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Genotype by Environment interactions of Chickens tested in Ethiopia

Two traits analysed:

BW in Ethiopia
Egg Number and Egg Weight in Oromia

Master Thesis (30 ECTS)

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Statutory declaration

I declare that I have prepared, developed, and written this thesis independently and I have not used any sources, thoughts or literature of others than clearly stated in the text. The master thesis was produced in completion of the International Master Program "Animal Breeding and Genetics". Degrees will be awarded at University of Natural Resources and Life Sciences, Vienna, Austria, and Wageningen University & Research, Wageningen, The Netherlands.

Place, date

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Abstract

Many African households rely on smallholder production for food and nutrition security. Global demand for animal protein is rising, with poultry production expected to be one of the major components. The African Chicken Genetic Gain (ACGG) project (https://africacgg.net/) aims to achieve an optimization on African smallholder poultry production by introducing commercial dual-purpose breeds into a new African environment.

BW in Ethiopia
Different breeds may be best suited for different environments of Ethiopia, which is a country with a wide range of Agro-Ecological Zones (AEZ). This study performed genotype environment interaction (GxE) analyses for body weight (BW) of growing male and female chickens, using ACGG data. Hence, research questions of this study were to investigate: 1) If a GxE does take place for BW? 2) Which breed performs best in which environment in terms of predicted BW?
Analyses was performed using predicted BW at four different ages (90, 120, 150 and 180 days) of five introduced breeds (Horro, Koekoek, Kuroiler, Sasso-Rhode Island Red (S-RIR) and Sasso) located in five Ethiopian Regions (Addis Ababa, Amhara, Oromia, South Region and Tigray) being part of three AEZ (cool humid, cool sub humid and warm semi-arid). 999 females and 989 males were present. GxE was highly significant ($p<0.0001$) for all analysis combinations. In line with previous research, Sasso was shown to have the highest predicted BW, especially at early age, followed by Kuroiler. Due to the young breeding program of Horro, it was often observed to be the worst performing breed. Best performances were observed in Tigray, Oromia, and Amhara regions, all mainly being part of the cool sub humid AEZ having highest predicted BW. Koekoek and Kuroiler were performing well in Amhara at late age, which can potentially be explained by high precipitation.

Egg Number and Egg Weight in Oromia
To measure benefits, genotype environment interaction (GxE) analyses guides by predicting effects of new environments breeds are placed in on production traits. A survey among Ethiopian poultry smallholders showed egg sale being most important purpose of keeping village chickens in Oromia. Data was available about laying of 894 ACGG chickens in Oromia. Hence current research questions were to investigate: 1) Does GxE take place? 2) Which breed performs best in which environment within Oromia regarding laying?
Traits investigated were egg number and egg weight of five breeds (Sasso-Rhode Island Red (S-RIR), Sasso, Horro, Kuroiler and Koekoek) located in three zones (East Hararge, East and West Shoa) among which 5 districts (Adami Tulu Jido Kombolcha, Bako Tibe, Dano, Dugda and Haromaya) in Oromia. Observations were taken as group measure performing weighted analyses. GxE was only present for egg number with magnitude strongest for zone as environment. S-RIR performed best for both traits in both environments, except Kuroiler performing better in East Shoa for egg number and Koekoek for egg weight. This indicates successs of crossbreed S-RIR. Sasso and Horro performed worst supported by previous research for Horro but not Sasso. Low precipitation in East Shoa caused bigger distance in egg number predictions, being higher for S-RIR and lower for Horro and Sasso compared to West Shoa.

While the results give clear answers to the research questions stated, the social context of breeding and data collection difficulties should not be forgotten. Also, other traits like survival are highly relevant and should be analysed.

Keywords: Ethiopia, smallholder farming, poultry, body weight, laying, genetic gains.

Zusammenfassung

Viele afrikanische Haushalte sind zur Sicherung ihrer Ernährung auf die Nahrungsmittelproduktion von Kleinbauern angewiesen. Die weltweite Nachfrage nach tierischem Eiweiß steigt, wobei die Geflügelproduktion voraussichtlich eine der Hauptkomponenten darstellen wird. Das Projekt African Chicken Genetic Gain (ACGG) (https://africacgg.net/) zielt darauf ab, eine Optimierung der afrikanischen kleinbäuerlichen Geflügelproduktion durch die Einführung kommerzieller Doppelnutzungsrassen in einem neuen afrikanischen Umfeld zu erreichen.

Körpergewicht in Äthiopien

Verschiedene Rassen eignen sich möglicherweise am besten für verschiedene Umgebungen in Äthiopien, einem Land mit einer breiten Palette von Agro-Ökologischen Zonen (AÖZ). In dieser Studie wurden Genotyp-Umwelt-Interaktionen (GxE) für das Körpergewicht (KG) von wachsenden männlichen und weiblichen Hühnern analysiert, wobei ACGG-Daten verwendet wurden. Folgende Forschungsfragen wurden untersucht: 1) Gibt es GxE für das KG? 2) Welche Rasse schneidet in welcher Umgebung in Bezug auf das vorhergesagte KG am besten ab?

Die Analysen wurden unter Verwendung des vorhergesagten KG in vier verschiedenen Altersstufen, (90, 120, 150 und 180 Tage) mit fünf eingeführten Rassen (Horro, Koekoek, Kuroiler, Sasso-Rhode Island Red (S-RIR) und Sasso) durchgeführt, die in fünf äthiopischen Regionen (Addis Ababa, Amhara, Oromia, South Region and Tigray) angesiedelt sind, welche wiederum zu drei AÖZ gehören (kühl-humid, kühl-sub-humid, und warm-semi-arid). Es wurden 999 weibliche und 989 männliche Hühner untersucht. Die GxE war für alle Analysekombinationen hoch signifikant ($p<0.0001$). In Übereinstimmung mit früheren Untersuchungen zeigte sich, dass Sasso das höchste vorhergesagte KG hat, insbesondere in jüngeren Altersstufen, gefolgt von Kuroiler. Aufgrund des noch jungen Zuchtprogramms von Horro wurde oft beobachtet, dass dies die Rasse mit der schlechtesten Leistung war. Die besten Leistungen wurden in den Regionen Tigray, Oromia und Amhara beobachtet, die alle hauptsächlich Teil der kühlen, sub-humiden AÖZ mit dem höchsten vorhergesagten KG waren. Koekoek und Kuroiler zeigten in Amhara in höheren Altersstufen gute Leistungen, was möglicherweise durch hohe Niederschläge erklärt werden kann.

Eizahl und Eigewicht in Oromia

Um den Nutzen zu messen, werden mit Hilfe von Genotyp-Umwelt-Interaktionsanalysen (GxE) Leitfäden zur Vorhersage der Auswirkungen neuer Umgebungen, in denen Rassen platziert werden, auf die Produktionsmerkmale erstellt. Eine Umfrage unter äthiopischen Geflügel-Kleinbauern zeigte, dass der Eierverkauf der wichtigste Zweck der Haltung von Dorfhühnern in Oromia ist. Es waren Daten über die Legeleistung von 894 ACGG-Hühnern in Oromia verfügbar. Daher sollten folgende Forschungsfragen untersucht werden: 1) Findet GxE statt? 2) Welche Rasse schneidet in welcher Umgebung innerhalb von Oromia in Bezug auf das Legen am besten ab?

Untersucht wurden Eizahl und Eigewicht von fünf Rassen (Sasso-Rhode Island Red (S-RIR), Sasso, Horro, Kuroiler and Koekoek), die sich in drei Zonen (Ost Hararge, Ost und West Shoa) befinden, die sich in insgesamt 5 Distrikte (Adami Tulu Jido Kombolcha, Bako Tibe, Dano, Dugda und Haromaya) teilen. Die Beobachtungen wurden als Gruppenmaß genommen und gewichtete Analysen durchgeführt. Signifikante GxE war nur für die Eizahl vorhanden. S-RIR schnitt bei beiden Merkmalen am besten ab, Ausnahmen waren Kuroiler, die in Ost Shoa bei der Eizahl und Koekoek, die beim Eigewicht besser abschnitten. Dies deutet auf einen Erfolg der Kreuzung S-RIR hin. Sasso und Horro schnitten am schlechtesten ab, was durch frühere Untersuchungen für Horro, nicht aber für Sasso belegt wird. Geringe Niederschläge in der östlichen Shoa verursachten einen größeren Unterschied bei der Vorhersage der Eizahl, der für die S-RIR höher und für Horro und Sasso niedriger war als für die westliche Shoa.

Während die Analysen klare Antworten auf die gestellten Fragen gaben, sollten der soziale Kontext der Zucht- und Datenerfassungsschwierigkeiten nicht vergessen werden. Zudem wird es wichtig sein, auch andere Merkmale wie die Überlebensrate und die Nutzungsdauer der Tiere zu analysieren

Schlüsselwörter: Äthiopien, Kleinbauernwirtschaft, Geflügel, Körpergewicht, Legeleistung, Zuchtfortschritt

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At first, I would like to greatly thank my main supervisor Johann Sölkner for introducing me to the ACGG project and giving me the opportunity to work with a topic so much of my interest. Secondly, also the colleagues from ILRI should be thanked for willingness to share data and advise on how to analyse it. Lastly the people from Wageningen and everybody of my student life in general should be thanked for supporting me while writing this second MSc thesis being the final product of my master student life.

Unfortunately, because of the COVID-19 pandemic a visit to the ILRI campus in Addis Ababa and villages the backyard poultry was kept did not take place. But from a distance it was definitely still a very interesting thesis and paper to work on. Therefore, a big thank you to everybody involved.

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Introduction

Smallholder farming plays a major socio-economic role in developing countries with a high percentage of African families being reliant on it. Poultry farming is much present in African countries and was shown to be contributing positively to the socio-economic lives of these families (Vernooij, Masaki and Meijer-Willems 2018; FAO, 2014). Livestock contributes 38,5% to the income of Ethiopian poultry keeping households (Goromela et al. 2019). The global demand for animal protein is rising and is expected to increase by 70-80% between 2012 and 2050, with poultry expected to have a bigger increase in production than other livestock, while having the least environmental impact (Alexandratos et al. 2006; Oonincx and de Boer, 2012; Alexandratos and Bruinsma, 2012).
Multidisciplinary research supports that local adaptation and tailoring of sustainable poultry production for Ethiopian smallholder farmers is important for flexible implementation of it (Bettridge et al. 2018). For all previously mentioned reasons, it is interesting to look for strategies to optimize this local African smallholder poultry production system. The African Chicken Genetic Gain (ACGG) project (https://africacgg.net/), led by the International Livestock Research Institute (ILRI) located in Addis, Ethiopia, is aiming to achieve this optimization (ILRI, 2018). One of the strategies of the project was introduction and testing of various commercial dual-purpose poultry breeds that are more productive and tropically adapted into different Agro-ecologies in the project countries; Ethiopia, Nigeria, and Tanzania (Appendix Figure 1). To find out whether such approach is beneficial, it is important to know, if these new environments the dual-purpose breeds are placed in, are having an effect on certain production traits. A common way to calculate this is by what is called a classical genotype environment interaction (GxE) analysis.

Classical GxE analyses can be defined as the change in phenotypic performance of two or more genotypes measured in different environments (Falconer, 1952; Falconer and Mackay, 1996). A genotype can be also defined as a single breed of which its performance can be looked at in different environments (Lozano-Jaramillo, 2019). Environment in GxE analysis is often addressed as a categorical or continuous variable (Calus, Bijma and Veerkamp, 2004; Lozano-Jaramillo, 2019). For example, herd size, climate, management strategy, or location. When environment is a continuous variable, GxE is commonly visualized by plotting the genotype's or breed's performance against this environment in a linear random regression model (Hayes, Daetwyler and Goddard, 2016; Lozano-Jaramillo, 2019). If the plotted lines are parallel there is no GxE present. Therefore, one genotype or breed is performing better than the other in both compared environments. But if the lines are not parallel, a GxE is present, meaning one breed or genotype is performing better in one environment compared to the other environment. It becomes most critical if even an intersection of the lines takes place causing a re-ranking of the genotypes or breeds. This means that the magnitude of the GxE is so big that the choice on which genotype or breed is best to use is determined by the environment it is placed in (Wakchaure, Ganguly and Praveen, 2016; Hayes, Daetwyler and Goddard, 2016). A clearer and more detailed visualization of examples of these plotted regression GxE models and all possible scenarios of interaction are given in Appendix Figure 2 (Mathur, 2003).

During the ACGG project five different genotypes being dual-purpose chicken breeds (Horro, Koekoek, Kuroiler, S-RIR and Sasso) were located across Ethiopia. The country is divided into multiple regions containing zones and eventually districts. Figure 1 shows a map of Ethiopia displaying which of these environments are chosen to place the ACGG breeds in. Horro is an indigenous Ethiopian breed originating from the Oromia region, more specifically the Horro district located in the cool and wet western highlands (Lozano-Jaramillo et al. 2019). Horro is improved by a breeding program which has been implemented since 2008 (Wondmeneh et al. 2014a). Egg production as well as growth performance seem to have a strong genetic correlation, having common genes in this breed, therefore utilizing those selection traits should be promising while breeding (Dana, Van der Waaij and Van Arendonk, 2011). The other four breeds were introduced to Ethiopia, of which S-RIR is a crossbreed between Sasso and Rhode Island Red specifically generated for the ACGG project (Aman et al. 2017).

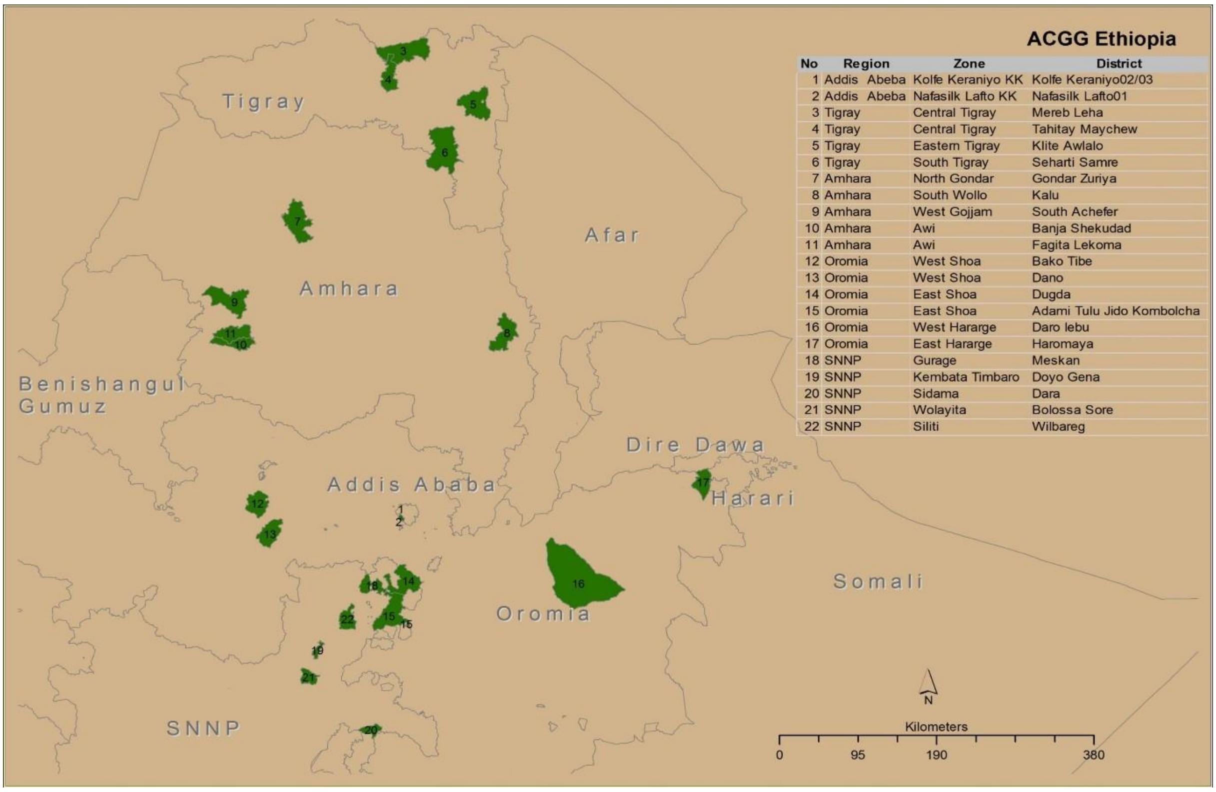


Figure 1. Map of Ethiopia including every region, zone and district households picked as environment to place chickens of the ACGG project in (https://africacgg.net/ethiopia/).

BW in Ethiopia

Lozano-Jaramillo (2019) using ACGC data, predicted breed by environment interaction running or using ecological modelling. The modelling tools she used were based on Geographic Information Systems (GIS) which only very recently have been applied in livestock research. In general, the findings reported showed that this alternative way of modelling could be beneficial in identifying breed suitability in different environments (Lozano-Jaramillo, 2019). Moreover, it showed that environment is definitely playing a role in productivity of certain breeds if kept under smallholder farm conditions.

More specifically, Lozano-Jaramillo et al. (2019) predicted body weight (BW) (during growing period: week 14-19 and adult period: week 20-72) using climate data from the different Agro-ecologies in Ethiopia where five of the ACGG breeds were placed. The result reported by Lozano-Jaramillo et al. (2019) were based on data from five Ethiopian Regions (Addis Ababa, Amhara, Oromia, Southern Nations Nationalities and People's Region (SNNP) in short Southern Region and Tigray) (Figure 1). Reported results showed that mean estimated male BW in the growing phase were highest for Sasso, followed by Kuroiler, while mean estimated female BW of Koekoek, followed by Sasso were the highest. The region these breeds performed best in was Tigray for male as well as female Sasso, Oromia for male Kuroiler and Amhara for female Koekoek. The phenotypic distribution models clearly showed the range in the predictions per breed throughout Ethiopia in what looks similar to a heat map (Appendix Figure 3).

Apart from these new analyses results using prediction models the classical GxE analyses can be conducted using ACGG data. Classical GxE analysis has not been performed with the ACGC data. Hence, the aim of this study was to perform a GxE analysis using BW during the growth period as production trait. The two key research questions are;

1) Does GxE take place, i.e. do different breeds react differently to the various Ethiopian environments.
2) Which breed performs best in which environment in terms of predicted BW. This is the most viable information for the Ethiopian smallholder farmers in their respective environments.

Egg Number and Egg Weight in Oromia

Oromia is the biggest Ethiopian province regarding human population and area. Its topography and climate are described as greatly physiographic diverse containing rich natural resource bases (FDRE, 2018). Performance data of ACGG breeds was obtained from various zones and districts of Oromia (Figure 1), making GxE analysis possible, considering breed as genotype and zone or district as environment. Hartman (1990) found GxE being more present for egg production of layers compared to weight traits of broilers in commercial poultry. Moreover, a baseline survey among Ethiopian smallholders showed egg sale being most important purpose of keeping in Oromia (Esatu and EIAR, 2016). Additionally, another survey showed African smallholders desiring physically well appearing birds, with hens having high egg production and hatchability traits (Goromela et al. 2019). Hence, there is big interest for optimizing laying traits.

Previous research found egg production of all five introduced ACGG breeds on Ethiopian smallholder farms being higher than that of an indigenous breed (Abegaz et al. 2019). S-RIR, followed by Kuroiler, Sasso, Koekoek and Horro had highest average weekly egg production till 50 weeks age. At the Ethiopian Debre Zeit research station, Horro scored lower for egg weight and hatchability than three breeds including Koekoek (Wondmeneh, Dawud and Adey, 2011). More on-station research predicted Sasso followed by S-RIR having highest hen-housed egg production in three African countries, including Ethiopia (Bamidele et al. 2019a). In Oromia, no GxE analysis on laying of ACGG breeds has yet been conducted.

Hence, the aim of the current study was to perform GxE analysis using egg number and egg weight as performance traits, comparing ACGG breeds in zones and districts of Oromia. Two key research questions were;
1) Does GxE take place? i.e. do different breeds react differently to zones and districts of Oromia?
2) Which breed performs best in which zone or district in terms of predicted egg number or egg weight? Answer to this last question exposing most viable information for Ethiopian smallholders in respective locations in Oromia.

Literature Review

Animal Breeding and GxE in African Chickens

Although Lozano-Jaramillo (2019) was using Geographic Information Systems (GIS) to predict breed by environment interaction, information about classical genotype environment interaction (GxE) is provided in the introduction and discussion of the PhD thesis. According to this and other literature sources the following review about animal breeding and GxE analyses of African chickens was made.

The biggest aim of animal breeding is to select and breed animals for efficient performance and production in the future (Lozano-Jaramillo, 2019). How well these eventually selected animals perform can also be highly dependent on the environment they are placed in. As explained before, it is classical GxE analyses which are commonly used to determine if different genotypes indeed react differently to diverse environments (Lozano-Jaramillo, 2019). GxE specifically defined as; the change in phenotypic performance of two or more genotypes measured in different environments (Falconer, 1952; Falconer and Mackay, 1996). Only since the late 1940's, quantitative genetic models have been used in animal breeding to evaluate phenotypic response to two or more environments, also called phenotypic plasticity (Via and Lande, 1985).

The sensitivity of a breed to the environment it is placed in is also very important in decision making while selecting animals in a breeding program (Lozano-Jaramillo, 2019). Falconer (1952) describes this urgent matter in his paper 'the problem of environment and selection.' As the environment in which the breeding program takes place and where animals are selected can differ from the environment the breed eventually has to produce in, a GxE effect can occur. It can happen that the magnitude of this GxE is so big that accounting for it is needed, using different breeding programs (Falconer, 1952; Mulder and Bijma, 2005). Recently, breeding programs became more internationally oriented, making this problem even more relevant (Mulder and Bijma, 2005). Also, in poultry breeding this problem is present. Strong GxE effects are observed comparing a bio-secure breeding environment with commercial production ones for body weight traits in boilers (Chu et al. 2019).

Poultry breeding in developing countries comes with even more difficulties. For successful selective breeding certain conditions are needed like; large populations, pedigrees, recording of performance and small environmental variation (Lozano-Jaramillo, 2019). Unfortunately, those conditions are often not present at smallholder poultry farms, which makes it hard to perform animal breeding in developing countries (Besbes, 2009; Dana et al. 2010). A solution commonly implemented (also in the ACGG project) is to perform animal breeding on research stations instead of directly on farm in villages. This overcomes the problem of the lacking conditions but does not solve the problem of a potential GxE due to different breeding (on-station) and production (on-farm) environments. Lozano-Jaramillo (2019) expressed her concern regarding these differences between central breeding station and on smallholder farm as a decrease in productivity could be observed, especially in commercial breeds exposed to tropical conditions. She thinks it is therefore important to know which specific environmental factors cause the change in performance (Lozano-Jaramillo, 2019).

Various other studies on African chickens kept under intensive on-station as well as extensive on-farm environments did indeed show a clear GxE presence (Bekele et al. 2009; Ali, Katula and Syrstad, 2000; Lwelamira, 2012). Performance in these studies revealed to be always better in the on-station environment. Performance was measured for a variety of traits and for different purposes (egg as well as meat) but mainly focussing on weight gain (Bekele et al. 2009; Ali, Katula and Syrstad, 2000; Lwelamira, 2012). A variation in importance of GxE for certain performance traits can be observed based on much literature mostly of commercial poultry (Hartman, 1990). In general, this literature shows that GxE is more seriously present for egg producing traits in laying hens compared to for weight traits in broiler chickens (Hartman, 1990).

Apart from the difficulties known about breeding of village poultry in developing countries many attempts have been performed using diverse strategies (Besbes, 2009). According to Lwelamira (2012) a potential solution for the difference in on-station and on-farm environments could be advising smallholder farmers a shift from the current extensive (on-farm) to more semi-intensive systems. However, what should not be forgotten is that smallholder farmers also have their own opinion on which farming practices are best according to their socioeconomic background. Not only farming but also breeding practices stay an eventual individual choice of the smallholder farmer. Flexible implementation of sustainable village poultry development, including breeding programmes, is achieved by locally designing and tailoring for it with personal inclusion of smallholder farmers (Sölkner, Nakimbugwe and Valle Zarate, 1998; Mueller et al. 2015; Bettridge et al. 2018). Dana et al. (2010) exposed interesting insights regarding the social context of village poultry breeding conducting a survey in different geographical regions in Ethiopia. The opinion of village poultry farmers about breed and trait preferences resulted in the following ultimate breeding goal; to develop a dual-purpose breed based on indigenous chicken genetic resources. Although, a variety of traits, like body plumage colour was preferred slightly different in each Ethiopian Region (Dana et al. 2010).

Despite all the difficulties pointed out about animal breeding for African village poultry and potential GxE effects it can be stated that GxE analysis is a useful tool in the process of breeding. Various papers have shown GxE presence between on-station and on-farm environments (Bekele et al. 2009; Ali, Katula and Syrstad, 2000; Lwelamira, 2012). Moreover, on-station data, being often more precise, are used to compare difference in genotype performance among stations or between different African countries (Bamidele et al. 2019a; Bamidele et al. 2019b; Lozano-Jaramillo, 2019). Lozano-Jaramillo (2019) tried to explain her preference of GIS over classical GxE, doing a similar analysis in her discussion. In her opinion classical GxE can be misleading because a breed can still perform differently in certain areas within an environment, which was in this case an entire country (Lozano-Jaramillo, 2019). More relevant research proofs GxE analyses to be useful while comparing different environments like housing systems or seasons African chickens were present in (Yakubu, Salako and Ige, 2007).

In this thesis environments will be Ethiopian Regions or Agro-Ecological Zones (AEZ) for body weight traits, and zones and districts for egg number and egg weight traits. Genotypes will be various dual-purpose chicken breeds. Recommendations based on GxE analysis in African chickens have proven to be insightful for animal breeding (Bekele et al. 2009; Ali, Katula and Syrstad, 2000; Lwelamira, 2012; Bamidele et al. 2019b; Lozano-Jaramillo, 2019; Yakubu, Salako and Ige, 2007). It can therefore be concluded that GxE analysis plays an important role while conducting animal breeding of African chickens, and the outcomes of this thesis will contribute to it. Yet, difficulties with breeding chickens for African smallholder farmers will remain present.

Background Information Breeds

Based on the PhD thesis of Lozano-Jaramillo (2019), most specifically on the discussion in the fourth chapter published as Lozano-Jaramillo et al. (2019) and on other external sources of literature a review was made about the chicken breeds evaluated in this thesis i.e.; Horro, Koekoek, Kuroiler, Sasso-Rhode Island Red (S-RIR) and Sasso.

Horro

Horro is the only native Ethiopian breed out of these five, belonging to an indigenous population in the western highlands of the country (Dana, Van der Waaij and Van Arendonk, 2011). The breed name is derived from the Horro district located in the Oromia region (Lozano-Jaramillo et al. 2019). The local chicken breed is the dominant breed type in the Horro district (only 2.8 to 7.2% being crossbreds) kept mainly under scavenging and low input conditions (Dessie et al. 2013). The Horro district is known for higher hatchability of eggs during the dry season due to a lower risk of diseases (Bettridge et al. 2018). Therefore, it can be stated that the Horro breed survives better during dry season (Lozano-Jaramillo et al. 2019).

Improved Horro hens (Getachew, Wondmeneh and Dessie, 2016).

The African Chicken Genetic Gain (ACGG) project (https://africacgg.net/), is the first attempt to look into adaptation possibilities of the breed to an on-farm environment and management conditions (Lozano-Jaramillo et al. 2019). The breeding program was established since 2008 only and is mainly focussing on genetical improvement of growth traits as this is preferred by local smallholder farmers (Wondmeneh et al. 2014a; Dana, Van der Waaij and Van Arendonk, 2011; Dana et al. 2010). It is found that egg production as well as body weight traits seem to have a strong genetic correlation, having common genes, making it a very promising dual-purpose breed to improve (Dana, Van der Waaij and Van Arendonk, 2011).

Esatu Wondmeneh published various papers about the genetic improvement of the indigenous Horro breed in Ethiopia while writing a PhD thesis. Main findings obtained from research at the Debre Zeit research station in Ethiopia are listed here. Most importantly, body weight at 16 weeks of age as well as egg number at week 45 of laying showed successful results of improvement after six generations of selection (Wondmeneh et al. 2014a). After seven generations, body weight, laying and survival performance traits were all significantly improved compared to the indigenous Horro population (Wondmeneh et al. 2016). Although, they mostly performed lower on these traits compared to a commercial layer breed and a crossbreed between RIR and improved Horro. On-farm testing in two districts in Oromia showed lower results for survival and especially laying traits compared to on-station for all four analysed breeds (Wondmeneh et al. 2016). On-station, improved Horro had the lowest hatchability of 35% to other commercial breeds and male life weight at 16 weeks was 103% of the local breed (Bamidele et al. 2019a). On-farm in Ethiopia, body weight of Horro females was about half the weight of the 4 introduced ACGG breeds (Koekoek, Kuroiler, S-RIR and Sasso), with higher egg producing performance of introduced than indigenous breeds (Abegaz et al. 2019). In general, results showed the mass-selection breeding to be successful for weight, laying and survival traits of local Horro (Wondmeneh and Dessie, 2019; Getachew, Wondmeneh and Dessie, 2016).

Other research on the Debre Zeit station showed the following. Horro obtained the lowest weight gain compared to another Egyptian Fayoumi breed during an experiment about effects of effective microorganisms addition to nutrition (Wondmeneh, Getachew and Dessie, 2011). This feed addition did result in a similar positive immunomodulatory effect in both indigenous African breeds, indicating

Horro has similar good immune responses to potential infectious diseases as other local breeds (Wondmeneh, Getachew and Dessie, 2012). In general, the Horro breed scores low for traits like egg weight, fertility, and hatchability but average for normal chick percentage and mean chick weight comparing it to three other breeds including Koekoek (Wondmeneh, Dawud and Adey, 2011). The survival levels of indigenous Horro is lower compared to Horro after seven generations of breeding for general improvement, while natural antibody levels are higher (Wondmeneh et al. 2015a). A crossbred between this 7th generation improved Horro and RIR had slightly higher survival and higher natural antibody levels compared to the purebred improved Horro breed (Wondmeneh et al. 2015a).

A benefit of genetically improving a local breed like Horro is that adoption by farmers is more accepted, as adoption of exotic breeds is more common among by Ethiopian farmers who have also other sources of income (Wondmeneh et al. 2014b). Although, interventions needed to achieve a higher productivity and income for smallholder farmers in Oromia using this improved Horror breed do not seem to outweigh the additional costs (Wondmeneh et al. 2015b).

Koekoek

Koekoek is a South African breed originating from a crossbred of three different breeds (Lozano-Jaramillo et al. 2019). This crossbred was made in the 1950's at the Potchefstroom Agricultural College using Black Australorp, White Leghorn and Barred Plymouth Rock as breed to cross (Getachew, Wondmeneh and Dessie, 2016). Therefore, the breed is also called Potchefstroom Koekoek in its complete name and can be considered as a locally developed breed. Roosters and culled hens are usually used for meat production. But the breed is also very popular amongst rural farmers from South Africa and neighbouring countries for meat as well as egg production and for the ability of hatching their own offspring (Lozano-Jaramillo et al. 2019; Getachew, Wondmeneh and Dessie, 2016). The colour pattern is based on a sex-linked gene which makes them easy to select while crossbreeding for egg producing traits (Getachew, Wondmeneh and Dessie, 2016).

Potchefstroom Koekoek chickens (Getachew, Wondmeneh and Dessie, 2016).

According to Lozano-Jaramillo et al. (2018) 13% of Amhara would be the best suitable Ethiopian Region for Koekoek based on GIS analysis, followed by 11% Oromia, 10% South Region and just 0.75% Tigray. This is due to Koekoek surviving better in areas having colder temperatures and with larger annual temperature fluctuations (Lozano-Jaramillo et al. 2018). In accordance with these findings, it was also shown that the Amhara region and areas with bigger temperature fluctuations are predicted to have higher male and female body weights for Koekoek using GIS (Lozano-Jaramillo et al. 2019). Additionally, Precipitation also seems to have an influence on predicted body weight especially when present during wet and warm periods (Lozano-Jaramillo et al. 2019).

More research of Koekoek performance in Ethiopia has been done. On-station, in the Southern Region (SR) Koekoek parent stock bred by European companies was ranked 2nd out of 5 breeds for lowest in feed consumption, body weight, egg production, and reproductive performance (Ibrahim et al. 2018). Most values found were comparable with an earlier report of Wondmeneh et al. (2011), apart from a lower feed intake and younger average age at first egg. On the Debre Zeit research station (45 km South-East of Addis Ababa, Oromia) Koekoek parent stock females scored 3rd out of 7 breeds for body weight with males scoring average while having a rather high feed intake (Ibrahim et al. 2019). Laying traits showed average performance again very similar to results of Wondmeneh et al. (2011). For hatchability and fertility traits Koekoek scored mostly highest with even more improvement when experimentally crossbred with other dual-purpose breeds (Ibrahim et al. 2019). On-farm in Oromia as well as on Debre Zeit station research confirm Koekoek to be more disease resistant compared to specialized crossbred layers when kept with low vaccination and management inputs (Esatu et al. 2011).

Research performed in Ethiopia, Nigeria and Tanzania looking at hatchability, body weight, egg and survival traits comparing the five ACGG breeds (Horro, Koekoek, Kuroiler, S-RIR and Sasso) showed to following for Koekoek. On-station in Ethiopia, male live weight at 16 weeks of age was only 167% of the local breed while this was 200-300% for most other commercial breeds (Bamidele et al. 2019a). On-farm in Ethiopia, female Horro weight was 56.3% of Koekoek, making Koekoek the lightest of all breeds (Abegaz et al. 2019). Egg production to 50 weeks of age were also lowest in comparison apart from the improved Horro breed (Abegaz et al. 2019).

Kuroiler

This is a dual-purpose breed, developed under humid conditions by Keggfarms in India to perform in low maintenance systems (Lozano-Jaramillo et al. 2019). This commercial hybrid chicken was made by crossing Rhode Island Red (RIR) females with either coloured broiler males or White Leghorn males (Getachew, Wondmeneh and Dessie, 2016). Kuroiler is known for having a low maintenance requirement and being able to thrive on household and agricultural waste, resulting in ability to produced 150-200 eggs annually under extensive management in Uganda (Getachew, Wondmeneh and Dessie, 2016).

Kuroiler chickens (Getachew, Wondmeneh and Dessie, 2016).

On station testing in Nigeria showed Kuroiler to be more suitable for the single purpose of meat production (Bamidele et al. 2019b). In this study Kuroiler had one of the lowest age at first egg (120 days) compared to five other breeds and mortality during brooding, growing, and laying was significantly higher compared to four breeds of local genetic sources (Bamidele et al. 2019b). Kuroiler tested on-farm in Uganda showed significantly higher predicted weight gain than indigenous chickens, indicating they can easily adapt and outperform local breeds under scavenging conditions (Sharma et al. 2015). Lozano-Jaramillo et al. (2019) showed with GIS analysis that the body weight distribution of Kuroiler was mostly influenced by environmental variables including precipitation. This supports the humid origin of Kuroiler and the statement of Ethiopian farmers preferring rain and precipitation causing higher vegetation and therefore lower predation of their chickens (Lozano-Jaramillo et al. 2019; Bettridge et al. 2018).

Comparing Kuroiler among the ACGG breeds (Horro, Koekoek, Kuroiler, S-RIR and Sasso) in Ethiopia, Nigeria and Tanzania gave the following performance for hatchability, body weight, egg, and survival traits. On-station in Tanzania Kuroiler had the lowest hatchability of 60% and lowest age at first egg of 123 days (Bamidele et al. 2019a). On-farm, female Kuroiler weight was 2nd heaviest after Sasso being 345% of local unimproved chickens in Tanzania and Horro being 46.2% of it in Ethiopia (Abegaz et al. 2019). Kuroiler also had the 2nd best egg producing traits on-farm in Tanzania and Ethiopia (Abegaz et al. 2019).

Sasso and S-RIR

Sasso is a commercial breed originating from warm and dry areas in Southern France where it was developed by breeding company SASSO (Getachew, Wondmeneh and Dessie, 2016; Lozano-Jaramillo et al. 2019). According to the GIS analysis of Lozano-Jaramillo et al. (2019) Sasso its weight performance is linked to temperature-associated variables supporting its warm origin. S-RIR is a crossbred of Sasso and Rhode Island Red (RIR) specifically made for the ACGG project on a private farm (Aman et al. 2017). Therefore, there are no other studies present about S-RIR performance evaluation under scavenging conditions (Lozano-Jaramillo et al. 2019). Diverse environmental variables were associated with body weight distribution of S-RIR at different ages, suggesting the breeds response to environment is depending on age (Lozano-Jaramillo et al. 2019).

Sasso rooster (Getachew, Wondmeneh and Dessie, 2016).

Lozano-Jaramillo et al. (2019) predicted the purebred Sasso to be heavier than S-RIR during a growing period of week 14 to 19 of age. Both breeds outperformed the other ACGG breeds (Horro, Koekoek and Kuroiler) indicating they can deal with low-input conditions and are interesting for further on-farm testing in Ethiopia (Lozano-Jaramillo et al. 2019). In Nigeria, purebred Sasso was shown to be more suitable for single purpose meat production while tested on-station (Bamidele et al. 2019b). In this study, Sasso had the highest hatchability of 89% but also a significantly higher mortality than four locally sourced chicken breeds during brooding, growing, and laying (Bamidele et al. 2019b).

Compared to the other ACGG breeds (Horro, Koekoek and Kuroiler) kept on-station in three African countries Sasso had the highest hatchability of 88% and 89% in Tanzania and Nigeria respectively while S-RIR had the highest in Ethiopia being 69% (Bamidele et al. 2019a). In Ethiopia, male live weight at 16 weeks of age was only 170% of the local breed for S-RIR, while this was 200-300% for most others including purebred Sasso. Sasso had the lowest age at first egg of 123 days in Tanzania and S-RIR had the lowest in Ethiopia of 124 days. Both breeds had the highest hen-housed egg production in all three countries being 166 for Sasso and 111 for S-RIR (Bamidele et al. 2019a).

On-farm performance in the same three countries comparing it to the same ACGG breeds showed Sasso to have the highest and S-RIR to have the second lowest female weights being 44.6% and 52.4% of Horro in Ethiopia (Abegaz et al. 2019). Egg production to 50 weeks of age was highest for S-RIR while Sasso was exactly producing in the middle compared to the other breeds. In Tanzania Sasso was the biggest egg producing breed over a 44-week period while also having the highest female body weight at 18 weeks of 364% unimproved local chicken. In general, it may be stated that the introduced breeds, among them Sasso and S-RIR, performed better for egg producing traits than indigenous breeds (Abegaz et al. 2019).

Ethiopian Environments

Ethiopa is a very diverse country having nine official regional states and five traditional Agro-Ecological Zones (AEZ) (Lozano-Jaramillo et al. 2018; Deressa, Ringler and Hassan,. 2010). For this reason, Lozano-Jaramillo et al. (2018) chose this country to perform her first GIS analysis about prediction of breed suitability for different AEZ. In this thesis a GxE analysis on body weight traits was performed, using five of those Ethiopian Regions or states (AA:Addis Ababa, AM:Amhara, OM:Oromia, SNNP:Southern Nations Nationalities and People's Region or SR:South Region and TG:Tigray) being part of three AEZ (cool humid, cool sub humid and warm semi-arid) as environments. Based on the PhD thesis of Lozano-Jaramillo (2019), information of the government of Ethiopia (FDRE, 2018), and other sources of literature the following review about the five Ethiopian Regions and three AEZ was made. Climate descriptions for Ethiopian environments chickens were placed in for the body weight and laying trait analyses are given in the Material & Methods section in Tables 1 and 4, respectively.

Ethiopian Regions

The five Ethiopian Regions were Addis Ababa (AA), Amhara (AM), Oromia (OM), Southern Nations Nationalities and People's Region (SNNP) or South Region (SR) and Tigray (TG) each being subdivided in zones and eventually districts (also called woredas) in which smallholder farmers were living who got chickens for the ACGG project assigned (Figure 1).

AA is a small region located right in the middle of Ethiopia being in a cool humid AEZ for body weight (BW) data of this thesis. It is covering the diplomatic capital, Addis Ababa, which is located at altitude of 2200-2500 meters above sea level (FDRE, 2018). Climate is described as mild, Afro-Alpine temperate and warm temperate with lowest and highest mean annual temperature between 10 and 25 °C (FDRE, 2018).

AM is located more up north bordering TG in the north and OM in the south. It is a much bigger region having a cool as well as cool sub humid AEZ in BW data used in this thesis. According to the government of Ethiopia AM can be divided into two main parts being highlands of 1500 meter and lowlands of 500-1500 meter above sea level (FDRE, 2018). The annual mean temperature is for most parts of AM between 15-21 °C while AM receives the highest percentage (80%) of total rainfall in Ethiopia (FDRE, 2018). It was therefore that AM had the highest predicted body weight for a breed as Koekoek, due to its large annual temperature fluctuations and high precipitation, the later causing higher vegetation and lower chicken predation (Lozano-Jaramillo et al. 2019; Bettridge et al. 2018).

OM is the biggest region of all five located in the middle of Ethiopia surrounding AA, being part of cool sub humid and warm semi-arid AEZ. The government of Ethiopia describes the topography and climate of the region as having great physiographic diversity with rich natural resource bases (FDRE, 2018). Its landscape includes mountain ranges, plateaus, gorges, and incised river valleys ranging from 500 meter above sea level till the 4607-meter-high Mt. Batu. The climatic types in OM could be grouped into three major categories: the dry climate, tropical rainy climate, and temperate rainy climate (FDRE, 2018). Annual mean temperatures with mean annual rainfall are 27°C to 39°C with less than 450 mm, 18°C to 27°C with 410-820 mm and less than 18°C in coolest month with 1200-2000 mm for all these categories respectively (FDRE, 2018).

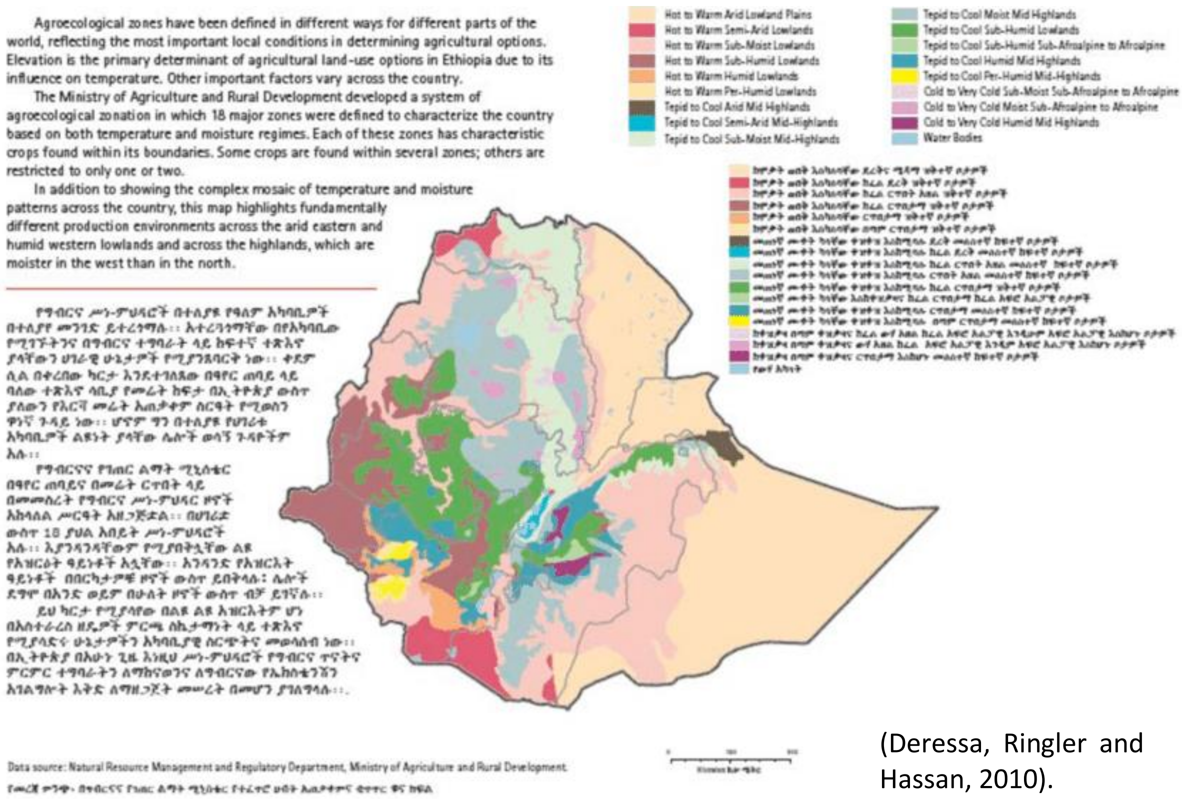
The indigenous Horro breed was obtained from OM, more specifically from the Horro district located in the western wet highlands of OM at an altitude of 2580 to 2810 meter above sea level (Dessie et al. 2013; Lozano-Jaramillo et al. 2019). The situation of the specific Horro district is not representative for all of OM as various studies show poultry keeping and climatic conditions in Horro are very different from other districts like Ada and Jarso (Dessie et al. 2013; Bettridge et al. 2018).

As the name explains SNNP or SR is located in the South. SR has just like AM and OM a big environmental variability and therefore two AEZ in the BW data being cool humid and cool sub humid. About 56 % of the total area of SR are found below 1500 meters elevation being mostly hot low land while the other 44% is found in the temperate climatic zone. Mean annual rainfall is 500-2200 mm and mean annual temperature is 15°C to 30°C (FDRE, 2018).

TG is located most up north of all regions and is included in the cool sub humid AEZ for the BW data in this thesis. Erosion, deforestation, and overgrazing caused TG to be dry and treeless (FDRE, 2018). Overall elevation ranges from 600-2700 meter above sea level with extremities of 550 gorges and 3250-3500 mountain chains including a 3935 'Kisad Gudo' peak. Three climate types can be found in TG being 39% semi-arid, 49% warm temperate and 12% temperate with mean annual rainfall between 450-980 mm (FDRE, 2018).

Agro-Ecological Zones (AEZ)
For this MSc thesis about BW traits three AEZ were in the data defined by the ACGG project being; cool humid, cool sub humid and warm semi-arid. According to the government of Ethiopia there are three principal climate groups in the country; tropical rainy climate, dry climate, and warm temperate rainy climate (FDRE, 2018). The mean maximum temperature is higher from March to May and mean minimum temperature is lower from November to December. There is a dry season from October to May and a rainy season from June to September in Ethiopia (FDRE, 2018). Three AEZ are recognized by the government of Ethiopia being; Dega (cool to cold temperature), Weina Dega (warm to cool climate) and Kolla (warm to hot climate) (FDRE, 2018). Average annual temperatures with altitudes for these AEZ are 10°C to 16°C with above 2500 meter, 16°C to 20°C with 1500 to 2500 meter and 20°C to 30°C with 500 to 1500 meter above sea level, respectively. Dega is typical for cool highlands, Weina Daga AEZ is also mostly in highlands while Kolla is the climate present in hot lowlands (FDRE, 2018).

Lozano-Jaramillo et al. (2018) referred to (Deressa, Ringler and Hassan, 2010) while defining AEZ for predicting breed suitability among them. According to Deressa, Ringler and Hassan (2010) there are five traditional AEZ of which three are similar to the ones recognized by the government of Ethiopia (FDRE, 2018). In reality the AEZ can be more subdivided in 18 major AEZ with eventually 49 AEZ based on combining growing periods with temperature and moisture regimes (Deressa, Ringler and Hassan, 2010). A map of Ethiopia displaying the 18 major AEZ and a table giving information about the five traditional AEZ are displayed below in Figure 2. Just like another map of a more recent paper of Amede et al. (2017) using similar descriptions as the AEZ of the ACGG project. It can be concluded that AEZ definition can slightly differ comparing various scientific sources, but a general idea about AEZ definition in Ethiopia can be derived from these examples (Figure 2).



(Deressa, Ringler and Hassan, 2010).

Table 1: Traditional climatic zones and their physical characteristics

Zone	Altitude (meters)	Rainfall (mm/year)	Average annual temperature (°C)
Wurch(upper highlands)	3200 plus	900 – 2200	>11.5
Dega(highlands)	2,300 – 3,200	900 – 1,200	17.5/16.0–11.5
Weynadega(midlands)	1,500 – 2,300	800 – 1,200	20.0–17.5/16.0
Kola(lowlands)	500 – 1,500	200 – 800	27.5 – 20.0
Berha(desert)	Under 500	Under 200	>27.5

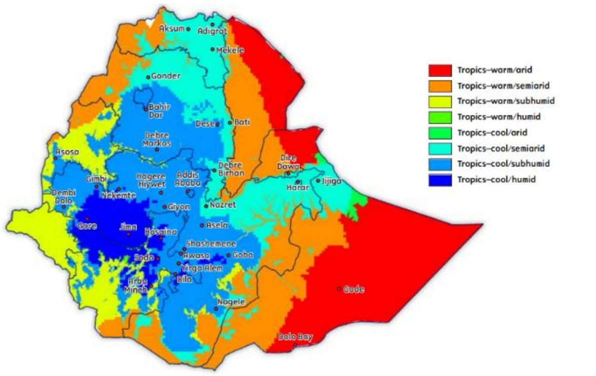


Figure 2. Agroecological zones of Ethiopia, based on Global 16 Class classification system (Sebastian 2009)

Figure 2. Map of Ethiopia showing 18 Agro-Ecological Zones (AEZ) based on combined growing periods with temperature and moisture regimes with table of five traditional AEZ of Deressa, Ringler and Hassan (2010). Another map of Ethiopia showing slightly different AEZ based on a research of Amede et al. (2017).

Material & Methods

BW in Ethiopia

Data Collection

Five chicken breeds (Horro, Koekoek, Kuroiler, S-RIR and Sasso) were placed and tested in over 63 villages in five Ethiopian Regions (Figure 1; AA:Addis Ababa, AM:Amhara, OM:Oromia, SR:South Region and TG:Tigray). Among the Ethiopian Regions broadly three different Agro-Ecological Zones (AEZ) were present (cool humid, cool sub humid and warm semi-arid). Table 1 describes climates of Ethiopian Regions indicating their AEZ. Six-week old chicks were placed in a total of 1393 households with approximately 25 chicks of one breed per household, while each of the different breeds were present in each village. Breed distribution started in August 2016 and data collection ended in January 2018 (Lozano-Jaramillo et al., 2019). Data on live body weight (BW) was collected every four weeks as a group measurement and average individual BW was derived from the total live body weight and dividing by number of birds. BW at four different ages (90, 120, 150 and 180 days) were predicted performing linear interpolation between neighboring ages of weighing obtained from the collected data.

Table 1. Climate description of five Ethiopian Regions (AA:Addis Ababa, AM:Amhara, OM:Oromia, SR:South Region and TG:Tigray) among which three Agro-Ecological Zones (AEZ) present (cool humid, cool sub humid and warm semi-arid) based on the government of Ethiopia (FDRE, 2018). Mean annual temperature and rainfall, altitudes and AEZ are given.

Region	**AA**	**AM**	**OM**	**SR**	**TG**
Climate description	Mild, Afro-Alpine temp-, warm temperate	25% cool to cold, 44% warm to cool, 31% warm to hot	Big diversity; dry, tropical rainy climate, temperate rainy	56% hottest lowland, 44% temperate	39% semi-arid, 49% warm temp-, 12% temperate
Temp. (˚C)	9.9-24.6	15-21	18-39	15-30	-
Rain (mm)	-	80% Ethiopia	410-2000	500-2200	450-980
Altitude (m)	2200-2500	High >1500, Low 500-1500	>500-4607	376-4207 56% <1500	600-2700
AEZ	Cool humid	Cool humid, cool sub humid	Cool sub humid, warm semi-arid	Cool humid, cool sub humid	Cool sub humid

Data Cleaning

The data was already partly cleaned before BW at the four specific ages (90, 120, 150 and 180 days) was predicted. This was done by excluding all chickens with age below 50 and above 300 days, and by excluding chickens with BW below 50 or above 6000 grams (Lozano-Jaramillo et al. 2019). The cleaned dataset contained a total of 1988 chickens of which 999 females and 989 males. After predicting BW at 90, 120, 150 and 180 days of age the data was checked for normality by making Q-Q plots of these BW plotted against as the Ethiopian Regions and AEZ. To reduce outliers made visible by these plots and to create similarity with growth curves in other scientific papers about other local African or introduced chickens the data was again cleaned per BW at specific age (Osei-Amponsah et al. 2014; Youssao et al. 2012). Restriction values for cleaning are given in Table 2.

Table 2. Restriction values used to clean data of predicted body weight (BW) at four different ages. Minimum and Maximum values are given in grams.

Age BW (days)	Min (g)	Max (g)
90	200	2500
120	300	3000
150	400	3500
180	500	4000

Ranges of numbers of birds at all different ages eventually used for analyses are displayed per breed, per sex, per environment in Table 3. Means and standard deviations per predicted BW at every certain age, per breed and per sex are given for as well Ethiopian Regions as AEZ in Appendix Table 1.

Table 3. Ranges of numbers of birds displayed per breed (Horro, Koekoek, Kuroiler, S-RIR and Sasso), per sex (F:female and M:male) and per environment (Ethiopian Region or Agro-Ecological Zone:AEZ) analysed. Five Ethiopian Regions (AA:Addis Ababa, AM:Amhara, OM:Oromia, SR:South Region and TG:Tigray) and three AEZ (cool humid, cool sub humid and warm semi-arid) are analysed. Ranges are based on number of birds available at four different ages (90, 120, 150 and 180 days) being mostly close to each other.

Region	**AA**		**AM**		**OM**		**SR**		**TG**	
Sex	**F**	**M**	**F**	**M**	**F**	**M**	**F**	**M**	**F**	**M**
Horro	37-39	32	7-41	3-43	44-47	26-29	17-23	28-30	0	8
Koekoek	82	61-63	105-108	81-85	61-62	35-37	33-35	36-39	0	73
Kuroiler	7-40	0-2	96-100	59-62	7-8	4-7	31-35	59-63	0	44
S-RIR	43	39-40	95-103	63-65	13-16	8	32-33	63-65	0	41-43
Sasso	0	0	95-98	71-72	31-40	4-5	32-35	58-61	0	9

AEZ	**cool humid**		**cool sub humid**		**warm semi-arid**	
Sex	**F**	**M**	**F**	**M**	**F**	**M**
Horro	44-79	35-66	45-48	44-48	19	18-19
Koekoek	135-138	100-102	112-122	164-167	26-27	26-27
Kuroiler	60-96	28-30	81-86	142-146	0	0
S-RIR	87-94	57-58	96-101	159-163	0	0
Sasso	52	33-36	106-121	109-111	0	0

Statistical Analysis

A fixed effects linear model was implemented, using PROC GLM, SAS version 9.4. Two models were used to calculate the effect of the genotype environment interaction (GxE) on the phenotype; predicted BW at four different ages. [1] being a simple model with the effects of breed and environment and their interaction and [2] being a complex model including additionally the sex of the birds and all types of interaction;

$$y_{ijk} = \mu + Breed_i + Environment_j + BxE_{ij} + e_{ijk} \quad [1]$$

$$y_{ijk} = \mu + Breed_i + Environment_j + Sex_k + BxE_{ij} + BxS_{ik} + ExS_{jk} + BxExS_{ijk} + e_{ijkl} \quad [2]$$

$y_{ijk(l)}$ is the predicted BW at either 90, 120, 150 or 180 days of age; μ is the mean; $Breed_i$ is the fixed effect of genotype, or breed (n=5); $Environment_j$ is the fixed effect of the environment, being either Ethiopian Region (n=5) or AEZ (n=3); Sex_k is the fixed effect of sex (n=2); BxE_{ij} is the fixed effect of breed by environment pairwise interaction, so the GxE; BxS_{ik} is the breed by sex interaction; ExS_{jk} is the environment by sex interaction; $BxExS_{ijk}$ is the triple interaction between all three main fixed effects; $e_{ijk(l)}$ is the random residual assumed to be $\sim N(0, I\sigma^2{}_e)$, with I being an identity matrix and $\sigma^2{}_e$ the residual variance.

Significance tests of the main as well as interaction components in models [1] and [2] were carried out using analysis of variance (ANOVA). Model [2] is the most complete version of the complex model eventually used. This complete model was adjusted in a stepwise manner to include only significant effects. The non-significant interaction effect with the highest P-value was excluded first and the model was run again. If non-significant effects were found, the effect with the highest p-value was again excluded. Non-significant main effects were only excluded if they were not involved in a significant interaction. In case of a significant three-way interaction, the full model was kept. Eventual derived complex models are displayed per age in the results section. Graphs showing the GxE were produced by plotting the breed's predicted BW, using the model derived from [2], against the environments (Ethiopian Region or AEZ) for each sex at each age separately.

Egg Number and Egg Weight in Oromia

Data Collection and Cleaning

Five chicken breeds (S-RIR, Sasso, Horro, Kuroiler and Koekoek) were distributed over 222 households located in 13 villages in the Ethiopian Oromia region. These are located in three zones of Oromia (East Hararge, East and West Shoa) among which 5 districts (Adami Tulu Jido Kombolcha, Bako Tibe, Dano, Dugda and Haromaya) all being part of a cool sub humid Agro-Ecological Zone. Information about climate of each district is given in Table 4. Fertile eggs of all introduced breeds (S-RIR, Sasso, Kuroiler and Koekoek) were imported in 2016 (Lozano-Jaramillo et al. 2019). Distribution started in August 2016 by giving away approximately 25 six-week old chicks of one breed per household. Data collection ended in January 2018 (Lozano-Jaramillo et al. 2019). Egg number and egg weight data was collected as a group measure per household resulting in a total of 1163 observations. Average egg number per hen and egg weight per egg were derived by dividing totals measured by number of ACGG hens per household and number of weighted eggs per household, respectively.

Table 4. Climate description of five Ethiopian districts (Adami Tulu Jido Kombolcha, Bako Tibe, Dano, Dugda and Haromaya) being part of three zones (East Hararge, East and West Shoa) in Oromia. Mean annual temperature and rainfall (or ranges of it) and altitudes are given.

Zone	**East Harage**	**East Shoa**		**West Shoa**	
District	**Haromaya**	**Adami Tulu**	**Dugda**	**Bako Tibe**	**Dano**
Climate	Tropical rainy + Tropical dry	Fluctuating bimodal rain pattern	Sub-tropical, bimodal rain pattern	70-80% rain received in June – Sept.	-
Temp. (˚C)	16.34 (10-26)	14-27	19-23	15-28	15-30
Rain (mm)	819.2	748	500-900	1244-1260	900-1400
Altitude (m)	High + low land areas	1500-2300	1500-2300	1586	80%: 1500-2200
Sources	(Mohammed, Mohammed and Kebeta, 2017) (Oromia BOFED, 2009)	(Shiferaw, 2008) (de Putter et al. 2012)	(Oromia BOFED, 2009)	(Oranu et al. 2018)	(Kassie et al. 2007)

For reliability, data cleaning was conducted. Data of households containing eggs of hens before ACGG breed introduction was deleted to prevent miscounting. Restrictions per hen were set to minimal 1 and maximal 30 eggs over a month (30 days) period for egg number and minimal 20 and maximal 80 grams for egg weight. 894 observations were left to analyse for both traits. Normality was checked making Q-Q plots, plotting egg number or egg weight against zone or district. Means and standard deviations are given per breed per traits per zone or district in Appendix Table 2.

Statistical Analysis

To calculate the effect of the genotype environment interaction (GxE) on the two phenotypes, a weighted fixed effects linear model was implemented, using PROC GLM, SAS version 9.4. The two phenotypes were egg number and egg weight. Household observations averages of those phenotypes were based on were added as weight statements, being number of ACGG hens and number of weighted eggs, respectively. Model and weight statement are;

$$y_{ijk} = \mu + Breed_i + Environment_j + BxE_{ij} + e_{ijk}$$

$$\sum w_{ijk} \left(y_{ijk} - \hat{y}_{ijk}\right)^2$$

$\hat{y}_{ijk}$ is the predicted egg number per hen per month or egg weight per egg; μ is the mean; $Breed_i$ is the fixed effect of genotype, or breed (n=5); $Environment_j$ is the fixed effect of the environment, being either Zone (n=3) or district (n=5); BxE_{ij} is the fixed effect of breed by environment pairwise interaction, so the GxE; e_{ijk} is the random residual assumed to be $\sim N(0, I\sigma^2{}_e)$ with identity matrix I and residual variance $\sigma^2{}_e$. w_{ijk} are the ACGG hen number and weighted egg number variables used in the weight statements for egg number and egg weight traits respectively; y_{ijk} is the observed value of both traits. Significance tests of the main effects as well as the interaction effects in the model were carried out using analysis of variance (ANOVA). Graphs showing the GxE were produced by plotting the breed's predicted egg number or egg weight against the environments (zone or district).

Results

BW in Ethiopia

Simple GxE Model

The results of model [1], including breed, environment (alternatively Ethiopian Region or AEZ) and their interaction showed high significance (p<0.0001) for main effects (breed and environment) as well as the GxE effect for all age classes (90, 120, 150 and 180 days). This was the case when taking Ethiopian Regions as well as AEZ as environment. GxE therefore seems to be present in all cases. Elaborate overview of the GxE plots derived from this simple GxE analysis is given in Appendix Figure 4.

Complex GxE Model for Ethiopian Regions

The complex model [2] with breed, environment, sex and all their two-way and three-way interactions showed highly significant GxE (i.e. Ethiopian Region by Breed) effects (p<0.0001; bold in Table 5) when using Ethiopian Region as environment. P-values of other effects in the derived models of [2] for predicted BW at different ages are also shown in Table 5, exposing the eventual structure of those models.

Table 5. Significance displayed as p-values of effects of eventually used models derived from the complex model [2] displayed per age (90, 120, 150 or 180 days) using Ethiopian Region as environment. GxE effect, in this case Region by Breed effect displayed in bold.

Effect:	Region	Breed	Sex	**RxB**	RxS	BxS	RxBxS
90	< 0.0001	< 0.0001	< 0.0001	**< 0.0001**	0.0419	0.0068	-
120	< 0.0001	< 0.0001	< 0.0001	**< 0.0001**	-	-	-
150	< 0.0001	< 0.0001	< 0.0001	**< 0.0001**	-	0.0011	-
180	< 0.0001	< 0.0001	< 0.0001	**< 0.0001**	-	0.0002	-

Figure 3 shows GxE plots for final models, using Ethiopian Region as environment, on data of which means, standard deviations and numbers are given in Appendix Table 1. Sex by Region plots made for each breed separately, derived using the same models and data, are given in Appendix Figure 5. Most important results taken from all these plots are that at an early age mainly Sasso has the highest predicted BW especially in the OM, AM and TG regions. At the later age, Kuroiler shows to have high predicted BW in AA and other regions while even later female S-RIR and Koekoek have high predicted BW in this region. Horro showed to have lowest predicted BW in every region except SR. SR did not show much spread of predicted BW compared to other regions. TG had the highest predicted BW at every age. No Sasso was present in AA and no females were present in TG. BW of females were predicted based on male data if no region by sex effect was present.

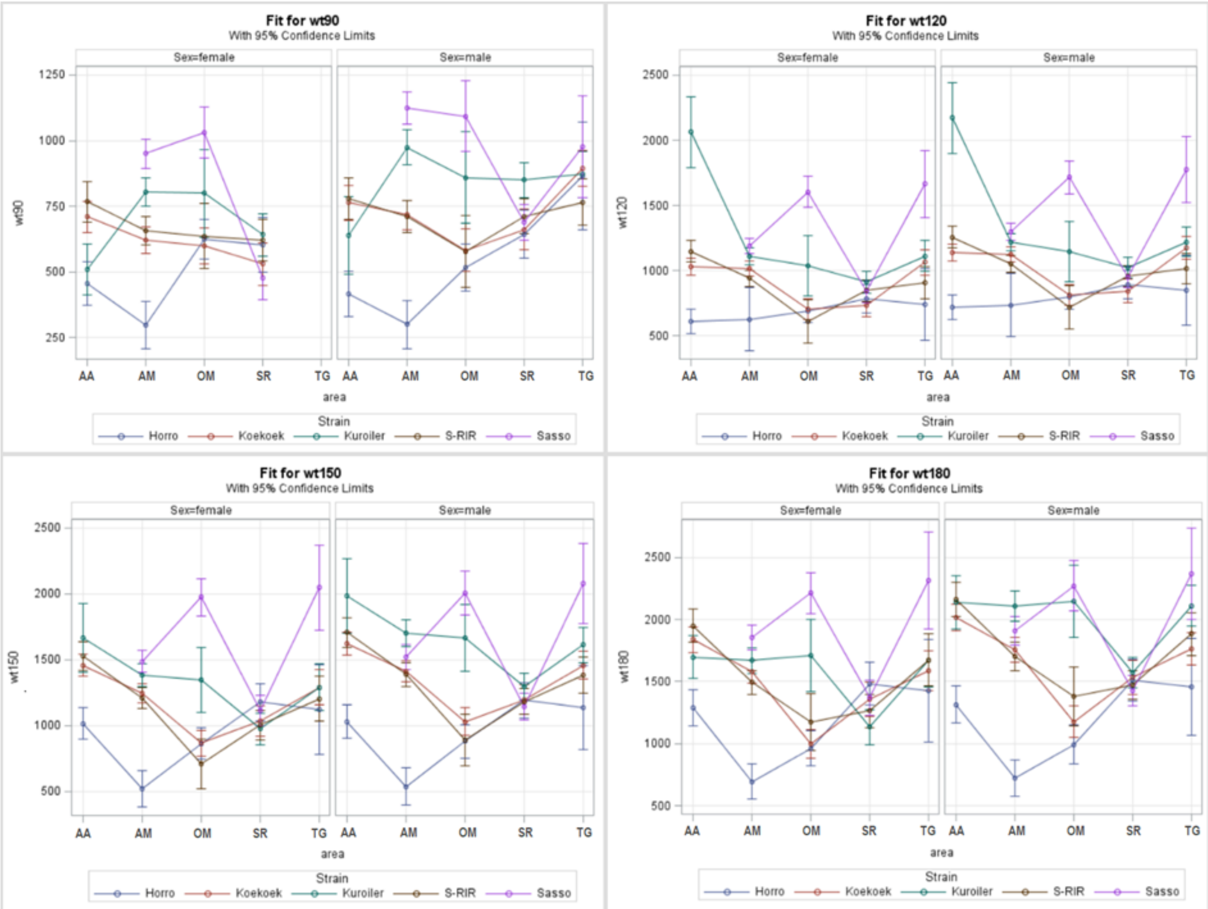


Figure 3. GxE plots made using derived models from complex model [2] (effects given in Table 5) displayed per sex (female or male) and per predicted BW at certain age (90, 120, 150 or 180 days). Ethiopian Region was used as environment while analysing.

Complex GxE Model for Agro-Ecological Zones

High significance (p<0.0001; bold in Table 6) of the GxE effects was found in models derived from complex model [2] when using Agro-Ecological Zone as environment. The eventual structure of those models is displayed in the form P-values of its effects shown in Table 6.

Table 6. Significance displayed as p-values of effects of eventually used models derived from the complex model [2] displayed per age (90, 120, 150 or 180 days) using Agro-Ecological Zones (AEZ) as environment. GxE effect, in this case AEZ by Breed effect displayed in bold.

Effect:	AEZ	Breed	Sex	**AxB**	AxS	BxS	AxBxS
90	0.0057	< 0.0001	0.0006	**< 0.0001**	0.8416	0.0016	< 0.0001
120	0.0001	< 0.0001	< 0.0001	**< 0.0001**	-	0.0087	-
150	< 0.0001	< 0.0001	< 0.0001	**< 0.0001**	-	< 0.0001	-
180	< 0.0001	< 0.0001	< 0.0001	**< 0.0001**	-	< 0.0001	-

GxE plots made while conducting the derived models, using AEZ as environment are shown in Figure 4. Means, standard deviations and numbers of data used for this analysis are given in Appendix Table 1. Sex by Region plots made for each breed separate, derived using the same models and data, are given in Appendix Figure 5. From these plots the following results can be derived; at an early age mainly Sasso has the highest predicted BW. This continues to be especially for the females in the cool sub-humid AEZ. At later ages also Kuroiler, Koekoek and S-RIR perform well, especially in cool sub-humid AEZ. Particularlsy at early age there was less spread present in this AEZ while having the highest predicted BW. At later age this lower spread became less clear for females, while at age 180 days cool humid had the highest predicted BW. Horro shows to have the lowest predicted BW in all AEZ, apart from female Koekoek at late age. No Kuroiler, S-RIR or Sasso was present in warm semi-arid AEZ.

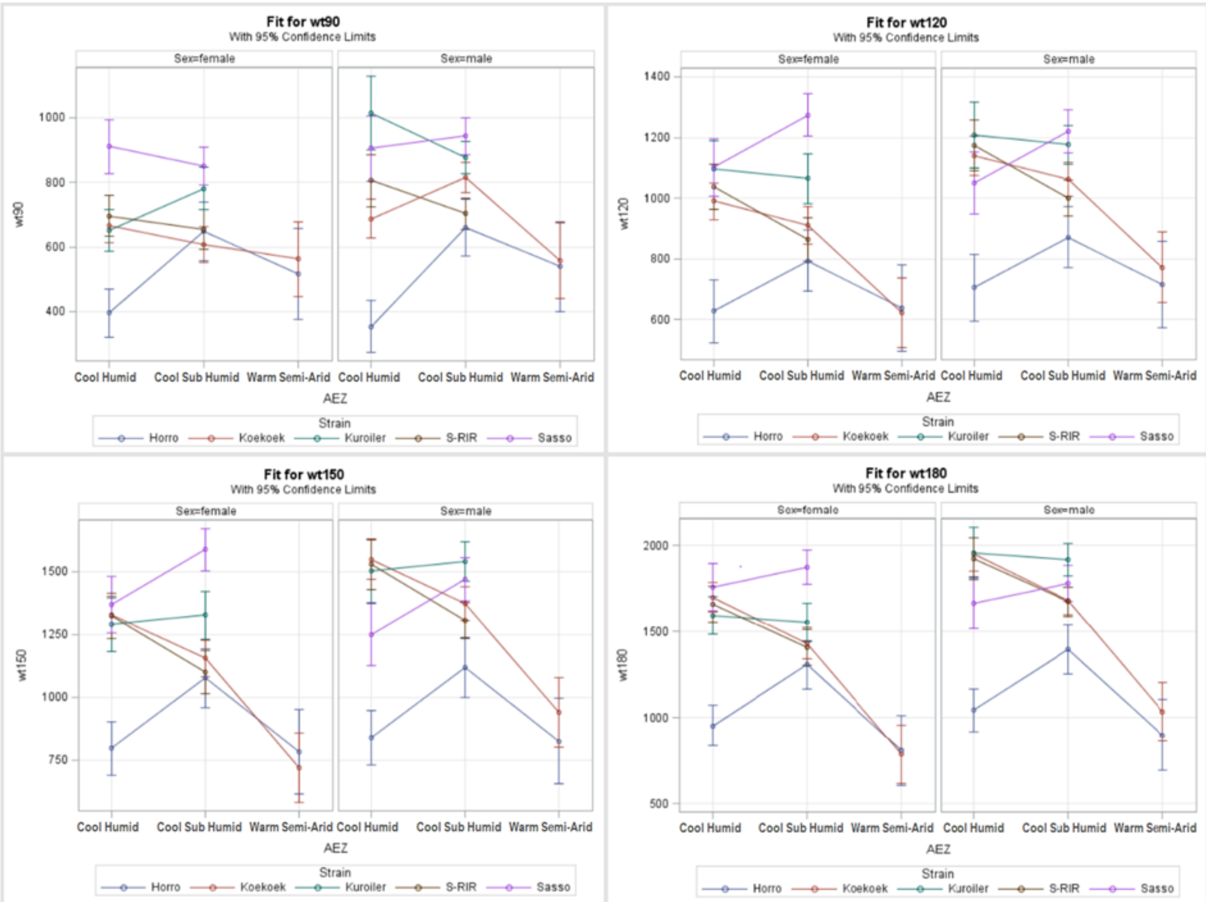


Figure 4. GxE plots made using derived models from complex model [2] (effects given in Table 6) displayed per sex (female or male) and per predicted BW at certain age (90, 120, 150 or 180 days). Agro-Ecological Zones (AEZ) used as environment while analysing.

Egg Number and Egg Weight in Oromia

Egg Number

The results of the GxE model, including breed, environment (alternatively zone or district) and their interaction showed significance ($p<0.01$) for main effects (breed and environment) as well as the GxE effect for the egg number trait. P-values are giving in Table 7 with GxE effects highlighted bold. Main effects and breed by zone effect were most highly significant, breed by district effect was significant to a lesser extent.

Table 7. Significance displayed as p-values of effects of GxE model looking at egg number as a trait. GxE effect is in this case Breed by Environment effect (BxE) displayed in bold with two environments analysed: zone and district.

Effect:	Breed	Environment	**BxE**
Zone	< 0.0001	< 0.0001	**0.0002**
District	0.0003	< 0.0001	**0.0057**

Figure 5 shows boxplots derived from GxE model predicting egg number per month per hen as a performance trait, environment being zone. Horizontal lines in the box represents breeds median, length box represents interquartile range and big circle in or close to box represents breeds mean. Exact Least square means (LSmean) and standard errors (SE) of GxE model given in Table 8. Nested zone district effect was not significant, hence no relevance of displaying analyses of district as environment. Numbers of observations, sums of weights, means and standard deviations of subsets of data per breed and zone/district are given in Appendix Table 2. Appendix Figure 6 displays GxE plots predicting egg number and egg weight, environments being both zone and district.

Key results were S-RIR being predicted to have the highest egg number in East Hararge, followed by Kuroiler in East Shoa. S-RIR was the only breed present in East Hararge zone (Figure 5, Appendix Table 2) and had highest predicted egg number in every zone compared to every breed apart from this exception of Kuroiler. East Hararge zone showed therefore highest predicted egg numbers. Kuroiler as a breed was only present in East Shoa zone, just like Koekoek was only present in West Shoa (Figure 5, Appendix Table 2). Horro and Sasso had similarly low predicted egg numbers. Predicted egg numbers of all breeds in West Shoa were closer to each other, or less spread, than in East Shoa. Meaning smaller distance between predicted egg number in West Shoa, being lower for S-RIR and higher for Horro and and Sasso compared to East Shoa. Predictions for Bako Tibe district, part of West Shoa zone were based on four observations only (Appendix Table 2).

Table 8. Least square means (LSmean) and standard errors (SE) of GxE model. GxE was Breed (S-RIR, Sasso, Horro, Kuroiler and Koekoek) Zone (East Hararge, East and West Shoa) effect on egg number.

	East Hararge	East Shoa	West Shoa
	LSmean(SE)	**LSmean(SE)**	**LSmean(SE)**
S-RIR	8.94(±0.37)	7.64(±0.35)	6.69(±0.42)
Sasso	-	3.96(±0.49)	5.61(±0.67)
Horro	-	3.50(±0.32)	5.76(±0.52)
Kuroiler	-	8.91(±0.49)	-
Koekoek	-	-	6.00(±0.63)

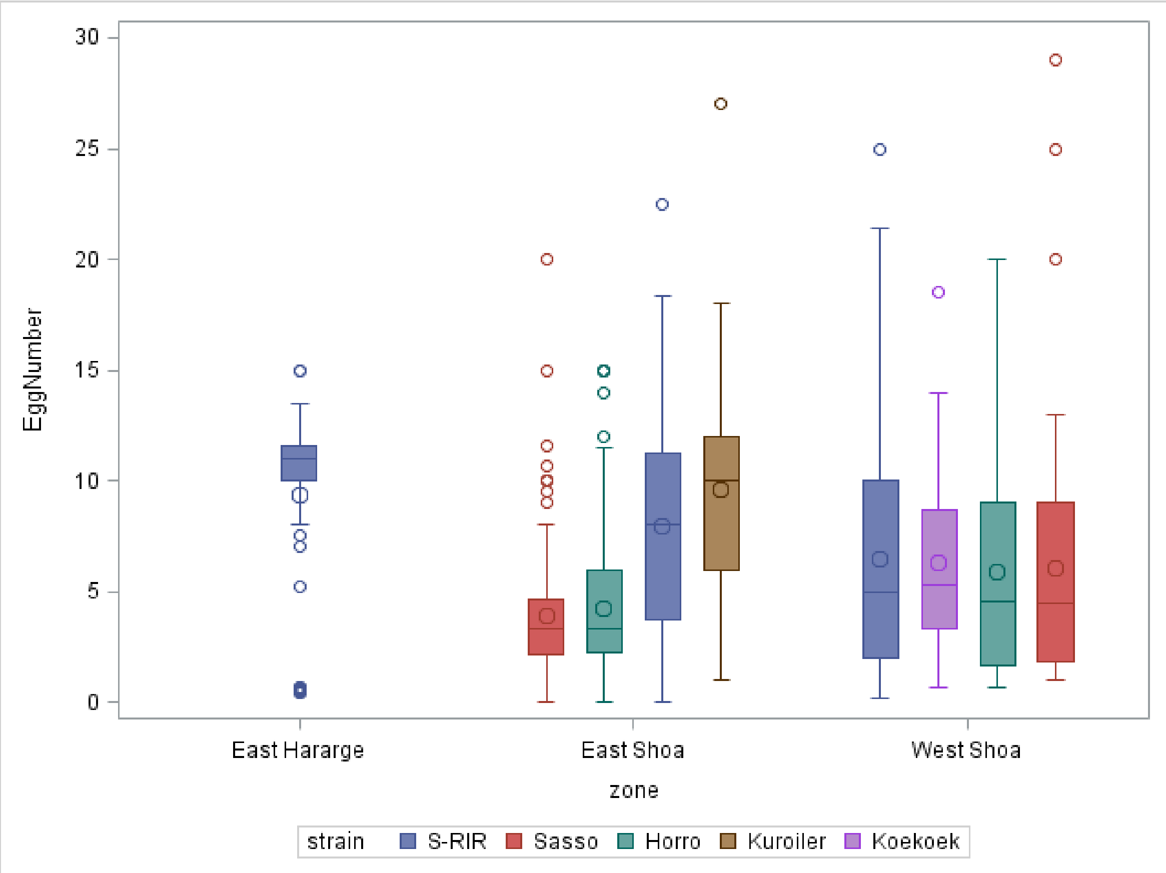


Figure 5. GxE model boxplots made using breed zone interaction model predicting egg number. Lines in box represents breed median, big circle breed mean. Tables 7 and 8 display model effects and least square means with standard errors, respectively.

Egg Weight

Table 9 shows p-values of main and GxE model effects for egg weight. For the zone effect both breed and environment were significant (p<0.05) and highly significant (p<0.0001). For the district effect only, environment was highly significant (p<0.0001). GxE effects are highlighted bold with none of them significant. GxE plots predicting egg weight but and egg number, are displayed in Appendix Figure 6, environments being both zone and district.

Table 9. Significance displayed as p-values of effects of GxE model looking at egg weight as a trait. GxE effect is in this case Breed by Environment effect (BxE) displayed in bold with two environments analysed: zone and district.

Effect:	Breed	Environment	**BxE**
Zone	0.0392	< 0.0001	**0.8137**
District	0.2248	< 0.0001	**0.1973**

Because of lacking GxE significance, LSmean and SE of model run containing only breed and zone main effects are given in Table 10. District as main effect is not displayed as nested zone district effect showed no significance.

Results showed Koekoek followed by S-RIR breed and West Shoa zone having highest predicted egg weights. Koekoek has high SE as it is based on n=35 animals. Sasso followed by Horro have low predicted egg weights.

Table 10. Least square means (LSmean) and standard errors (SE) of model containing breed and zone main effects on egg weight.

		LSmean(SE)
Breed	S-RIR	49.62(±0.64)
	Sasso	46.20(±1.19)
	Horro	47.56(±0.98)
	Kuroiler	48.65(±1.20)
	Koekoek	51.39(±1.81)
Zone	East Hararge	53.05(±1.50)
	East Shoa	35.30(±0.64)
	West Shoa	57.70(±0.77)

Discussion

BW in Ethiopia

The GxE was shown to have a highly significant effect ($p<0.0001$) while using the simple model [1] as well as the final models derived from the complex model [2] including sex (Tables 5 and 6 in bold). This directly answers the first research question meaning different breeds do react differently to the environments of the various Ethiopian Regions or AEZ for predicted BW at all ages.

To answer the second research question i.e. which breed performs best in which environment in terms of predicted BW, more in depth looks to GxE plots of final models derived from [2] needed be done. This research question was most important as this information is very beneficial for the Ethiopian smallholder farmers in their respective environments.
Results of the GxE plots using Ethiopian Regions as environments showed that at an early age Sasso was mainly having the highest predicted BW especially in the OM, AM and TG regions followed by Kuroiler in AA (Figure 3). This shows similarity with Lozano-Jaramillo et al*.* (2019) predicting BW of males in the growing phase (week 14-19) to be highest for Sasso followed by Kuroiler. Results reported by Lozano-Jaramillo et al. (2019) on females predicted BW did differ slightly from current results as it was Koekoek followed by Sasso being the highest. Current results were mostly similar for both sexes apart from BW of female S-RIR followed by Koekoek being predicted highest in AA region at a late age stage (Figure 3). Abegaz et al*.* (2019) also reported that female BW of Sasso, followed by Kuroiler, to be highest while measured on-farm in Ethiopia. Current results predicted Horro to have the lowest BW in every region apart from SR. These results are very similar to the analysis of Lozano-Jaramillo et al. (2019) and Abegaz et al*.* (2019) as Horro was also predicted to have the lowest BW in all cases. Another similarity found was TG being the region having the highest predicted BW and Sasso also performed best in TG in Lozano-Jaramillo et al*.* (2019). Take note that the current analyses in TG was based on males only and therefore not much data (Table 3, Appendix Table 1; n=175-177).
Using AEZ as environment in GxE analysis, again Horro and Sasso had the lowest and highest predicted BW, respectively, in all regions. Sasso especially at an early age of for females mainly in the cool sub-humid AEZ which was the AEZ having mostly the highest predicted BW. In general, similarities have been found with previous reports regarding to Sasso and Horro having the highest and lowest predicted BW in Ethiopia, respectively. Therefore, the current study supports this previous research of Lozano-Jaramillo et al*.* (2019) and Abegaz et al*.* (2019).

There are multiple explanations why particular breeds perform well or not in certain environments. The breeding program of Horro got established in 2008 only, making it quite young to genetically improve this originally indigenous breed (Wondmeneh et al., 2014a; Dana, Van der Waaij and Van Arendonk, 2011). On-station research showed that BW and other traits did improve after 6 or 7 generations of breeding comparing it to original indigenous Horro, marking the program as successful (Wondmeneh et al., 2014a; Wondmeneh et al., 2016). Although, on-farm testing in two districts in OM showed the improved Horro to still perform less well than the other four ACGG breeds (Wondmeneh et al., 2016). The only region Horro did not perform lowest was SR, being the Ethiopian Region having least spread of predicted BW for all breeds (Figure 3). Explanation for this remains unresolved, as SR is a climatically diverse region included in two AEZ being cool humid and cool sub humid while having sufficient data to analyze on (Table 1; FDRE, 2018) (Table 3, Appendix Table 1; n=403-409).

Sasso followed by Kuroiler having often the highest predicted BW is not surprising, as both breeds had been previously classified as better suited for single purpose meat production while tested on-station in Nigeria (Bamidele et al. 2019b). On-farm testing in Uganda showed Kuroiler to significantly outperform indigenous chicken breeds considering predicted BW, indicating the breed can easily adapt to scavenging conditions (Sharma et al. 2015). Lozano-Jaramillo et al. (2019) also predicted Sasso and even S-RIR to be outperforming the other ACGG breeds, leading to the assumption that they can deal with low-input conditions and being therefore interesting for further on-farm testing in Ethiopia (Lozano-Jaramillo et al. 2019).

The three Ethiopian Regions Sasso and Kuroiler were performing well in were TG, OM and AM (Figure 3). TG being the most northern region and part of the cool sub humid AEZ only was the region having highest average predicted BW of all breeds combined. OM being the biggest region is located more centrally in Ethiopia, surrounding the capital's cool humid AA region. OM is known for having great environmental variability included in cool sub humid as well as the only warm semi-arid AEZ which is based on little data (Table 1; FDRE, 2018) (Table 3, Appendix Table 1; n=89-92). This diversity results in various studies comparing poultry keeping and climatic conditions among OM districts showing the high altitude Horro district the indigenous breed comes from, varies much from other districts like Ada and Jarso (Dessie et al. 2013; Bettridge et al. 2018). AM is located in between TG and OM bordering those regions in the north and south respectively. This region also has big climatic diversity being part of cool humid as well as cool sub humid AEZ, having some very humid parts making this region receiving the highest amount (80%) of rain in Ethiopia (Table 1; FDRE, 2018).

Lozano-Jaramillo et al. (2018) predicted Koekoek to have the highest BW in AM. This was explained by the big annual temperature fluctuations in AM and findings of Bettridge et al. (2018) that high precipitation is preferable because of low chicken predation which is associated to more vegetation. The BW distribution of Kuroiler was also previously predicted to be mostly influenced by precipitation variables (Lozano-Jaramillo et al. 2019) which is logically explained by its humid Indian origin. Current results show indeed Koekoek and Kuroiler to be performing well in AM especially at a later age (Figure 3). As it is presented in Table 1; bigger temperature ranges are present in other regions than AM, indicating high precipitation to be main climatic cause for these results. Current results are in line with previous findings reported on Koekoek and Kuroiler performing well in AM due to precipitation but not as convincing as in the reports of Lozano-Jaramillo et al. (2018) and Lozano-Jaramillo et al. (2019) in which 13% of AM was predicted to be the best suitable for Koekoek. AM, just as OM and the region having the best performances; TG, are all being part of the cool sub humid AEZ, which was the AEZ having the highest performances especially at later ages of birds (Figure 4).

Egg Number and Egg Weight in Oromia

To answer the first research question; does GxE take place considering various zones and districts in Oromia, results indicated that it does take place for egg number (Table 7) but not for egg weight (Table 9). These findings are supported by Hartman (1990) stating more serious consequences of GxE present for egg producing traits, particularly large effects expected for laying rate. We note that conclusions of Hartman (1990) were based on commercial poultry, not backyard poultry. Statement remains relevant anyway as Hartman (1990) remarks GxE present between experimental stations and commercial farms while breeding for improved backyard farm poultry also takes place on research stations, causing GxE in a similar manner. Environment (alternatively zone or district) always had highly significant effects on both traits while breed had a high significant effect on egg number only (Tables 7 and 9). This indicates that environment plays an important role in both traits.

Answers to the second key research question; which breed performs best in which zone or district in terms of predicted egg number or egg weight, needs a more elaborated review. This review contains viable information for the local smallholder farmers in Oromia.
Generally, it can be stated that the S-RIR breed performs best for both traits in most environments. Exceptions are S-RIR being outperformed by Kuroiler for egg number and Koekoek for egg weight based on limited observations (Figure 5, Tables 8 and 10, Appendix Figure 6) (Appendix Table 2; n=35). This is supported by various previous research. Abegaz et al. (2019) predicted average weekly egg production highest for S-RIR followed by Kuroiler at smallholder farms across Ethiopia. At research stations in three African countries, including Ethiopia, Bamidele et al. (2019a) predicted the S-RIR breed to have one of the highest hen-housed egg productions. Wondmeneh, Dawud and Adey (2011) predicted Koekoek having highest average egg weight compared to three other breeds, including Horro, at the Debre Zeit station in Ethiopia.
Results indicate that crossbreeding Sasso with Rhode Island Red, i.e. producing S-RIR, gave successful layers under Ethiopian smallholder conditions. S-RIR was specifically generated for the ACGG project (Aman et al. 2017). Kuroiler having high predicted egg number is beneficial as this breed is also performing well on BW and meat traits in other African countries (Sharma et al. 2015; Bamidele et al. 2019b). This makes Kuroiler dual-purpose suitable and scavenging conditions adaptive. Koekoek having high predicted egg weight is also beneficial for Ethiopian smallholders various reasons. Koekoek is confirmed to be more disease resistant compared to specialized crossbred layers when kept with low vaccination and management inputs in Oromia (Esatu et al. 2011). Moreover, the colour pattern of Koekoek is a sex-linked gene which alleviates selection by smallholder farmers while crossbreeding for egg producing traits (Getachew, Wondmeneh and Dessie, 2016).

Generally, Sasso and Horro perform worst for both laying traits in most environments while comparing to the other ACGG breeds. For Horro, these current findings are supported by previous research, while previous results for Sasso were partly contradictory to current findings. Horro kept on Ethiopian smallholder farms had lowest weekly egg production, while production of the Sasso breed was average compared to other ACGG breeds, exactly two ACGG breeds performing higher or lower (Abegaz et al. 2019). Horro also performed worst for laying in two districts in Oromia (Ada and Horro) and for egg weight at the Debre Zeit research station in Ethiopia (Wondmeneh et al. 2016; Wondmeneh, Dawud and Adey, 2011). Most contradictory results were of Bamidele et al. (2019a) predicting Sasso having even highest hen-housed egg production on research stations in three African countries, including Ethiopia.
Low performance of Horro can be explained by its young breeding program, implemented in 2008 only (Wondmeneh et al. 2014a). Yet, after seven generations of breeding improved Horro had significantly better laying, weight gain and survival than its ancestral population (Wondmeneh et al. 2016). Improvement in Wondmeneh et al. (2016), measured as LSmeans differences of improved minus indigenous Horro were 57.8, 30.0, 26.0 and 25.4% hen housed egg production at 3, 6, 9 and 12 months respectively, 204.8, 260.8, 264.9 and 279.4 grams body weight at 8, 12, 16 and 20 weeks respectively,

and 10.0% survival rate at week 20. Breeding success and Ethiopian smallholders preferring a dual-purpose breed based on indigenous chicken genetic resources, favours Horro as village poultry (Dana et al. 2010). Moreover, farmers having livestock as main income are shown to less likely adopt exotic chickens, although adoption rate increases when having other sources of income (Wondmeneh et al. 2014b). Wondmeneh et al. (2015) provides arguments against improved Horro, stating interventions needed to rise productivity, leading to higher income of farmers in Oromia, do not seem to outweigh additional costs. In literature, Sasso performs high to average on laying and very well on weight gain traits. Sasso was predicted heavier than other ACGG breeds on Ethiopian smallholder farms and on farms in three African countries including Ethiopia (Lozano-Jaramillo et al. 2019; Abegaz et al. 2019). This indicates Sasso can deal with low-input conditions, making the breed interesting for further on-farm testing in Ethiopia (Lozano-Jaramillo et al. 2019). Moreover, Sasso performed high for meat production on Nigerian research stations (Bamidele et al. 2019b). Despite current low laying results (Figure 5, Tables 8 and 10, Appendix Figure 6), Sasso remains promising for dual-purpose breeding, especially for body weight, based on other literature.

Egg number predictions were closer to each other in the West Shoa zone, including the Bako Tibe and Dano districts, compared to East Shoa. Dano generally has higher precipitation (900-1400 mm) and bigger annual temperature fluctuations (15-30 ˚C) than other districts (Table 4). Predictions of Bako Tibe were based on four observations only, making this district less relevant. Dano was based on 264 observations. East Shoa contained 78 observations in Dugda and 468 observations in Adami Tulu, making it the most relevant district. Dugda has constant mean annual temperature fluctuations (19-23 ˚C) and low precipitation (500-900 mm), Adami Tulu has lowest mean annual rainfall of 748 mm (Table 4). This indicates that especially wet environment, but also bigger temperature fluctuations decrease differences between laying performances between breeds. Dryer conditions with smaller temperature fluctuations show higher differences between predicted egg numbers, being highest for S-RIR and lowest for Horro and Sasso.

Interestingly, Lozano-Jaramillo et al. (2019) previously stated that the Horro breed survives better during dry season and therefore potentially also in dryer areas. This assumption was partly made based on Bettridge et al. (2018) identifying the Horro district as being known for higher hatchability of eggs during the dry season due to lower risk of diseases. The Horro breed originates from a wet environment containing two rainy and one dry season, while purebred Sasso originates from warm and dry areas in Southern France (Lozano-Jaramillo et al. 2019; Getachew, Wondmeneh and Dessie, 2016).

General Remarks

From previous statements about current interpreted results and Figures 3-5, some general ideas about answers to the research questions for each performance trait (BW, Egg Number and Egg Weight) can be made. But before drawing final conclusions three other factors should not be forgotten, being the social context of breed preference by local smallholder farmers, BW or Egg Number and Egg Weight not being the only ways to measure breed performance and difficulties of collecting data on smallholder farms.

Preferences of local Ethiopian farmers should not be ignored while breeding for them as multiple sources claim that local adaptation and tailoring of sustainable poultry production is important for flexible implementation of it (Sölkner, Nakimbugwe and Valle Zarate, 1998; Mueller et al. 2015; Bettridge et al. 2018). Abegaz et al. (2019) highlights the importance of a trait preference study of farmers for making final breed choices in an abstract about on-farm chicken testing in three African countries. Regarding the social context, a range of studies have been done with Ethiopian poultry farmers, inquiring their opinion while breeding village poultry. Dana et al. (2010) state that different traits and breeding practices are preferred per Ethiopian Region, but the ultimate breeding goal would be to develop a dual-purpose breed based on indigenous chicken genetic resources. Moreover, Wondmeneh et al. (2014b) showed that farmers are more likely to adopt exotic chicken breeds when they have other sources of income. Both sources therefore indicate that introducing a breed like improved Horro would be most preferred by farmers having their main income from livestock, despite the breed performing mostly lowest in current and other analyses (Wondmeneh et al. 2016; Bamidele et al. 2019a; Abegaz et al. 2019). Although, Wondmeneh et al. (2015) state that the interventions needed to achieve rising productivity of improved Horro leading to higher income for poultry farmers in Oromia do not seem to outweigh the additional costs. This finding is contradictory to a marketing survey in Ethiopia, Nigeria and Tanzania which suggests that integrating dual-purpose improved breeds in village chicken production system would have significant contribution to improve income of producers, enhance supply of eggs and live chicken, and generate employment opportunities for the rural youth and other marketing actors along the value chain (Yitayih et al. 2019). Nevertheless, it was also observed that the proportion of indigenous chicken goes down while exotic is growing in a baseline survey among Ethiopian poultry smallholder farmers (Esatu and EIAR, 2016).

This baseline and another survey indicate that egg sale and high egg producing traits in chickens are very important to African chicken smallholder farmers (Esatu and EIAR, 2016; Goromela et al. 2019). In Oromia specifically egg sale was shown to be the most important purpose of keeping village poultry according to the baseline survey (Esatu and EIAR, 2016). It should not be forgotten that many other traits can be measured to estimate performance of a breed and not just BW or egg number and egg weight. Other growth and laying related traits, survival rates, feed intake to indicate efficiency and fertility traits are relevant while investigating African poultry performance and therefore interesting for similar future on-farm research in the region (Lozano-Jaramillo, 2019; Wondmeneh et al. 2014a; Wondmeneh et al. 2016; Bamidele et al. 2019a; Bamidele et al. 2019b; Abegaz et al. 2019; Ibrahim et al. 2019).

Lastly, it is known that collecting on-farm data for animal breeding in developing countries can cause various problems as conditions like large populations, pedigrees, performance recording and small environmental variation are often lacking (Lozano-Jaramillo, 2019; Besbes, 2009; Dana et al. 2010). Moreover, quite big proportions of Ethiopian smallholder farmers tend to drop out of research due to high chicken mortality or lack of motivation (Wondmeneh et al. 2016). Those lacking on-farm breeding conditions may be solved by on-station data collection and breeding. But this often causes new GxE of on-station African chickens significantly outperforming on-farm (Bekele et al. 2009; Ali, Katula and Syrstad, 2000; Lwelamira, 2012). Getachew et al. (2019) plead that Ethiopia should invest in proper data collection to achieve faster genetic gains.

Conclusion

BW in Ethiopia

For the first research question, i.e. does GxE take place, it may be concluded that the ACGG breeds do react differently to the different environments of Ethiopian Regions or AEZ in terms of predicted BW, as GxE was shown to be highly significant ($p<0.0001$) while using a simple and more complex model at various ages (90, 120, 150 and 180 days). Regarding the second research question i.e. which breed performs best in which environment in terms of predicted BW, it can be concluded that Sasso was mainly performing best, especially in the OM, AM and TG regions followed by Kuroiler, while Horro was mostly performing lowest. These findings are in line with previous research and explained by Horro being the product of a very young breeding program. TG, being the region having the highest predicted BW, also high in OM and AM, were all being part of cool sub humid AEZ, which was the AEZ having the highest performances, especially at late age. Koekoek and Kuroiler performed well in AM at a later age, which can potentially be explained by high precipitation.

Egg Number and Egg Weight in Oromia

Considering the first research question, i.e. does GxE take place, results indicate GxE for egg number, but not for egg weight. For the second research question, i.e. which breed performs best in which zone or district in terms of predicted egg number or egg weight, can be stated that S-RIR performed best for both traits compared to most breeds, indicating success of crossbreeding strategy. Exceptions were S-RIR being outperformed by Kuroiler in East Shoa for egg number and by Koekoek for egg weight. Sasso and Horro performed lowest for both traits. Previous research supports current findings of Horro while current findings of Sasso are only partly supported. Smaller temperature fluctuations, but especially dry environment gives bigger distance between predicted egg number, i.e. higher for S-RIR and lower for Horro and Sasso in East compared to West Shoa.

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Appendix

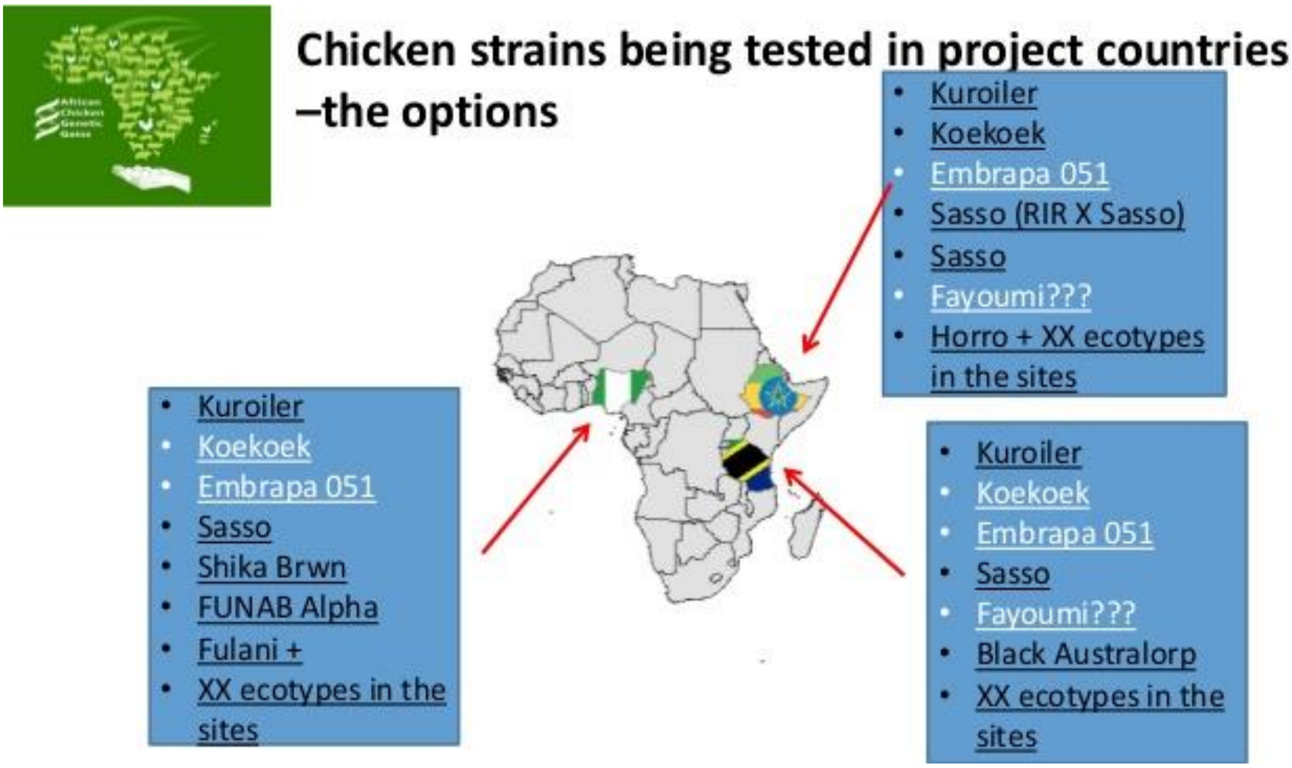
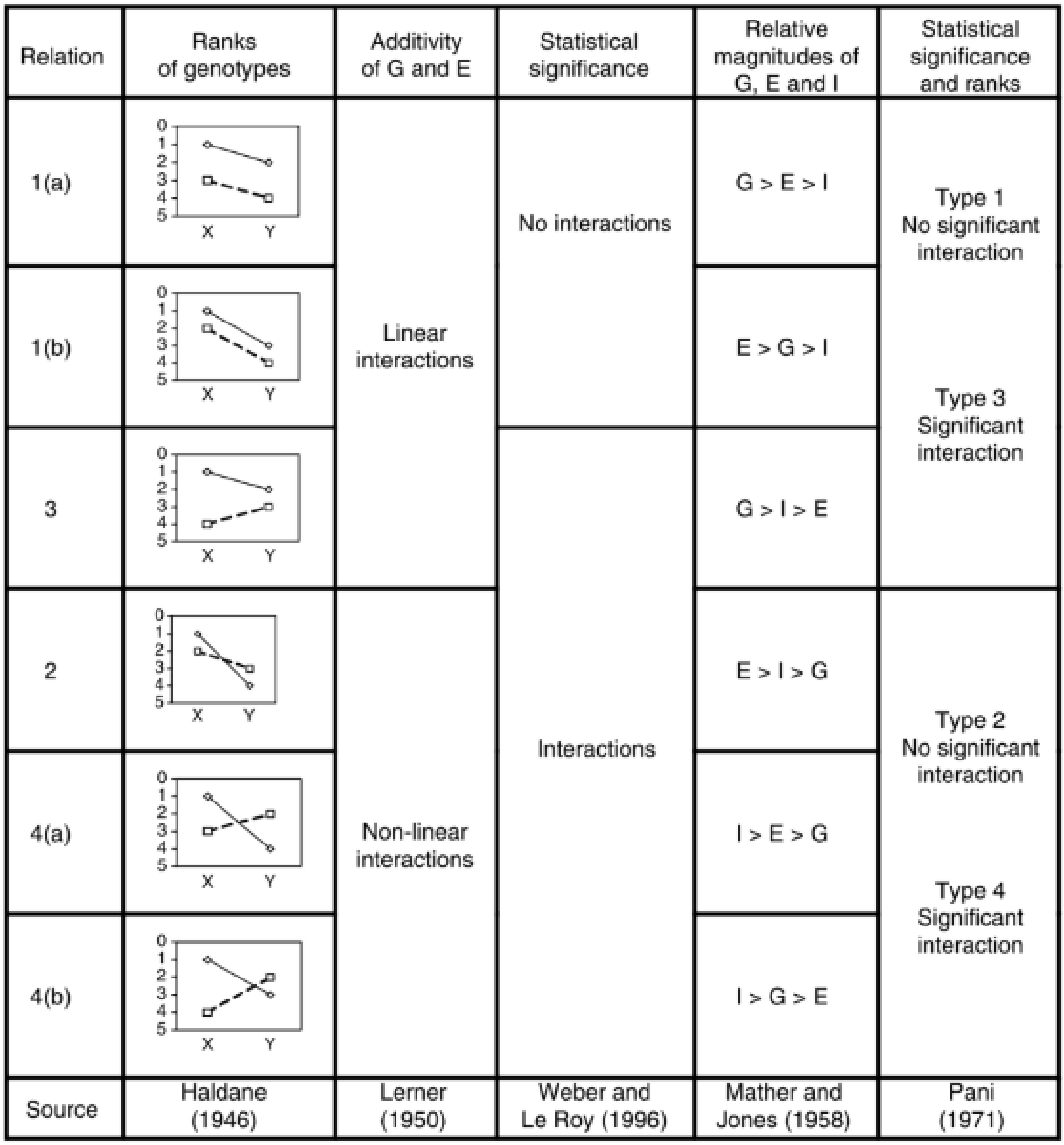


Figure 1. Map of Africa showing the three countries of the ACGG project (Ethiopia, Nigeria and Tanziania) and chicken breeds tested in them (https://africacgg.net/about/).



Relation	Ranks of genotypes	Additivity of G and E	Statistical significance	Relative magnitudes of G, E and I	Statistical significance and ranks
1(a)		Linear interactions	No interactions	G > E > I	Type 1 No significant interaction
1(b)				E > G > I	Type 3 Significant interaction
3			Interactions	G > I > E	
2		Non-linear interactions		E > I > G	Type 2 No significant interaction
4(a)				I > E > G	Type 4 Significant interaction
4(b)				I > G > E	
Source	Haldane (1946)	Lerner (1950)	Weber and Le Roy (1996)	Mather and Jones (1958)	Pani (1971)

Fig. 6.1. Classification and terminology for genotype–environment interactions. ◇ A, □ B are genotypes; X, Y are environments; G, E and I are the average effects of genotypes, environments and interactions, respectively. (Source: Mathur and Horst, 1994a.)

Figure 2. Examples of plotted regression GxE models and all possible scenarios of interaction, significance and intersection of lines (Mathur, 2003).

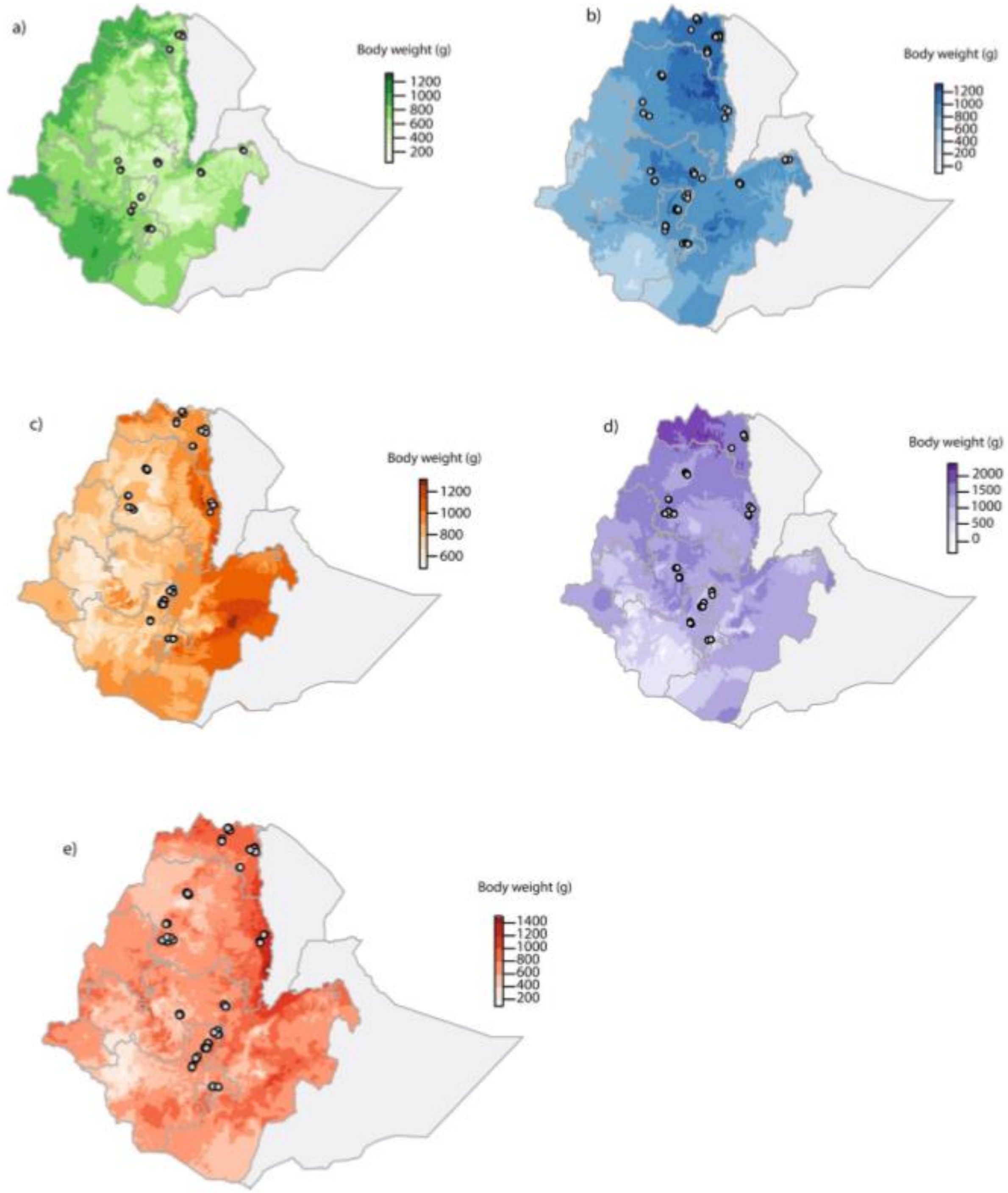


Figure 2. Predicted current phenotypic measures for male body weight in grams during the growing period (weeks 14 to 19) for (**a**) Horro, (**b**) Koekoek, (**c**) Kuroiler, (**d**) Sasso, and (**e**) Sasso-RIR. Circles in the maps denote the household locations where the phenotypic data was collected. Color scales in each of the maps reflect the predicted body weight, where darker colors indicate higher live weight predicted.

Figure 3. Example of ‘heat’ map of Ethiopia derived from Lozano-Jaramillo et al. (2019). Darker spots are representing higher predicted body weights for a breed in that area.

Table 1. Means and Standard deviations (Sd) of predicted body weight (BW) at four different ages (90, 120, 150 and 180 days) per breed (Horro, Koekoek, Kuroiler, S-RIR and Sasso) per sex (F:female and M:male) are given per environment (Region or Agro-Ecological Zone:AEZ) analysed. Five Ethiopian Regions (AA:Addis Ababa, AM:Amhara, OM:Oromia, SR:South Region and TG:Tigray) and three AEZ (cool humid, cool sub humid and warm semi-arid) are analysed. Means are derived of Data after cleaning as explained in Material & Methods Table 2.

		Region:	AA		AM		OM		SR		TG	
Age days	**Sex**	**Breed**	**N**	**Mean(Sd)**	**N**	**Mean(Sd)**	**N**	**Mean(Sd)**	**N**	**Mean(Sd)**	**N**	**Mean(Sd)**
90	**F**	Horro	38	444.4(199.9)	30	333.7(336.8)	47	607.7(276.3)	17	612.4(389.6)	-	-
		Koekoek	82	736.2(262.4)	108	620.6(219.9)	62	606.0(191.3)	33	451.4(161.5)	-	-
		Kuroiler	35	508.4(252.5)	100	790.0(253.5)	8	822.0(589.9)	34	675.0(207.7)	-	-
		S-RIR	43	725.7(193.0)	101	654.7(283.8)	16	670.9(505.1)	32	666.9(354.6)	-	-
		Sasso	-	-	95	955.9(315.2)	31	1017.6(474.9)	32	471.9(156.2)	-	-
		Tot	198	637.7(265.8)	434	721.2(318.7)	164	701.2(375.5)	148	572.3(271.3)	-	-
	M	Horro	32	430.8(170.4)	25	255.7(27.4)	29	544.6(114.8)	30	638.6(185.2)	8	866.7(281.3)
		Koekoek	61	727.2(242.2)	85	717.7(264.1)	35	569.9(113.3)	39	727.2(526.0)	73	894.2(350.6)
		Kuroiler	-	-	62	995.2(401.2)	5	822.0(415.7)	63	831.7(342.8)	44	870.8(172.3)
		S-RIR	39	825.6(261.2)	65	714.6(281.7)	8	509.3(291.0)	63	688.7(235.1)	43	766.2(190.8)
		Sasso	-	-	71	1116.2(490.0)	5	1170.2(376.0)	60	691.2(380.3)	9	976.6(169.9)
		Tot	132	684.4(275.7)	308	827.3(424.3)	82	607.0(241.1)	255	724.6(354.1)	177	860.3(272.1)
	Tot		330	656.4(270.4)	742	765.2(369.7)	246	669.8(339.1)	403	668.7(334.0)	177	860.3(272.1)
120	**F**	Horro	37	637.1(129.1)	7	805.9(819.8)	44	729.2(212.5)	21	714.0(237.7)	-	-
		Koekoek	82	1044.0(237.0)	108	1021.9(453.3)	62	747.4(154.1)	35	639.2(167.2)	-	-
		Kuroiler	7	2025.7(849.0)	96	1072.9(374.5)	7	1080.9(629.2)	31	881.8(337.7)	-	-
		S-RIR	43	1106.4(256.9)	95	930.1(411.0)	13	676.0(287.8)	32	892.6(407.2)	-	-
		Sasso	-	-	98	1192.9(421.4)	35	1608.0(689.1)	34	899.2(632.3)	-	-
		Tot	169	1011.5(386.6)	404	1050.2(435.3)	161	938.3(523.3)	153	809.4(411.2)	-	-
	M	Horro	32	691.1(195.9)	3	324.3(35.0)	27	742.9(166.0)	30	947.5(331.0)	8	851.1(137.1)
		Koekoek	63	1120.6(303.1)	85	1116.4(479.6)	37	744.2(121.1)	38	935.7(390.2)	73	1176.4(360.7)
		Kuroiler	1	2437.5(-)	59	1285.1(512.7)	4	1078.6(446.3)	62	1039.8(379.5)	44	1222.3(275.1)
		S-RIR	40	1306.1(330.8)	64	1071.3(407.9)	8	620.4(222.8)	64	936.0(433.3)	43	1015.2(242.7)
		Sasso	-	-	71	1297.2(551.4)	4	1701.8(313.2)	61	916.8(397.5)	9	1775.7(394.7)
		Tot	136	1083.8(384.7)	282	1178.5(503.6)	80	796.0(287.0)	255	957.9(394.3)	177	1164.4(351.5)
	Tot		305	1043.7(386.8)	686	1102.9(468.5)	241	891.0(462.8)	408	902.2(406.6)	177	1164.4(351.5)
150	**F**	Horro	39	1046.6(425.3)	26	582.6(430.4)	44	861.3(189.5)	23	1057.8(400.7)	-	-
		Koekoek	82	1445.3(474.9)	108	1236.0(491.3)	62	915.0(192.6)	35	997.1(251.9)	-	-
		Kuroiler	11	1651.5(900.0)	96	1375.5(514.2)	8	1320.2(608.6)	33	1003.5(309.1)	-	-
		S-RIR	43	1551.0(444.4)	96	1193.7(453.0)	16	750.0(176.3)	33	997.6(331.6)	-	-
		Sasso	-	-	98	1488.7(503.6)	38	1954.1(621.6)	34	1129.8(451.5)	-	-
		Tot	175	1395.4(526.6)	424	1276.3(529.0)	168	1139.6(577.0)	158	1035.9(351.9)	-	-
	M	Horro	32	991.8(271.4)	25	470.3(45.0)	27	881.2(218.8)	30	1283.8(478.5)	8	1134.9(356.5)
		Koekoek	63	1636.6(477.3)	83	1423.8(564.6)	37	944.3(202.2)	36	1230.6(404.1)	73	1457.0(406.5)
		Kuroiler	1	2125.0(-)	60	1711.5(653.0)	6	1701.7(519.3)	61	1278.3(485.4)	44	1610.9(406.5)
		S-RIR	40	1680.4(365.1)	65	1410.8(604.7)	8	804.4(151.5)	65	1183.2(526.6)	43	1379.9(438.4)
		Sasso	-	-	72	1515.1(600.6)	5	2165.6(636.7)	59	1133.6(479.8)	9	2080.6(408.7)
		Tot	136	1501.3(490.5)	305	1421.0(650.6)	83	1038.6(445.5)	251	1213.5(483.5)	177	1493.7(444.0)
	Tot		311	1441.7(513.0)	729	1336.9(586.9)	251	1106.2(538.3)	409	1144.9(445.4)	177	1493.7(444.0)
180	**F**	Horro	38	1297.7(418.6)	41	717.0(336.6)	45	965.0(209.9)	22	1419.3(522.5)	-	-
		Koekoek	82	1777.7(519.0)	105	1559.2(554.4)	61	1040.4(260.0)	35	1474.4(491.2)	-	-
		Kuroiler	40	1704.8(580.4)	99	1658.7(555.7)	8	1726.5(559.7)	35	1150.0(329.3)	-	-
		S-RIR	43	2025.6(475.1)	103	1457.3(488.6)	16	1259.2(313.0)	33	1234.0(373.5)	-	-
		Sasso	-	-	98	1817.3(533.1)	40	2233.5(587.3)	35	1451.7(555.4)	-	-
		Tot	203	1726.0(553.9)	446	1537.0(592.3)	170	1354.0(634.9)	160	1341.3(471.9)	-	-
	M	Horro	32	1302.0(435.8)	34	697.1(141.5)	26	988.5(285.1)	28	1559.5(506.4)	8	1455.7(650.2)
		Koekoek	63	2093.7(753.9)	81	1779.9(703.2)	36	1102.2(340.9)	38	1425.3(429.5)	73	1764.4(492.2)
		Kuroiler	2	1990.9(252.2)	60	2124.6(827.6)	7	2124.6(574.2)	59	1562.4(649.6)	44	2109.7(423.2)
		S-RIR	40	2080.6(551.4)	63	1759.6(773.4)	8	1213.4(298.5)	65	1488.0(725.6)	41	1885.4(694.7)
		Sasso	-	-	72	1959.1(714.7)	5	2123.9(980.4)	58	1375.8(666.1)	9	2369.7(706.0)
		Tot	137	1903.4(708.0)	310	1765.3(811.0)	82	1226.6(547.2)	248	1477.9(631.7)	175	1896.6(578.6)
	Tot		340	1797.5(625.7)	756	1630.7(699.0)	252	1312.6(609.6)	408	1424.4(577.6)	175	1896.6(578.6)

		AEZ:	cool humid		cool sub humid		warm semi-arid	
Age days	**Sex**	**Breed**	**N**	**Mean(Sd)**	**N**	**Mean(Sd)**	**N**	**Mean(Sd)**
90	**F**	Horro	68	395.6(272.5)	45	648.0(358.2)	19	516.5(59.4)
		Koekoek	138	665.3(257.4)	120	607.3(227.0)	27	562.2(103.4)
		Kuroiler	92	651.5(225.9)	85	781.0(331.0)	-	-
		S-RIR	92	696.0(256.2)	100	653.8(340.0)	-	-
		Sasso	52	911.1(269.4)	106	849.8(430.7)	-	-
		Tot	442	656.2(287.8)	456	710.3(351.3)	46	543.3(90.0)
	M	Horro	57	354.0(155.2)	48	659.1(221.7)	19	539.4(63.4)
		Koekoek	102	687.5(277.2)	164	815.7(366.4)	27	557.3(91.7)
		Kuroiler	28	1014.0(335.6)	146	877.6(337.5)	-	-
		S-RIR	57	805.2(240.0)	161	702.8(255.9)	-	-
		Sasso	36	905.2(381.5)	109	942.8(501.8)	-	-
		Tot	280	704.2(339.8)	628	811.3(365.8)	46	549.9(80.9)
	Tot		722	674.8(309.7)	1084	768.8(363.1)	92	546.6(85.2)
120	**F**	Horro	44	664.0(334.1)	46	753.4(252.4)	19	653.7(63.8)
		Koekoek	138	1027.8(306.3)	112	856.5(397.9)	27	679.8(101.0)
		Kuroiler	60	1105.7(457.5)	81	1058.4(480.9)	-	-
		S-RIR	87	1005.7(350.0)	96	893.6(408.4)	-	-
		Sasso	52	1091.9(300.9)	115	1278.0(659.3)	-	-
		Tot	381	1001.8(367.6)	460	994.9(514.4)	46	669.0(87.7)
	M	Horro	35	659.7(214.3)	46	912.7(296.3)	19	700.4(59.7)
		Koekoek	102	1088.8(350.3)	167	1102.2(425.6)	27	715.5(100.6)
		Kuroiler	28	1191.5(355.0)	142	1179.3(446.0)	-	-
		S-RIR	58	1223.5(313.5)	161	983.6(405.9)	-	-
		Sasso	36	1063.2(368.9)	109	1215.9(580.5)	-	-
		Tot	259	1068.5(370.6)	625	1095.1(458.1)	46	709.3(85.6)
	Tot		640	1028.8(369.9)	1085	1052.6(485.1)	92	689.1(88.5)
150	**F**	Horro	65	861.0(481.9)	48	991.3(323.7)	19	770.9(63.9)
		Koekoek	138	1345.9(471.8)	122	1116.2(419.0)	27	804.4(107.8)
		Kuroiler	64	1269.7(459.4)	84	1340.8(603.0)	-	-
		S-RIR	87	1298.1(431.2)	101	1121.6(492.2)	-	-
		Sasso	52	1407.5(492.1)	118	1570.9(618.4)	-	-
		Tot	406	1253.9(496.0)	473	1258.0(554.6)	46	790.5(92.9)
	M	Horro	57	763.1(331.4)	46	1206.5(448.6)	19	836.1(102.9)
		Koekoek	101	1525.0(520.1)	164	1401.4(462.1)	27	852.4(115.4)
		Kuroiler	29	1544.9(448.5)	143	1532.0(586.0)	-	-
		S-RIR	58	1566.7(376.0)	163	1292.8(565.8)	-	-
		Sasso	34	1190.8(431.5)	111	1486.8(644.5)	-	-
		Tot	279	1339.4(537.8)	627	1403.8(561.1)	46	845.7(109.3)
	Tot		685	1288.7(514.8)	1100	1341.1(562.7)	92	818.1(104.6)
180	**F**	Horro	79	996.4(475.9)	48	1234.7(410.4)	19	809.6(137.9)
		Koekoek	135	1696.1(531.8)	122	1419.0(500.9)	26	863.8(185.8)
		Kuroiler	96	1593.0(473.1)	86	1552.7(649.2)	-	-
		S-RIR	94	1644.1(527.1)	101	1408.1(530.4)	-	-
		Sasso	52	1706.7(536.0)	121	1896.7(626.2)	-	-
		Tot	456	1543.7(567.8)	478	1545.9(598.6)	45	840.9(167.7)
	M	Horro	66	990.4(439.9)	44	1475.9(524.7)	18	893.0(140.4)
		Koekoek	100	1954.1(785.9)	165	1687.8(530.5)	26	954.6(220.9)
		Kuroiler	30	1957.4(477.1)	142	1919.8(752.9)	-	-
		S-RIR	58	1949.1(573.5)	159	1665.1(764.2)	-	-
		Sasso	33	1751.5(738.2)	111	1756.8(782.6)	-	-
		Tot	287	1708.5(752.3)	621	1732.4(703.2)	44	929.4(192.7)
	Tot		743	1607.3(649.8)	1099	1651.3(665.9)	89	884.7(184.9)

Table 2. Numbers (N), sum of weights (W), Means and Standard deviations (Sd) of predicted Egg Numbers (Egg N.) and Egg Weights (Egg W.) of data used to calculate genotype environment interaction (GxE) on these two traits. Data is displayed per breed (S-RIR, Sasso, Horro, Kuroiler and Koekoek) and per environment (Zone or District) taken as GxE. Three zones (East Hararge, East and West Shoa) among which 5 districts (Adami Tulu Jido Kombolcha, Bako Tibe, Dano, Dugda and Haromaya) are taken as environments. Means and standard deviations are derived of Data after cleaning as explained in Material & Methods; Egg Number and Egg Weight in Oromia; Data Collection and Cleaning.

Breed:	**S-RIR**			**Sasso**			**Horro**			**Kuroiler**			**Koekoek**		
Egg N.	**N**	**W**	**Mean(Sd)**	**N**	**W**	**Mean(Sd)**	**N**	**W**	**Mean(Sd)**	**N**	**W**	**Mean(Sd)**	**N**	**W**	**Mean(Sd)**
E. Hara.	76	607	8.9(12.9)	-	-	-	-	-	-	-	-	-	-	-	-
E. Shoa	172	704	7.6(8.8)	100	358	4.0(6.1)	175	816	3.5(6.2)	99	356	8.9(9.1)	-	-	-
W. Shoa	101	488	6.7(11.6)	54	189	5.6(10.1)	64	318	5.8(11.6)	-	-	-	49	215	6.0(8.7)
Adami	138	600	7.4(9.1)	74	259	3.6(5.4)	157	766	3.4(6.3)	99	356	8.9(9.1)	-	-	-
Bako	3	5	6.0(4.8)	-	-	-	-	-	-	-	-	-	1	7	5.4(-)
Dano	96	483	6.7(11.8)	54	189	5.6(10.1)	64	318	5.8(11.6)	-	-	-	48	208	6.0(8.8)
Dugda	34	104	8.8(7.4)	26	99	5.0(7.4)	18	50	5.2(5.1)	-	-	-	-	-	-
Haro.	76	607	8.9(12.9)	-	-	-	-	-	-	-	-	-	-	-	-
Egg W.	**N**	**W**	**Mean(Sd)**	**N**	**W**	**Mean(Sd)**	**N**	**W**	**Mean(Sd)**	**N**	**W**	**Mean(Sd)**	**N**	**W**	**Mean(Sd)**
E. Hara.	75	1003	54.0(19.9)	-	-	-	-	-	-	-	-	-	-	-	-
E. Shoa	131	2709	36.4(40.0)	62	878	33.0(34.6)	107	1687	33.9(24.5)	72	1714	35.3(29.1)	-	-	-
W. Shoa	74	1226	58.4(67.3)	46	619	54.9(46.4)	50	796	57.2(61.5)	-	-	-	35	639	60.4(47.1)
Adami	118	2509	36.6(40.1)	43	618	30.9(24.9)	94	1535	33.8(23.1)	72	1714	35.3(29.1)	-	-	-
Bako	3	17	61.8(23.9)	-	-	-	-	-	-	-	-	-	-	-	-
Dano	71	1209	58.3(68.6)	46	619	54.9(46.4)	50	796	57.2(61.5)	-	-	-	35	639	60.4(47.1)
Dugda	13	200	33.4(37.9)	19	260	38.0(45.8)	13	152	35.0(33.7)	-	-	-	-	-	-
Haro.	75	1003	54.0(19.9)	-	-	-	-	-	-	-	-	-	-	-	-

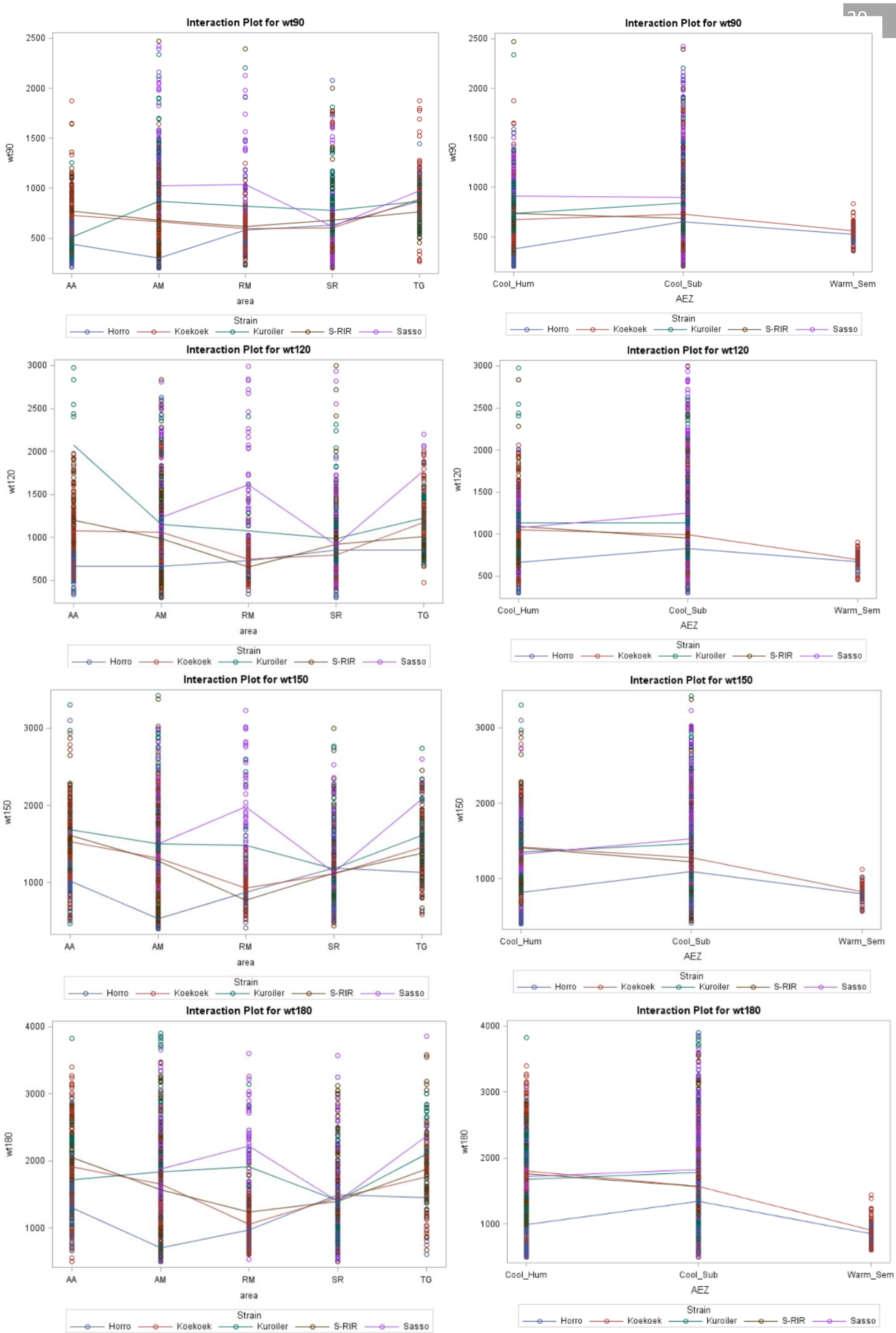


Figure 4. GxE plots using the simple interaction model [1] in which all main (breed and environments) and GxE effects showed high significance (p<0.0001). Plots are displayed by age (90 to 180 days from top to bottom) and by environment (Ethiopian Region left, AEZ right). Oromia abbreviated as RM.

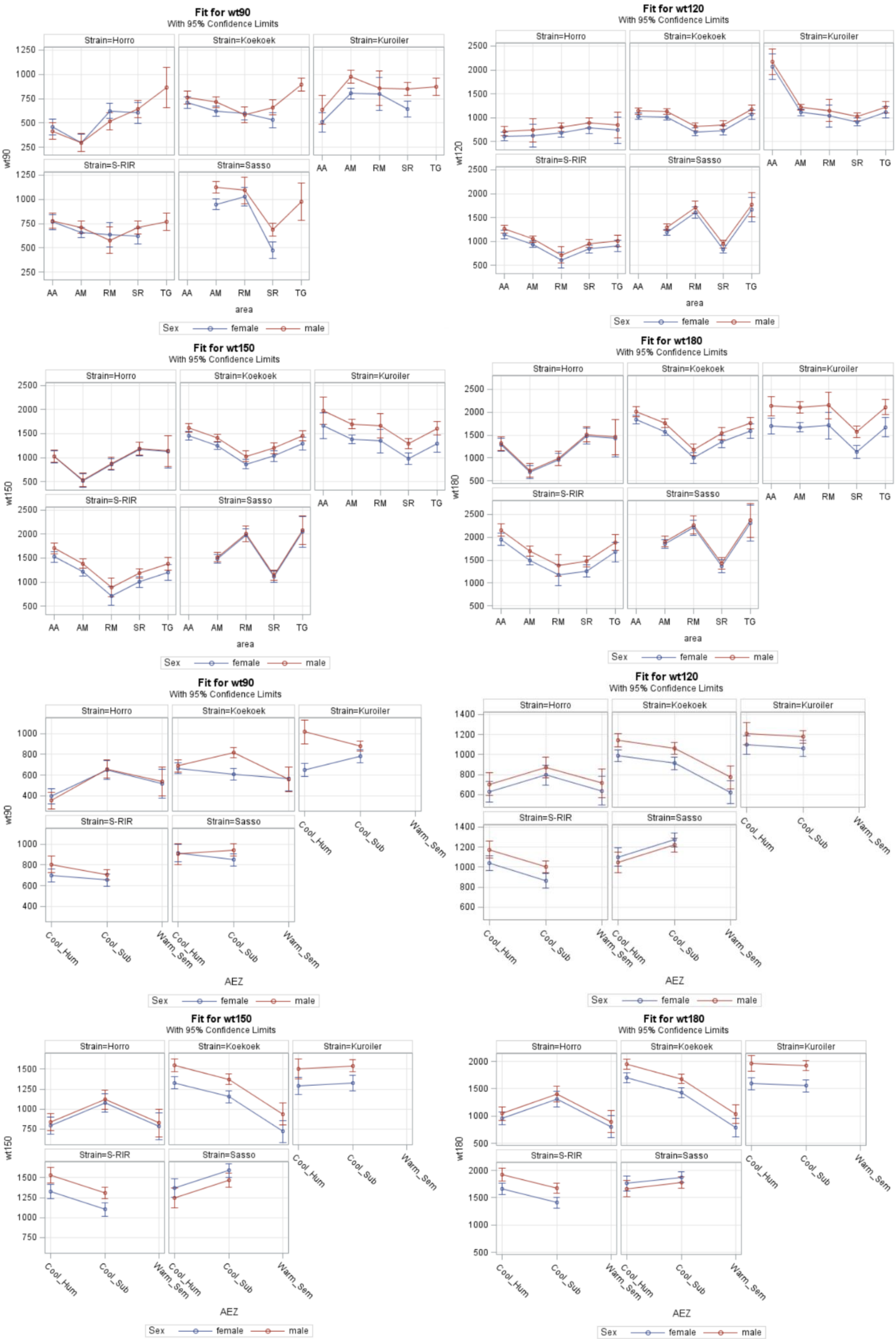


Figure 5. Sex by Environment plots made for each breed separate derived using derived models from complex model [2] (effects given in Tables 5 and 6) displayed per breed (Horro, Koekoek, Kuroiler, S-RIR and Sasso) and per predicted BW at certain age (90, 120, 150 or 180 days). Ethiopian Region used as environment is given in the top four plots, Agro-Ecological Zones (AEZ) used as environment in the bottom four plots. Oromia abbreviated as RM.

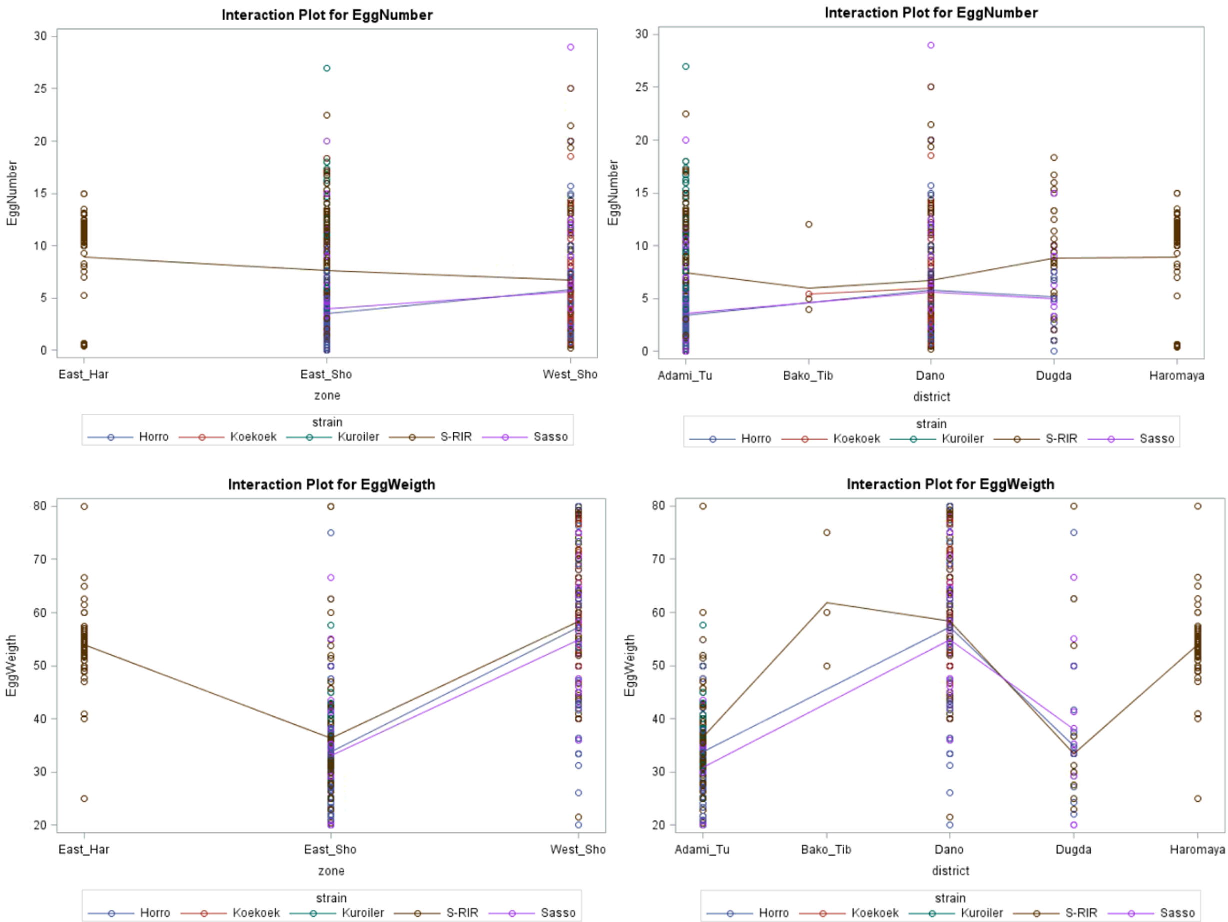


Figure 6. GxE plots made using a breed by environment interaction model analysing egg number and egg weight as traits (effects given in Tables 7 and 9). Environment being either zone (East Hararge, East or West Shoa) displayed left or district (Adami Tulu Jido Kombolcha, Bako Tibe, Dano, Dugda or Haromaya) displayed right.