bambara	247	233	645	1606	1515	4193
Pigeon pea	859	-	-	2355	-	-
	Allocation of arable land (% of total land) to crops					
Cereals						
Maize	35.8^{b}	32.0^{b}	17.5^{a}			
Millet	1.2	21.0	4.6			
Sorghum	5.0	2.0	15.1			
Rice	26.8	8.7	3.8			
Legumes						
Cowpea	4.2	16.6	13.2			
Groundnut	12.8^{a}	4.5^{a}	29.6^{b}			
Soybean	5.4	12.8	1.2			
Bambara	0.4^{a}	1.4^{a}	9.2^{b}			
Pigeon pea	2.9	-	-			
Others***	5.5	1.0	5.9			

*NR=Northern region, UER=Upper East region, UWR=Upper West region

**Fodder yield was calculated based on the harvest index for legumes reported in Franke et al. (2018), maize and sorghum in Baudron et al. (2014)

a,b,c Means in a row with different superscripts differ significantly ($p < 0.05$) between regions

***Others include crops such as yam, cassava, sweet potato and vegetables

pea was grown, and about 3% of the arable land is allocated this crop. Grain and fodder yields of groundnut were higher in NR and UWR than in UER. Soybean yields were higher in NR than in UER and UWR (Table 5).

3.5 Household income sources

Table 6 presents the major sources of HH incomes of farmers in our three case regions. In both NR and UWR, crop production was the main source of income, followed by livestock production. In UER, however, income from both crop and livestock production was equally important. Sources of off-farm income, such as petty trading, remittances, and formal employment, were relatively more important in UER than in NR and UWR. To a limited extent, farmers in UER also earned some income from the sale of crop residues, which is part of the other sources of income.

Table 6. Contribution (% of total income) of sources of income for households in the three study regions in northern Ghana.

Income sources	Regions		
	Northern (n=50)	Upper East (n=49)	Upper West (n=50)
On-farm			
Crops	59.4^{b}	37.4^{a}	66.3^{b}
Livestock	30.8^{b}	38.2^{c}	20.8^{a}
Off-farm			
Services/labour	3.6	4.1	5.5
Formal employment	0.8	3.9	1.0
Remittances	3.2^{a}	9.3^{b}	1.6^{a}
Petty trading	2.0	5.8	3.9
Others*	0.3	1.4	0.8

^{a,b,c} Means in a row with different superscripts differ significantly ($p < 0.05$) between regions

* Others include the sale of crop residues, charcoal burning and mining of gold.

3.6 Uses of grain legume fodders

The major uses of GLFs differed between the study regions. Generally, GLFs are either collected for stall-feeding during the dry seasons, grazed on the fields or left on the field as mulch (Table 7). In UER, the majority of the GLF (87%) was brought home and stall-fed, whereas in UWR GLF was mainly used for mulching (61%). In NR, both stall feeding and grazing of GLF was important. The proportion of GLF burnt on the fields to ease land preparation for the next cropping was similar in both NR and UWR. In UER, however, none of the GLF was burnt on the field (Table 7). The use of GLF for other minor purposes, such as compost, fuel and selling for income, was relatively unimportant in all regions.

Table 7. Grain legume fodder use (% of biomass) by farmers in mixed-crop livestock systems in the three study regions in northern Ghana (standard errors in parentheses).

Fodder use	Regions		
	Northern (n=50)	Upper East (n=49)	Upper West (n=50)
Grazing	25.6^{c} (3.03)	5.3^{a} (1.77)	17.5^{b} (3.34)
Stall feeding	43.2^{b} (3.65)	87.3^{c} (2.65)	11.9^{a} (2.92)
Mulching	22.0^{b} (3.01)	3.3^{a} (1.38)	60.8^{c} (4.51)
Burned	8.2^{b} (1.37)	0.0^{a} (0.00)	7.4^{b} (2.72)
Sold	0.0^{a} (0.00)	1.5^{b} (0.69)	0.0^{a} (0.00)
Compost	0.0 (0.00)	0.8 (0.43)	0.8 (0.75)
Fuel	0.9 (0.65)	0.0 (0.00)	0.3 (0.37)
Others*	0.0 (0.00)	1.3 (1.28)	1.0 (0.00)

^{a,b,c} Means in a row with different superscripts differ significantly ($p < 0.05$) between regions.

*Others uses include roofing and weaving of baskets and mats.

3.7 Seasonal contribution of major livestock feed resources in ruminant diets

The proportion of feed resources in ruminants diets is presented for four seasons in Table 8, while monthly contribution and availability of major feed resources are illustrated in Figs. S1 – S3 (*see supplementary material*). During the early dry season (November – January) and late dry season (February – April), GLFs brought home for stall feeding constituted between 35 – 40% of ruminant diets in NR and UER, and only about 6% in UWR. The proportion of cereal residues brought home for feeding did not differ among regions and varied between 6 – 11% of the diet in both early and late dry seasons. During the same period, open grazing (where livestock graze freely in communal areas) contributed for about 40% to the diet in NR and UER and for about 70% to the diet in UWR. During the early rainy (May – July) and late rainy (August – October) seasons, feeds were supplied to livestock through open grazing, tethering and cut and carry feeding (fodder trees and roadside weeds are cut and brought to the animals in pens). During this period, animals are restricted from open grazing in areas with cropping activities to prevent unwanted consumption of crops. The animals are, however, shepherded during grazing around uncropped areas.

Table 8. Seasonal contribution of feed resources to ruminant diets in the three study regions in northern Ghana (scale of 0-10, with 0 being 0%, 5 being 50% and 10 being 100%).

Seasonal feed resources	Regions		
	Northern (n=50)	Upper East (n=49)	Upper West (n=50)
Early-dry (Nov-Jan)			
Legume residues	4.0^{b}	3.8^{b}	0.6^{a}
Cereals residues	0.2^{a}	1.1^{b}	0.9^{b}
Open grazing	3.9^{a}	4.2^{a}	7.7^{b}
Tethering	0.1	0.2	0
Cut and carry	0^{a}	0.4^{b}	0.3^{b}
AIBP*	0.6^{b}	0.1^{a}	0.1a
SEM**	0.12	0.11	0.14
Late-dry (Feb-Apr)			
Legume residues	3.5^{b}	3.5^{b}	0.6^{a}
Cereals residues	0.2^{a}	1.0^{b}	0.9^{b}
Open grazing	4.4^{a}	3.9^{a}	7.1^{b}
Tethering	0.2^{a}	0.7^{b}	0.6^{b}
Cut and carry	0.1^{a}	0.5^{b}	0.5^{b}
AIBP	0.5^{b}	0.1^{a}	0.1^{a}
SEM	0.11	0.1	0.13
Early-rainy (May-Jul)			
Legume residues	0.9^{b}	1.1^{b}	0.2^{a}
Cereals residues	0.2	0.3	0.5
Open grazing	5.0^{b}	2.8^{a}	2.8^{a}
Tethering	1.4^{a}	4.8^{b}	4.5^{b}
Cut and carry	1.2^{b}	0.6^{a}	1.4^{b}
AIBP	0.3^{b}	0.1^{a}	0.2^{ab}
SEM	0.11	0.11	0.11
Late-rainy (Aug-Oct)			
Legume residues	0.4	0.1	0.4
Cereals residues	0.4	0	0.5
Open grazing	2.3	2.9	2.5
Tethering	3.1^{a}	6.2^{c}	4.7^{b}
Cut and carry	2.9^{c}	0.5^{a}	1.5^{b}
AIBP	0.3^{b}	0.1^{a}	0.2^{ab}
SEM	0.1	0.03	0.11

^{a,b,c} Means in a row with different superscripts differ significantly ($p < 0.05$) between regions.

*AIBP is agro-industrial by-products; **SEM is standard error of means

Chapter 2

The availability of feeds from natural sources (grazing, tethering and cut and carry) follows rainfall distribution in all places in northern Ghana and increases from June to October (Figs. S1 – S3). Availability of feeds from natural sources continues until December and then declines as the dry season proceeds.

4.0 Discussion

4.1 Drivers of grain legume fodder use in MCL systems

The objective of this study was to assess and describe the variation in the use of GLFs and understand potential drivers for their use in MCL systems in northern Ghana. Variation in GLF use between MCL systems was studied by comparing their use in three regions. Since these regions differed in population pressure and agro-ecological conditions, we expected different farming systems. A high population density exerts pressure on land and other natural resources and leads to conversion of grazing lands to croplands and use of land for construction of residences and infrastructure (Duncan et al., 2016; Tamou et al., 2018; Valbuena et al., 2015). A high population density also creates a market demand for agricultural products (Migose et al., 2018). Pressure on land and market opportunities may result in intensification of land use and market orientation of farming. Livestock can contribute to intensification of land use since the livestock density can be gradually increased when feeds are imported into the farming system or when use of available crop residues increases. Hence, livestock often becomes more important in intensifying MCL farming systems. In addition, cattle may be important in intensifying crop systems for provision of draught power especially in areas where tractors are scarce (Diao et al., 2014; Doumbia et al., 2012).

UER was more densely populated than NR and UWR (Table 1), and we, therefore, expected land use here to be more intensive than in NR and UWR. This expectation was confirmed by the higher livestock density, the higher proportion of HH income from livestock production (Table 6) and the relatively high use of cattle for draught power (Table 4, Diao et al., 2014). NR and UWR had approximately similar, relatively low population densities and so we expected relatively extensive land use. UWR was indeed relatively extensive and is a cropping region characterized by a high HH income from crops. NR was in between UER and UWR regarding the relative importance of livestock and crops for HH income. NR has favourable conditions for crop production, which is reflected in the relatively high crop yield obtained here, and a good market situation in Tamale, which is one of the major cities of Ghana.

So it seems justified to assume that our study regions represent a land-use intensification gradient with an associated livestock intensification gradient in the order of descending land-use intensity: UER, NR, UWR. The importance of livestock in the farming systems followed this intensification gradient and the importance of livestock was associated with the role and use of GLFs in the MCL systems. In UER, HHs invested labour in collecting and stall-feeding GLFs and a high proportion of GLFs was used for feeding. In NR, where livestock and crops were both important for HH income, GLFs were used for livestock feeding, but through grazing after harvest of the grains. In UWR, feeding of GLFs was limited and they were left in the fields for mulching. In UWR and to some extent in NR where cropping is important, leaving the GLFs in the field is vital for N mineralisation to increase soil fertility for increased yield of a subsequent cereal crop in rotation with the grain legume (Kermah et al., 2019). So we conclude that increasing importance of livestock implies increased use of GLFs as feed in line with Valbuena et al. (2012b) and Duncan et al. (2016).

Although GLFs are valuable for livestock feeding in UER, farmers in the regions allocate a lower percentage of their arable land to legume production (Table 5). This phenomenon could be due to the relatively low yield of grain legumes as a result of poor soils and low rainfall in the region compared with the other two regions (Table 5). The high allocation of land to cereals could also be due to food insecurity in the region where farmers consider grain legumes more as cash crops than as food crops. In terms of regional distribution, UER has the worst food insecurity status (28% of the population is food insecure) followed by UWR (16% of the population is food insecure) and NR (10% of the population is food insecure) (WFP, 2012). Besides the low soil fertility, scarcity of arable land in UER constrains farm expansion leading to low volumes of food produced. In an attempt to reduce the food insecurity status, farmers tend to cultivate more cereal crops (especially maize and millet) than grain legumes. It is likely that farmers in UER collect a higher portion of their GLFs for livestock feed due the low total production of GLFs from the small cultivated areas of grain legumes. Also the keeping of livestock is a strategy to cope with the relatively unfavourable conditions for crop farming in UER (Nkegbe et al., 2017). Hence population pressure driving land intensification is not the only reason why livestock is important in UER. It seems justified to conclude that use of GLFs follows the importance of livestock in the farming system rather than population pressure per se.

Other factors facilitate the use of GLFs in the regions. For instance, the organisation of crop fields around the settlement or homestead of HH may be important. The distance from the fields to the homestead is shorter in UER (where cultivated fields are just around the homestead) than in NR and UWR, (where homesteads are clustered in communities and cropping lands are at a distance from the community). Carrying GLFs to the homestead for stall-feeding, therefore, requires less labour in UER than in NR and UWR which could also explain the higher use of GLFs and the higher prevalence of stall-feeding in UER compared to NR and UWR.

Moreover, in UER, most households which own cattle manage the herd by themselves and need to collect and use GLFs from crop fields. In both NR and UWR HHs give the responsibility for the herding of their cattle to *Fulani* herdsmen and consequently, they are not greatly concerned about the collection and use of GLFs. This *Fulani* herding explains also why farmers in UWR had a relatively low valuation of manure production as a function of livestock. In the *Fulani* herding, the livestock owners do not have access to the manure produced.

The consequence of increased and intensified use of GLFs in intensifying MCL systems is that GLFs turn from being a communal resource, that could once be freely grazed during the dry season, into a private resource. This development is aggravated by the fact that more and more GLFs are collected and traded for feeding in fattening systems (Konlan et al., 2018; Samireddypalle et al., 2017). Traditional herding systems like the pastoral systems of *Fulani* who alternate between rainy season grazing of Savanna pastures and dry season grazing of crop residues in crop regions will be affected since they lose access to the cropland in the dry season (Tamou et al., 2018).

4.2 Seasonal availability of feed resources and contribution to ruminant diet

To confirm the importance of GLFs as livestock feed in the MCL system in northern Ghana, we hypothesized that GLFs would constitute a major component of the seasonal ruminant feed calendar in UER and NR compared with UWR in relation to other available feed resources. Our study showed that a high proportion (approximately 40%) of the ruminant diet in both early and late dry season of the year consisted of GLFs in UER and NR (Table 8). Open grazing was still the major component of the ruminant diet in the region across all seasons (see Table 8 and supplementary Fig. S3). These observations are in agreement with other studies in the region (Amole and Ayantunde, 2016; Konlan et al., 2018, 2016) which also showed the importance of open grazing throughout the year and of GLFs during the dry season in market-oriented livestock systems. Availability of natural grassland might be sufficient to maintain current production levels, but with decreasing grassland areas and increasing livestock production, crop residue feeding will become more important in the future.

5.0 Conclusion

The study confirms that there is variation in the use of GLFs in the MCL system in northern Ghana. The two major roles of GLFs are that they are either fed to livestock or left on the field as a mulch. Use of GLFs followed the importance of livestock in the farming systems across the three study regions. We conclude that with increasing importance of livestock in intensified systems, GLFs become more important and more valuable for feeding especially in the dry season. The consequence of increased use of GLFs in intensifying MCL systems is that GLFs turn from being a communal resource that can be freely grazed during the dry season into a private resource with restrictions on use.

Acknowledgements

We thank the Bill & Melinda Gates Foundation for funding through a grant to Wageningen University to support the project N2Africa: Putting Nitrogen Fixation to Work for Smallholder Farmers in Africa (www.N2Africa.org). We are also grateful to farmers Agricultural Extension Agents in the regions. We thank Robert Atawura, Fuseini Abdulai, Augustine Tambie from Upper West region, Baba Iddrisu, Abraham Takora, Awudu Rufai, Alhassan Sulemana from Northern region and Sorogo Sariki, Osman Fulailu, Abukari Mohammed from Upper East for their assistance during data collection. We are also indebted to Suzanne Roelen for developing the data entry templates.

Conflict of interest

The authors declare no conflicts of interest.

Supplementary Materials

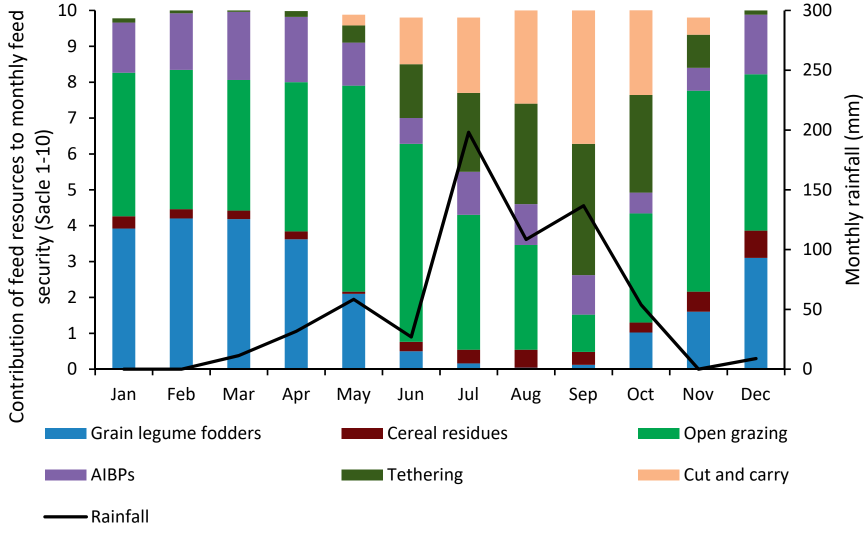


Fig. S1. Contribution of feed resources to ruminant diets and monthly rainfall during 2016 in the Northern region. (AIBPs = agro-industrial by-products; 'cut and carry' includes green fodder, grass and leaves collected for stall-feeding)

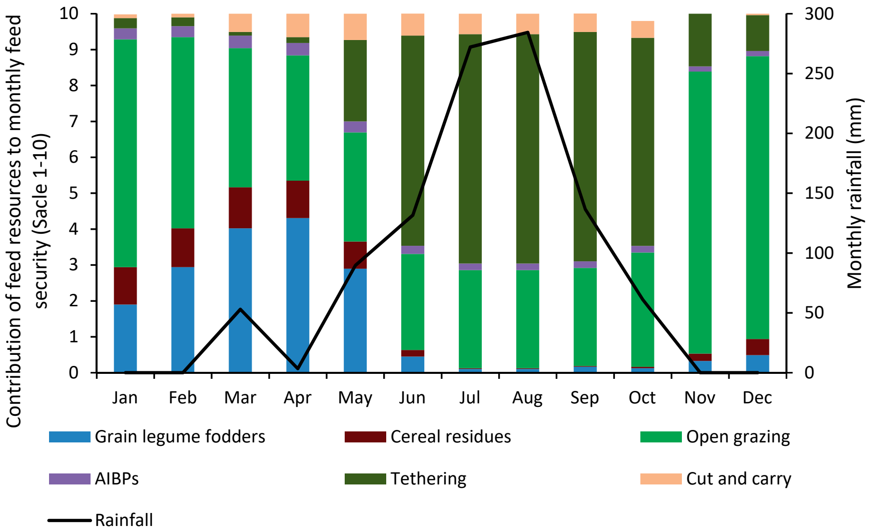


Fig. S2. Contribution of feed resources to ruminant diets and monthly rainfall during 2016 in the Upper East region. (AIBPs = agro-industrial by-products; 'cut and carry' includes green fodder, grass and leaves collected for stall-feeding)

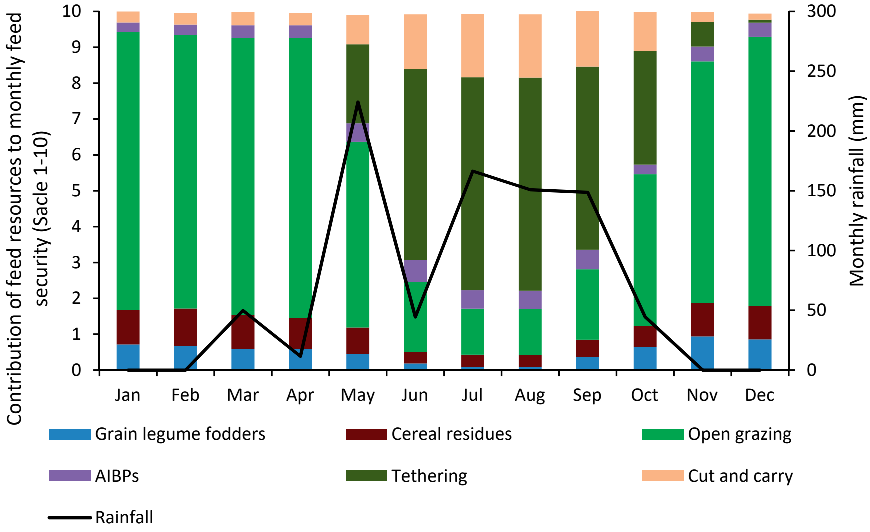


Fig S3. Contribution of feed resources to ruminant diets and monthly rainfall during 2016 in the Upper West region. (AIBPs = agro-industrial by-products; 'cut and carry includes' green fodder, grass and leaves collected for stall-feeding)

Chapter 3

Do inoculation and phosphorus fertilization of grain legumes improve yield and fodder quality? Evidence from the Guinea Savanna of Ghana*

*This chapter is submitted as:
Akakpo, D.B., Oosting, S.J., Adjei-Nsiah, S., Duncan, A.J., de Boer, I.J.M, Giller, K.E., *Do inoculation and phosphorus fertilization of grain legumes improve yield and fodder quality? Evidence from the Guinea Savanna of Ghana*. Experimental Agriculture.

And a part of this chapter was presented as:
Akakpo, D B.; Oosting, S.J.; Adjei-Nsiah, S.; Duncan, A.J; Giller, K.E.; de Boer, I.J.M.; (2016). *The Influence of Rhizobia Inoculation and Phosphorus Fertilizer on Yield and Quality of Cowpea Fodder in Northern Ghana*. In book of abstracts of Pan-African Grain legume & World Cowpea Conference, Livingstone, Zambia – p. 145-146

Abstract

Grain legumes are important smallholders crops in the mixed crop-livestock farming systems in Guinea savanna agro-ecological zone of West Africa. They provide food and cash for humans, fodder for animals and improve soil fertility through biological nitrogen fixation. However, grain and fodder yields of grain legumes remain low due to poor soil fertility and inadequate input use. Therefore, we evaluated the effect of rhizobium inoculation and phosphorus fertilization on grain and fodder yield and fodder quality of three major grain legumes (cowpea, soybean and groundnut) in the southern Guinea Savana (SGS) and the northern Guinea savanna (NGS) agro-ecological zones (AEZs) of northern Ghana. Three most commonly grown varieties of each grain legume type were subjected to four different combinations of phosphorus (P) fertilizer (at 30 kg P ha^{-1}) and rhizobium inoculation (I) treatments: inoculant only (I-only), phosphorus fertilizer only (P-fert), inoculant + P fertilizer (P+I), and no inoculation and no fertilizer, i.e. the control treatment. Grain yield of cowpea and fodder yield of cowpea and soybean increased due to inoculation with rhizobium. P-fert also increased both grain and fodder yields in cowpea and soybean. Across AEZs and all crops, the average grain yield was 60% higher in SGS than in NGS (P=0.002). Soybean had a higher grain yield (1094 kg ha^{-1}) than cowpea (761 kg ha^{-1}) and groundnut (614 kg ha^{-1}). In cowpea, for example, I-only increased grain yield by 44%, P-fert by 102% and P+I by 123% compared to the control treatment. A similar trend of increasing order in the grain yield among treatments was also observed in cowpea fodder yield as follows: control < I-only < P-fert < P+I. The P-fert and inoculation treatments did not affect any of the fodder quality traits measured within crop varieties. However, there were significant differences among crops (P<0.001) in all fodder quality traits (i.e. Ash content, crude protein, neutral and acid detergent fibre, lignin and *in-vitro* organic matter digestibility) evaluated. The effect of AEZ on yields and observed in our study suggests that targeting of crops and their varieties to the length of the growing season can help to bridge the yield differences. The increase in fodder yield as a result of rhizobium inoculation and phosphorus fertilization suggests that extra quantity of quality fodder is produced to enhance livestock production in the region.

Keywords: Grain legumes, crop residues, fibre, crude protein, *in-vitro* digestibility

1.0 Introduction

Grain legumes are important crops in the mixed crop-livestock systems of West Africa. They provide food and cash for humans, fodder for animals, promote the diversification of cropping systems, and are also an important source of edible oils. According to the FAO (2007), soybean and groundnut are ranked third and fourth in world oil production, after cottonseed and rapeseed, respectively. In addition, the residues of grain legumes, also known as grain legume fodders (GLFs) are used as feed for livestock (Larbi *et al.*, 1999; Prasad *et al.*, 2010; Dada *et al.*, 1999; Singh *et al.*, 2011) and enhance soil fertility through biological nitrogen (N_2) fixation (Giller, 2001; Kermah *et al.*, 2017a). Major grain legumes grown in West Africa are cowpea (*Vigna unguiculata* (L.) Walp.), groundnut (*Arachis hypogaea* L.) and soybean (*Glycine max* (L.) Merr.).

Scarcity and high cost of livestock feed are major challenges for animal production in the savanna zones of West Africa, especially in the dry season from December to April. In Ghana, crop residues are the second largest source of livestock feed after grazing, and GLFs are particularly important (Konlan *et al.*, 2014; Ayantunde *et al.*, 2014). Smallholder farmers generate extra household income through the sale of GLFs to livestock, fatteners and traders as feed. Studies by Ayantunde *et al.* (2014) and Konlan *et al.* (2018) revealed that the value of GLFs is rising and that these residues have become tradable resources in West Africa. Therefore, cereal residues and GLFs have changed from being communal resources to being private resources in the last two decades. When compared to cereal straws and stovers, such as those of maize, rice and sorghum, GLFs are relatively more palatable and have higher energy and especially protein contents (Grings *et al.*, 2012; Singh *et al.*, 2011). Increasing demand for livestock products will further increase the demand for extra feed and fodder for livestock production.

To satisfy this future demand for legume grains and fodders, crop breeders have developed various dual-purpose grain legume varieties with increased yields of both grain and fodder (Reddy *et al.*, 2003; Samireddypalle *et al.*, 2017). Some of these new varieties were evaluated previously by researchers for their grain and fodder yield potentials and nutritional qualities for livestock e.g. cowpea (Singh *et al.*, 2011; Ansah *et al.*, 2016) groundnut (Anele *et al.*, 2010; Larbi *et al.*, 1999; Blümmel *et al.*, 2013) and soybean (Maheri-Sis *et al.*, 2011; Blount *et al.*, 2006; Wang *et al.*, 2014). Grain and fodder yields can also be increased through the use of improved agronomic and crop management practices. These practices include the use of agricultural inputs, such as rhizobium inoculants (Giller, 2001;

Rurangwa *et al.*, 2017) and phosphorus (P) fertilizers (Kyei-Boahen *et al.*, 2017; Ronner *et al.*, 2016). Most previous studies have focused on varieties of a single grain legume, and we found no study which compared grain yields, fodder yields and fodder quality traits among grain legumes. Possible influences of the agro-ecological conditions and agronomic inputs on the nutritional qualities of fodders are rarely studied. The objective of the current study was to evaluate and compare the effects of rhizobium inoculation and phosphorus fertilization on grain and fodder yield and fodder quality of the major grain legumes (cowpea, soybean and groundnut) in two agro-ecological zones of northern Ghana.

2.0 Materials and methods

2.1 Study area

The study was conducted on farmers' fields under rain-fed conditions in two agro-ecological zones (AEZs) in northern Ghana: the southern Guinea Savana (SGS) and the northern Guinea Savanna (NGS). One district in each AEZ was selected for the study, i.e. the Savelugu-Nanton district (9°34'47.1"N 0°52'57.8"W) in SGS and the Binduri district (10°56'01.6"N 0°18'53.7"W) in NGS. Both AEZs have a unimodal rainfall regime with a mean annual rainfall of 1100 mm in SGS and 900mm in NGS. The rainy season is from May to October with a peak in August/September in SGS, and from June to October with a peak in August in NGS. According to the Interim Ghana soil classification system, soils in Savelugu-Nanton municipality are Savanna-ochrosols, while soils in the Binduri district are groundwater Laterites (Adjei-Gyapong and Asiamah, 2002). In each district, four villages (Fig. 1) were selected with the help of agricultural extension agents. One farmer was finally selected in each village to host one replicate of the trial on his/her farm. Most of the selected experimental fields were previously cropped with maize in the SGS and maize or millet in the NGS.

2.2 Experimental design, treatments and crop management

The study comprised three separate sub-experiments, each with one of the three major grain legumes (cowpea, groundnut and soybean) grown in Ghana. Of each grain legume, three varieties (V) were used for the study: cowpea – Songotra (IT97K-499-35), Apagbaala (4554/CBE+) and Padituya (SARC 3-122-2); groundnut – Samnut 22 (M 572.80I), Samnut 23 (ICGV-IS96894) and Chinese (SHITAOCHI); and for soybean – Jenguma (TGX1448-2E), Soun-poungun (TGX 1799-8F) and Afayak (TGX 1834-5E). The experiments were laid out in a split-plot design with variety as a main-plot factor. The sub-plot treatments (T) were:

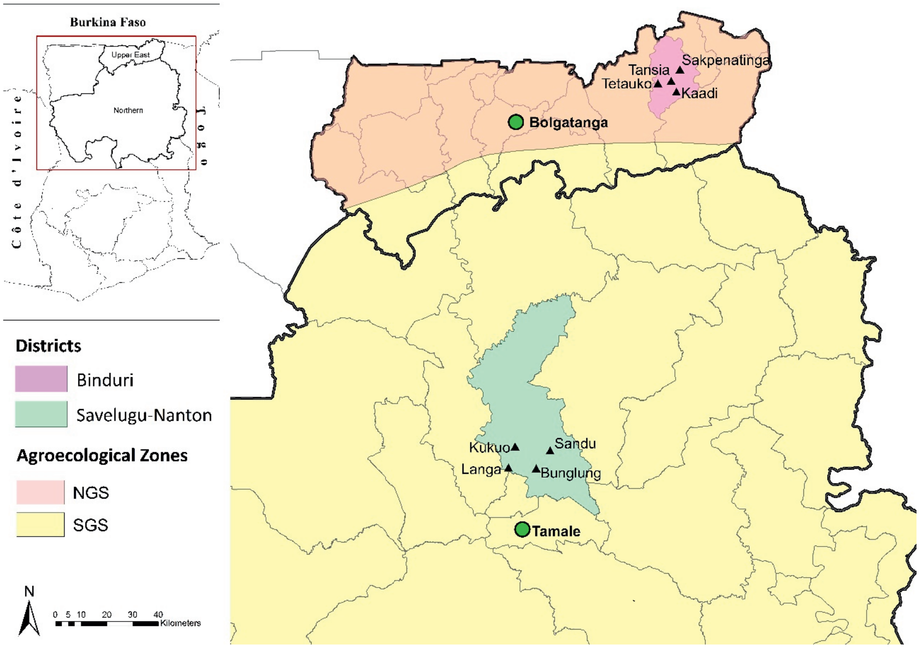


Fig. 1. Map of northern Ghana (inset) showing the villages where the field trials were conducted. Source: authors mapping in ArcMap 10.5.

inoculation only (I-only), phosphorus fertilizer only (P-fert), phosphorus fertilizer and inoculation (P+I) and no-inoculation and no-fertilizer (control) for each grain legume species. One experimental block was laid-out on each of the four selected farms per village serving as replicates within an AEZ. Seeds were of good quality and were obtained from the International Institute of Tropical Agriculture (IITA) - Ghana office.

The following rhizobium inoculants were used: *Bradyrhizobium pachyrhizi* strain - BR 3267 containing 10^8 cells gram^{-1} (obtained from EMBRAPA through Savanna Agricultural Research Institute, SARI – Ghana) for cowpea, *Bradyrhizobium japonicum* strain (Nodumax® from IITA, Ibadan-Nigeria) containing 10^8 cells gram^{-1} of USDA 110 strain for soybean and *Bradyrhizobium japonicum minimum* (HiStick® from BASF Chemical Company, South Africa Ltd.) containing 4 x 10^9 viable cells gram^{-1} for groundnut. Seeds were moistened and stirred in a bowl while the inoculant was added at 5 g kg^{-1} seed and stirring continued until all the seeds were covered entirely with the inoculant. Inoculated seeds were spread on a sheet of polyethene material and air-dried for at least 30 min in the shade before sowing. Un-inoculated treatments were sown first to avoid contamination. The P treatment was triple superphosphate (TSP) fertilizer (46 % P_2O_5) at the rate of 30 kg P ha^{-1} applied at planting, except cowpea which was fertilised seven days after sowing. The fertilizer was applied 5-10 cm away from the planting line, in a 2-5 cm deep trench and covered. There were ten rows of each crop planted in 6 m x 5 m plots at an inter-row spacing of 60 cm for all crops, intra-row spacing of 20 cm for cowpea and groundnut, and 10 cm for soybean at two seeds per stand.

The experimental fields were ploughed with tractors and levelled manually with hoes in the SGS while ploughing and ridging were done in NGS with the use of bullocks. Sowing was done on the flat in SGS and on top of ridges in NGS to reflect the common practice in each AEZ. Groundnut and soybean were sown on July 6 and 7, 2015 in SGS and on July 8 and 9, 2015 in NGS. Cowpea, on the other hand, was sown on August 14 and August 16, 2015, in SGS and NGS, respectively, to reflect the local practice of late sowing for cowpea in order to harvest the crop at the beginning of the dry season. Cowpea was sprayed twice at flowering and podding, with a recommended insecticide (Lambda Super 2.5EC) according to the manufacturer's recommendation. Weed control was done once between fifth and seventh week after sowing using hoes.

2.2 Data Collection

2.2.1 Soil sampling and yield determination

Prior to land preparation, soil samples were collected randomly from 0–20 cm depth from five different spots across each selected field using a soil auger. The soil samples of each field were mixed thoroughly, and a composite sample was taken, air–dried and sieved to pass through a 2-mm screen for physical and chemical analysis at the analytical services laboratory of the International Institute of Tropical Agriculture (IITA) at Ibadan, Nigeria. Soils were analysed for pH by the 1:1 soil to H_2O ratio method, organic C by the Walkley-Black method, total N by the Kjeldahl method, P was by the Mehlich method and exchangeable K, Ca and Mg by IITA (1981) standard procedures. The results of the physical and chemical analysis are presented in Table 2.

Grain and fodder were harvested for yield determination at physiological grain maturity in each plot from a net area of 14.4 m^2 (6 rows of 4 m length) from the six middle rows of the plots to avoid border effects. Cowpea pods were harvested at two different times and bulked, dried and threshed to determine grain yield. Fodder yield was determined by cutting and weighing all plants (after grain harvest) of the plot area harvested for grain yield assessment at the ground level. Grain and fodder sub-samples of 200 and 500 g, respectively, for each plot, were placed in paper bags and oven-dried at 70 °C for 48 hours to determine air-dry matter.

NIRS prediction and chemical analyses

Grain legume fodder samples were analysed for chemical composition and nutritional value using Near Infrared Reflectance Spectroscopy (NIRS) and conventional chemistry. NIRS prediction was made according to de Boever et al. (1995) and Fekadu et al. (2010). A total of 70 samples (20 cowpea, 20 groundnut, and 30 soybean) were selected for conventional chemical analysis. This comprised of Ash/Organic matter (OM), Dry Matter (DM) and Crude Protein (CP) according to the procedure of the Association of Official Analytical Chemists (AOAC, 1990), Neutral Detergent Fibre (NDF) following Van Soest and Robertson (1985)Van and *In-Vitro* Organic Matter Digestibility (IVOMD) by the Menke and Steingass (1988) in vitro gas production procedure using rumen fluid. The results from the conventional chemical analysis were used to update the NIRS general legume crop calibration equations developed at ILRI - Ethiopia.

Statistical Analyses

The Linear Mixed Model procedure in GenStat (VSN, 2017) was used for data analyses. Data for all crops were analysed together to determine the differences in yield and quality traits among crops due to location, crop type and treatment. The analysis was also done separately for each crop across AEZs and later within AEZs where crop type was replaced with variety in the reduced model. Per AEZ, varieties and P and inoculation treatments were the fixed factors with varieties nested into replicates (blocks) as the random factor of the model to test for the effects. The full ANOVA model (equation 1) used for combined analysis was:

$$Y_{ijkl} = \mu + B_i + L_j + C_k + T_l + (LC)_{jk} + (LT)_{jl} + (CT)_{kl} + (LCT)_{jkl} + \varepsilon_{ijkl} \qquad [1]$$

Where; Y_{ijk} is an agronomic or fodder quality trait, μ is the general mean, B_i is the block effect (i=1 to 8), L_j is the location effect (j=1 to 2), C_k is the crop effect (k=1 to 3), T is the treatment effect (l=1 to 4), $(LC)_{jk}$ is the interaction of the location and the crop type, $(LT)_{jl}$ is the interaction of location and treatment, $(CT)_{kl}$ is the interaction of the crop type and treatment, $(LCT)_{jkl}$ is a three-way interaction among location, crop type and treatment and ε_{ijkl} is the residual error. In the analysis of the crop varieties, we replaced the crop type with the crop varieties in the model, equation 1. Pearson's correlation coefficients between yield and quality traits were estimated. The effect of different factors and their interactions were compared by computing the standard errors of difference (SED). Least significant differences (LSD) was used to compare treatment means. Only significant differences ($P < 0.05$) are referred to as differences unless otherwise stated.

3.0 Results

3.1 Rainfall and soil properties

About 60 – 70% of the annual rainfall occurred between July and September. There were 40 rainy days in NGS compared with 52 in SGS. The amount of seasonal rainfall received in NGS was higher than in SGS (Fig. 2). The wettest month in SGS was September with 225 mm of rain while August was the wettest month in NGS with 271 mm of rain. The pH across the soils of the two AEZs was slightly acidic ranging from 5.7-5.9 in SGS and 5.5-6.2 in NGS (Table 1). Soil available P varied more among the samples taken in SGS than among those taken in NGS. The range of available P observed in the experimental fields was above the critical value of 10 mg P kg^{-1} needed for crop growth in sub-Saharan Africa (Fairhurst, 2012). The soil organic carbon in the two AEZs was below the reported critical value of 15 g kg^{-1} in all experimental fields. Exchangeable cations were slightly above the critical values of 0.5 cmol kg^{-1} for Ca and 0.2 cmol kg^{-1} for Mg. However, the K concentrations below 0.2 cmol kg^{-1} suggested it may have been limiting in the soils of the experimental fields. The physical properties of the soils also varied among experimental fields and AEZs. The sandier soils in NGS were likely to have low water holding capacity for crop production (Table 1).

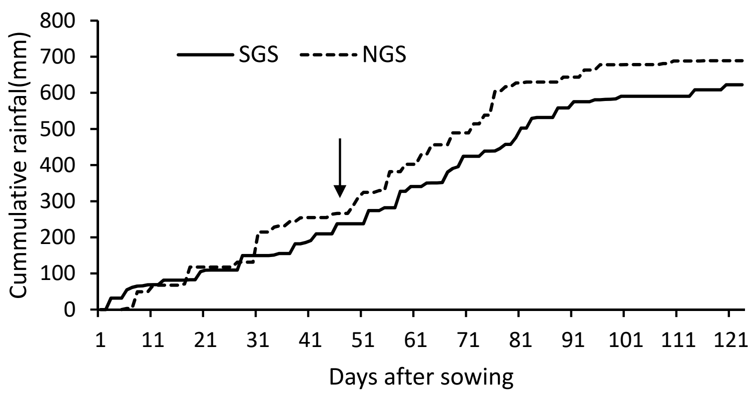


Fig. 2. Cumulative rainfall during the 2015 growing seasons in Southern Guinea savanna (SGS) and Northern Guinea savanna (NGS) in northern Ghana. The arrow represents the sowing time of cowpea (Source: SARI).

Table 1. Mean and range of soil physical and chemical properties (0-20 cm) across trial locations in the southern Guinea savanna (SGS) and northern Guinea savanna (NGS) of northern Ghana. Part of these data is reported in Adjei-Nsiah et al. (submitted).

Soil properties	SGS		NGS	
	Mean	Range	Mean	Range
pH	5.9	5.7-5.9	5.9	5.5-6.2
OC (g kg^{-1})	3.85	2.85-4.48	4.22	3.08-5.60
N (g kg^{-1})	0.47	0.23-0.75	0.50	0.32-0.65
Meh P (mg kg^{-1})	29.7	19.5-47.1	20.2	17.4-24.4
Ca (cmol+ kg^{-1})	1.73	0.73-2.65	2.15	1.11-3.19
Mg (cmol+ kg^{-1})	0.52	0.25-0.66	0.54	0.35-0.81
K (cmol+ kg^{-1})	0.15	0.09-0.28	0.17	0.15-0.28
Na (cmol+ kg^{-1})	0.08	0.06-0.09	0.07	0.06-0.09
ECEC (cmol+ kg^{-1})	2.48	1.16-3.49	2.94	1.71-4.22
Sand (g kg^{-1})	638	524-684	732	704-764
Silt (g kg^{-1})	212	114-328	139	120-160
Clay (g kg^{-1})	150	128-176	129	116-136

ECEC: Effective Cation Exchange Capacity

3.2 Development of NIRS equation and component predictions of grain legume fodders

NIRS calibration and validation statistics for the prediction of Ash, CP, NDF, ADF, ADL and IVOMD (on DM bases) of GLFs are presented in Table 2. The results show that IVOMD was the most accurately predicted trait with a

Table 2. Equation statistics of the calibration and validation of grain legume residues (Cowpea, Soybean and Groundnut) for predicting fodder quality traits

Parameter (g kg^{-1})	Calibration			Validation		Laboratory Values		NIRS predicted Values	
	R^2_c	SEC	n	R^2_v	SEV	Mean (g kg^{-1})	SD	Mean (g kg^{-1})	SD
Ash	0.97	1.41	1287	0.87	2.61	164	7.9	177	8.8
CP	0.97	1.26	1323	0.94	1.15	198	6.9	192	6.7
NDF	0.95	2.60	747	0.91	3.71	404	12.0	390	12.4
ADF	0.93	1.82	424	0.93	2.67	361	7.0	350	9.9
ADL	0.91	0.61	578	0.61	1.39	55	2.0	53	1.8
IVOMD	0.97	0.20	329	0.99	0.76	692	12.0	736	10.8

CP=crude protein; NDF=neutral detergent fibre; ADF=acid detergent fibre; ADL=acid detergent lignin; IVOMD=*in-vitro* organic matter digestibility; n=number of samples; SEC=Standard Error of Calibration; R^2_c=coefficient of correlation in calibration; R^2_v =coefficient of determination in validation; SEV=Standard error of validation; SD=Standard Deviation.

coefficient of determination in validation (R^2_v) of 0.99 and Standard Error of Validation (SEV) of 0.76. Similarly, high accuracies in predicting Ash, CP, NDF and ADF were observed. The mean predicted values of the cell wall components: NDF (390 g kg^{-1}), ADF (350 g kg^{-1}) and ADL (53 g kg^{-1}) using NIRS were close to values obtained from laboratory analyses of 404, 361 and 55 g kg^{-1}, respectively.

3.3 Grain and fodder yields and fodder quality across legume crops and AEZs

The combined analysis of the effects of treatments on grain and fodder yield and fodder nutritional quality traits of cowpea, groundnut and soybean in SGS and NGS of northern Ghana are reported in Table 3. On average, grain yield combined for all the grain legume crops was 60% larger in SGS than in NGS.

Table 3. Combined analysis of the effects of rhizobium inoculation and phosphorus fertilizer on grain and fodder yield (kg ha^{-1}) and fodder quality traits (g kg^{-1} DM) of cowpea, groundnut and soybean in southern Guinea Savanna (SGS) and northern Guinea Savanna (NGS) of northern Ghana in 2015. For AEZ, data represent means across all treatments; for legume species, data represent means across AEZs and treatments; and for treatments, data represent means combined for all crops and AEZs.

	Grain yield	Fodder yield	Ash	CP	NDF	ADF	ADL	IVOMD
AEZ								
SGS	1178	1903	118	119	561	472	105	636
NGS	468	1381	141	131	503	429	106	643
P-value	0.002	0.153	0.003	0.259	0.019	0.047	0.876	0.568
LSD	347.0	781.5	12.1	23.1	45.1	42.7	9.7	28.0
Crop								
Cowpea	761	1253	164	148	510	418	112	681
Groundnut	614	1769	137	155	447	405	93	679
Soybean	1094	1904	87	72	639	529	111	558
P-value	0.005	0.009	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
LSD	259.4	395.4	18.0	20.5	35.8	33.5	7.0	18.5
Treatment								
Control	578	1235	132	126	530	449	106	641
I-only	728	1553	129	128	526	446	105	645
P-Fert	1007	1857	128	121	538	457	106	635
P+I	979	1923	129	125	534	451	105	635
P-value	<0.001	0.001	0.443	0.057	0.235	0.183	0.845	0.061
LSD	78.5	171.7	4.9	5.6	11.9	10.5	2.2	8.7

CP=crude protein; NDF=neutral detergent fibre; ADF=acid detergent fibre; ADL=acid detergent lignin; IVOMD=*in-vitro* organic matter digestibility.

Among the crops, soybean had higher grain yield than cowpea and groundnut (Table 3). There was an increase in grain yield with I-only (26%), P-fert (74%) and P+I (69%) relative to the control combined for all crops, varieties and AEZs. However, the effect of I-only was only significant for cowpea. Significant interactions for grain yield were observed between AEZ x treatment (T), crop (C) x T and AEZ x C x T. P-fert and P+I produced similar yield responses among the different grain legumes but both induced significantly greater yields than I-only. However, within each crop, the yield differences among treatments were not consistent.

Fodder yields did not differ between AEZs. Cowpea produced the least fodder yield (41% less than groundnut and 51% less than soybean; Table 3). P+I increased fodder yield by 56%, while P alone increased the yield by 50% and I-only by 26% compared with the control. Among the fodder quality traits measured, Ash, NDF and ADL were different between AEZs and also among the different grain legume crops. For instance, CP content was 51% (cowpea) and 54% (groundnut) higher than in soybean (Table 3). However, NDF and ADF concentrations were greater in soybean than in cowpea and groundnut (Table 3). Fodder quality traits were not significantly affected by I-only, P-fert or P+I when compared with the control (Table 3).

3.4 Grain and fodder yield and fodder quality traits as affected by different varieties of grain legume crops

3.4.1 Cowpea

Across AEZs, cowpea grain yield was 60% higher in SGS than in NGS (Fig. 3; Table 4). Grain yield differed among the varieties. For example, Padituya had the lowest grain yield of 622 kg ha^{-1} while Apagbaala had the highest (868 kg ha^{-1}; Table 4). Compared with the control treatment, I-only increased grain yield by 44%, P-fert by 102% and P+I synergistically by 123%. Cowpea fodder yield was also higher in SGS than in NGS. Padituya produced the highest fodder yield among the varieties and Songotra the least. The increasing order of the fodder yield among treatments was as follows: control < I-only < P-fert < P+I (Table 4).

Within SGS, there were no differences in grain yield among varieties, but yield differed between treatments. For instance, I-only yielded 199 kg ha^{-1} more grain than the control while P-fert and P+I yielded similar grain yield but higher than I-only (Fig. 3). P+I did not produce higher grain yield compared to P-fert alone. A similar trend was observed in NGS. Fodder production among varieties was

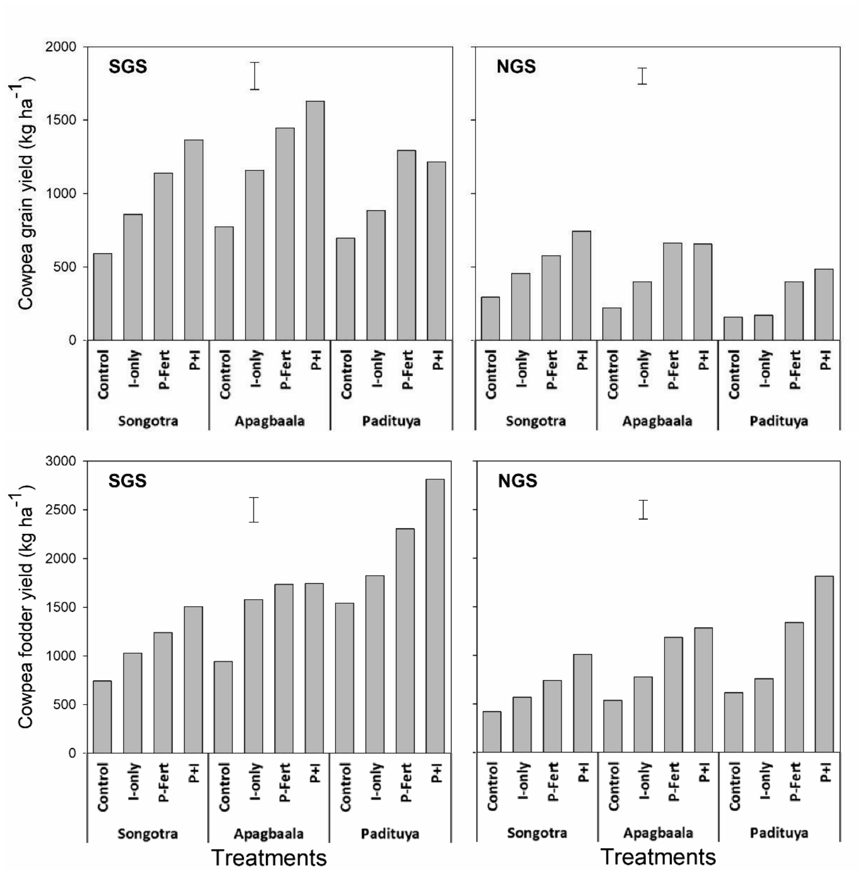


Fig. 3. Effects of rhizobium inoculation and phosphorus fertilization on grain and fodder yield (kg ha^{-1}) of three different cowpea varieties) in Southern Guinea Savanna (SGS) and Northern Guinea Savanna (NGS) in 2015. The error bar represents the standard error of difference (SED) between means

also different. There was no consistent varietal and treatment effect on the fodder quality traits except IVOMD which was influenced by the treatments within both AEZs (data not shown).

Table 4. Effects of rhizobium inoculation and phosphorus fertilizer on grain and fodder yield (kg ha^{-1}) and fodder qualities traits (g kg^{-1} DM) of three cowpea varieties in southern Guinea Savanna (SGS) and northern Guinea Savanna (NGS) of northern Ghana in 2015

	Grain yield	Fodder yield	Ash	CP	NDF	ADF	ADL	IVOMD
SGS	1087	1583	146	134	537	434	105	686
NGS	435	922	183	161	483	401	120	676
P-value	0.012	0.022	0.072	0.284	0.234	0.411	0.050	0.65
LSD	449.0	529.4	41.7	55.6	100.8	90.3	14.93	51.2
Padituya	662	1627	169	156	492	400	109	698
Apagbaala	868	1223	166	142	515	425	113	686
Songotra	753	908	158	145	524	427	115	677
P-value	0.03	<0.001	0.483	0.144	0.096	0.054	0.183	0.076
LSD	145.3	210.6	20.2	14.3	30.0	23.8	6.77	16.2
Control	455	801	169	148	514	425	116	672
I-only	654	1091	165	153	495	404	112	695
P-Fert	919	1424	159	141	526	432	112	673
P+I	1016	1696	164	149	505	410	109	684
P-value	<0.001	<0.001	0.369	0.264	0.160	0.100	0.060	0.021
LSD	107.7	159.0	11.9	12.7	27.8	24.8	6.04	17.0

CP=crude protein; NDF=neutral detergent fibre; ADF=acid detergent fibre; ADL=acid detergent lignin; IVOMD=*in-vitro* organic matter digestibility.

3.4.2 Soybean

Soybean grain yield was 64% higher in SGS than in NGS (Fig. 4; Table 5). Soybean grain yield, however, did not differ among varieties but was different among treatments. Compared to the control treatment, I-only increased grain yield by 19%, P-fert by 47% and P+I increased grain yield by 40% which was not different from P-fert. Soybean fodder yield was similar in both SGS and NGS with no difference among the varieties. There was a treatment effect similar to grain yield where I-only increased fodder yield by 29%, P-fert by 62% and P+I by 60%, which was similar to P-fert (Table 5).

Soybean grain and fodder yield in both SGS and NGS are represented in Fig. 4. Within SGS, there were no differences in grain yield among varieties, but treatments differed. P-fert had the highest effect on grain yield producing 2174 kg ha^{-1} while the lowest grain yield (1053 kg ha^{-1}) was produced in the control

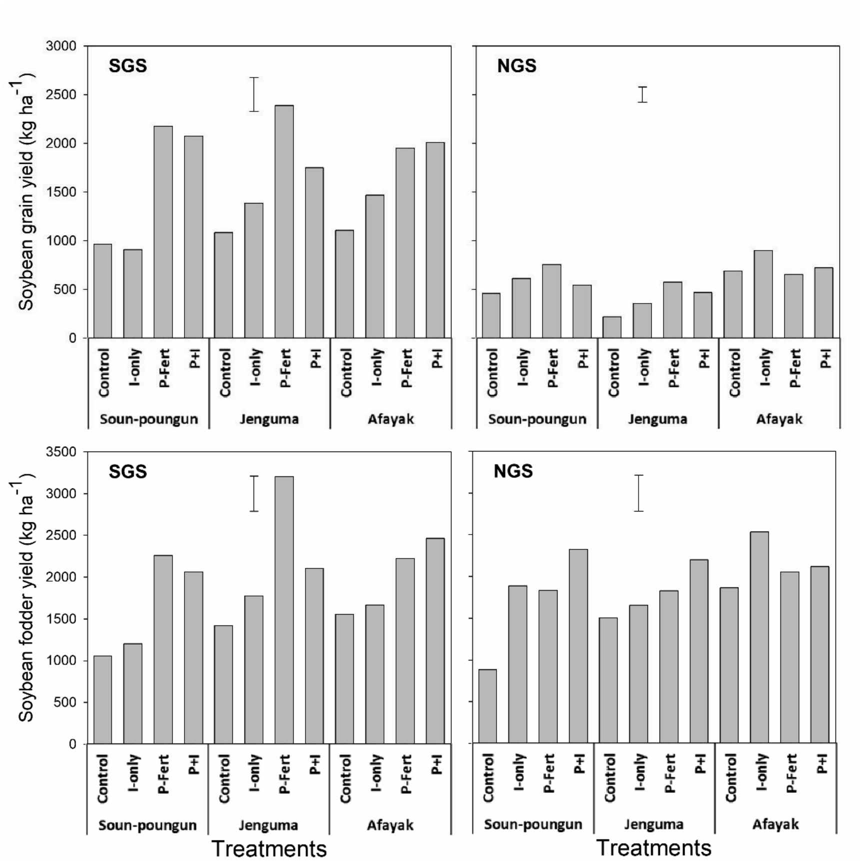


Fig. 4. Effects of rhizobium inoculation and phosphorus fertilization on grain and fodder yield (kg ha^{-1}) of three different soybean varieties in Southern Guinea Savanna (SGS) and Northern Guinea Savanna (NGS) in 2015. The error bar represents the standard error of difference (SED) between means

treatment (Fig. 4). Contrary to the SGS, there was no treatment effect on grain yield, but varietal differences were observed in NGS. Afayak had a higher (743 kg ha^{-1}) grain yield compared to Soun-pongun and Jenguma which produced 595 kg ha^{-1} and 406 kg ha^{-1}, respectively (Fig. 4).

In soybean, there was a location effect on all the fodder quality traits excepts IVOMD (Table 4). CP and Ash content, as well as NDF, ADF and ADL, were higher in NGS than in SGS. These differences suggest that soybean fodder quality is relatively better in NGS than in SGS. However, no varietal and treatment differences were found in soybean fodder quality traits.

Table 5. Effects of rhizobium inoculation and phosphorus fertilizer on grain and fodder yield (kg ha^{-1}) and fodder quality traits (g kg^{-1} DM) of three soybean varieties in southern Guinea Savanna (SGS) and northern Guinea Savanna (NGS) of northern Ghana in 2015

	Grain yield	Fodder yield	Ash	CP	NDF	ADF	ADL	IVOMD
SGS	1607	1917	79	61	679	562	119	545
NGS	581	1891	95	84	599	492	104	572
P-value	0.008	0.952	0.005	0.012	0.002	0.006	0.002	0.057
LSD	639.3	1017.1	9.3	16.1	36.8	38.9	6.9	28.3
Soun-poungun	1063	1689	80	68	656	544	114	550
Jenguma	1030	1962	90	76	630	521	111	559
Afayak	1187	2061	91	73	629	523	109	565
P-value	0.387	0.332	0.095	0.448	0.063	0.055	0.147	0.185
LSD	255.0	540.1	10.7	12.3	25.6	20.1	5.5	16.5
Control	755	1381	88	76	631	519	109	566
I-only	939	1788	86	74	638	531	113	561
P-Fert	1419	2234	86	68	642	534	112	554
P+I	1263	2213	89	72	642	532	111	552
P-value	<0.001	<0.001	0.918	0.224	0.74	0.482	0.363	0.505
LSD	190.9	303.2	9.3	7.9	23.0	20.5	4.4	21.0

CP=crude protein; NDF=neutral detergent fibre; ADF=acid detergent fibre; ADL=acid detergent lignin; IVOMD=*in-vitro* organic matter digestibility.

3.4.3 Groundnut

Groundnut grain yield was 54% higher in SGS than in NGS. Grain yield was different among the varieties. For example, Samnut 22 had the highest grain yield (676 kg ha^{-1}) while Chinese variety had the lowest (518 kg ha^{-1}; Table 6). The grain yield of P-fert and P+I were not different from I-only but differed from the control treatment. Groundnut fodder yield did not differ across AEZs. Within SGS, Samnut 22 yielded more fodder (3009 kg ha^{-1}) than Chinese (1818 kg ha^{-1}) and Samnut 23 (1804 kg ha^{-1}). Grain yield, on the other hand, did not differ among varieties. (Fig.. 5). Contrary to SGS, in NGS, there was a treatment effect on grain yield, but fodder yield was unaffected (Fig 5).

3.5 Relationship between grain, fodder yield and fodder quality traits

The correlation coefficients of grain legume yield and fodder quality traits are presented in Table 7. The relationship between grain and fodder yield across AEZs and varieties within legume crops studied were positively correlated. Both

Chapter 3

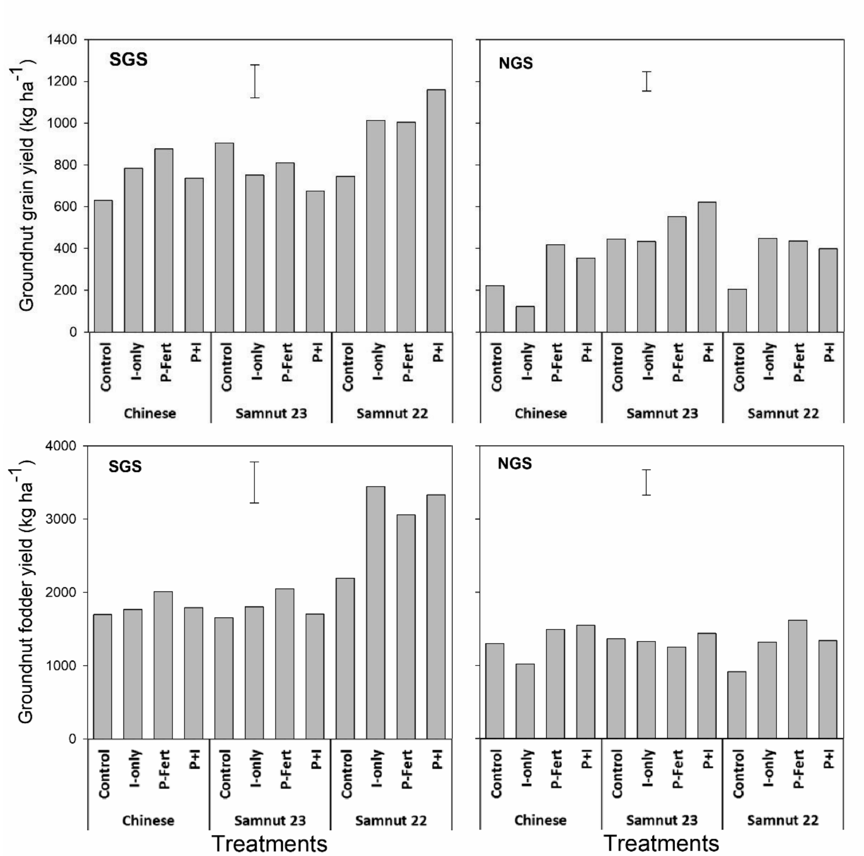


Fig. 5. Effects of rhizobium inoculation and phosphorus fertilization on grain and fodder yield (kg ha^{-1}) of three different groundnut varieties in Southern Guinea Savanna (SGS) and Northern Guinea Savanna (NGS) in 2015. The error bar represents the standard error of difference (SED) between means.

grain and fodder yield of cowpea were inversely correlated with CP but directly with NDF. In soybean, grain yield was weakly and negatively correlated with CP and IVOMD and positively with the fibre fractions. In groundnut, however, grain and fodder yields positively correlated with CP, NDF, ADF but they had no significant correlation with IVOMD.

Table 6. Effects of rhizobium inoculation and phosphorus fertilizer on grain and fodder yield (kg ha^{-1}) and fodder quality traits (g kg^{-1} DM) of three different groundnut varieties in southern Guinea Savanna (SGS) and northern Guinea Savanna (NGS) of northern Ghana in 2015

	Grain yield	Fodder yield	Ash	CP	NDF	ADF	ADL	IVOMD
SGS	841	2210	128	163	468	421	92	677
NGS	388	1328	145	148	427	389	94	681
P-value	0.01	0.108	0.047	0.105	0.023	0.087	0.832	0.747
LSD	300.8	1142.9	16.2	19.3	32.9	38.5	16.3	26.0
Chinese	518	1579	136	150	450	412	96	673
Samnut 23	649	1575	142	159	439	389	92	686
Samnut 22	676	2154	132	157	452	406	91	677
P-value	0.034	0.079	0.014	0.013	0.043	0.007	0.002	0.032
LSD	112.3	576.3	5.8	5.9	11.1	9.2	2.8	9.1
Control	525	1522	138	155	445	401	93	685
I-only	592	1781	135	158	444	402	91	680
P-Fert	683	1914	138	154	446	404	93	680
P+I	658	1860	136	153	454	411	94	669
P-value	0.005	0.095	0.808	0.604	0.562	0.487	0.539	0.037
LSD	91.5	329.7	7.0	8.5	15.7	14.3	3.9	11.0

CP=crude protein; NDF=neutral detergent fibre; ADF=acid detergent fibre; ADL=acid detergent lignin; IVOMD=*in-vitro* organic matter digestibility.

Table 7. Correlation between grain, fodder yield and fodder quality traits of three major grain legumes (cowpea, groundnut and soybean) in Southern Guinea Savanna (SGS) and Northern Guinea Savanna (NGS) of northern Ghana

Item	Fodder yield	CP	IVOMD	NDF	ADF	ADL
Cowpea						
Grain	0.58***	-0.51***	-0.17ns	0.57***	0.51***	-0.30*
Fodder	-	-0.34***	0.09ns	0.27**	0.18ns	-0.46**
Soybean						
Grain	0.52***	-0.37***	-0.23*	0.39***	0.38***	0.32*
Fodder	-	0.02ns	0.05ns	-0.01ns	0.00ns	-0.01ns
Groundnut						
Grain	0.77***	0.33**	0.03ns	0.40***	0.37***	-0.03ns
Fodder	-	0.31**	0.06ns	0.27**	0.25*	0.03ns

CP=crude protein; NDF=neutral detergent fibre; ADF=acid detergent fibre; ADL=acid detergent lignin; IVOMD=*in-vitro* organic matter digestibility, *Correlation coefficient is significant < 0.05; **< 0.01; ***< 0.001. ns =not significant

Chapter 3

4.0 Discussion

4.1 Grain and fodder yield

We evaluated the effects of rhizobium inoculation and phosphorus fertilization on grain and fodder yield and fodder quality of cowpea, soybean and groundnut, the major grain legumes in two agro-ecological zones of northern Ghana. Grain yield of cowpea and fodder yield of cowpea and soybean were increased by inoculation with selected rhizobium strains. The effect of inoculation on grain yields of cowpea and soybean observed was less pronounced than reported recently in soybean (Boddey et al., 2017; Ronner et al., 2016), but similar to results obtained in other studies in the region (Abaidoo et al., 2016; Michael Kermah et al., 2017; Kyei-Boahen et al., 2017; van Heerwaarden et al., 2018). No effect of inoculation was observed in groundnut as also found by Yusuf et al. (2012) in Nigeria. The success of rhizobium inoculation in increasing crop growth depends on several factors including i) the population of native rhizobia in the soil, ii) the effectiveness and competitive ability of the strains in the inoculant, and iii) the soil available P and N (Abaidoo et al., 2016; Giller, 2001; Van Kessel and Hartley, 2000). Grain and fodder yields of all crops were increased with the addition of P fertilizer as commonly reported in the Guinea savanna of West Africa (Ronner et al., 2016; van Heerwaarden et al., 2018). However, combination of P and I (P+I) generally did not increase yield compared with P-fert except in cowpea. Work done by van Heerwaarden et al. (2018) showed that legume genotypes varied in their response to inoculation and they explained that this might be due to promiscuous varieties which form symbiosis with less effective N fixing indigenous rhizobia, which are abundant in the soils. It seems that the comparable grain and fodder yields of P+I and P-fert are limited by P deficiency in the soil (Adjei-Nsiah et al., 2020). Solomon et al. (2012) also found in Ethiopia that symbiotic N fixation by legumes is largely dependent on phosphorus.

We observed varietal differences in both grain and fodder yield in cowpea and grain in groundnut. Across AEZs, cowpea grain yields of Apagbaala and Songotra varieties were higher compared to Padituya, whereas Padituya produced more fodder than Apaagbala and Songotra. Padituya, therefore, can be seen as fodder or dual-purpose variety, ideal for the NGS where fodder is valuable as livestock feed. Samnut 22 is a longer duration groundnut variety (2 weeks longer than other varieties), which resulted in more grain and fodder yields in SGS but not in NGS. Comparable results were obtained in past studies with similar varieties in Ghana (Oteng-Frimpong et al., 2017) and Nigeria (Ekeleme et al., 2011). In general, short duration varieties with appreciable grain and fodder yields are better suited than long duration varieties for drier locations with the shorter growing season.

Grain and fodder yield differences observed among crop species was probably due to genetic make-up, agronomic practices, soil and environmental conditions. Across AEZs, soybean responded most strongly to P and yielded the most grain, while groundnut resulted in relatively lower yields compare to cowpea (Table 3). Our results demonstrate an important effect of environment on grain and fodder yield: both grain and fodder yields were higher in SGS than in NGS. These higher grain yields in SGS can be attributed to more favourable rainfall distribution, soil conditions. We observed more rainy days and less dry spells in SGS (52) than in NGS (40) during the growing season. Both sites are relatively poor in N (Table 1), but the sandier nature of the soils in NGS than in SGS may limit nutrient availability and moisture holding capacity for crop growth. Previous studies (Ekeleme et al., 2011; Michael Kermah et al., 2017; Ronner et al., 2016) also demonstrated that yields of crops are higher in SGS than in NGS.

Fodder

GLFs are used by many smallholder farmers in West Africa as sole livestock feed or as a supplement, especially during the dry seasons of the year. These farmers also sell GLFs to livestock fatteners and traders as a source of extra income from their crop farms (Ayantunde et al., 2014; Konlan et al., 2018; Samireddypalle et al., 2017). These GLFs are relatively nutritious and palatable compared to residues of cereals and some grasses. CP content and IVOMD are the main positive fodder quality indicators, while NDF, ADF and ADL are the negative ones. According to Owen and Jayasuriya (1989), crop residues are good ruminants feeds if IVOMD > 50 g kg^{-1}, and CP > 60 g kg^{-1}. The GLFs in our study were better than these thresholds levels.

Fodder quality traits differed among crops, and some traits were different among AEZs. NDF and ADF were higher in soybean than in cowpea and groundnut fodder associated with higher IVOMD in cowpea and groundnut than in soybean. The high fibre content observed in soybean in the present study is because soybean is left to dry in the field before harvest by which time almost all leaves have fallen. Among the food crops grown in northern Ghana, soybean is the last crop to be harvested. Groundnut and cowpea, on the other hand, are generally harvested relatively fresh with leaves still present. The ratio between botanical fractions (leaf-stem ratio) of harvested fodder is an important determinant of nutritional qualities (Blümmel et al., 2003; Larbi et al., 1999). The differences observed across AEZs in Ash, NDF and ADF contents might be due to variations in rainfall pattern and growing conditions (Ddamulira *et al.*, 2015). Our finding confirms that fodder quality traits of different crops are influenced by several factors, such as genetic makeup, crop growing and harvesting conditions, soil fertility, climatic factors and threshing method(Reddy et al., 2003).

Despite effects on the quantity of fodder produced, we observed no effects of rhizobium inoculation and P fertilization on any of the fodder quality traits in all of the crops (Table 3-6). Ansah et al. (2016) also found no difference in CP content, digestible organic matter (DOM) content and in-vitro gas production of fodder of four varieties of cowpea to different rates of P fertilization. Varietal differences regarding all fodder quality traits studied were found in groundnut, but not in cowpea and soybean.

The negative correlation between yield and CP of cowpea implies that increase in yield will decrease the CP content of the fodder, but even the lowest CP in our study is high compared to the results of (Samireddypalle et al., 2017). (2017). IVDOM will not be affected by yield increase which will still make the fodder valuable. The positive correlation between both grain and fodder yield of groundnut and fodder quality parameters in the current study makes groundnut fodder a better feed resource compared to cowpea and soybean fodders. Groundnut is a better feed is because an increase in both grain and fodder yield may increase the quality of the groundnut fodder.

The increase in fodder yields as a result of P and I in cowpea illustrates that farmers can keep and feed extra animals in the dry season when he/she uses rhizobium inoculant and/or P fertilizer. For example, a farmer feeds an average weighted (12-15 kg) sheep or goat with 450g day^{-1} air dry matter (Anele et al., 2010; Ayantunde et al., 2007) of cowpea fodder for five months, representing the length of the dry season in SGS and NGS in West Africa. The feed required for this period is 67.5 kg per animal. From our current fodder yield of cowpea (Table 4), the farmer could feed 11 animals from one hectare of the control treatment, an additional four animals from I only, nine more from P-fert and 13 more animals when P+I was used.

5.0 Conclusion

In the mixed crop-livestock farming systems of West Africa, grain legumes provide grain and GLFs which are both important for the livelihood of the farming households and their animals. Good agronomic management may increase both grain and fodder yields and the benefit for smallholder farmers from grain legume production. The findings of our study indicate the possibility of improving both grain and fodder yields of grain legumes simultaneously through the application of P-fert and rhizobium inoculants in cowpea and soybean. Groundnut on the other hand only responded to P-fert but not to rhizobium inoculant. Soybean benefited more from P-fert than cowpea and groundnut when grown under the same soil and climatic conditions. Our results suggest that efforts to improve the access of smallholder farmers to phosphorus fertilizers and rhizobium inoculants are warranted. Furthermore, the yield difference observed between SGS and NGS can be bridged through the use of early maturing varieties in the NGS, since the length of the growing season is shorter than in the SGS. The positive correlation between grain yield and fodder yield in the current study suggests that varieties of each legume used in the study are suitable to produce quality fodder for livestock feeding without a reduction in grain yield.

Acknowledgements
We thank the Bill and Melinda Gates Foundation for funding this research through N2Africa: Putting nitrogen fixation to work for smallholder farmers in Africa project at Wageningen University & Research. We are also grateful to IITA-Ghana, CSIR-SARI, Nyankpala and ILRI-Ethiopia for the use of their facilities to carry out this work.

Conflict of interest
The authors declare no conflict of interest.

Evaluating the effects of storage conditions on dry matter loss and nutritional quality of grain legume fodders in West Africa*

* This chapter is published as:

Akakpo, D.B., de Boer, I.J.M., Adjei-Nsiah, S., Duncan, A.J, Giller, K.E., Oosting, S.J., (2020). Evaluating the effects of storage conditions on dry matter loss and nutritional quality of grain legume fodders in West Africa. Anim. Feed Sci. Technol. https://doi.org/10.1016/j.anifeedsci.2020.114419

Abstract
Feed scarcity is a major challenge for livestock production in West Africa, especially during the dry season when grass quality and quantity on grazing lands are inadequate. In the dry season, crop residues are a key source of livestock feed. The residues of grain legumes, also known as grain legume fodders (GLFs), are stored and traded for feeding in the dry season. The objectives of our experiment were to evaluate the effects of storage conditions and duration on dry matter (DM) and nutritional quality of GLFs, and to assess the risk of aflatoxin in stored groundnut fodder. The experiment was designed as a factorial trial arranged in a split-split plot design with 18 treatment combinations with four replicates (4 farms). The treatments included: whole plot: 3 types of GLFs (cowpea, groundnut and soybean fodder), sub-plot: 3 types of storage locations (rooftop, room and tree-fork), and sub-sub-plot: 2 types of packaging (packed in polythene sacks and unpacked but tied with rope). Over a 120 day storage period, DM quantity reduced by an average of 24% across all storage conditions, showing a range from 14% in the best condition (sacks and rooms) to 35% in the worst condition (bundles tied with rope and stored on rooftops or tree-forks). Soybean fodder had no leaves, the lowest crude protein content (CP) and organic matter digestibility (OMD), and the highest content of cell wall components compared to cowpea and groundnut fodder. These nutritional quality parameters in soybean fodder hardly changed during storage. Cowpea and groundnut fodder showed a decrease in leaf-to-stem ratio (LSR), CP and OMD, and an increase in the content of cell wall components during storage, but their nutritional value remained better than that of soybean fodder. Storage in sacks resulted in less DM loss, in less reduction of LSR and in a smaller increase of the content of cell wall components than storage of bundles tied with rope. Our study shows that the DM loss, the decrease in LSR, and the increase in the content of cell wall components can be prevented partly by storing GLFs in sacks instead of tying bundles with rope, and to a minor extent by storing in rooms instead of in the open air. Aflatoxin was not detectable in the groundnut fodder samples. Our results highlight that attention to storage conditions can improve the feeding value of GLFs which are key for livestock nutrition during the dry season.

Keywords: Crop residues, storage, fibre, crude protein, aflatoxin, *in-vitro* digestibility

1.0 Introduction

Feed scarcity and high feed cost are major challenges for livestock production in West Africa, especially during the dry season (Ayantunde et al., 2014; FAO, 2014). Natural pasture and crop residues represent the majority of the feed for ruminants in West Africa. The importance of crop residues in smallholder systems in West Africa is increasing for two main reasons. First, natural pastures on communal lands are reducing due to the conversion of rangelands to croplands to feed the increasing human population. Second, crop residues can be traded and can contribute to mitigate feed shortages or create additional income in a prolonged dry season. The residues of grain legumes, also known as grain legume fodders (GLFs), such as groundnut and cowpea haulms, are intensively traded (Ayantunde et al., 2014; Konlan et al., 2018; Samireddypalle et al., 2017). In northern Ghana and other sub-Saharan countries, such as Nigeria, Burkina Faso, Mali and Niger, GLFs are harvested, dried and stored, and used by farmers or sold to other livestock farmers, fatteners and traders. Sale of GLFs is a source of additional income to farming households. GLFs have better nutritional quality than cereal residues, such as maize and rice straw (López et al., 2005; Schiere et al., 2004). GLFs show good results when used as supplementary or sole feed for the fattening of ruminants in the region (Ayantunde et al., 2007; Dada et al., 1999; Larbi et al., 1999).

In northern Ghana, feed availability to animals increases after crop harvest, whereas a shortage occurs in the dry season and this shortage becomes critical towards the end of the dry season, i.e. from February to April (Konlan et al., 2018). To ensure feed supply and to secure prices for GLFs in this critical period of the dry season, farmers and middlemen store GLFs till the late dry season from January to April. During the storage of GLFs, the nutritional quality is not checked before use or before marketing to other buyers. Even though storage aims to preserve the quality and quantity of fodders for later use, losses of nutrients during the storage process have been reported, particularly in crude protein content (Lemus, 2009; Guerrero et al., 2010). According to Guerrero et al. (2010) and Feyissa et al. (2014), factors, such as sunlight, heat, and precipitation, affect the quality of forages during storage. Another quality factor of concern is the development of mould during storage which may lead to mycotoxin contamination. Considerable variability in mycotoxin occurrences and concentration levels has been reported in forages which were attributed to environmental and forage management related factors (Gallo et al., 2015). These factors can be controlled by managing storage conditions. Little is known, however, about the impact of different storage conditions on the dynamics of nutritional quality and development of aflatoxin in GLFs during storage. Therefore, the objectives of the present study were to evaluate the effects of storage conditions and duration on dry matter and nutritional quality of GLFs and to assess the risk of aflatoxin in stored groundnut fodder.

2.0 Materials and methods

2.1 Source of grain legume fodders and experimental design

The study was conducted in four villages (i.e. Tansia, Tetauko, Kaadi, and Kupalgoga) in Binduri district (10°56'01.6"N, 0°18'53.7"W) in the Upper East Region of Ghana during the dry season (December 2015 to April 2016). This district is located in the northern Guinea Savanna (NGS) ecological zone, which is dominated by monocrops of maize, sorghum and millet that benefit greatly from rotation with grain legumes (Woomer et al., 2013). In this district like other districts in NGS, farmers experience feed shortages during the long dry season, and GLFs can contribute to mitigate these feed shortages (Amole et al., 2014). The present study used harvested fodder from an earlier study about the effect of rhizobium inoculation and phosphorus fertilization on grain and fodder yield and quality of three grain legume crops: cowpea (*Vigna unguiculata* (L) Walp), groundnut (*Arachis hypogaea* L.) and soybean (*Glycine max* (L) Merr). Details of this agronomic trial were described by Akakpo et al. (2020b). One farmer was selected in each village to host one replicate of the present study on his or her farm. Farmers could only participate if they had facilities to store GLFs, i.e. a rooftop, a storeroom (indoors) and mature live trees with forks suitable for holding a substantial volume of GLF. Only trees, such as neem (*Azadirachta indica* A. Juss.) and shea (*Vitellaria paradoxa* C. F. Gaertn) that were located within 20 metres radius of the homesteads, were selected.

The weather data recorded at the Manga station of the Savanna Agricultural Research Institute (SARI) in the district indicated that the average annual minimum and maximum temperatures of the area were 23.3 and 36.7 °C, respectively with a mean of 30.0 °C. During the study year, the total annual rainfall was 919 mm, but there was no rainfall during the study (storage) period from December 2015 to April 2016 (Fig. 1).

The experiment was designed as a 3x3x2 factorial trial and was arranged in a split-split plot design with 18 treatment combinations replicated four times in different villages (farms). The treatments included: whole plot: 3 types of GLFs (cowpea, groundnut and soybean), sub-plot: 3 types of storage locations (rooftop, room and tree-fork), and sub-sub-plot: 2 types of packaging (3 kg of GLFs

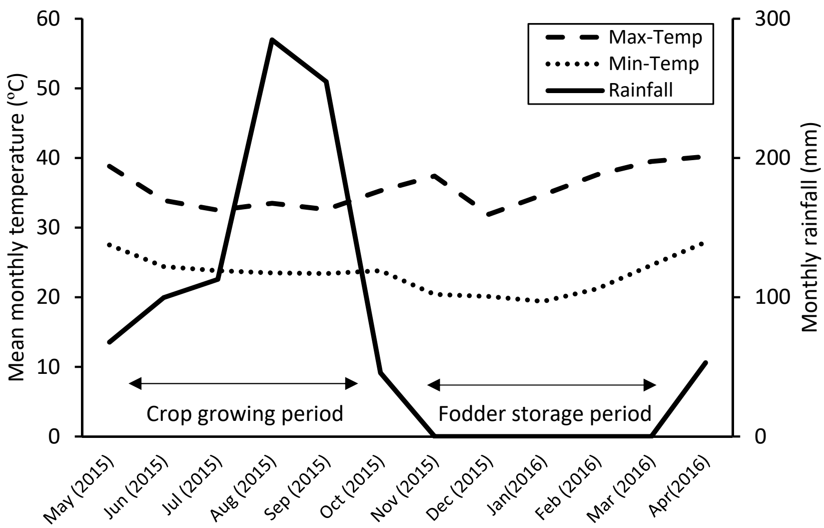


Fig. 1. Mean monthly maximum and minimum temperature and monthly rainfall in the Binduri district during the experimental period (2015 - 2016). The arrows show the duration of the crop growing period and fodder storage period

bundled and packed in polythene sacks or unpacked but tied with rope). For each treatment combination, five bundles were used as an experimental unit.

At the time of harvest at each farm, fodders of each crop were collected on one heap and thoroughly mixed and left to dry for six days to attain constant weight. Per fodder heap, about 20 handfuls of samples were taken, pooled and mixed. Of this pooled sample three sub-samples of 200 g were taken for initial quality evaluation (Table 1) at the start of storage, which is also referred to as pre-storage quality. The sampled fodders were separated into leaf and stem fractions for groundnut and cowpea but not for soybean fodder, which consisted only of stems and threshed pods at harvest. After the six days of drying, each heap was mixed again and bundled in 3 kg weights. The bundles were either packed in polythene sacks or unpacked but tied with rope. The packaged and tied fodders were assigned to the storage locations according to the experimental design.

The stored fodders were weighed, and samples were taken monthly (30 days interval) for laboratory analyses. At each sampling time, about 40 g of fodder from each of the five bundles in each treatment were carefully sampled. For estimation of dry matter loss, we corrected for the quantities removed during sampling. Each sample was carefully separated into leaf and stem fractions. The

Table 1. Pre-storage leaf-to-stem ratios and nutritional composition of leaf and stem fractions of cowpea, groundnut and soybean fodder

Nutritional Parameter	Botanical fractions	Cowpea	Groundnut	Soybean[1]
Leaf-to-stem ratio (LSR)		0.42	0.49	0
Crude protein	Leaf	165	180	
(CP; g kg^{-1})	Stem	162	165	97
Organic matter digestibility[2]	Leaf	737	677	
(OMD; g kg^{-1})	Stem	746	644	548
Ash (g kg^{-1})	Leaf	144	151	
	Stem	150	150	80
Neutral detergent fibre	Leaf	465	397	
(NDF; g kg^{-1})	Stem	432	446	652
Acid detergent fibre	Leaf	319	368	
(ADF; g kg^{-1})	Stem	323	397	550
Acid detergent lignin	Leaf	85	90	
(ADL; g kg^{-1})	Stem	78	97	105
Cellulose (g kg^{-1})	Leaf	234	278	
	Stem	245	300	445
Hemi-cellulose (g kg^{-1})	Leaf	146	29	
	Stem	109	49	102

[1]Soybean fodder contained no leaf in this study. [2] *in-vitro* organic matter digestibility.

fractions were weighed, placed in paper bags, labelled and oven-dried at 70°C for 48 hours to determine dry matter. The dried samples were ground to pass through a 1 mm screen with a laboratory hammer mill at the Soil Chemistry Laboratory of the Savana Agricultural Research Institute (SARI) – Nyankpala, Ghana. The ground fodder samples were stored at ambient temperature and later air-freighted to the animal nutrition laboratory of International Livestock Research Institute – Ethiopia for analyses. The samples were freighted under the permission (Permit No.12113) of the Ministry of Agriculture and Natural Resources in Ethiopia.

2.2 Fodder quality and aflatoxin analysis.

Fodder samples were analysed for chemical composition and nutritional traits using conventional chemistry and Near Infrared Reflectance Spectroscopy (NIRS). The conventional chemical analysis implied quantifying the ash/organic matter (OM), dry matter (DM) and crude protein (CP) content and neutral detergent fibre (NDF) content, according to the methods described in AOAC (1990). The *in-vitro* organic matter digestibility (OMD), was assessed according to the in-vitro gas production procedure as described in Van Soest and Robertson (1985). Reference samples were selected and analysed by conventional wet chemical analysis. Results from the conventional wet chemical analysis were used to calibrate and update the NIRS equations to predict the nutritional composition for a wide range of legume forages, such as groundnut, cowpea and soybean. NIRS predictions were made using FOSS Forage Analyzer 5000 with software package WinISI, according to de Boever et al. (1995), and included predictions of ash, nitrogen (N) (crude protein = N × 6.25), neutral detergent fibre (NDF), acid detergent fibre (ADF), and acid detergent lignin (ADL) contents, and *in-vitro* organic matter digestibility (OMD). Hemicellulose was calculated as NDF – ADF and cellulose as ADF – ADL, according to Rinne et al. (1997). Finally, we calculated NDF residual as a percentage of pre-storage NDF in DM residue at each sampling time. Neutral detergent soluble (NDS) residual was calculated as 100 – NDF according to Mertens (2009).

Groundnut fodder samples were analysed for aflatoxin B1 and B2, produced by *Aspergillus flavus* and *A. parasiticus* and aflatoxin G1 and G2 which are produced by *A. parasiticus* and other related species. Aflatoxin analysis was conducted at the pathology and mycotoxin laboratory of the International Institute of Tropical Agriculture (IITA) - Nigeria according to the protocol of Cole and Dorner (1994). For aflatoxin analysis known positive reference samples were included in the protocol to ensure the method was working.

Chapter 4

2.3 Calculations and statistical analyses

The experiment was designed to investigate the effect of storage location, duration and packaging on DM loss and nutritional quality of GLFs. First, we analysed the leaf and stem fractions of cowpea and groundnut to determine the nutritional quality differences between leaf and stem fractions. Second, to analyse the data across all crops (cowpea, groundnut and soybean), we reconstituted leaf and stem fractions of cowpea and groundnut mathematically to represent the fodder (leaf and stem) by taking the weighted average of the fractions. The weighted averages were analysed together with soybean fodder (stems and pods) data which contain no leaf by using a mixed-effect analysis of variance model (Searle et al., 1992) in GenStat version 19 (VSN, 2017). In this model (Equation 1 below), replications (block), crop, storage location, packaging types and duration were fixed factors, while blocks nested with crops within village were random factors.

$$Y_{ijklmn} = \mu + B_i + C_j + L_k + P_l + (CLP)_{jkl} + BC_{ijkl} + D_m + (CLPD)_{jklm} + \varepsilon_{ijklmn} \qquad [1]$$

where, Y = the response variable (DM and nutritional compositions of the reconstituted fodder), μ = the overall mean, Bi = effect of i^{th} block (villages), C_j = effect of j^{th} crop (j = cowpea, groundnut and soybean), L_k = effect of k^{th} storage location (k = rooftop room, tree-fork), P_l = effect of l^{th} packaging type (l = sack, tied), $(CLP)_{jkl}$ =interaction effect of the main factors (crop, storage location and packaging type), D_m = effect of m^{th} storage duration (m = at the start of the experiment (day 0, 30, 60, 90, 120), $(CLPD)_{jklm}$ = the interaction effects main factors with duration, BC_{ijkl} and ε_{ijklmn} = the random effect for crops within villages and residual error respectively assumed to be normally and independently distributed around zero with variance σ^2_{crop} and $\sigma^2\varepsilon$ respectively. The differences between means were determined using the Fisher's least significance difference (LSD) test ($P < 0.05$).

The means of the data were subjected to polynomial regression analysis (Equations 2) to determine the trend of changes in measured parameters due to the duration of storage according to the model:

$$Y = \beta_0 + \beta_1 X + \beta_2 X^2 + \varepsilon \quad [2]$$

where Y = the response variable, β_0 = the intercept, β_1 = regression coefficient for linear effect of X on Y, X = duration (days), β_2 = regression coefficient for quadratic effect on Y, and ε = random error term. A linear model was fitted first to the fodder data, and if the linear term was significant, then a quadratic term was added.

3.0 Results

3.1 Effects of storage conditions on composition and nutritional quality

The dry matter residues (DMR) of all crops reduced during storage for 120 days (Table 2; Figs. 2a, b and c). Soybean tended (P<0.07) to have a higher mean DMR than cowpea and groundnut, whereas room storage tended (P<0.07) to have a higher mean DMR than rooftop. Also, the mean DMR differed between fodder stored in sacks and tied fodder (Table 2). The rate of reduction of DMR differed among packaging types and equalled 0.12% per day for fodder stored in sacks and 0.21% per day for tied fodder (Table S1, Fig. 2c). On average, DMR decreased by 24% across all storage conditions, with a range of 14% for bundles packed in sacks and stored in rooms to 35% for bundles tied with rope and stored on roofs or tree-forks (Figs. 2a, b and c).

Table 2. Leaf-to-stem ratio (LSR), dry matter residue (DMR) percentage and nutritional composition of grain legume fodders stored at different storage locations and in different types of packaging for 120 days

Treatments			Nutritional composition of grain legume fodders (g kg^{-1} DM)							
	DMR (%)	LSR	CP	OMD	Ash	NDF	ADF	ADL	Cellulose	Hemi-cellulose
Crop (C)										
Cowpea	88.1^{b}	0.32^{b}	126^{b}	699^{a}	109^{b}	521^{b}	419^{b}	86^{c}	334^{b}	101^{a}
Groundnut	89.3^{ab}	0.36^{a}	148^{a}	662^{b}	132^{a}	472^{c}	433^{b}	101^{b}	332^{b}	39^{b}
Soybean	90.0^{a}		99^{c}	571^{c}	95^{c}	641^{a}	543^{a}	111^{a}	432^{a}	98^{a}
P-value	0.07	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
LSD	1.67	0.022	6.6	14.8	3.9	17.0	19.0	4.1	15.3	3.7
Location (L)										
Rooftop	88.4^{b}	0.34^{ab}	125	647	113	550	467	102^{a}	366	82^{a}
Room	90.2^{a}	0.35^{a}	126	645	112	536	460	97^{b}	363	76^{b}
Tree-fork	88.8^{ab}	0.32^{b}	122	640	111	549	469	100^{ab}	369	80^{a}
P-value	0.07	0.07	ns	ns	ns	ns	ns	0.07	ns	0.004
LSD	1.67	0.026	6.6	14.8	3.9	17.0	19.0	4.1	15.3	3.7
Packaging (P)										
ck	93.5^{a}	0.36^{a}	126	649	113^{a}	533^{b}	455^{b}	97^{b}	358^{b}	78
Tied	84.8^{b}	0.31^{b}	122	639	112^{b}	556^{a}	476^{a}	102^{a}	374^{a}	81
P-value	<0.001	<0.001	ns	ns	0.05	0.002	0.009	0.001	0.017	ns
LSD	1.36	0.022	5.4	12.1	3.2	13.9	15.5	3.4	12.5	3.0
P-values for duration (D)										
D	<0.001	<0.001	<0.001	0.02	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
D x C	ns	0.062	<0.001	<0.001	<0.001	ns	<0.001	<0.001	<0.001	<0.001
D x L	ns	ns	ns	ns	ns	<0.001	ns	0.031	ns	0.007
D x P	<0.001	ns	ns	0.059	ns	0.017	0.018	0.001	0.033	ns

CP=crude protein; NDF=neutral detergent fibre; ADF=acid detergent fibre; ADL=acid detergent lignin; IVOMD=*in-vitro* organic matter digestibility; ns=not significant. Means with different letters in a column of each treatment factor are significantly different ($p<0.05$). LSR only applies to cowpea and groundnut fodders because soybean fodder contained no leaves.

Chapter 4

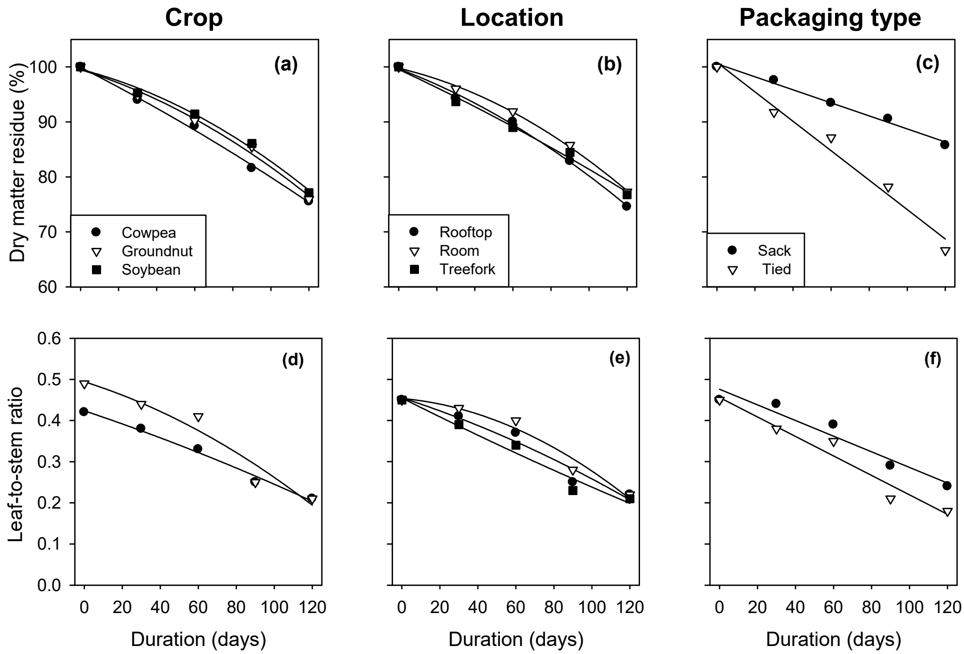


Fig. 2. Effect of storage duration on dry matter loss (a, b, and c) and leaf-to-stem ratio (d, e, and f) among grain legume fodders at different storage locations and in different types of packaging. Soybean fodder contained no leaves.

LSR of groundnut and cowpea reduced during storage for 120 days, from 0.45 at pre-storage to 0.21 at the end of the storage (Fig. 2d). Mean LSR was higher in groundnut than in cowpea, but the difference in LSR between cowpea and groundnut reduced with storage duration and LSR of both fodders became similar at the end of storage. Room storage tended ($P<0.07$) to have a higher mean LSR than storage on tree-fork (Fig. 2e). Also, the mean LSR differed between fodder stored in sacks and tied fodder (Table 2f). The rate of reduction of LSR differed among packaging types and equalled 0.0019 per day for fodder stored in sacks and 0.0024 per day for tied fodder (Table S1, Fig. 2f).

Mean CP content differed among crops (Table 2). The mean CP content of roundnut was higher than that of cowpea, while soybean had the lowest CP content (Table 2). There was no effect of storage location and packaging type on CP content during storage. The CP content of GLFs declined rapidly in the first 30 days of storage and stabilized thereafter, with an interaction between duration and crop (Table 2; Fig. 3a). After 120 days of storage, CP content had reduced by 31% in cowpea and by 21% in groundnut (Table S1). During storage, the CP content of stem fractions of cowpea and groundnut reduced quadratically, but that of the leaf fraction remained relatively constant (Data not shown).

Mean OMD differed among crops. Cowpea had the highest OMD, followed by groundnut, while soybean had the lowest OMD (Table 2). There was a duration effect on OMD of GLFs with a significant interaction between duration and crop (Table 2). OMD of cowpea reduced quadratically, illustrating a decline in the first 30 days of storage and remaining relatively constant after that, whereas OMD of groundnut and soybean remained relatively constant during storage (Fig. 3d). During storage, the OMD of the stem fraction of cowpea reduced quadratically, but that of the leaf fraction remained relatively constant (Data not shown).

The mean ash content and cell wall components (NDF, ADF, ADL, cellulose and hemi-cellulose) differed among crops (Table 2). Soybean had the lowest ash content and, in most cases, the highest content of cell wall components compared to cowpea and groundnut (Table 2). Room storage had lower mean ADL and hemi-cellulose contents than storage on tree-fork and rooftop, whereas fodder stored in sacks had lower means for NDF and ADF and a higher mean for ADL than tied fodder. There was a

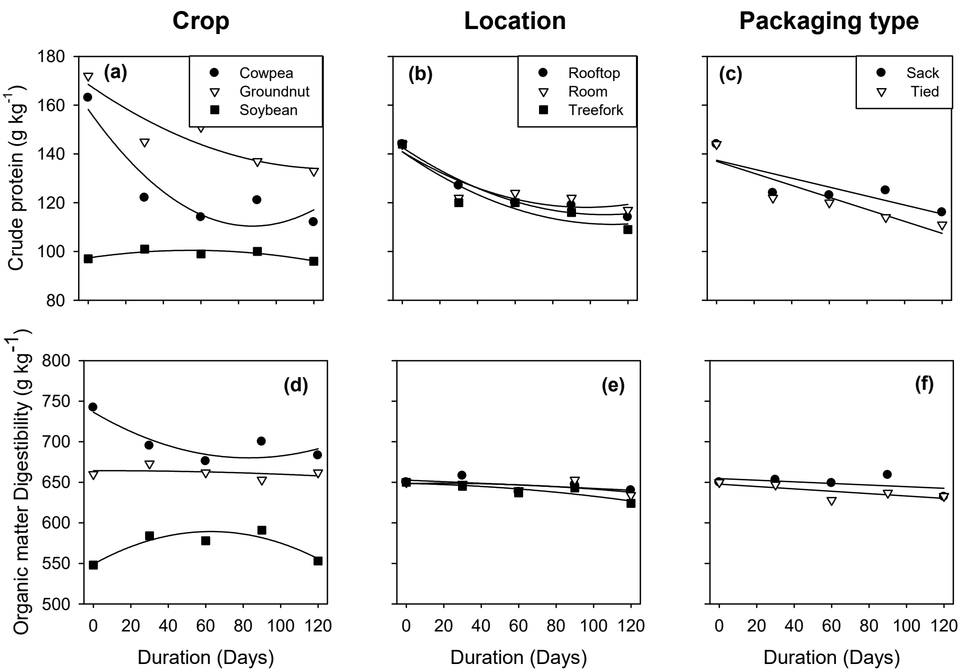


Fig. 3. Effect of storage duration on crude protein (a, b, c) and in-vitro organic matter digestibility (d, e, f) of grain legume fodders at different storage locations and in different types of packaging.

duration effect on the ash content and cell wall components (Table 2 and Fig. 4) with some of these components showing significant interactions between duration and crop, duration and location and duration and packaging type. Noteworthy findings regarding these interactions are that NDF and ADF increased quadratically during storage for cowpea and groundnut fodder, but there was no change for soybean fodder. After 120 days of storage, NDF had increased by 22% in cowpea and 15% in groundnut (Table S2). Moreover, the rates of change in NDF and ADF were different between packaging type and showed a linear rate of increase (Table S2, Figs. 4).

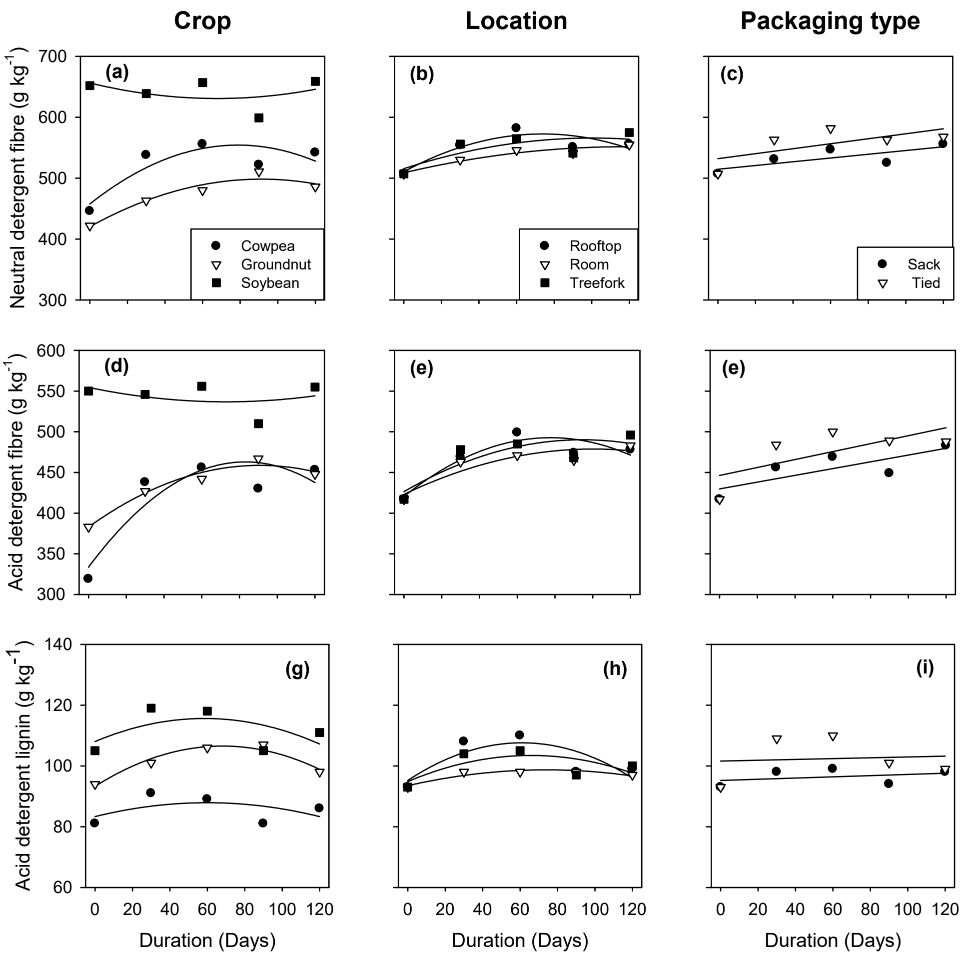


Fig. 4. Effect of storage duration on the fibre content: neutral detergent fibre (a, b, c), acid detergent fibre (d, e, f) and acid detergent lignin (g, h, i) of grain legume fodders at different storage locations and in different types of packaging

Table 3. Mean neutral detergent fibre residues (NDFR) and neutral detergent soluble residues (NDSR) of leaf and stem fractions of grain legume fodders stored at different storage locations and in different types of packaging for 120 days

Treatments	NDFR (%)		NDSR (%)	
	Stem	Leaf	Stem	Leaf
Crop (C)				
Cowpea	118[c]	51[b]	77[b]	78[a]
Groundnut	106[b]	74[a]	88[a]	69[b]
Soybean	88[a]		93[c]	
P-value	<0.001	<0.001	<0.001	<0.001
LSD	4.9	6.8	3.5	4.5
Location (L)				
Rooftop	103	61[ab]	86	73[ab]
Room	104	69[a]	87	78[a]
Tree-fork	106	58[b]	86	69[b]
P-value	ns	0.034	ns	0.014
LSD	4.9	8.4	3.5	5.5
Packaging (P)				
Sack	107[a]	73[a]	91[a]	80[a]
Tied	102[b]	52[b]	82[b]	69[b]
P-value	<0.029	<0.001	<0.001	<0.001
LSD	3.9	6.8	2.8	4.5
P-values for duration (D)				
D	<0.001	<0.001	<0.001	<0.001
D x C	<0.001	0.001	<0.001	0.022
D x L	ns	ns	ns	ns
D x P	<0.001	0.014	<0.001	0.009

Means with different letters in a column of each treatment factor are significantly different ($p<0.05$). Leaf only applies to cowpea and groundnut fodders because soybean fodder contained no leaves

Mean neutral detergent fibre residue (NDFR) of leaf and stem fractions differed among crops and packaging types (Table 3). There was a location effect on NDFR of the leaf fractions where room storage had higher NDFR than storage on tree-fork.

There was a duration effect with interactions between duration and crops, duration and packaging type for both leaf and stem fractions. (Table 3; Figs. 5a and b). NDFR of the cowpea stem fraction increased by 15%, that of groundnut by 5% while that of soybean reduced by 22% after 120 days of storage (Fig. 5). At the end of storage, however, NDFR of the leaf fraction reduced in cowpea by 76% and in groundnut by 60% (Fig. 5).

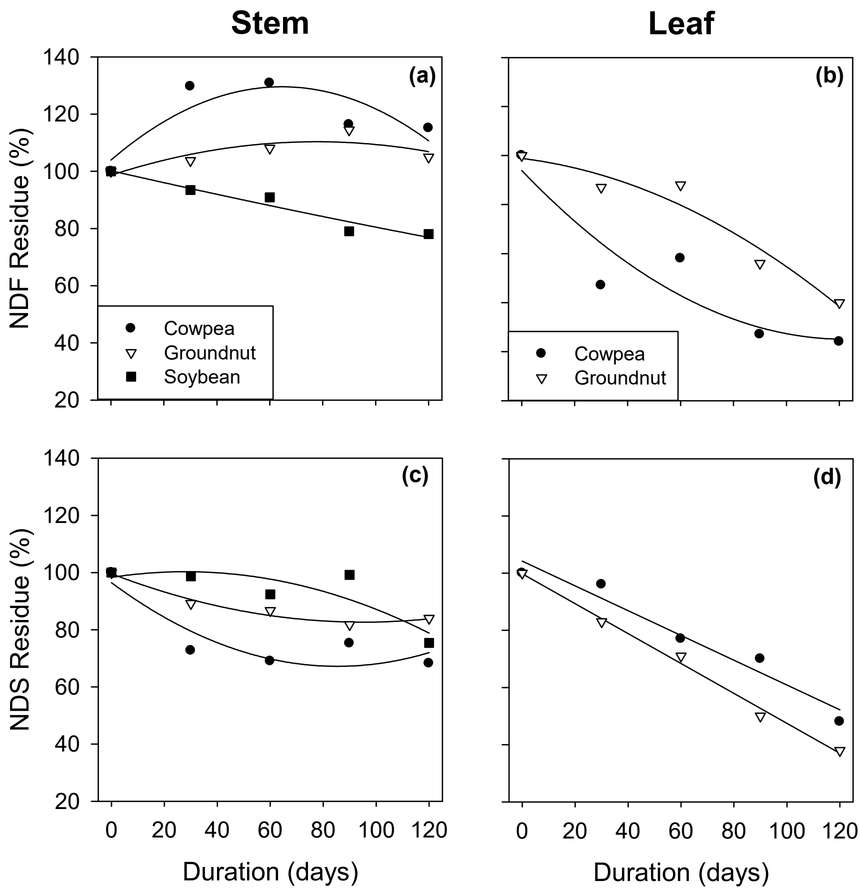


Fig. 5. Effect of storage duration on the neutral detergent fibre (NDF) residue and neutral detergent soluble (NDS) residue of stem (a, c) and leaf (b, d) fractions of grain legume fodders as percentage of dry matter residue (DMR) of grain legume fodders at different storage locations and in different types of packaging.

Mean neutral detergent soluble residue (NDSR) of leaf and stem fractions generally reduced among crop and packaging types. Room storage had a higher NDSR in leaf than storage on tree-fork. Sack storage had a lower NDSR than tied fodder in both stem fraction (9 and 18%, respectively) and leaf fraction (20% and 31%, respectively) (Table 3). There was a duration effect with interactions between duration and crop and between duration and packaging types (Table 3). In contrast to NDFR, stem NDSR of the cowpea stem fraction reduced by 32%, that of groundnut by 16% and soybean by 25% after 120 days of storage (Fig. 5). At the end of storage, however, NDSR of the leaf fraction was reduced in cowpea by 52% and in groundnut by 62% (Fig. 5).

3.2 Aflatoxin in groundnut fodder

All groundnut samples analysed for aflatoxin contamination showed no detectable levels (parts per billion) of any of the toxins in the samples.

4.0 Discussion

In the present study, differences in pre-storage nutritional quality were observed among crops (Table 1). Soybean fodder had a lower CP content and OMD, and a higher content of cell wall components (NDF, ADF ADL and cellulose) than cowpea and groundnut stems and leaves. These results are typical of these crops at harvest (Anele et al., 2010; Dada et al., 1999; Larbi et al., 1999). These nutritional differences are largely due to variation in the maturity stage of the crops at the time of harvest. In the present study, groundnut was the first crop to be harvested followed by cowpea. Both crops were green and included leaves at the time of harvest. Soybean, on the other hand, was harvested at an advanced stage of maturity when almost all leaves had fallen. These results were in line with the observations by Rinne et al. (1997) and Coleman and Moore (2003), who reported increasing cell wall and decreasing CP contents and OMD with increasing maturity. The groundnut varieties in our study were dual-purpose varieties, i.e. developed for grain and forage production, which may explain the higher LSR of 0.49 of the varieties in our study than the LSR of 0.34 of the varieties in the study of Larbi et al. (1999). The higher cell wall contents in stems than in leaves is in line with studies by Feyissa et al. (2014); Larbi et al. (1999); and Schiere et al. (2004).

The results of the present study showed that storage conditions affected the quantity and nutritional quality of GLFs. On average, DM quantity reduced by 24% across all storage conditions, with a range from 14% in the best condition (sacks and in rooms) to 35% in the worst condition (bundles tied with rope and stored on roofs or on tree-forks (Table 2, Fig. 2). Our present study shows that part of the DM loss can be prevented by storing GLFs in sacks instead of tying bundles with rope, and to a minor extent in rooms instead of in the open air (Coblentz et al., 2013; Guerrero et al., 2010).This reduction in DM can be attributed to two processes. First, respiration and microbial digestion can convert NDS into volatile components, and fungal activity may even degrade part of the NDF (Nayan et al., 2018). Second, due to drying, brittle plant parts may pulverize and be blown away by wind or draught.

In stem fractions of GLFs, respiration seemed the most important process in the present study, because NDSR reduced at a higher rate than NDFR indicating that losses should be attributed to respiration and microbial digestion. NDS consists of cell contents which are metabolized during respiration or digested by micro-organisms. Respiration and microbial digestion of NDS may have been facilitated by the high ambient temperature (Fig. 1) at the experimental site (Coblentz et al., 2013; Guerrero et al., 2010; Shayo and Udén, 1999) as well as by the relatively early physiological stage of harvest for cowpea and groundnut. NDFR in stems even increased. It is unknown whether this is observation is caused by measurement errors or by recovery of fungal matter in the NDF. Fungal cell walls consist of chitin which is insoluble in the neutral detergent used for NDF analysis (Nayan et al., 2018; Zhao et al., 2015).

The rate of reduction of NDFR in leaves was comparable to that of NDSR in leaves. This parallel reduction in NDFR and NDSR could imply that pulverization may have caused this loss of leaves. The storage period occurred during the dry season of the year (Fig. 1) and was characterised by no precipitation, low relative humidity and high temperatures. These weather conditions may have promoted the faster rates of drying and pulverisation of the brittle leaf fractions of GLFs during storage (Shinners et al., 2010). However, it cannot be excluded that respiration and microbial activity caused part of the loss of leaves too, or facilitated the pulverization. The increase in the cell wall components (NDF and ADF) of cowpea and groundnut in our study corroborates the results of Feyissa et al. (2014) and Guerrero et al. (2010). These authors worked on hays from a natural pasture and alfalfa (*Medicago sativa*), respectively and reported that prolonged storage of these forages was associated with an increase in content of cell wall components. The high content of cell wall components in a feed is negatively correlated with OMD (Feyissa et al., 2014; Larbi et al., 1999) and dry matter intake in ruminants (Oosting, 1993).

Our study also shows that nutritional quality (CP content and OMD) of cowpea and groundnut reduced most during the first 30 days of storage, while the content of cell wall components increased in the same period (Figs. 3 and 4, Table S1 and S2). These observations can also be explained by the relatively high losses of NDS, which is the fraction with the highest CP content and the highest digestibility (Oosting, 1993). The initial difference between crops had reduced after storage: nevertheless, soybean fodder remained the worst, whereas groundnut had the highest CP content and cowpea the best OMD. The differences in CP content and OMD between cowpea and groundnut agreed with Konlan et al. (2018) and Samireddypalle et al. (2017), who also found high CP content and low OMD in groundnut while the reverse was found in cowpea during a survey of feed markets in Nigeria and Ghana. The nutritive value of soybean fodder was relatively stable during storage when compared with cowpea and groundnut fodder, but remained the lowest. Due to the poor nutritional quality of soybean fodder, including the low intake, it is rarely used for livestock feeding (FAO, 2014; Samireddypalle et al., 2017). The low nutritive quality of soybean fodder (Table

2; Maheri-Sis et al., 2011; Wang et al., 2014) suggests the need to breed dual-purpose soybean varieties for food and feed in the future.

Additionally, GLFs stored in rooms and sacks are of better nutritional quality than those stored in treefook and rooftop and tied with rope (Tables 2 and 3). These results are in line with the findings of Feyissa et al. (2014) and Guerrero et al. (2010), who found that storage conditions are the main factors responsible for DM and nutritional loss or retention during storage. They further stated that loss in DM and nutritional quality is more and faster when hays are stored outdoor and unprotected from adverse weather conditions. According to (Guerrero et al., 2010), unprotected hays stored under high temperatures experience further drying compared to hay tarpaulin covered hays stored under shade.

The absence of aflatoxin in our groundnut fodder samples indicated that it could be used as livestock feed without negative health implications when stored under dry and hot conditions. The prevalence of aflatoxin in animal feed (especially in groundnut and its products) is of great concern for livestock producers, so further research is suggested to ensure aflatoxin does not develop in fodders stored under more moist conditions.

5.0 Conclusion

This paper shows that storage conditions affected the quantity of the dry matter of stored GLFs and the nutritional quality of GLFs. We found that dry matter loss during storage for 120 days was on average 24% across all storage conditions, 35% for the worst condition (tied in bundles and stored on roofs or tree-forks) and 14% for the best condition (sacks and in rooms). During storage, the CP content and OMD decreased, and the content of cell wall components increased. The reduction of nutritional quality was lowest when GLFs were stored in sacks. Storage in sacks and to a lesser extent, storage in rooms (indoor) may reduce the loss of DM and nutritive quality during storage compared to tying in bundles with rope and outdoor storage. Soybean fodder had lower nutritional quality than cowpea and groundnut fodder. The absence of aflatoxin in the groundnut fodder samples indicated that there is no risk of aflatoxin development when stored under dry conditions as in our study.

Acknowledgements

We thank the Bill and Melinda Gates Foundation for funding this research through N2Africa: Putting nitrogen fixation to work for smallholder farmers in Africa project at Wageningen University & Research. We are also grateful to International Institute of Tropical Agriculture (IITA) in Ghana and Nigeria, International Livestock Research

Institute (ILRI)-Ethiopia and CSIR-Savanna Agricultural Research Institute, Nyankpala for the use of their facilities to carry out this work.

Supplementary Materials

Table S1. Effects of storage duration on dry matter residues (DMR), leaf-to-stem ratio (LSR), crude protein (CP) and organic matter digestibility of grain legume fodders packaged differently with their linear and quadratic levels of significance.

Crop	Duration	DMR (%)	LSR*	Sack storage ($g\ kg^{-1}$)		DMR (%)	LSR	Tied storage ($g\ kg^{-1}$)	
				CP	OMD			CP	OMD
Cowpea	0	100	0.42	163	742	100	0.42	163	742
	30	95.6	0.39	128	703	92.4	0.36	117	686
	60	92.3	0.34	120	702	86.2	0.32	108	651
	90	89.5	0.29	128	717	73.7	0.21	114	683
	120	85.7	0.24	116	682	65.3	0.19	108	684
	Mean	92.6	0.34	131	709	83.5	0.30	122	689
	RMSE	0.48	0.05	13.0	16.1	1.65	0.026	17.2	31.1
	P values								
	Linear	<0.001	0.007	0.11	0.14	0.001	0.003	0.129	0.313
	Quadratic	0.004	0.005	0.16	0.41	0.070	0.036	0.111	0.131
Groundnut	0	100	0.49	172	660	100	0.49	172	660
	30	98.3	0.48	146	678	91.2	0.39	145	667
	60	93.1	0.45	152	665	87.4	0.37	149	658
	90	89.9	0.3	147	659	81.1	0.21	128	646
	120	86.1	0.24	138	667	65.8	0.18	128	657
	Mean	93.5	0.39	151	666	85.1	0.33	144	658
	RMSE	0.94	0.36	8.2	8.7	3.13	0.035	8.5	7.2
	P values								
	Linear	0.001	0.017	0.082	0.868	0.006	0.005	0.030	0.322
	Quadratic	0.013	0.049	0.254	0.937	0.030	0.005	0.120	0.674
Soybean	0	100		97	548	100		97	548
	30	98.9		98	579	91.7		104	588
	60	95.0		96	580	87.8		103	575
	90	92.3		100	602	79.9		99	581
	120	85.4		95	547	68.9		98	559
	Mean	94.3		97	571	85.6		100	570
	RMSE	0.85		2.19	16.4	1.85		2.46	11.5
	P values								
	Linear	0.007		0.792	0.821	0.002		0.807	0.816
	Quadratic	0.011		0.799	0.243	0.012		0.312	0.246

*LSR only applies to cowpea and groundnut fodders because soybean fodder contained no leaves.

RMSE: root mean square error

Chapter 4

Table S2. Effect of storage duration on the fibre content: neutral detergent fibre (NDF), acid detergent fibre (ADF) and acid detergent lignin (ADL) of grain legume packaged differently with their linear and quadratic levels of significance.

Crop	Duration	Sack storage (g kg^{-1})			Tied storage(g kg^{-1})		
		NDF	ADF	ADL	NDF	ADF	ADL
Cowpea	0	446	319	81	446	319	81
	30	514	416	88	562	460	94
	60	525	427	83	587	486	95
	90	502	404	77	543	457	85
	120	533	447	86	551	460	87
	Mean	504	403	83	538	436	88
	RMSE	26.6	35.5	5.0	51.6	57.7	6.9
	P values						
	Linear	0.150	0.118	0.953	0.326	0.224	0.899
	Quadratic	0.272	0.241	0.990	0.188	0.122	0.451
Groundnut	0	422	383	94	422	383	94
	30	451	418	97	476	437	104
	60	470	433	103	489	451	109
	90	485	444	103	537	490	111
	120	466	433	95	506	464	101
	Mean	459	422	98	486	445	104
	RMSE	6.2	2.9	4.8	25.6	14.2	1.8
	P values						
	Linear	0.098	0.007	0.634	0.066	0.065	0.401
	Quadratic	0.033	0.007	0.170	0.920	0.064	0.036
Soybean	0	652	550	105	652	550	105
	30	628	535	110	650	556	128
	60	646	548	111	668	564	124
	90	588	499	103	610	521	107
	120	670	568	114	648	542	109
	Mean	637	540	109	646	547	115
	RMSE	35.7	30.4	4.8	23.1	16.5	10.4
	P values						
	Linear	0.974	1.00	0.521	0.558	0.401	0.755
	Quadratic	0.659	0.698	0.843	0.874	0.730	0.481

RMSE: root mean square error

Assessing the nutritional quality of stored grain legume fodders: Correlations among farmers' perceptions, sheep preferences, leaf-stem ratios and laboratory analyses*

*This chapter is peer-reviewed and resubmitted as:
Akakpo, D.B., de Boer, I.J.M., Adjei-Nsiah, S., Duncan, A., Giller, K.E. and Oosting, S.J. Nutritional quality of grain legume fodders stored under different conditions: Correlation among farmers' perception, sheep preference, botanical characteristics and laboratory analyses. (Small Ruminant Research).

A part of this chapter was presented as:
Akakpo, D.B., Oosting, S.J., Adjei-Nsiah, S., Duncan, A., Giller, K.E. and de Boer, I.J.M. (2018) Evaluating the Traditional Feed Storage Systems of Grain Legume Fodders in Northern Ghana. In: Book of abstracts Tropentag 2018. - Weikersheim : Margraf Publishers - ISBN 9783823617600 - p. 118.

Abstract
Crop residues have the potential to alleviate annual feed shortages and nutrient deficiencies experienced in the dry season in the savanna zones of West Africa. Farmers in West Africa especially value the residues of grain legumes, also known as grain legume fodders (GLFs), as animal feed. In this study, therefore, we assessed the nutritional quality of GLFs as affected by storage conditions using four different methods: farmers' perception score (FPS), sheep preference score (SPS), leaf-to-stem ratio (LSR), and laboratory analysis of organic matter digestibility (OMD), crude protein content, neutral detergent fibre (NDF) and acid detergent fibre (ADF). We also determined correlations among these variables. The fodder of cowpea, groundnut and soybean were stored separately in three locations (rooftop, room and treefork) and with two packaging types (polythene sacks or tied with ropes) for 60, 90 and 120 days. FPS was determined by scoring the perceived quality of GLFs on a scale of 1 to 10 (1 = bad and 10 = good) based on physical characteristics by a group of farmers. SPS was assessed by a cafeteria feeding trial based on the rate of dry matter intake of GLFs by a flock of 12 sheep during a 14 hr period. LSR was determined based on the mass of the botanical fractions, i.e. leaf (leaf blade only) and stem (stem and petioles) of 200 g samples separated carefully by the hand. Laboratory analysis was done by near infra-red spectroscopy (NIRS). Results showed that all quality assessment methods successfully discriminated GLF quality differences among crops. Only farmers and sheep could distinguish quality differences among all storage conditions and packing types, whereas laboratory analyses methods could not. These findings could be due to that fact that farmers use LSR to evaluate feed quality, though colour, texture and smell of the fodder could also contribute. We found significant correlations (ranging from 0.35 to 0.88) between all the quality assessment methods across all treatments. There were few within crop correlations between the fodder quality assessment methods, i.e. only FPS and LSR for groundnut and cowpea, FPS and CP for groundnut, and all laboratory analyses parameters among each other for all crops. Hence, the differences among crops were the important determinants of the correlations. From this study, we conclude that farmers have experience and knowledge about nutritional quality of feed and livestock preference for feed. Development programmes and projects could benefit from using such knowledge when formulating and implementing interventions.

Keywords: Crop residues, storage, palatability, dry matter intake, relative feed value

1.0 Introduction

Crop residues are important livestock feeds, which form a major link between crop production and animal production in West Africa (FAO, 2014). They are the second largest feed resource for livestock after grazing, especially in the dry season. The residues of grain legumes, also known as grain legume fodders (GLFs) such as those of groundnut, cowpea and soybean, are considered more valuable feed resources than cereal crop residues, since they have relatively high nitrogen contents and digestibility (López et al., 2005; Schiere et al., 2004). Moreover, supplementation of cereal-straw based rations of ruminants with small quantities of GLFs may improve intake and utilisation of low quality feeds by supplying the limiting nitrogen, and hence contribute to improved animal productivity (Oosting, 1993).

In northern Ghana and other West African countries, such as Nigeria, Burkina Faso, Mali and Niger, GLFs are harvested, dried and stored, and used by the farmers or sold to other livestock farmers, fatteners and traders as feed (Ayantunde et al., 2007a; FAO, 2014; Samireddypalle et al., 2017). During the use and the marketing of these GLFs, their nutritional qualities are not determined. Market prices of GLFs could be indicative of nutritional quality, but these prices are rather determined by scarcity than by quality per se and by local preference (Ayantunde et al., 2014; Samireddypalle et al., 2017).

In determining forage quality, laboratory analyses, including wet chemical analyses (Van Soest and Robertson, 1985) and predictions based on Near Infrared Reflectance Spectroscopy (NIRS) (de Boever et al., 1995; Stubbs et al., 2010) are accepted as standard methods. Organic matter digestibility (OMD), crude protein content (CP) and fibre components are important parameters considered. Fibre components such as neutral detergent fibre (NDF) and acid detergent fibre (ADF) are combined to develop fodder quality indices, for example, the relative feed value (RFV). RFV is widely used by hay sellers and buyers in the United States of America who seek simple means of deciding which hay offers the best quality relative to the cost (Redfearn et al., 2004). However, such formal laboratory analyses are slow and expensive to conduct and are also not widely available in low-income countries.

Alternatively, fodder quality can be assessed by farmers based on the physical characteristics of the fodder using their knowledge and experience. Physical characteristics, such as colour, leafiness, maturity stage, softness and smell, are potential indicators of fodder quality. Leafiness is measured as the leaf-stem-ratio

(LSR) of the fodder. Generally, more leaves means better quality, for example, of fodder from leguminous trees (Mekoya et al., 2008; Thorne et al., 1999) and pasture (Tamou et al., 2018). LSR has not been assessed as an indicator of nutritional quality for stored GLFs.

Another method of validating the quality of fodders is assessing its effect on animal performance and productivity (Coleman and Moore, 2003). However, it is challenging to conduct long-term animal performance tests with many feeds because of time and financial resource constraints. Therefore, a proxy for these tests is to evaluate forage quality by an animal preference test which assesses the rate of voluntary intake of a feed when offered in a choice experiment with other feeds. This proxy test is the so-called cafeteria feeding experiment (Dikmen et al., 2009; Larbi et al., 1993) or choice feeding experiment (Meier et al., 2012). In this experimental setting, with ruminants, two or more feeds are offered separately at the same time for a period of time. During that period, the amount of feed consumed is the indicator of preference for the feeds on offer.

Some studies report the relationship between farmers' local knowledge about forage quality and conventional laboratory analyses. Such studies have been conducted for multi-purpose fodder trees (Mekoya et al., 2008; Thorne et al., 1999) and non-conventional feeds, such as agricultural by-products (Talore, 2015), but not yet for GLFs in sub-Saharan Africa. Moreover, the relationship between farmers' local knowledge and animal preferences is unknown. In the present study, therefore, we assessed the nutritional quality of stored GLFs using four different quality assessment methods. We explored relationships among farmers' perception score (FPS), sheep preference score (SPS), leaf-to-stem ratio (LSR), and laboratory analyses of the nutritional quality of GLFs as affected by storage conditions.

2.0 Materials and methods

2.1 Experimental design

The study was conducted in four villages (Tansia, Tetauko, Kaadi, and Kupalgoga) in Binduri district (10°56'01.6"N, 0°18'53.7"W) in the Upper East Region of Ghana during the dry season from December 2015 to April 2016. In this district, grain legumes are cultivated as intercrops or in a rotation with maize, sorghum and millet. These cereal grain crops benefit from these combinations with grain legumes. In this district, farmers experience feed shortages during the long dry season (November to April), and GLFs can contribute to mitigating such feed shortages. The present study used harvested fodder from an earlier study (Akakpo et al., 2020b) about the effect of rhizobium inoculation and phosphorus fertilisation on grain and fodder yield and quality of three grain legume crops: cowpea (*Vigna unguiculata* (L.) Walp), groundnut (*Arachis hypogaea* L.) and soybean (*Glycine max* (L.) Merr.). One farmer was selected in each village to host one replicate of the trial on his or her farm. Farmers could only participate if they had facilities to store GLFs, i.e. a rooftop, a storeroom and mature live trees with forks suitable for holding enough GLF. Only trees, such as neem (*Azadirachta indica* A. Juss) and shea (*Vitellaria paradoxa* C. F. Gaertn), that were located within a 20-metre radius of the homesteads, were selected.

The experiment was designed as a 3 × 3 × 2 factorial trial and was arranged in a split-split plot design with 18 treatment combinations replicated four times in different villages (farms). The treatments included: whole plot: three types of GLFs (cowpea, groundnut and soybean), sub-plot: three types of storage locations (rooftop, room and tree-fork), and sub-sub-plot: two types of packaging (3 kg of GLFs bundled and packed in polythene sacks or unpacked but tied with ropes).

At the time of harvest at each farm, fodders of each crop were collected on one heap and thoroughly mixed and left to dry for six days to attain constant weight. After the six days of drying, each heap was mixed again and separated into 3 kg bundles. For each treatment combination, five bundles were stored.

2.2 Sampling

The fodders were sampled after 60, 90 and 120 days of storage. At each sampling time, about 40 g of fodder from each of the five bundles in each treatment was carefully sampled. We created 200 g samples, and these samples were subsequently placed in paper bags, labelled and oven-dried at 70 ^{o}C for 48 hours to determine the dry matter. The dried samples were ground to pass through a 1 mm screen with a laboratory hammer mill at the soil chemistry laboratory of the Savanna Agricultural Research Institute (SARI) – Nyankpala, Ghana. The ground fodder samples were stored at ambient temperature and later air-freighted to the animal nutrition laboratory of the International Livestock Research Institute (ILRI) in Addis Ababa, Ethiopia for analyses. The samples were freighted under the permission (Permit No.12113) of the Ministry of Agriculture and Natural Resources in Ethiopia.

At each sampling time, LSR of the GLFs was estimated for cowpea and groundnut fodder (but not for soybean fodder, which consisted only of stems and threshed pods after harvest). To estimate LSR, about 40 g of fodder from each of the five bundles in each treatment was carefully sampled, pooled and mixed. The pooled samples collected were hand separated into leaf (leaf blade only), and stem (stem and petioles) fractions and an LSR, based on mass was determined (Lemus et al., 2002).

At each sampling time, 1 kg of fodder from each treatment was put into 20-litre plastic feeding troughs to determine the farmers' perception score (FPS) and the sheep preferences score (SPS). To determine the FPS, a group of 40 farmers (10 per village) who feed GLFs to their livestock was purposively (they should own sheep and feed them with GLFs) selected from the villages. To reduced biased scoring results, the scoring procedure was explained to the selected farmers in their local language with the help of extension workers and other educated farmers who were sensitized on the subject. The farmers were asked individually to score each fodder of each treatment on a scale of 1 to 10 (1= bad livestock feed and 10=good livestock feed) based on their knowledge on fodder quality indicators.

Furthermore, to determine the SPS, we randomly selected 12 sheep per village from the flock of the farmer participating in the experiment. If the farmer's flock was less than 12 mature animals, then sheep of a neighbour were added. The average body weight of the selected sheep was 15.0 kg (S.D.±3.1). At each sampling time, in a cafeteria feeding experiment (Dikmen et al., 2009; Farid et al., 2010), the 1 kg samples used in FPS determination were fed to the selected sheep. Before each preference scoring test, the sheep were penned and deprived of feed and water for 18 h overnight (20:00 to 15:00 hours). In the afternoon of the following day, the 1 kg samples were placed randomly in a confined and unroofed area of about 40 – 60 m^2. In this set-up, all sheep could select feed from any of the feeding troughs for 14 hours (from 15:00 – 5:00 hours) the following day. Water was also provided *ad libitum* during this period. Intake was determined by gathering and weighing the leftovers around and in the troughs and subtracted from the quantity offered.

2.3 Sample analysis

Fodder samples were analysed for chemical composition and *in-vitro* organic matter digestibility (OMD) using conventional wet chemistry and Near Infrared Reflectance Spectroscopy (NIRS). The conventional chemical analysis involved quantifying the organic matter (OM), dry matter (DM), crude protein (CP) content and neutral detergent fibre (NDF) concentration, according to AOAC, (1990) and the OMD according to the Van Soest and Robertson, (1985). Reference samples were selected and analysed by conventional wet chemical analysis. Results from the conventional wet chemical analysis were used to calibrate the NIRS equations to predict the nutritional composition for a wide range of legume forages, such as groundnut, cowpea and soybean. NIRS predictions were made using a FOSS Forage Analyzer 5000 with software package WinISI, according to de Boever et al., (1995) and included predictions of nitrogen (N) (crude protein = N × 6.25), neutral detergent fibre (NDF), acid detergent fibre (ADF) and *in-vitro* organic matter digestibility (OMD). NIRS calibrations and prediction equation statistics were reported by Akakpo et al. (2020b).

Results of laboratory and NIRS analyses of NDF and ADF were used to calculate relative feed value (RFV) of the GLFs. The RFV is widely used by hay buyers and sellers in the United States of America. Fodder with higher RFV indicates better nutritional quality and *vice versa*. The RFV was calculated using the formula by Redfearn et al. (2004) in equation 1:

$$RFV = 93 \times (88.9 - 0.779 \times NDF) / ADF\ (\%\ DM) \qquad [1]$$

where ADF is acid detergent fibre, and NDF is neutral detergent fibre concentration as a percentage of dry matter (DM).
This RFV was formulated relative to a typical forage quality of alfalfa hay at full bloom. If a full bloom alfalfa hay contains about 41 % NDF and 53 % ADF, the calculated RFV is 100 (Redfearn et al., 2004). The marketing grades of hays using RFV are: prime (>151), 1 (125-151), 2 (101-124), 3 (86-100), 4 (77-85), and fair (<77).

2.4 Statistical analyses

The data about FPS, SPS, LSR and laboratory analyses of nutritional quality were statistically analysed by using a mixed-effect analysis of variance model (Searle et al., 1992) in GenStat version 19 (VSN, 2017). In this model (Equation 2 below), replications (block), crop, storage location, packaging types and duration were fixed factors, while blocks nested with crops within village were random factors.

$$Y_{ijklmn} = \mu + B_i + C_j + L_k + P_l + (CLP)_{jkl} + BC_{ijkl} + Dm + (CLPD)_{jklm} + \varepsilon_{ijklmn} \qquad [2]$$

where, Y_{ijklmn} is the response variable (FPS, SPS, LSR and laboratory analyses of nutritional quality of the GLFs), μ is the overall mean, B_i is the effect of i^{th} block

Chapter 5

(villages), C_j is the effect of j^{th} crop (j = cowpea, groundnut and soybean), L_k is the effect of k^{th} storage location (k = rooftop room, tree fork), P_l is the effect of l^{th} packaging type (l = sack, tied), $(CLP)_{jkl}$ is the interaction effect of the main factors (crop, storage location and packaging type), D_m is the effect of m^{th} storage duration (m = at the start of the experiment (day 60, 90, 120), $(CLPD)_{jklm}$ is the interaction effect of the main factors with duration, BC_{ijkl} and ε_{ijklmn} = the random effect for crops within villages and residual error respectively assumed to be normally distributed around zero with variance σ^2_{crop} and $\sigma^2\varepsilon$ respectively. The differences between means were tested using the Fisher's least significance difference (LSD) test ($P < 0.05$). Pearson correlation analyses were carried out across all observations (n = 216) between nutritional quality assessment methods (FPS, SPS and laboratory analyses) of the GLFs except LSR. Correlation analyses between LSR and other nutritional quality assessment methods was for cowpea and groundnut only (n = 144) since soybean was not evaluated for LSR. Correlations referred to are significant ($P < 0.05$), unless stated otherwise.

3.0 Results

3.1 Differences in farmers perceptions, sheep preferences, leaf-stem-ratios and nutritional composition among stored GLFs

Mean FPS differed among crops. Farmers prefer cowpea the most (6.3) FPS followed by groundnut (5.5), and soybean the least (2.3) FPS (Table 1). The type of storage location affected FPS. Room storage resulted in the highest FPS, followed by rooftop, while tree-fork resulted in the lowest FPS (Table 1). FPS differed for packaging type, namely GLFs packed in sacks resulted in a higher FPS than those tied. FPS of GLFs decreased with increasing duration, a significant interaction between duration and crop (Table 1). There were significant interactions between crop and location and crop and packaging type. These interactions, however, did not change the ranking order of the crops or the duration effect.

Mean SPS differed among crops. Sheep prefer cowpea, followed by groundnut, and soybean the least (Table 1). The type of storage locations affected SPS. Room storage resulted in a higher SPS than rooftop and tree-fork (Table 1). Similarly, packaging affected SPS, namely GLFs packed in sacks resulted in a higher SPS than those tied. There was no duration effect on SPS.

Mean LSR tendered to be higher (P=0.054) in groundnut than in cowpea. There was also a tendency (P=0.08) for a location effect on LSR where room storage had

Table 1. Farmers' perception score (FPS), sheep preference score (SPS), Leaf to stem ratio (LSR) and nutritional composition of grain legume fodders stored at different storage locations and in different types of packaging

Treatments	FPS	SPS (g DMI $14hr^{-1}$ 12 $sheep^{-1}$)	LSR[2]	Nutritional composition (g kg^{-1} DM)		RFV
				CP	OMD	
Crop (C)						
Cowpea	6.3	787	0.26	116	686	96
Groundnut	5.5	705	0.29	140	659	103
Soybean	2.3	472	-	97	571	68
P-value	<0.001	<0.001	0.054	<0.001	<0.001	<0.001
LSD	0.16	70.3	0.027	8.3	19.7	7.3
Location (L)						
Rooftop	4.7	648	0.28	117	639	87
Room	4.9	710	0.30	121	643	92
Tree-fork	4.6	605	0.26	115	635	88
P-value	<0.001	0.015	0.08	ns	ns	ns
LSD	0.16	70.3	0.033	8.3	19.7	7.3
Packaging (P)						
Sack	4.9	696	0.31	121	645	95
Tied	4.5	613	0.25	115	633	58
P-value	<0.001	0.006	<0.001	ns	ns	0.008
LSD	0.13	57.4	0.027	6.8	16.1	6.0
Duration (D)						
60	5.2	677	0.37	121	639	88
90	4.6	621	0.25	118	645	91
120	4.4	665	0.21	114	633	88
P-value	<0.001	ns	<0.001	0.004	0.05	ns
LSD	0.18	55.9	0.035	4.7	10.2	4.0
Interactions						
C × L	0.004	ns	ns	ns	ns	ns
C × P	<0.001	ns	ns	ns	ns	ns
L × P	ns	ns	ns	ns	ns	ns
D × C	<0.001	ns	ns	0.002	0.005	<0.001
D × L	ns	ns	ns	ns	ns	ns
D × P	ns	ns	ns	ns	ns	ns

CP=crude protein; OMD=*in-vitro* organic matter digestibility; ns=not significant.
[2] LSR only applies to cowpea and groundnut fodders because soybean fodder contained no leaves

a higher LSR than tree-fork (Table 1). LSR for packaging type also differed where GLFs packed in sacks had a higher LSR than those tied. LSR decreased from 0.37 to 0.21 throughout the storage period.

Mean CP and OMD of GLFs differed among crops (Table1). There was also a duration effect on CP and OMD of GLFs with a significant interaction between duration and crop (Table 1). The interaction, however, did not affect the ranking order of the crops or the duration.

Mean RFV differed among crops. Soybean had the lowest (68) RFV belonging to the fair grade of the RFV grading standard compared to cowpea (96) in grade 3 and groundnut in grade 2 (Redfearn et al., 2004). The mean RFV for packaging type differed, where GLFs packed in sacks (95) had a higher RFV than those tied (58). There was no duration effect on RFV of GLFs, but there was a significant interaction between duration and crop. The interactions indicated a change in the ranking order of RFV of the GLFs with changes in duration. The ranking order of RFV on the 60^{th} and 120^{th} day was groundnut > cowpea > soybean while the ranking order on the 90^{th} day was cowpea > groundnut > soybean.

3.2 Relationships among nutritional quality assessment methods

Correlations among FPS, SPS, LSR and laboratory analyses of nutritional quality of GLFs are presented in Table 2. FPS correlated significantly with SPS, LSR, RFV, CP content and OMD (Table 2), ranging from 0.30 for LSR to 0.71 for OMD. Since soybean had no leaves, the correlation between LSR and other parameters is included only for cowpea and groundnut in Table 2. Farmers distinguish GLFs of different crops, and they prefer crops as feed in the order: cowpea > groundnut > soybean. Crop, therefore, was an important determinant of the correlation between FPS and quality parameters (illustrated in Figs. 1 - 3). Within crops, there

Table 2. Correlation among farmers' perception score (FPS), sheep preference score (SPS), leaf-to-stem ratio (LSR) and nutritional composition of grain legume fodders stored under different conditions and duration. For LSR only cowpea and groundnut were included in the analysis since soybean contained no leaf.

Factors	FPS	SPS	LSR	CP	OMD
SPS	0.56				
LSR	0.30	0.00ns			
CP	0.49	0.35	0.24		
OMD	0.71	0.50	0.01ns	0.67	
RFV	0.59	0.46	0.17	0.84	0.88

CP=crude protein; OMD=*in-vitro* organic matter digestibility; RFV=relative feed value; ns = not significant

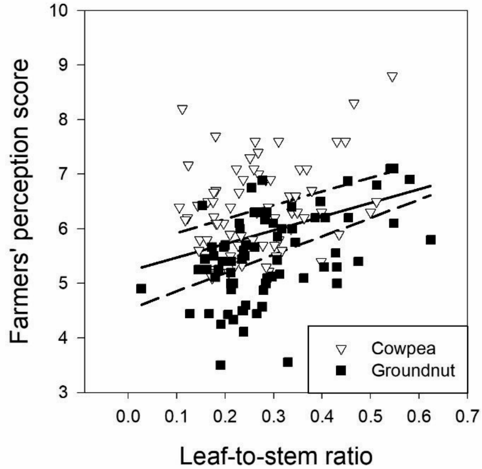


Fig. 1. Relationship between farmer's perception score (Y) and leaf-stem-ratio (X) of grain legume fodders stored under different conditions and duration.

The regression relationships for individual crops and pooled data were:

Cowpea: $y = 2.523x + 5.6749$ ($r = 0.31$; $p = 0.007$; $n = 72$)

Groundnut: $y = 3.3618x + 4.518$ ($r = 0.49$; $p < 0.001$; $n = 72$)

Pooled relationship: $Y = 9.4847X + 2.9772$ ($r = 0.30$; $p < 0.001$; $n = 144$).

The solid line represents the pooled regression

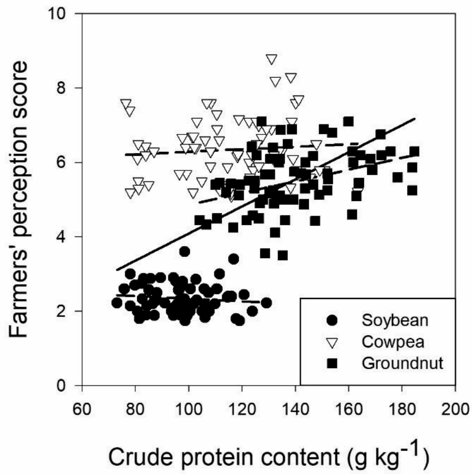


Fig. 2. Relationship between farmer's perception score (Y) and crude protein content (g kg^{-1}) (X) of grain legume fodders stored under different conditions and duration.

The regression relationships for individual crops and pooled data were:

Cowpea: $Y = 0.0034X + 5.9495$ ($r = 0.08$; $p = 0.48$; $n = 72$)

Groundnut: $Y = 0.0158X + 3.2802$ ($r = 0.39$; $p < 0.001$; $n = 72$)

Soybean : $Y = -0.0035X + 2.6851$ ($r = -0.11$; $p = 0.36$; $n = 71$)

Pooled relationship: $Y = 0.0364X + 0.4481$ ($r = 0.49$; $p < 0.001$; $n = 215$)

The solid line represents the pooled regression

Chapter 5

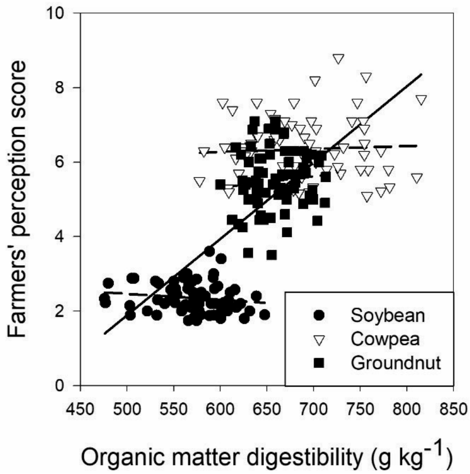


Fig. 3. Relationship between farmer's perception score (Y) and organic matter digestibility (g kg^{-1}) (X) of grain legume fodders stored under different conditions and duration.

The regression relationships for individual crops and pooled data were:
Cowpea: Y = 0.0008X + 5.7916 (r = 0.05; p = 0.65; n = 72)
Groundnut: Y = 0.003X + 3.5175 ((r = 0.1; p = 0.4; n = 72)
Soybean : Y = -0.0016X + 3.2835 (r = -0.11; p = 0.2; n = 71)
Pooled relationship: Y = 0.0205X - 8.3441 (r = 0.71; p < 0.001; n = 215).
The solid line represents the pooled regression

were significant relationships among FPS and LSR for cowpea and groundnut (Fig. 1) and among FPS and CP for groundnut (Fig. 2).

SPS correlated significantly with FPS, CP content and RFV (Table 2) and ranged from 0.35 for CP content to 0.56 for FPS. Assessment of SPS was done in each period only with the crops stored for one duration, and the crops were offered to sheep that were starved for 18 h. Hence, it was expected that SPS would, at best, be able to discriminate among treatments within duration but not among durations (confirmed in Table 1). Within duration, correlations among SPS and other nutritive quality parameters were of similar magnitude as the ones across all durations (data not shown). The laboratory assessed parameters CP, OMD and RFV were all significantly correlated across crops (Table 2) and within crops (data not shown). Within cowpea and groundnut LSR was not significantly associated with laboratory analyses of nutritional quality, except for the CP content in groundnut (r=0.34) (data not shown).

4.0 Discussion

The present study compared different methods to assess the nutritional value of stored GLFs, namely farmers perception score (FPS), sheep preference score (SPS) based on dry matter intake), leaf-to-stem ratio (LSR) and laboratory analyses. The results indicated that all four assessment methods were able to distinguish the nutritional quality differences among the GLFs of the three crops similarly. It was noteworthy, however, that only farmers and sheep could distinguish the various storage locations and packaging types, whereas the most commonly used laboratory analyses parameters to approach nutritive quality, i.e. CP content and OMD, could not.

GLFs have been stored and fed to livestock for several generations in the study area. Farmers' experience would have generated a general knowledge about the nutritive quality of the GLFs and the assessment of nutritive quality differences, between and within GLFs. Such knowledge is most likely to be passed on from one generation to the other and is an element of the local knowledge of farmers (Tamou et al., 2018). Farmers in the study area use their local knowledge to assess fodder quality from its physical appearance and in some situations from its smell. These physical fodder characteristics used in the quality assessment included: colour (deep green was considered to be of better quality), stage of maturity, leafiness (more leaves means better quality) and tenderness (animals prefer softer to fibrous fodders). This local knowledge was also used by farmers to evaluate the nutritional status of soils in Africa (Adjei-Nsiah, 2012; Giller, 2000). In situations where fodder is stored, the fodder should not be mouldy or rotten with a foul smell. Employing the above criteria to evaluate GLFs could be the reason why farmers were able to distinguish nutritional quality among GLFs obtained from different storage conditions, whereas laboratory assessment methods could not do. Other studies (Mekoya et al., 2008; Talore, 2015; Thorne et al., 1999) also found that forages with high ranked scores by farmers correlated positively with CP content, OMD and negatively with NDF and ADF content. In addition, farmers' local knowledge has been used in some tropical regions to determine the nutritive values of fodder trees and of grazing land (Mekoya et al., 2008; Tamou et al., 2018; Thorne et al., 1999).

Our results indicate that cowpea is appreciated over groundnut, while soybean is least appreciated by both farmers and sheep (Table 1). Within crops, the LSR is possibly the criterion that farmers use to judge nutritive quality as indicated by the significant correlation among FPS and LSR for cowpea and groundnut. Soybean fodder has no leaves as it is harvested dry in the field after all leaves have senesced and fallen and farmers scored this fodder very low with limited variation among storage conditions. As described in the results section, it was not expected that sheep could differentiate among GLFs with different storage durations, and this was confirmed by the results (Table 1). The SPS could distinguish between various storage conditions, in line with the fact that the overall and within duration correlation among SPS and other nutritional quality parameters were significant.

In the present study, for SPS, we offered 1 kg of GLF from each treatment to the sheep. We found that only in two cases, there was no residue of groundnut fodder after the SPS assessment. Nevertheless, the limited quantity of fodder offered could have resulted in the phenomenon that the most preferred fodder was eaten first, and forcing sheep to move to a less preferred fodder. Savadogo et al. (2000) and Zemmelink (1980) examined the effect of the amount of feed offered and selective consumption on voluntary intake of crop residues by sheep. They found that sheep tend to eat more of the preferred fodder if the quantity offered was higher. Hence, it is likely that if we had offered more, the differences among GLFs and treatments might have been larger than now (Degen et al., 2010). Consequently, the observed differences may underestimate the real sheep preference differences. Nevertheless, GLF feeding generally is done at low levels of feed offered as a supplement to enhance the intake of low quality cereal residues such straws of maize, rice and sorghum (Abdou et al., 2011; Ayantunde et al., 2007b; Savadogo et al., 2000) in West Africa. These findings might make the present study to well reflect the practical situation of GLF feeding in northern Ghana.

The low RFV of soybean as compared to groundnut and cowpea (Table 1) was due to higher fibre components (NDF and ADF) as reported by Akakpo et al. (2020a). NDF and ADF are often used as negative indices for the nutritional quality of fodders (Van Soest, 1994) which accounted for the poor nutritive quality and ranking of the soybean fodder. These poor quality indicators could be explained by the stage of maturity at which the fodder was harvested. Plant maturity is one of the most important factors affecting forage quality. As a plant matures, fibre content and indigestible lignin accumulate. In this study, soybean fodder was the last crop harvested among the three legume crops as is often the case in the farming system of northern Ghana when almost all the leaves had fallen (Akakpo et al., 2020b).

The fact that leaves and stems of cowpea and groundnut were quite similar in OMD and those of cowpea in CP (Akakpo et al., 2020a) explains why variation in LSR did not explain variation in these laboratory analyses of nutritional quality. For groundnut we observed a positive correlation between LSR and CP, which can be explained by the higher CP content in leaves than in stems (Akakpo et al., 2020a). This contradicts Larbi et al. (1999) who reported that the LSR has limited potential to predict forage quality, including CP content among groundnut varieties. In other crops such as cereals, the LSR is an important determinant of straw quality (Blümmel et al., 2010). Among and within the GLFs in the present study, OMD, CP and RFV were significantly correlated. Cowpea has a slightly higher OMD than groundnut, which may explain why it was preferred by farmers and sheep over the other GLFs.

Nevertheless, groundnut fodder tended to have higher LSR and higher CP content than cowpea fodder. LSR, at similar OMD and CP content, may have a significant correlation with intake because of the relative brittleness of leaves which facilitates particle size reduction through chewing and rumination and the passage from the rumen. This correlation was not confirmed in the present experiment, where within crops no significant correlation was found between LSR and SPS (data not shown).

5.0 Conclusion

We observed that all quality assessment methods successfully discriminated GLF quality between crops. Only farmers and sheep could distinguish quality differences among storage conditions, whereas laboratory assessment methods could not. These findings could be due to that fact that farmers use sensory criteria (LSR, colour (vision), smell, texture) to evaluate feed quality and that laboratory assessment methods do not assess these directly. This finding implies that farmers have experience and knowledge about nutritional quality of feed and livestock preference for feed. Development programmes and projects could benefit from using such knowledge when formulating and implementing interventions.

Acknowledgements

We thank the Bill & Melinda Gates Foundation for funding through a grant to Wageningen University to support the project N2Africa: Putting Nitrogen Fixation to Work for Smallholder Farmers in Africa (www.N2Africa.org). We are also grateful to farmers in the study area and Mr Ebenezer Nartey, a veterinary officer with Heifer International for his assistance in the selection of healthy animals for the study. We acknowledge Mr Jonas Asmare and KVSV Prasad of International Livestock Research Institute (ILRI) and Mr Emmanuel Vorleto of CSIR-Savanna Agricultural Research Institute, Nyankpala for their technical assistance with the laboratory analyses.

Conflict of interest

The authors declare no conflicts of interest.

General discussion

1.0 Introduction

Feed scarcity and high feed costs are major challenges for livestock production in West Africa, especially during the dry season (Ayantunde et al., 2014; FAO, 2014). Natural pasture and crop residues represent the majority of the feed for ruminants. The importance of crop residues in smallholder mixed crop-livestock (MCL) systems is increasing for two main reasons. First, the area of natural pastures on communal grazing lands is reducing due to the conversion of rangelands to croplands and residential facilities to feed and house the increasing human population. Second, crop residues can help mitigate feed shortages on-farm and can be traded to create additional income. The residues of grain legumes (GLs), also known as grain legume fodders (GLFs) such as those of groundnut, cowpea and soybean, are considered more valuable feed resources than cereal crop residues, since they have relatively high protein contents and digestibility (López et al., 2005; Schiere et al., 2004). Besides the function as feed, GLFs may have a function as fuel, construction material and mulch for soil improvement. Currently, research and development activities are being implemented by governmental and non-governmental organizations to expand the use of grain legumes for smallholder farmers in northern Ghana.

To get insights into the scope for further development of the use of GLFs for livestock feed in northern Ghana, knowledge is required about the use of GLFs in the MCL systems, factors driving their use, and technical options to increase their use. So far, such knowledge has not been published. The main objective of this study, therefore, was to understand the roles of grain legume fodders in mixed crop-livestock systems and identify options to improve their quality and utilisation by smallholders in northern Ghana.

To address this main objective of the study, I formulated four sub-objectives to guide the research process. The first was to assess and describe the variation in the use of GLFs and understand the potential drivers for their use in MCL systems (Chapter 2). In our quest to identify options to improve the quality and use of GLFs we explored agronomic and storage possibilities. We evaluated and compared the effects of rhizobium inoculation and phosphorus fertilization on grain and fodder yield and fodder quality of the major grain legumes in two agro-ecological zones of Ghana (Chapter 3). In addition, we evaluated the effects of storage conditions and duration on dry matter loss and nutritional quality of GLFs, and assessed the risk of aflatoxin prevalence in stored groundnut fodder (Chapter 4). Finally, we assessed the nutritional quality of stored GLFs using four different quality assessment methods, including farmers' perception, sheep preference, leaf-to-stem ratio and laboratory analyses (Chapter 5).

Before I reflect on and discuss the implications of the key findings of this thesis, I will discuss some methodological challenges in the research process in the following section.

2.0 Methodological challenges

This study used different methods to obtain data. All data were collected in a few villages in districts in the Northern region (NR), the Upper East region (UER), and the Upper West region (UWR). The case districts selected were districts that already participated in the ongoing N2Africa project. We conducted stakeholder consultation and field visits to select the study villages in these districts, to ensure the villages were representative of the district and region. However, it must be noted that the study of the sampled villages gave detailed insights into the prevailing circumstances and practices in the region, but that this study cannot be used to estimate their prevalence or regional implications.

Another methodological challenge (Chapter 2) was how to estimate land size, livestock herd size and crop yields from intercropped fields. It is well established that during surveys, farmers tend to under-estimate or over-estimate their resources based on their perception of the objectives of the study (Carletto et al., 2015, 2013). The most appropriate way of estimating land size and livestock herd size is through field measurement, using for example global positioning system devices and counting of the animals by the researchers themselves. However, such field measurements are time-consuming to conduct and consequently expensive. In this study, we asked farmers to report their arable landholding and herd size. Most farmers in our study know the size of their land-based on measurement done by tractor operators during ploughing. To cross-check if farmers were telling us the truth about their arable landholding, we first asked them about the total size of land. This was later validated by follow up questions, such as number of plots of land owned and individual plot sizes. Additionally we cross-checked total land-use by summing the land sizes allocated to individual crops. If estimates differed widely we asked the farmers again to recall the land sizes and in some cases we asked the wife or the eldest son of the household head to confirm. This cross-checking and follow-up procedures indicated that less than 5% of respondents provided inconsistent landholding estimates.

Farmers are also known to under- or over-estimate their crop yields in surveys because of intercropping. In calculating the yield from intercropped plots we adopted approaches from previous work done (Benson and Fermont, 2011; Waldman et al., 2016) i.e. by dividing the cropped area equally for the two crops. In this study, we confirmed the yields reported by the farmers by counting the number of bags of crops in storage and multiplying it with the estimated weight per bag.

Our agronomic (Chapter 3) and storage (Chapters 4 and 5) studies were conducted under on-farm conditions. The challenges of on-farm studies are that it is difficult to control conditions due to the following reasons. First, on-farm there may be a lack of facilities, such as good water control, pest control systems, and equipment for operations, such as for land preparation and for processing of harvest. Second, there may be huge variation in soil fertility status between farms and between fields within a farm. Third, the research farms often are very poorly accessible due to their remoteness or poor roads. All these above-mentioned reasons hamper timely farm operations and data collection. To address these challenges of on-farm research we adopted the standard principles of experimental design, e.g. replication, randomisation, and blocking (Gomez and Gomez, 1984; Piepho et al., 2011) and we selected farms which were easily accessible. We also recruited trained research assistants to ensure timely farm operations and data collection.

I discuss in the next sections the implications of the key findings for the MCL system and the contribution of this thesis to the framework of sustainable intensification (SI). I will also discuss the implications of findings for some national policies and programmes in Ghana and future research. Finally, I will end with major conclusions from the study.

3.0 Reflection on key findings

3.1 The role and variation in the use of grain legume fodders

Farming systems in Ghana, which are mainly rain-fed, low-input smallholder MCL systems, have developed over time as a way to adapt to agro-ecological and market conditions. In our study, we selected the three regions with differences regarding agro-ecological conditions, population density and market situation, and consequently expected differences in farming system development (Akinola et al., 2016). We also expected that the overall development of these farming systems would determine their specific use of GLFs. We identified major uses of GLFs as ruminant feed (stall feeding and grazing) and mulch. Minor uses of GLFs were for fuel, compost and for sale to generate income. The overarching driver for the different uses of GLFs was the importance of livestock in the farming system, which can be explained by the following three reasons.

First, an intensification gradient of land-use can affect the importance of livestock in farming systems. We observed a land-use intensification gradient in the regions, varying from extensive land-use in UWR, semi-intense land-use in NR to relatively intensive land-use in UER. Livestock is often used to intensify land-use, since livestock density can be increased by use of feeds which are not produced on the farm such as grazing, cut and carry of road side grasses and shrubs. In UER MCL systems had a higher livestock density than in NR, which is an indication that farmers indeed increased the land-use intensity by increasing the livestock density making livestock a more important component of their farms. With this importance of livestock, GLFs became more valuable in the farming systems and farmers invested in their collection (Chapter 2).

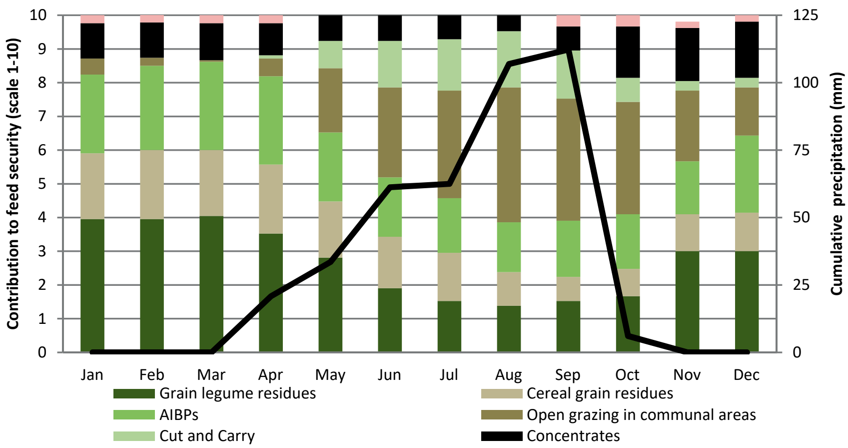
Second, the conditions for crop production can affect the importance of livestock in farming systems. UER, for example, has relatively unfavourable conditions (poor soils and a relatively short rainy season) for crop production causing low crop yields (Chapters 2 and 3). Such unfavourable conditions for crop farming force farmers to focus on livestock production as a source of income. The income from sales of livestock can provide cash for the purchase of staple foods and farm inputs (Smith et al., 2013). So GLFs are important in the UER MCL systems because livestock is important for the household's livelihood. However, this does not mean that UER farmers allocate a high proportion of their arable landholdings to GLs. Rather their household food security situation forces them to grow food crops such as maize, rice and millet.

Third, the function of livestock can affect the use of GLFs in farming systems. In UER, for example, cattle are used mainly for land preparation, and they, therefore, are kept on the farm during the entire year. In NR and UWR, livestock are generally not kept for land preparation because contractors are hired to plough the land with tractors. In NR and UWR, the predominant function of livestock is to store wealth. These livestock are not kept on-farm for part of the year, but herded by Fulani throughout the year and they are away from the farms for a considerable part of the year. Hence, feeding of the livestock is outsourced to the Fulani herders. Besides the importance of livestock within a farming system, demand for GLFs from peri-urban livestock traders and fatteners (see

Text Box 1. Annual feed calendars of livestock traders and fatteners

In peri-urban areas, traders and fatteners may keep livestock on small lands (kraals) before they sell them. These livestock keepers practice some grazing in the rainy season, but most of the feeds are imported into the farming system. This causes a high demand for feed and markets for collected green fodder, grass and leaves for stall-feeding (cut and carry), crop residues (especially grain legume fodders (GLFs)) and agro-industrial by-products (AIBPs) have developed. The figure below shows a typical annual feed calendar and precipitation pattern for livestock traders and fatteners in Upper East region of Ghana. It shows that GLFs are a major component of the diet of livestock kept by traders 'and fatteners throughout the year. In the dry season (November to April), GLFs form over 30% of the diet which reduces to about 15% in the rainy season. The traders and fatteners stated that the continued use of GLFs in the rainy season prevents their livestock from getting diarrhoea after eating fresh grasses.

Traders and fatteners depend solely on smallholder farmers in the rural areas for the supply of GLFs. Fatteners in the Upper East region in general, practice less grazing throughout the year by making use of nutrient dense feeds such as concentrates, AIBPs and GLFs. The use of these feeds translate to a shorter fattening period among fatteners in Upper East compared with the other two case regions.



Source: unpublished field data 2017

textbox 1) drives the use of GLFs in the regions. Most of these trader and fatteners are not crop farmers because availability of cropland is limited in the peri-urban areas.

An additional driver for use of GLFs will be the continuous increasing demand for livestock products due to population increase (FAOSTAT, 2019) and an increasing economic status of middle-class workers. In Ghana, for example, the number of livestock and meat and milk imports have increased from the year 2000 until the present day (FAOSTAT, 2019; MOFA, 2017). The number of cattle increased from 1.3 million in 2000 to 1.8 million in 2017, whereas the number of small ruminants (sheep and goats) increased from 5.8 million in 2000 to 11 million in 2017 (Fig. 1). If this rate of increase continues, there will be a need to increase feed production to feed these animals. However, presently, farmers in Ghana still depend on grazing and crop residues to feed their animals.

Many interventions to introduce feed production in Ghana have failed (Amankwah, 2013), in part because it requires farmers to change their objectives drastically. Increased use of GLFs may be a first step in the provision of more and better feeds for livestock in Ghana, since they can come with a gradual transition of farm objectives: their use does not imply replacement of food crops by fodder crops, but they do support a more important role of livestock within farming systems.

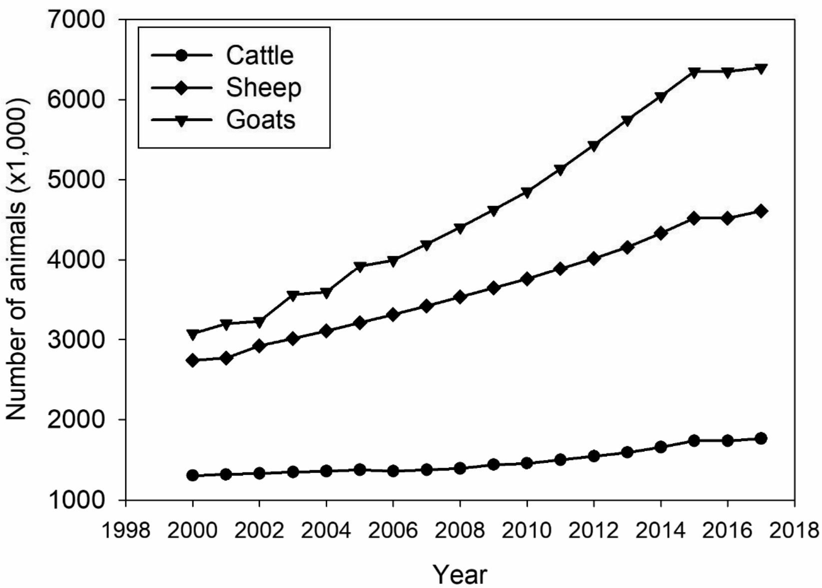


Fig. 1. Trend of livestock population in Ghana. Source: (FAOSTAT, 2019)

3.2 Options to improve the quality and use of grain legume fodders

With the current increase of demand for livestock products, production systems will need to intensify to meet the demand for higher quality products, while

Chapter 6

remaining environmentally sustainable. As production systems intensify, the inability of farmers to adequately feed their livestock year-round will be more important. The feed value of GLFs, in general, is needed to meet the dry season feed gap, whereas an additional benefit of feeding GLFs may be the increased intake of cereal crop residues when they are fed along with the GLFs (López et al., 2005). Agronomic management practises (e.g. rhizobium inoculation and phosphorus fertilizers) of grain legume production may increase both grain and fodder yield (Chapter 3).

Storage conditions and storage duration affect the recovery of the fodder quantity, and the quality of the stored fodder in general (Guerrero et al., 2010). Storage conditions affect the loss of dry matter and of quality (Fekede et al., 2014; Guerrero et al., 2010). The loss in nutritional quality is more and faster when fodder is stored outdoor due to exposure to adverse weather conditions (Chapter 4), and it can be assumed that outdoor storage as presently predominant in northern Ghana (Fig. 2), is not the best method regarding conserving the quantity and nutritional quality of GLFs. Our study showed that storage in sacks is an improvement compared to the open-air storage.

Fig 2. Farmers' methods of storing crop residues in northern Ghana

4.0 Implications of key findings

4.1 Implication for sustainable intensifications of smallholder farming system

Recently, the concept of sustainable intensification has become popular. Sustainable intensification has many definitions, but most agree on the definition that more output per unit of land, labour and capital is produced while negative environmental impacts are minimized and ecosystems are preserved (Pretty et al., 2011; Garnett et al., 2013; Vanlauwe et al., 2014b). In sub-Saharan Africa (SSA), this concept should contribute to enhance crop and livestock production, improve the livelihoods of smallholder farmers, and minimize contributions to climate change and disturbance of natural ecosystems. Most smallholder farmers grow grain legumes with little or no fertiliser which results in low yields. Most mineral fertiliser is targeted to cereals crops (e.g. maize and rice).

From our research we have shown (Chapter 3) that the smallholder MCL system could be sustainably intensified by introducing grain legumes, use of agricultural inputs (e.g. phosphorus (P) fertilizers and rhizobium inoculants) to increase both grain and fodder yields. In our studies about cowpea, for example, application of inoculation alone increased grain yield by 44%, P-fertilizer alone increased grain yield by 102% while the combination of P and inoculation increased grain yield by 123% compared to the control treatment where no input was applied (Chapter 3). A similar trend was observed for fodder yield. This is an illustration of intensification. The question is how this intensification of land-use by use of GLs impacts the environment? GLs are crops producing food and feed and their feed production does not come with competition for land. Because of the benefits from N_2-fixation, they have a positive effect on soil nutrient status and may improve yields of crops that follow the GL in the crop rotation (Franke et al., 2018; Rurangwa et al., 2018; van Vugt et al., 2018). Other benefits of inclusion of GLs in the crop rotation include improvement of soil physical properties and control of diseases and pests in cereals (Giller, 2001; Trenbath, 1993). Therefore, intensification interventions to GL such as application of P and rhizobium inoculants have the potential to sustainably increase yields per unit area while preserving the natural resource base.

Chapter 6

Additionally, the increased yield of GLFs can be fed to livestock and the storage of GLFs in sacks to prevent losses in quantity and quality (Chapter 4) also contributes to higher livestock outputs. Moreover, the sale of GLFs is a source of additional income for farmers in SSA (Ayantunde et al., 2014; Preston, 2007; Samireddypalle et al., 2017). Though not reported in this thesis, farmers mentioned that sack storage helps them to quantify the amount of feed offered to their animals daily and also reduces the labour in feeding livestock. Hence, intensification of land-use by use of GLs and GLFs in MCL systems in the Guinea Savanna ecological zone enhances food security and socio-economic conditions of farmers. Moreover, feeding GLFs which are of better nutritional quality than cereal crop residues, has a positive effect on GHG emission intensity of livestock systems i.e. the GHG-emissions per unit produce (Gerber et al., 2011).

4.2 Implication for policy

In Ghana, agriculture remains a key sector of her economy, accounting for 20% of the national GDP in 2016. Agriculture employs 45% of the economically active population and 52% of households in Ghana owns and operates a farm. Farming is mostly rural, engaging about 83% of rural households (GSS, 2014). Since 2003, successive governments have been committed to the African Union's Maputo declaration to spend 10% of the national budget in support of agriculture. However, smallholder farmers continue to face increasing challenges in their attempts to sustain their livelihoods, as a result of poor soil fertility and unfavourable climatic conditions (Adjei-Nsiah et al., 2018; Fairhurst, 2012).

In recent years the government of Ghana through the Ministry of Food and Agriculture (MoFA) has developed programmes and projects to motivate farmers to adopt improved agricultural technologies. The goal of some of these programmes was to stimulate the expansion of farms and encourage youth to enter into agricultural production to increase crop productivity. For example, the "Planting for Food and Jobs" (PFJ) programme was launched by the president of Ghana in April 2017, to facilitate access to both inputs and output markets thereby creating employment opportunities in the agricultural value chain (MOFA, 2017). The PFJ programme is anchored on the five main pillars to transform Ghanaian agriculture. These pillars include the provision of improved seeds, the supply of fertilizers, the provision of dedicated extension services, a marketing strategy and the use of e-Agriculture. The president of Ghana again in June 2019, launched the "Rearing for Food and Jobs" (RFJ) programme (MOFA, 2019). In this programme, 3,000 cattle and 40,500 sheep and goats will be distributed to farmers in rural areas for breeding. This programme will run simultaneously with the PFJ programme. The RFJ programme will run for four years, from 2019 to 2023. This programme plans to address the seasonal inadequacy of feed, both in quantity and quality, through development of low-tech ways of transforming crop residues into high-quality animal feed.

To achieve this, the government plans to procure and subsidise forage harvesting machines such as balers and other equipment to enable livestock farmers to conserve enough crop residues for dry season feeding of livestock (MOFA, 2019). The nutritional quality of these crop residues is low. While the quality of GLFs is better than that of cereal crop residues, the availability of GLFs is still rather low and probably insufficient to feed the livestock distributed under the RFJ-programme. Therefore, the findings of this thesis could support the implementation of the PFJ- and RFJ-programmes since they show that GLFs are a source of relatively good ruminant feed and their yield can be improved through technologies. The yield increase as a result of P-fertilization and rhizobium inoculants suggests that it will be beneficial for the government to subsidize P fertilizer and ensure supply of inoculants in the country for GL production (Chapter 2). Since these inputs increased both grain and fodder yields for food and feed, respectively, the intervention ultimately reduces the competition for land and intensifies the land-use. Farmers can also conserve crop residues for longer periods if fodder is stored in sacks or under cover (Chapter 4). To achieve this, there should be education of farmers about technologies such as the use of forage balers to reduce the bulkiness of crop residues. Reduction in bulkiness will facilitate transportation and bulk storage of GLFs. In additions farmers should also be educated to store GLFs in sacks or under cover. Furthermore, farmers in our study (Chapter 5) and other smallholders farmers in the world have demonstrated experience and knowledge about nutritional quality of feed and livestock preference for feed (Degen et al., 2010; Mekoya et al., 2008; Tamou et al., 2018; Thorne et al., 1999). Development programmes and projects could benefit from using such knowledge when formulating and implementing interventions.

4.3 Implications for future research

The role of livestock in supplying the increasing demand for food driven by expanding populations and urbanization in developing countries is clear. However, the availability of fodder for ruminants from grazing lands has diminished due to the increased demand for land for crop cultivation and for infrastructural development. Pastoralists (*Fulani*) may be less able to graze their livestock with the reduction of the area of grazing lands. Because of the high demand for crops, the land area used for feed crops should be minimized. As a consequence, the feed base for livestock in SSA including Ghana will continue to depend heavily on crop residues which are generally low-quality feedstuffs. To increase yield and quality of GLFs to provide enough good quality fodder, research programmes targeting breeding and selection of fodder quantity and quality among existing GL varieties and new breeding lines will be beneficial. In such work the fodder nutritional quality traits should be considered by plant breeders as a criterion for developing new varieties. Similar to the haulm, future studies should consider the nutritional value of the grain as human food and how they relate with haulm and yield parameters. Moreover, new varieties should also be bred or selected for their ability to fix N_2 into the soil. Apart from the varietal selection and breeding of new lines, agronomic management practices (e.g. fertilizer application, inoculation, weed and pest control, time of harvesting) may play a major role on yield of both grain and fodder of GLs. As demonstrated in this thesis (Chapter 4) there was a substantial loss in quantity and quality during storage. Therefore, further research should aim to establish proper feeding systems considering storage location, storage method and storage duration in ruminant production in northern Ghana. Finally, the results presented in this thesis support the use of knowledge of farmers and other stakeholders in future multi-stakeholder projects and programmes where farmers' and stakeholders' opinions are taken into considerations. We have shown that farmers in our study have valuable knowledge about their animals and environment which is challenging to assess by researchers in manners other than through farmers' participation. Involving farmers to co-design projects and programmes also ensures adoption of the best technologies and practices to improve their productivity and livelihoods (Ronner et al., 2019). The recommendations made in this thesis represent the **d**esign section of the DEED cycle since they were made with inputs from farmers and other stakeholders in the research process.

5.0 Key conclusions

- GLFs are important feed resources in smallholder MCL systems, especially in the dry season. The variation in their use as feed in the farming systems is related to the importance of livestock in the farming system. GLF is a more important source of feed if livestock is more important in the farming system.
- Application of agronomic technologies such as rhizobium inoculation and P-fertilization improve the yield of both grain and fodder but not the nutritional quality of the fodder.
- The methods of storing GLFs affects their quantity and nutritional quality during storage. Storage in sacks and to a lesser extent, storage in rooms (indoor) reduces the loss of DM and nutritive quality during storage compared to tying in bundles with rope and outdoor storage.

- There was no detectable level of aflatoxin in the groundnut fodder samples during storage. This is a positive indication that GLFs can be stored in dry conditions with minimal risk of aflatoxin contamination.
- There was a complementarity among farmers' perception, sheep preference and laboratory evaluation of the nutritional quality of GLFs. Farmers possessed local knowledge about nutritional quality of the feed resources they use to feed their animals.

Summary

Mixed crop-livestock (MCL) farming is common in West Africa: it is practised by about two-thirds of the farmers and produces about 70% of the food. In MCL systems, livestock support crop production through the supply of manure and draught power, whereas crops supply crop residues as a major feed for livestock. In West Africa, feed scarcity is a major challenge for livestock production, especially during the dry season when grass quality and quantity on grazing lands are inadequate. In northern Ghana, as in other West African countries, population pressure is affecting the development of farming systems. The pressure on land calls for the intensification of farming systems as a way of enhancing productivity. Grain legume crops are often introduced into the farming system as a route to intensification. Grain legumes are important crops in the MCL systems because they provide food and cash for humans, fodder for animals and improve soil fertility through biological nitrogen fixation. The residues of grain legumes, also known as grain legume fodders (GLFs), have better nutritional quality than cereal residues, such as maize and rice straw. Besides their function as livestock feed, GLFs supply fuel, construction material and mulch for soil improvement. However, knowledge about factors that drive the diversity of use of GLFs in different farming systems in West Africa is lacking. Also, the grain and fodder yields of grain legumes remain low across West Africa due to poor soil fertility and inadequate input use. The main objective of this PhD thesis was to understand the roles of grain legume fodders in mixed crop-livestock systems and identify options to improve their quality and utilisation by smallholders in northern Ghana. To address this objective of the study, we adopted a multi-disciplinary research process to study four sub-objectives. These sub-objectives were addressed in Chapters 2, 3, 4 and 5.

In Chapter 2, we aimed to assess the variation in the use of GLFs and to identify potential drivers for their use in MCL systems in northern Ghana. The variation between MCL systems was studied by comparing three regions with different population pressure and agro-ecological conditions, and consequently, different farming systems. Through focus group discussions and household interviews, we studied the use of GLFs in MCL systems in the Northern region (NR), the Upper East region (UER), and the Upper West region (UWR) of northern Ghana. In UER, most of the GLFs (87%) was brought home and stall-fed, whereas in UWR GLFs were for a considerable extent (61%), left on the field and used for mulching. In NR, both stall-feeding and grazing of GLFs was important. Compared to UWR and NR, UER had a high population density, low potential

for crop production and low level of mechanisation of crop production, which all are explanations for the relatively high importance of livestock in the farming systems. We conclude that with increasing importance of livestock in intensified systems, GLFs become more important and more valuable for feeding, especially in the dry season. The consequence of increased use of GLFs in intensifying MCL systems is that GLFs turn from being a communal resource that can be freely grazed during the dry season into a private resource with restrictions on use.

Chapter 3 evaluated the effects of rhizobium inoculation and phosphorus (P) fertilization on grain and fodder yield and fodder quality of the major grain legumes (cowpea, soybean and groundnut) in two agro-ecological zones of northern Ghana. This was done through field agronomic and laboratory studies. The findings of Chapter 3 indicate the possibility of improving both grain and fodder yields of grain legumes simultaneously through the application of P and rhizobium inoculants. In this chapter, in cowpea, for example, application of inoculation alone increased grain yield by 44%, P-fertilizer alone increased grain yield by 102% while the combination of P and inoculation increased grain yield by 123% compared to the control treatment where no input was applied. The positive correlation between grain yield and fodder yield in the current study implies that agronomic interventions may contribute to increasing availability of fodder for livestock feeding without a reduction in grain yield. Also the nutritive quality of GLFs was not affected by these interventions.

Chapter 4 evaluated the effects of storage conditions on dry matter recovery and the nutritional quality of GLFs during storage. In this chapter we also tracked the development of aflatoxins in groundnut fodder during storage. GLFs of cowpea, groundnut and soybean were stored separately in three locations (rooftop, room and tree-fork) and with two packaging types (polythene sacks or tied with ropes) for 120 days. Stored GLFs were evaluated for loss in dry matter and nutritional quality at day 0, 30, 60, 90, and 120. We found that dry matter loss during storage for 120 days was on average 24% across all storage conditions, 35% for the worst condition (tied in bundles and stored on roofs or tree-forks) and 14% for the best condition (sacks and in rooms). During storage, the CP content and OMD decreased, and the content of cell wall components increased. The reduction of nutritional quality was lowest when GLFs were stored in sacks. Storage in sacks and to a lesser extent, storage in rooms (indoor) may reduce the loss of DM and nutritive quality during storage compared to tying in bundles with rope and outdoor storage. The absence of aflatoxin in the groundnut fodder samples indicated that there is a minimal risk of aflatoxin development when stored under dry conditions as in our study.

In Chapter 5, we further assessed the nutritional quality of stored GLFs from Chapter 4 using four different methods: farmers' perception, sheep preference, leaf-to-stem ratio, and laboratory analysis of organic matter digestibility, crude protein content, neutral detergent fibre and acid detergent fibre. We also determined correlations among these variables. Selected farmers scored the perceived quality of GLFs on a scale of 1 to 10 (1 = bad and 10 = good) based on physical characteristics. Sheep preference was assessed by a cafeteria feeding trial based on the rate of dry matter intake of GLFs by a flock of 12 sheep during a 14 hr period. leaf-stem ratio was determined based on the mass of the botanical fractions, i.e. leaf (leaf blade only) and stem (stem and petioles) samples separated carefully by the hand. Laboratory analysis was done by near infra-red spectroscopy (NIRS). Results showed that all quality assessment methods successfully discriminated GLF quality between crops. Only farmers and sheep could distinguish quality differences among storage conditions, whereas laboratory assessment methods could not. We reasoned that these findings could be due to that fact that farmers use sensory criteria (leafiness, colour (vision), smell, texture) to evaluate feed quality and that laboratory assessment methods do not assess these directly. These findings show that farmers are knowledgeable in predicting what their sheep prefer to consume and how to evaluate the quality of GLFs through storage.

Finally in Chapter 6, I integrated and reflected on implications of the findings of the previous chapters for sustainable intensification, policy and future research. Major uses of GLFs are ruminant feed (stall feeding and grazing) and mulch. Minor uses of GLFs were for fuel, compost and for sale to generate income. The overarching driver for the different uses of GLFs was the importance of livestock in the farming system. In the future, the importance of livestock will increase in the farming systems because of the increasing demand for animal-source food leading to increase in number of livestock and a higher livestock productivity. In Ghana for example, the government of Ghana recently launched the "Rearing for Food and Jobs" (RFJ) programme to increase livestock production for food security while creating jobs for the citizens. As a result, the livestock production systems in Ghana will need to intensify in a sustainable way to which conserving feed for stall-feeding may contribute. The smallholders currently depend heavily on crop residues, especially GLFs, which are generally low-quality feedstuffs. To increase yield and quality of GLFs to provide enough good quality fodder,

research programmes should target breeding and selection for fodder quantity and quality in existing grain legume varieties and new breeding lines. In such work the fodder nutritional quality traits should be considered by plant breeders as a criterion for developing new varieties. In addition, there should be further research work done on the storage of GLFs to maintain their quantity and nutritional quality for a longer time.

References

Abaidoo, R., Dare, M.O., Killani, S., Opoku, A., 2016. Evaluation of early maturing cowpea (Vigna unguiculata) germplasm for variation in phosphorus use efficiency and biological nitrogen fixation potential with indigenous rhizobial populations. J. Agric. Sci. 155, 102–116.

Abdou, N., Nsahlai, I.V., Chimonyo, M., 2011. Effects of groundnut haulms supplementation on millet stover intake, digestibility and growth performance of lambs. Anim. Feed Sci. Technol. 169, 176–184. https://doi.org/10.1016/j.anifeedsci.2011.07.002

Adjei-Nsiah, S., 2012. Role of Pigeonpea Cultivation on Soil Fertility and Farming System Sustainability in Ghana. Int. J. Agron. 2012, 1–8. https://doi.org/10.1155/2012/702506

Adjei-Nsiah, S., Alabi, B.U., Ahiakpa, J.K., Kanampiu, F., 2018. Response of grain legumes to phosphorus application in the Guinea savanna agro-ecological zones of Ghana. Agron. J. 110, 1089–1096. https://doi.org/10.2134/agronj2017.11.0667

Adjei-Nsiah, S., Ndungu, S.M., Thuita, M., Kanampiu, F., 2020. Response of different soybean genotypes to phosphorus and Rhizobium inoculation in the Southern Guinea Savanna agro-ecological zone of Ghana. Submitted.

Akakpo, D.B., Boer, I.J.M. de, Adjei-Nsiah, S., Duncan, A.J., Giller, K.E., Oosting, S.J., 2020a. Evaluating the effects of storage conditions on dry matter loss and nutritional quality of grain legume fodders in West Africa. Anim. Feed Sci. Technol. https://doi.org/10.1016/j.anifeedsci.2020.114419.

Akakpo, D.B., Oosting, S.J., Adjei-Nsiah, S., Duncan, A.J., de Boer, I.J.M., Giller, K.E., 2020b. Do inoculation and phosphorus fertilization of grain legumes improve yield and fodder quality? Evidence from the Guinea Savanna of Ghana. Expl. Agric (Submitted).

Akinola, A.A., Abdoulaye, T., Valbuena, D., Erenstein, O., Haileslasie, A., Germaine, I., Shehu, M., Ayedun, B., 2016. Determinants of crop residue use along an intensification gradient in West Africa's Savannah zones. Tropicultura 34, 396–410.

Amankwah, K., 2013. Enhancing food security in Northern Ghana through smallholder small ruminant production and marketing. Thesis. Wageningen University, Wageningen, The Netherlands.

Amankwah, K., Klerkx, L., Oosting, S.J., Sakyi-Dawson, O., Van Der Zijpp, A.J., Millar, D., 2012. Diagnosing constraints to market participation of small ruminant producers in northern Ghana: An innovation systems analysis. NJAS - Wageningen J. Life Sci. 60–63, 37–47. https://doi.org/10.1016/j.njas.2012.06.002

Amole, T.A., Ayantunde, A.A., Duncan, A.J., 2014. Assessment of existing and potential feed resources to improve livestock productivity in resources to improve livestock. Int. Livest. Res. Inst. 13. https://doi.org/10.13140/RG.2.1.1569.9683

Amole, T.A., Ayantunde, A.A., 2016. Assessment of existing and potential feed resources for improving livestock productivity in Niger. Int. J. Agric. Res. 11, 40–55. https://doi.org/10.3923/ijar.2016.40.55

Anele, U.Y., Arigbede, O.M., Südekum, K.H., Ike, K.A., Oni, A.O., Olanite, J.A., Amole, G.A., Dele, P.A., Jolaosho, A.O., 2010. Effects of processed cowpea (Vigna unguiculata L. Walp) haulms as a feed supplement on voluntary intake, utilization and blood profile of West African dwarf sheep fed a basal diet of Pennisetum purpureum in the dry season. Anim. Feed Sci. Technol. 159, 10–17. https://doi.org/10.1016/ j.anifeedsci.2010.05.004

Ansah, T., Algma, H.A., Dei, H.K., 2016. Variety and phosphate fertilizer dose effect on nutrient composition, in vitro digestibility and feeding value of cowpea haulm. J. Anim. Sci. Technol. 58, 19.

AOAC, 1990. Official Methods of Analysis, 14th edn. Association of Official Analytical Chemists, Washington, DC, USA.

Ayantunde, A.A., Blummel, M., Grings, E., Duncan, A.J., 2014. Price and quality of livestock feeds in suburban markets of West Africa's Sahel: Case study from Bamako, Mali. Rev. d'élevage médecine vétérinaire des pays Trop. 67, 13–21. https://doi.org/10.19182/ remvt.10155

Ayantunde, A.A., Delfosse, P., Fernandez-Rivera, S., Gerard, B., Dan-Gomma, A., 2007. Supplementation with groundnut haulms for sheep fattening in the West African Sahel. Trop. Anim. Health Prod. 39, 207–216. https://doi.org/10.1007/s11250-007-9009-1

Baudron, F., Jaleta, M., Okitoi, O., Tegegn, A., 2014. Conservation agriculture in African mixed crop-livestock systems: Expanding the niche. Agric. Ecosyst. Environ. 187, 171–182. https://doi.org/10.1016/j.agee.2013.08.020

Benson, T., Fermont, A., 2011. Estimating Yield of Food Cropos Grown by Smallholder Farmers: A review in the Uganda context. IFPRI Discuss. Pap. 68.

Blount, A.R.S., Wright, D.L., Sprenkel, R.K., Hewitt, T.D., Myer, R.O., 2006. Forage soybeans for grazing, hay and silage. University of Florida. IFAS Extension.

Blümmel, M., Tui, S.H.-K., Valbuena, D., Duncan, A.J., Herrero, M., 2013. Biomass in crop-livestock systems in the context of the livestock revolution. Sci. Chang. planétaires/Sécheresse 24, 330–339.

Blümmel, M., Vishala, A., Ravi, D., Prasad, K., Ramakrishna Reddy, C., Seetharama, N., 2010. Multi-environmental investigations of food-feed trait relationships in Kharif and Rabi sorghum (Sorghum bicolor (L) Moench) over several years of cultivars testing in India. Anim. Nutr. Feed Technol. S 10, 11–21.

Blümmel, M., Zerbini, E., Reddy, B.V.S., Hash, C.T., Bidinger, F., Ravi, D., 2003. Improving the production and utilization of sorghum and pearl millet as livestock feed: Methodological problems and possible solutions, in: Field Crops Research. pp. 123–142. https://doi.org/10.1016/S0378-4290(03)00145-X

Boddey, R.M., Fosu, M., Atakora, W.K., Miranda, C.H.B., Boddey, L.H., Guimaraes, A.P., Ahiabor, B.D.K., 2017. Cowpea (Vigna unguiculata) crops in Africa can respond to inoculation with rhizobium. Exp. Agric. 53, 578–587.

Carletto, C., Gourlay, S., Winters, P., 2015. From guesstimates to GPStimates: Land area measurement and implications for agricultural analysis. J. Afr. Econ. 24, 593–628. https://doi.org/10.1093/jae/ejv011

Carletto, C., Savastano, S., Zezza, A., 2013. Fact or artifact: The impact of measurement errors on the farm size-productivity relationship. J. Dev. Econ. 103, 254–261. https://doi.org/10.1016/j.jdeveco.2013.03.004

Coblentz, W.K., Coffey, K.P., Young, A.N., Bertram, M.G., 2013. Storage characteristics, nutritive value, energy content, and in vivo digestibility of moist, large rectangular bales of alfalfa-orchardgrass hay treated with a propionic acid-based preservative. J. Dairy Sci. 96, 2521–2535. https://doi.org/10.3168/jds.2012-6145

Cole, R.J., Dorner, J.W., 1994. Extraction of aflatoxins from naturally contaminated peanuts with different solvents and solvent/peanut ratios. J. AOAC Int. 77, 1509–1511.

Coleman, S.W., Moore, J.E., 2003. Feed quality and animal performance. F. Crop. Res. 84, 17–29. https://doi.org/10.1016/S0378-4290(03)00138-2

Dada, S.A.O., Adeneye, J.A., Akinsoyinu, A.O., Smith, J.W., Dashiell, K.E., 1999. Performance of sheep fed soybean stover and cassava crumb based diets. Small Rumin. Res. 31, 229–238. https://doi.org/10.1016/S0921-4488(98)00143-6

Degen, A.A., El-Meccawi, S., Kam, M., 2010. Cafeteria trials to determine relative preference of six desert trees and shrubs by sheep and goats. Livest. Sci. 132, 19–25. https://doi.org/10.1016/j.livsci.2010.04.016

Degen, A.A., Pandey, L.N., Kam, M., Pandey, S.B., Upreti, C.R., Osti, N.P., 2010. Goat production and fodder leaves offered by local villagers in the mid-hills of Nepal. Hum. Ecol. 38, 625–637. https://doi.org/10.1007/s10745-010-9342-2

Diao, X., Cossar, F., Houssou, N., Kolavalli, S., 2014. Mechanization in Ghana: Emerging demand, and the search for alternative supply models. Food Policy 48, 168–181. https://doi.org/10.1016/j.foodpol.2014.05.013

Dikmen, S., Ustuner, H., Turkmen, I.I., Ogan, M., 2009. Fattening performance and feed source preference of native Awassi lambs fed individually in a cafeteria feeding system. Trop. Anim. Health Prod. 41, 485–491. https://doi.org/10.1007/s11250-008-9212-8

Doumbia, D., Van Paassen, A., Oosting, S.J., Van Der Zijpp, A.J., 2012. Livestock in the rice-based economy of Office du Niger: The development potential for increased crop-livestock integration through multi-actor processes. NJAS - Wageningen J. Life Sci. https://doi.org/10.1016/j.njas.2012.07.002

Duncan, A., York, L., Lukuyu, B., Samaddar, A., Stür, W., 2012. Feed Assessment Tool (FEAST): A systematic method for assessing local feed resource availability and use with a view to designing intervention strategies aimed at optimizing feed utilization. Questionnaire for Facilitators.

Duncan, A.J., Bachewe, F., Mekonnen, K., Valbuena, D., Rachier, G., Lule, D., Bahta, M., Erenstein, O., 2016. Crop residue allocation to livestock feed, soil improvement and other uses along a productivity gradient in Eastern Africa. Agric. Ecosyst. Environ. https://doi.org/10.1016/j.agee.2016.05.011

Ekeleme, F., Kwari, J.D., Omoigui, L.O., Chikoye, D., 2011. Phosphorus effects on growth and yield of groundnut varieties in the tropical savannas of northeast Nigeria. J. Trop. Agric. 49, 25–30.

Fairhurst, T., 2012. Handbook for integrated soil fertility management.

FAO, 2014. Crop residues and agro-industrial by-products in West Africa - Situation and way forward for livestock production. Rome. https://doi.org/10.2307/302397

FAOSTAT, 2019. Statistical database: Food and Agriculture Organization of the United Nations. Rome, Italy.

FAOSTAT, 2019. Statistical database: Food and Agriculture Organization of the United Nations. Rome, Italy.

Farid, M.F.A., Shawket, S.M., Hassan, N.I., 2010. Diet selection , feed intake capacity and performance of growing female camels : Effects of type of roughage and level of concentrates offered. J. Am. Sci. 6, 317–326.

Fekadu, D., Bediye, S., Sileshi, Z., 2010. Characterizing and predicting chemical composition and in vitro digestibility of crop residue using near infrared reflectance spectroscopy (NIRS). Vitr. 131, 51.5-58.1.

Fekede, F., Shiv, P., Getnet, A., Seyoum, B., Getu, K., Aemiro, K., Gezahegne, K., 2014. Dynamics in nutritional characteristics of natural pasture hay as affected by harvesting stage, storage method and storage duration in the cooler tropical highlands, African Journal of Agricultural Research. https://doi.org/10.5897/ajar2014.8652

Feyissa, F., Prasad, S., Assefa, G., Bediye, S., Kitaw, G., Kehaliew, A., Kebede, G., 2014. Dynamics in nutritional characteristics of natural pasture hay as affected by harvesting stage, storage method and storage duration in the cooler tropical highlands. African J. Agric. Res. Full Length Res. Pap. Afr. J. Agric. Res 9, 3233–3244. https://doi.org/10.5897/AJAR2014.8652

Franke, A.C., van den Brand, G.J., Vanlauwe, B., Giller, K.E., 2018. Sustainable intensification through rotations with grain legumes in Sub-Saharan Africa: A review. Agric. Ecosyst. Environ. 261, 172–185. https://doi.org/10.1016/j.agee.2017.09.029

Gallo, A., Giuberti, G., Frisvad, J.C., Bertuzzi, T., Nielsen, K.F., 2015. Review on mycotoxin issues in ruminants: Occurrence in forages, effects of mycotoxin ingestion on health status and animal performance and practical strategies to counteract their negative effects. Toxins (Basel). https://doi.org/10.3390/toxins7083057

Gerber, P., Vellinga, T., Opio, C., Steinfeld, H., 2011. Productivity gains and greenhouse gas emissions intensity in dairy systems. Livest. Sci. 139, 100–108. https://doi.org/10.1016/j.livsci.2011.03.012

Ghana Statistical Service, 2012. 2010 Population and housing census final results, National analytical report. URL www.statsghana.gov.gh/pop_html

Giller, K.E., 2000. Translating science into action for agricultural development in the tropics: an exemple from decomposition studies. Appl. Soil Ecol. 14, 1–3.

Giller, K.E., 2001. Nitrogen fixation in tropical cropping systems. CABI, Walingford, UK.

Gomez, K.A., Gomez, A.A., 1984. Statistical procedures for agricultural research, Second. ed. John Wiley & Sons, New York, USA.

Grings, E.E., Tarawali, S.A., Blummel, M., Musa, A., Fatokun, C.A., Hearne, S., Boukar, O., 2012. Cowpea in evolving livestock systems, in: Innovative Research along the Cowpea Value Chain: Proceedings of the Fifth World Cowpea Conference on Improving Livelihoods in the Cowpea Value Chain through Advancement in Science, Held in Saly, Senegal, 27 September -1 October 2010. pp. 322–333.

GSS, 2012. 2010 Population and housing census final results, National analytical report. Accra, Ghana.

GSS, 2014. Ghana Living Standards Survey Round 6. Accra, Ghana.

Guerrero, J.N., Calderón-Cortés, J.F., Montaño-Gómez, M.F., González-Vizcarra, V., López-Soto, M.A., 2010. Effect of storage system and tarpaulin color on nutritional quality and digestibility of stored lucerne hay in the irrigated Sonoran Desert. Anim. Feed Sci. Technol. 162, 28–36. https://doi.org/10.1016/j.anifeedsci.2010.08.015

Herrero, M., Thornton, P.K., Notenbaert, A.M., Wood, S., Msangi, S., Freeman, H.A., Bossio, D., Dixon, J., Peters, M., Van De Steeg, J., Lynam, J., Rao, P., MacMillan, S., Gerard, B., McDermott, J., Seré, C., Rosegrant, M., 2010. Smart investments in sustainable food production: Revisiting mixed crop-livestock systems. Science (80). 327, 822–825. https://doi.org/10.1126/science.1183725

IBM, C., 2017. Released 2017. IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY.

IITA, 1981. Analytical Services Laboratory Manual. International Institute of Tropical Agriculture, Ibadan, Nigeria.

Kermah, M, Franke, A.C., Adjei-Nsiah, S., Ahiabor, B.D.K., Abaidoo, R.C., Giller, K.E., 2017. N2-fixation and N contribution by grain legumes under different soil fertility status and cropping systems in the Guinea savanna of northern Ghana. Agric. Ecosyst. Environ.

Kermah, M., Franke, A.C., Adjei-Nsiah, S., Ahiabor, B.D.K., Abaidoo, R.C., Giller, K.E., 2017. Maize-grain legume intercropping for enhanced resource use efficiency and crop productivity in the Guinea savanna of northern Ghana. F. Crop. Res. 213, 38–50.

Kermah, M., Franke, A.C., Ahiabor, B.D.K., Adjei-Nsiah, S., Abaidoo, R.C., Giller, K.E., 2019. Legume–maize rotation or relay? Options for ecological intensification of smallholder farms in the Guinea Savanna of northern Ghana. Exp. Agric. 55, 1–19. https://doi.org/10.1017/S0014479718000273

Konlan, S.P., Ayantunde, A.A., Addah, W., Dei, H.K., Avornyo, F.K., 2016. Evaluation of Feed Resource Availability for Ruminant Production in Northern Ghana. Int. J. Livest. Res. 6, 39–59.

Konlan, S.P., Ayantunde, A.A., Addah, W., Dei, H.K., Karbo, N., 2018. Emerging feed markets for ruminant production in urban and peri-urban areas of Northern Ghana. Trop. Anim. Health Prod. 50, 169–176. https://doi.org/10.1007/s11250-017-1418-1

Kuivanen, K.S., Alvarez, S., Michalscheck, M., Adjei-Nsiah, S., Descheemaeker, K., Mellon-Bedi, S., Groot, J.C.J., 2016. Characterising the diversity of smallholder farming systems and their constraints and opportunities for innovation: A case study from the Northern Region, Ghana. NJAS - Wageningen J. Life Sci. 78, 153–166. https://doi.org/10.1016/j.njas.2016.04.003

Kyei-Boahen, S., Savala, C.E.N., Chikoye, D., Abaidoo, R., 2017. Growth and Yield Responses of Cowpea to Inoculation and Phosphorus Fertilization in Different Environments. Front. Plant Sci. 8, 1–13. https://doi.org/10.3389/fpls.2017.00646

Larbi, A., Dung, D.D., Olorunju, P.E., Smith, J.W., Tanko, R.J., Muhammad, I.R., Adekunle, I.O., 1999. Groundnut (Arachis hypogaea) for food and fodder in crop-livestock systems: Forage and seed yields, chemical composition and rumen degradation of leaf and stem fractions of 38 cultivars. Anim. Feed Sci. Technol. 77, 33–47. https://doi.org/10.1016/S0377-8401(98)00238-7

Larbi, A., Jabbar, M.A., Orok, E.J., Idiong, N.B., Cobbina, J., 1993. Alchornea cordifolia, a promising indigenous browse species adapted to acid soils in southeastern Nigeria for integrated crop-livestock agroforestry production systems. Agrofor. Syst. 22, 33–41. https://doi.org/10.1007/BF00707468

Lemus, R., 2009. Hay storage : dry matter losses and quality changes. Mississippi State Univ. Ext. Serv. 2540.

Lemus, R., Brummer, E.C., Moore, K.J., Molstad, N.E., Burras, C.L., Barker, M.F., 2002. Biomass yield and quality of 20 switchgrass populations in southern Iowa, USA. Biomass and Bioenergy 23, 433–442. https://doi.org/10.1016/S0961-9534(02)00073-9

Liebman, M., Dyck, E., 1993. Crop Rotation and Intercropping Strategies for Weed Management. Ecol. Appl. 3, 92–122. https://doi.org/10.2307/1941795

Livingston, G., Schonberger, S., Delaney, S., 2011. Sub-Saharan Africa : The state of smallholders in agriculture, in: IFAD Conference on New Directions for Smallholder Agriculture. pp. 1–36.

López, S., Davies, D.R., Giráldez, F.J., Dhanoa, M.S., Dijkstra, J., France, J., 2005. Assessment of nutritive value of cereal and legume straws based on chemical composition and in vitro digestibility. J. Sci. Food Agric. 85, 1550–1557. https://doi.org/10.1002/jsfa.2136

Maheri-Sis, N., Abdollahi-Ziveh, B., Salamatdoustnobar, R., Ahmadzadeh, A., Aghajanzadeh-Golshani, A., Mohebbizadeh, M., 2011. Determining nutritive value of soybean straw for ruminants using nylon bags technique. Pak. J. Nutr 10, 838–841.

Meier, J.S., Kreuzer, M., Marquardt, S., 2012. Design and methodology of choice feeding experiments with ruminant livestock. Appl. Anim. Behav. Sci. 140, 105–120. https://doi.org/10.1016/j.applanim.2012.04.008

Mekoya, A., Oosting, S.J., Fernandez-Rivera, S., Van der Zijpp, A.J., 2008. Multipurpose fodder trees in the Ethiopian highlands: Farmers' preference and relationship of indigenous knowledge of feed value with laboratory indicators. Agric. Syst. 96, 184–194. https://doi.org/10.1016/j.agsy.2007.08.001

Menke, K.H., Steingass, H., 1988. Estimation of the digestibility and metabolizable energy content of ruminant feedstuffs from the gas production when they are incubated with rumen liquor in vitro. Anim. Res. Dev. 28, 7–55.

Mertens, D.R., 2009. Impact of NDF content and digestibility on dairy cow performance. WCDS Adv. Dairy Technol. 21, 191–201.

Migose, S.A., Bebe, B.O., de Boer, I.J.M., Oosting, S.J., 2018. Influence of distance to urban markets on smallholder dairy farming systems in Kenya. Trop. Anim. Health Prod. 50, 1417–1426. https://doi.org/10.1007/s11250-018-1575-x

MoFA, 2016. Agriculture in Ghana, facts and figures. Ministry of Food and Agriculture, Statistics, Research and Information Directorate (SRID). Accra, Ghana.

MOFA, 2017. Agriculture in Ghana: Facts and figures. Accra, Ghana.

Nayan, N., Sonnenberg, A.S.M., Hendriks, W.H., Cone, J.W., 2018. Screening of white-rot fungi for bioprocessing of wheat straw into ruminant feed. J. Appl. Microbiol. 125, 468–479. https://doi.org/10.1111/jam.13894

Nkegbe, P.K., Abu, B.M., Issahaku, H., 2017. Food security in the Savannah Accelerated Development Authority Zone of Ghana: An ordered probit with household hunger scale approach. Agric. Food Secur. 6, 35. https://doi.org/10.1186/s40066-017-0111-y

Oosting, S.J., 1993. Wheat straw as ruminant feed: Effect of supplementation and ammonia treatment. PhD thesis, Wageningen University, The Netherlands.

Oosting, S.J., Udo, H.M.J., Viets, T.C., 2014. Development of livestock production in the tropics: farm and farmers' perspectives. Animal 8, 1238–1248. https://doi.org/10.1017/s1751731114000548

Oteng-Frimpong, R., Konlan, S.P., Denwar, N.N., 2017. Evaluation of Selected Groundnut (Arachis hypogaea L.) Lines for Yield and Haulm Nutritive Quality Traits. Int. J. Agron. 2017, 1–9. https://doi.org/10.1155/2017/7479309

Owen, E., Jayasuriya, M.C.N., 1989. Use of crop residues as animal feeds in developing countries. Res. Dev. Agric. 6, 129–138.

Pandey, L.N., Kam, M., Pandey, S.B., Upreti, C.R., 2009. Indigenous knowledge of fodder tree selectivity by local goats in the mid-hills of Nepal. J. Enterprising Communities People Places Glob. Econ. 3, 241–255. https://doi.org/10.1108/17506200910982000

Piepho, H.P., Richter, C., Spilke, J., Hartung, K., Kunick, A., Thöle, H., 2011. Statistical aspects of on-farm experimentation. Crop Pasture Sci. 62, 721–735. https://doi.org/10.1071/CP11175

Prasad, K., Khan, A.A., Vellaikumar, S., Devulapalli, R., Ramakrishna Reddy Ch, N.S.N., Blümmel, M., 2010. Observations on livestock productivity in sheep fed exclusively on haulms from ten different genotypes of groundnut. Anim. Nutr. Feed Technol. S 10, 121–126.

Preston, T.R., 2007. Better utilization of crop residues and by-products in animal feeding : research guidelines 2 . A practical manual for research workers. FAO, Rome, Italy.

Reddy, B.V.S., Reddy, P.S., Bidinger, F., Blümmel, M., 2003. Crop management factors influencing yield and quality of crop residues. F. Crop. Res. 84, 57–77. https://doi.org/10.1016/S0378-4290(03)00141-2

Redfearn, D., Zhang, H., Caddel, J., 2004. Forage Quality Interpretations, Division of Agricultural Sciences and Natural Resources, Oklahoma State University. Oklahoma.

Rinne, M., Jaakkola, S., Huhtanen, P., 1997. Grass maturity effects on cattle fed silage-based diets. 1. Organic matter digestion, rumen fermentation and nitrogen utilization. Anim. Feed Sci. Technol. 67, 1–17. https://doi.org/10.1016/S0377-8401(96)01141-8

Ronner, E., Descheemaeker, K., Almekinders, C., Ebanyat, P., Giller, K.E., 2019. Co-design of improved climbing bean production practices for smallholder farmers in the highlands of Uganda. Agric. Syst. 175, 1–12. https://doi.org/10.1016/j.agsy.2019.05.003

Ronner, E., Franke, A.C., Vanlauwe, B., Dianda, M., Edeh, E., Ukem, B., Bala, A., Van Heerwaarden, J., Giller, K.E., 2016. Understanding variability in soybean yield and response to P-fertilizer and rhizobium inoculants on farmers' fields in northern Nigeria. F. Crop. Res. 186, 133–145.

Rurangwa, E., Vanlauwe, B., Giller, K.E., 2018. Benefits of inoculation, P fertilizer and manure on yields of common bean and soybean also increase yield of subsequent maize. Agric. Ecosyst. Environ. 261, 219–229. https://doi.org/10.1016/j.agee.2017.08.015

Rusinamhodzi, L., Corbeels, M., Giller, K.E., 2016. Diversity in crop residue management across an intensification gradient in southern Africa: System dynamics and crop productivity. F. Crop. Res. 185, 79–88. https://doi.org/10.1016/j.fcr.2015.10.007

Samireddypalle, A., Boukar, O., Grings, E., Fatokun, C.A., Kodukula, P., Devulapalli, R., Okike, I., Blümmel, M., 2017. Cowpea and groundnut haulms fodder trading and its lessons for multidimensional cowpea improvement for mixed crop livestock systems in West Africa. Front. Plant Sci. 08, 30. https://doi.org/10.3389/fpls.2017.00030

Savadogo, M., Zemmelink, G., Nianogo, A.J., 2000. Effect of selective consumption on voluntary intake and digestibility of sorghum (Sorghum bicolor L. Moench) stover, cowpea (Vigna unguiculata L. Walp.) and groundnut (Arachis hypogaea L.) haulms by sheep. Anim. Feed Sci. Technol. 84, 265–277. https://doi.org/10.1016/S0377-8401(00)00115-2

Savadogo, M., Zemmelink, G., Van Keulen, H., Nianogo, A.J., 1999. Contribution of crop residues to ruminant feeding in different agroecological zones of Burkina Faso. Rev. Elev. Méd. vét. Pays trop. 52, 255–262.

Schiere, J.B., Joshi, A.L., Seetharam, A., Oosting, S.J., Goodchild, A. V., Deinum, B., Van Keulen, H., 2004. Grain and straw for whole plant value: Implications for crop management and genetic improvement strategies. Exp. Agric. 40, 277–294. https://doi.org/10.1017/S0014479704001814

Schiere, J.B., Joshi, A.L., Seetharam, A., Oosting, S.J., Goodchild, A. V., Deinum, B., Van Keulen, H., 2004. Grain and straw for whole plant value: Implications for crop management and genetic improvement strategies. Exp. Agric. 40, 277–294. https://doi.org/10.1017/S0014479704001814

Searle, S.R., Casella, G., McCulloch, C.E., 1992. Variance Component. John Wiley & Sons., New York, USA. http://dx.doi.org/10.1002/9780470316856

Shayo, C.M., Udén, P., 1999. Nutritional uniformity of neutral detergent solubles in some tropical browse leaf and pod diets. Anim. Feed Sci. Technol. 82, 63–73. https://doi.org/10.1016/S0377-8401(99)00098-X

Shinners, K.J., Boettcher, G.C., Muck, R.E., Weimer, P.J., Casler, M.D., 2010. Harvest and storage of two perennial grasses as biomass feedstocks. Trans. Asabe 53, 359–370.

Singh, A., Baoule, A.L., Ahmed, H.G., Dikko, A.U., Aliyu, U., Sokoto, M.B., Alhassan, J., Musa, M., Haliru, B., 2011. Influence of phosphorus on the performance of cowpea (Vigna unguiculata (L) Walp.) varieties in the Sudan savanna of Nigeria. Agric. Sci. 2, 313.

Smith, J., Sones, K., Grace, D., MacMillan, S., Tarawali, S. and Herrero, M., 2013. Beyond milk, meat, and eggs: Role of livestock in food and nutrition security. Animal Frontiers, 3(1), pp.6-13.

Solomon, T., Pant, L.M., Angaw, T., 2012. Effects of Inoculation by Bradyrhizobium japonicum Strains on Nodulation, Nitrogen Fixation, and Yield of Soybean (Glycine max L. Merill) Varieties on Nitisols of Bako, Western Ethiopia. ISRN Agron. 2012, 1–8. https://doi.org/10.5402/2012/261475

Stubbs, T.L., Kennedy, A.C., Fortuna, A.M., 2010. Using NIRS to predict fiber and nutrient content of Dryland cereal cultivars. J. Agric. Food Chem. 58, 398–403. https://doi.org/10.1021/jf9025844

Talore, D.G., 2015. Evaluation of major feed resources in crop-livestock mixed farming systems, southern Ethiopia: Indigenous knowledge versus laboratory analysis results. J. Agric. Rural Dev. Trop. Subtrop. 116, 157–166.

Tamou, C., De Boer, I.J.M., Ripoll-Bosch, R., Oosting, S.J., 2018a. Traditional ecological knowledge underlying herding decisions of pastoralists. Animal 12, 831–843. https://doi.org/10.1017/S1751731117002130

Tamou, C., Ripoll-Bosch, R., de Boer, I.J.M., Oosting, S.J., 2018b. Pastoralists in a changing environment: The competition for grazing land in and around the W Biosphere Reserve, Benin Republic. Ambio 47, 340–354. https://doi.org/10.1007/s13280-017-0942-6

Thorne, P.J., Subba, D.B., Walker, D.H., Thapa, B., Wood, C.D., Sinclair, F.L., 1999. The basis of indigenous knowledge of tree fodder quality and its implications for improving the use of tree fodder in developing countries. Anim. Feed Sci. Technol. 81, 119–131. https://doi.org/10.1016/S0377-8401(99)00048-6

Thorne, P.J., Subba, D.B., Walker, D.H., Thapa, B., Wood, C.D., Sinclair, F.L., 1999. The basis of indigenous knowledge of tree fodder quality and its implications for improving the use of tree fodder in developing countries. Anim. Feed Sci. Technol. 81, 119–131. https://doi.org/10.1016/S0377-8401(99)00048-6

Thornton, P.K., 2010. Livestock production: Recent trends, future prospects. Philos. Trans. R. Soc. B Biol. Sci. 365, 2853–2867. https://doi.org/10.1098/rstb.2010.0134

Timler, C., Michalscheck, M., Klapwijk, C., Mashingaidze, N., Ollenburger, M., Falconnier, G., Kuivanen, K., Descheemaeker, K., Groot, J., 2014. Characterization of farming systems in Africa RISING intervention sites in Malawi, Tanzania, Ghana and Mali.

Trenbath, B.R., 1993. Intercropping for the management of pests and diseases. F. Crop. Res. 34, 381–405. https://doi.org/10.1016/0378-4290(93)90123-5

Valbuena, D., Erenstein, O., Homann-Kee Tui, S., Abdoulaye, T., Claessens, L., Duncan, A.J., Gérard, B., Rufino, M.C., Teufel, N., van Rooyen, A., van Wijk, M.T., 2012. Conservation Agriculture in mixed crop-livestock systems: Scoping crop residue trade-offs in Sub-Saharan Africa and South Asia. F. Crop. Res. https://doi.org/10.1016/j.fcr.2012.02.022

Valbuena, D., Tui, S.H.K., Erenstein, O., Teufel, N., Duncan, A., Abdoulaye, T., Swain, B., Mekonnen, K., Germaine, I., Gérard, B., 2015. Identifying determinants, pressures and trade-offs of crop residue use in mixed smallholder farms in Sub-Saharan Africa and South Asia. Agric. Syst. https://doi.org/10.1016/j.agsy.2014.05.013

van Heerwaarden, J., Baijukya, F., Kyei-Boahen, S., Adjei-Nsiah, S., Ebanyat, P., Kamai, N., Wolde-meskel, E., Kanampiu, F., Vanlauwe, B., Giller, K., 2018. Soyabean response to rhizobium inoculation across sub-Saharan Africa: Patterns of variation and the role of promiscuity. Agric. Ecosyst. Environ. https://doi.org/10.1016/j.agee.2017.08.016

Van Kessel, C., Hartley, C., 2000. Agricultural management of grain legumes: has it led to an increase in nitrogen fixation? F. Crop. Res. 65, 165–181.

Van Soest, P.J., 1994. Nutritional ecology of the ruminant. Comstock Publishing Associates, Ithaca.

Van Soest, P.J., Robertson, J., 1985. Analysis of forages and fibrous foods. Cornell University, Ithaca.

van Vugt, D., Franke, A.C., Giller, K.E., 2018. Understanding variability in the benefits of N 2 -fixation in soybean-maize rotations on smallholder farmers' fields in Malawi. Agric. Ecosyst. Environ. 261, 241–250. https://doi.org/10.1016/j.agee.2017.05.008

Verma, L.R., Nelson, B.D., 1983. Changes in round bales during storage. Trans. ASABE 26, 328–332.

VSN, 2017. Genstat for Windows 19th edition. Hemel Hempstead, UK.

Waldman, K.B., Ortega, D.L., Richardson, R.B., Clay, D.C., Snapp, S., 2016. Preferences for legume attributes in maize-legume cropping systems in Malawi. Food Secur. 8, 1087–1099. https://doi.org/10.1007/s12571-016-0616-4

Wang, C., Song, E., Wang, Z., Liu, X., Nian, H., Zhang, J., 2014. Variations in the nutritive value of soybean straw and their use with agronomic traits for breeding assays. J. Anim. &Plant Sci. 22, 3399–3406.

WFP, 2012. Comprehensive Food Security & Vulnerability Analysis, World Food Programme. Accra, Ghana.

Wiggins, S., 2009. Expert Meeting on how to feed the world in 2050: Can the smallholder model deliver poverty reduction and food security for a rapidly growing population in Africa? FAO, Rome, Italy.

Woomer, P., Huising, J., Giller, K., Kantengwa, S., Boahen, S., Wolf, J. De, Franke, L., Abaidoo, R., Dianda, M., Sanginga, J.M., Ronner, E., Den, G. Van, 2013. N2Africa : Final Report of the First Phase N2Africa Putting nitrogen fixation to work for smallholder farmers in Africa.

Yusuf, A.A., Jemo, M., Ncho, C., Abaidoo, R.C., 2012. Effect of rhizobium inoculation and phosphorus sources on the productivity of groundnut in Samaru, northern Guinea savanna of Nigeria. TSP 139, 16.39.

Zemmelink, G., 1980. Effect of selective consumption on voluntary intake and digestibility of tropical forages. Cent. Agric. Publ. Doc. Wageingen University.

Zhao, X., Gong, J., Zhou, S., OuYang, K., Song, X., Fu, C., Xu, L., Qu, M., 2015. Effect of fungal treatments of rape straw on chemical composition and in vitro rumen fermentation characteristics. BioResources 10, 622–637. https://doi.org/10.15376/biores.10.1.622-637

Acknowledgements

First and foremost I thank God, Almighty for granting me good health and strength throughout this PhD journey. I must confess that it is not a fair task to acknowledge all the people who made this PhD study possible with a few words. However, I will try to do my best to extend my appreciation to everyone who helped me scientifically and emotionally throughout this study. Should I forget to mention your name here, please forgive me!

I shall begin with my supervisory team which I always refer to as my PhD family. I was fortunate to have Prof. Imke de Boer as mother, Prof. Ken Giller as father, Dr Simon Oosting as my brother, and Dr Alan Duncan and Dr Samuel Adjei-Nsiah as my uncles to advice and support me during this journey.

To my first promoter Prof. Imke de Boer, I want to thank you very much for your care and support during my stay in your enviable chair group Animal Production Systems (APS). Thank you for making complex situations look simple as you always asked at the beginning of every meeting to start a new article, 'what is your message to the world?' This helped me to be ready with my story line before meeting you. I sincerely appreciate your readiness to assist in other situations other than academics. *Heel erg bedankt!*

To my second promoter Prof. Ken Giller, I thank you for critically reading and commenting on the manuscripts. It amazes me how you manage to detect mistakes in references even when referencing software was used. I also enjoyed the informal and personal talks we had, including with your wife, Irene. Thanks for your special interest in supporting and training many African researchers through the Plant Production Systems group in Wageningen.

To my co-promoter and daily supervisor Dr Simon Oosting, I am grateful for your high level patience and understanding throughout this journey. Coming from a crop science background with little knowledge in animal sciences, you have inculcated in me the love for livestock. Thanks for sharing with me your rich experience and knowledge in tropical livestock production system. My words may not be enough to express my indebtedness to you. To you I say *tige tank!*

To my other co-supervisors Dr Alan Duncan and Dr Samuel Adjei-Nsiah, I am grateful for your valuable contribution to the making of this thesis. Alan, your constructive criticism of the manuscripts have helped me to improve my writing style . You are always quick to suggest better ways of doing things. Samuel, you were always there to assist anytime I was in Ghana for data collection. You made time to visit my experimental sites regularly to advice. To the two of you, I say thank you. This is just the beginning of our collaboration.

I also want to say thank you to Dr Bas Engel and Dr Joost van Heerwaarden for your statistical support whenever reviewers comments needed to be addressed.

My stay in the APS group was made special by all the staff. I enjoyed all the coffee and lunch breaks we shared together for which I was a regular member. To Lia, Theo and Fokje, thank you for your administrative and technical support in the group. Fokje, I sincerely thank you for your help in designing my conference posters, presentations, thesis cover and formatting my thesis. Simon Fraval, thanks for being available for general assistance during this journey and proofreading part of this thesis. Thank you to Aart, Abigail, Aimable, Akke, Alejandro, Cindy, Charles, Corina, Evelien, Hannah, Heleen, Iris, Laura, Louise, Margret, Pim Mostert, Pim Post, Raimon, Sally, Nyokabi, Titis, Windi, Ben and Cecilia for being supportive group mates. My special thanks to Eddie, Kees and Henk, thank you for your advisory roles in the group. To Ollie and Loekie, I am grateful for accepting and serving as my paranymphs. Dear Suzanne, thanks for coming to Ghana to support my research as part of your MSc thesis. You did a lot by developing all the data entry templates. I am also grateful for the support of the staff of the WIAS secretariat, Janneke, Marianne and Bernie.

Thank you to all the staff and PhDs in the Plant Production Systems group for all the graduation dinners and field trips we had together. Special thanks to Martin, Maya, Katrien, Gerrie, Bert, Marcel, Marloes, Esther, Michael, Ashenafi, Comfort, Samuel, Linda, Jannike, Wytze, Eva, Eduoard, Alain, and many others. To the PPS secretariat staff, Linda, Charlotte, Karen and Alex-Jan, I thank you for your administrative support.

I also want to extend my appreciation to the entire Ghanaian community in Wageningen (a.k.a. *Sikaman*), for the trust you had in me to serve as your president (the *Abusuapenyin*). It was an honour serving you all and I enjoyed every bit of it. Greg Mensah, thanks for picking me from the airport and showing me around Wageningen. My sincere thanks also goes to the Hoek family especially Aunty Monica and Uncle Steve for allowing us (all Africans) into your home any time any day. Mr Sampson Nibi, your genuine concerns and love for *Sikaman* is well appreciated. I am grateful to Dr Confidence Duku for helping me to map my study sites and also to your lovely wife Elizbeth for the lasagne recipe and tutorials.

Thank you to my former colleagues at IITA for your support during my data collection period in Ghana. To name but a few, I would like to specially thank you Dr Larbi, Dr Bekele, Dr Dugje and Mr. Obeng for your leadership role you have played. The rest are Nurudeen, Sarfo, Eric, Kojo, Nartey, Samed, Aziz, Amankwah, Dokurugu, Dawuda, Portia, Afua, Linda, and many others. Thank you all!

I also acknowledge with great appreciation, the immense support of some of the staff of the Savanna Agricultural Research Institute (SARI), Nyankpala. I thank the director, Dr Steve Nutsugah granting me access to some facilities in the institute. Dr Benjamin Ahiabor, thanks for your encouraging words. I am also grateful to Mr Emmanuel Vorleto and Mr Abduali Alhassan for assisting me in the lab.

I was privileged to conduct part of my laboratory work in the animal nutrition lab at the International Livestock Research Institute (ILRI), Addis Ababa. My gratitude extends to the lab team, especially, Yonas, Prassad, Degsew and Zewde for your unreserved assistance and helps during laboratory works. Dr Endalkachew Wolde-meskel and Dr Michael Blummel, are thanked for welcoming me to Addis with open arms.

I was also assisted by many people on the field when collection data in Ghana. I would like to thank some staff of the Ministry of Food and Agriculture in the study districts, especially, Mahama, Peace, Richard, Rashid and many others. I am grateful to Robert Atawura, Fuseini Abdulai, Augustine Tambie from Upper West region, Baba Iddrisu, Abraham Takora, Awudu Rufai, Alhassan Sulemana from Northern region and Sorogo Sariki, Osman Fulailu, Abukari Mohammed and Elisha Tampigu from Upper East region for your assistance during data collection. To the many farmers who allowed me and enumeration team into your homes and to your farms, I say thank you.

I am also greatly indebted to Prof. Kumaga and Dr Naa Lamle Amissah, who were my BSc and MPhil supervisors, respectively, at the University of Ghana where my research life begun. Thank you very much for recommending me for this position.

My thanks also go to Mr. Ken Kinney, the executive director of the Development Institute for having given me the opportunity to represent the organization at many meetings and conferences both in Ghana and abroad. Thanks also for checking on me regularly and anytime you were in the Netherlands.

I would also like to appreciate the company of many friends I made here in Wageningen during the PhD period, especially, Kabir, Nazri, Eli, Bandan, Tesfaye, Alan, Eliakera, Edem, Hamza, James, John, Sebastian, Lotte and the rest. To all my corridor mates at Dijkgraaf 2A, I thank you for the nice times we spent together. I want to thank all my church members at Amazing Grace Parish, Wageningen especially, Pastor Farai, Pastor Busi, Pastor Adesua and Ikenna for your support. Petra and Johan, thank you very much for allowing me into your home and for your support.

I am indebted to my parents-in-law, Mr and Mrs Afenyo for taking care of my wife and daughter while I was away. To the two of you, I say God bless you!

I owe a special thanks to my family, especially my late mom and dad. I also thank all my siblings, Torgbui Solaga, Michael, Harrison, Reuben, Charles, Peter, Edward, Emmanuel, Alice, Tina and Mary. I dedicate this work to the entire family. I love you all. To Harrison, I thank you specially for paying my school fees and training me. I dedicate this thesis to you, Bro! I know you are proud of me.

I also dedicate this Ph.D. thesis to my daughter Selikem; you were the first diploma I got during this PhD. God brought you to my life during this journey to show me that there is hope. You are the pride and joy of my life. Selikem, Daddy loves you more than anything.

At last I do not know how to begin with saying thank you to my soul mate, my permanent roommate, my dearest wife and my best friend, Phil, as I passionately call you. I love you for everything, for being so understanding and for putting up with me through the toughest moments of my life. I thank God for enlightening my life with your presence. One morning, I vividly remembered you asking me from the other side of the telephone, how long does it take to do a PhD? Understanding the loneliness you felt and realizing the sadness in your voice, I told you, four years. I promised you that it would be over soon because everything which has a beginning has an end. The PhD has finally ended. It is time to live together again as a family to take care of Selikem. Sweet heart, I love you! *Akpe!*

Daniel Brain Akakpo

About the author

debrainy@yahoo.com

Daniel Brain Akakpo was born in Keta, a coastal town in the Volta region of Ghana on March 18, 1979. He obtained a Bachelor of Science (BSc) degree in General Agriculture (Crop Science option) in 2007 from the University of Ghana, Legon. He successfully completed a mandatory national service and served as a teaching assistant in the Crop Science Department of the same University. He proceeded to obtain a Master of Philosophy (MPhil) degree in Crop Science (Agronomy Option) in 2011 from the same University.

While pursuing his master's degree, he served as a volunteer for the Development Institute (an environmental NGO in Ghana). After obtaining his master's degree, he got employed as a project officer in charge of agricultural value chains. During his tenure with the Development Institute, he helped implement the adaptation to climate change- project (ADAPTS; www.adapts.nl) in collaboration with Acacia Water, The Institute for Environmental Studies (IVM) and Both Ends. He also collaborated with Alliance for a Green Revolution in Africa (AGRA) and the Soil Research Institute of Ghana to monitor and evaluate the implementation of the Ghana Fertilizer Subsidy Programme (GFSP) between 2010 and 2012.

He later joined Calli - Ghana, a subsidiary of Arystal LifeScience as a Cocoa Agronomist where he collaborated with the Cocoa Research Institute of Ghana (CRIG) in testing, registration and marketing of agro-chemical products.

He worked for the International Institute of Tropical Agriculture (IITA) of the CGIAR in Ghana as a Research Associate from 2013 to 2014, working for the Africa Research In Sustainable Intensification for Next Generation programme (Africa RISING). Later in 2014, he left IITA to start his PhD programme at Wageningen University in the Netherlands.

Daniel Brain is particularly interested and passionate in using Agriculture Research for Development (AR4D) programmes to improve productivity and reduce hunger among smallholder farmers in Africa and beyond.

Mr. Akakpo enjoys cooking, travelling, swimming, talking and sharing meals with friends when he is not working. He is married to Philicia and got a daughter, Selikem.

Publications

Peer-reviewed scientific journals

Akakpo, D.B., de Boer, I.J.M., Adjei-Nsiah, S., Duncan, A., Giller, K.E., Oosting, S.J., (2020). Evaluating the effects of storage conditions on dry matter loss and nutritional quality of grain legume fodders in West Africa. Anim. Feed Sci. Technol. https://doi.org/10.1016/j.anifeedsci.2020.114419

Akakpo, D.B., de Boer, I.J.M., Adjei-Nsiah, S., Duncan, A., Giller, K.E., Oosting, S.J., (2020). Nutritional quality of grain legume fodders stored under different conditions: Correlation among farmers' perception, sheep preference, botanical characteristics and laboratory analyses. (Peer-reviewed and resubmitted to Small Ruminants for publication)

Akakpo, D.B., Oosting, S.J., Adjei-Nsiah, S., Duncan, A., de Boer, I.J.M., Giller, K.E. Do inoculation and phosphorus fertilization of grain legumes improve yield and fodder quality? Evidence from the Guinea Savanna of Ghana. (Submitted to Experimental Agriculture)

Daniel Brain Akakpo , Imke J.M. de Boer, Ken E. Giller, Fokje A. Steenstra, Samuel Adjei-Nsiah, Alan Duncan and Simon J. Oosting. Understanding variation in the use of grain legume fodders in smallholder mixed crop-livestock systems in northern Ghana. (In preparation for NJAS-Wageningen Journal of Life Sciences)

Daniel Brain Akakpo, Naalamle Amissah, Julius Yeboah, Essie Blay (2014). Effect of Indole 3-Butyric Acid and Media Type on Adventitious Root Formation in Sheanut Tree (Vitellaria paradoxa C. F. Gaertn.) Stem Cuttings, American Journal of Plant Sciences, 2014, 5, 313-318

Naalamle Amissah, **Brain Akakpo**, Julius Yeboah, Essie Blay (2013) Asexual Propagation of Sheanut Tree (Vitellaria paradoxa C.F. Gaertn.) Using a Container Layering Technique, American Journal of Plant Sciences, 2013, 4, 1758-1764

Yirzagla, J., Denwar, N.N., Dogbe, W., Kanton, R.A.L., Inusah, I.Y.B., **Akakpo, D.B.**, Mohammed, I. (2013). Compatibility of Millet and Legume under Relay Cropping Condition, Journal of Biology, Agriculture and Healthcare ISSN 2224-3208 (Paper) ISSN 2225-093X (Online) Vol.3, No.15, 2013

Adjei-Nsiah, S., Vanlauwe, B., Ahiabor, B.D.K., Abaidoo, R.C., van Heerwaarden, J., **Akakpo, D.B.**, Alabi, B.U., Adjei, J., Sangodele, E., Kanampiu, F., Asungre, P., Giller, K.E. Improving biological nitrogen fixation in cowpea in West African smallholder farming systems (Submitted)

Conference Proceedings

Akakpo, D.B., Oosting, S.J., Adjei-Nsiah, S., Duncan, A., Boer, I.J.M. de (2019). Correlating farmers' perception and sheep preference with the nutritional quality of grain legume fodders stored under different conditions. In: Book of abstracts of WIAS Science Day 2019: Trade-Offs in Science - Keeping the balance - Lunteren, the Netherlands,. p. 20

Akakpo, D.B., Oosting, S.J., Adjei-Nsiah, S., Duncan, A., Giller, K.E., de Boer, I.J.M. (2018) Evaluating the Traditional Feed Storage Systems of Grain Legume Fodders in Northern Ghana. In: Book of abstracts of Tropentag 2018 conference: Global food security and food safety: The role of universities, Ghent, Belgium - Weikersheim : Margraf Publishers - ISBN 9783823617600 - p. 118

Akakpo, D.B., Oosting, S.J., Adjei-Nsiah, S., Duncan, A., Giller, K.E., de Boer, I.J.M. (2018). Effects of location and time of storage on the nutritional quality of grain legume fodder in northern Ghana. In: Book of abstracts: Book of abstracts of WIAS Science Day 2018: Work on your Impact in Animal Sciences and Society - Wageningen University & Research - p. 1

Akakpo, D.B., Oosting, S.J., Adjei-Nsiah, S., Duncan, A., Giller, K.E., de Boer, I.J.M. (2016). The Influence of Rhizobia Inoculation and Phosphorus Fertilizer on Yield and Quality of Cowpea Fodder in Northern Ghana. In: Book of abstracts of Pan-African Grain legume & World Cowpea Conference 2016, Livingstone, Zambia

Larbi, A., Kotu, B., Nurudeen, A.R., **Akakpo, D.B.,** Asante, M., Mellon, S. (2016a) Insecticide Spray Regime Effect on Cowpea Yield and Financial Returns in Northern Ghana. In: Book of abstracts of Pan-African Grain legume & World Cowpea Conference 2016, Livingstone, Zambia

Larbi, A., Abdul Rahman, N., Kotu, B., Hoeschle-Zeledon, I., **Akakpo, D**., Mellon, S.B., (2016b). Nitrogen Rate and Variety Effect on Profitability of Maize Production in Northern Ghana, In: Africa RISING Planning and Review Meeting 2016, Accra. IITA, Ibadan, Nigeria

Larbi, A., Abdul Rahman, N., Kotu, B., Hoeschle-Zeledon, I., **Akakpo, D.B**., Mellon, S.B., (2016c). Integrated Soil Fertility Management Affect Profitability of Soybean in Northern Ghana, In: Africa RISING Planning and Review Meeting 2016, Accra. IITA, Ibadan, Nigeria

Education Certificate **Completed Training and Supervision Plan**		**Graduate School WIAS**
EDUCATION AND TRAINING	**Year**	**Credit**
The Basic Package		**4.0**
WIAS Introduction Day	2014	
Course on philosophy of science and/or ethics	2014	
PERC Weekend	2014	
Course on essential skills	2014	
Disciplinary Competences		**16.1**
Writing PhD research proposal	2015	
Quantitative Research Methodology and Statistics (MAT 22306)	2015	
Introduction to R for statistical analysis	2016	
Statistics for life sciences	2017	
Resilience in living systems	2018	
Professional Competences		**13.4**
Information Literacy including Endnote introduction	2014	
Data Management planning	2015	
Scientific Writing (SWR)	2015	
WIAS Science Day (Organizing Member)	2017	
Brain Training	2017	
Project and time management	2017	
Reviewing scientific paper	2017	
Essentials of scientific writing and presenting	2017	
Career perspective	2017	
Orientation on teaching (Start to teach)	2018	
Societal Impact	2018	
The final touch: Writing General Introduction and Discussion	2018	
Wageningen OneWorld Celebration (Organizing member)	2018	
Survival guide to peer review	2019	
Presentation Skills		**4.0**
International Cowpea Conference, (Poster) Livingstone, Zambia	2016	
Tropentag Conference, (Poster) Ghent, Belgium	2018	
WIAS Science Day, (Poster) Wageningen, The Netherlands	2018	
WIAS Science Day (Oral), Lunteren, The Netherlands	2019	
Teaching competences		**1.0**
Masters Student Supervision	2016	
Education and Training Total (minimum 30 credits)		**38.5***

*With the activities listed the PhD candidate has complied the educational requirements set by the Graduate School of Wageningen Institute of Animal Sciences (WIAS) of Wageningen University & Research, which comprises of a minimum of 30 ECTS (European Credit Transfer and accumulation System). One ECTS equals a study load of 28 hours.

Colophon

The research described in this thesis was financially supported by the Bill & Melinda Gates Foundation through the project N2Africa: Putting Nitrogen Fixation to Work for Smallholder Farmers in Africa (www.N2Africa.org).

Financial support from Wageningen University for printing of this thesis is gratefully acknowledged.

Images used in this thesis were taken by Daniel Brain Akakpo

Cover design by Daniel Brain Akakpo and Fokje Steenstra

Printed by Proefschriftmaken (www.proefschriftmaken.nl)